

DEPARTMENT OF PHYSICS

# JYFL

UNIVERSITY OF JYVÄSKYLÄ



ANNUAL  
REPORT  
2006

# JYFL



## ANNUAL REPORT 2006

DEPARTMENT OF PHYSICS • UNIVERSITY OF JYVÄSKYLÄ

DEPARTMENT OF PHYSICS  
UNIVERSITY OF JYVÄSKYLÄ

P.O. BOX 35  
FI-40014 UNIVERSITY OF JYVÄSKYLÄ  
FINLAND

Tel. +358 14 260 2350

Fax +358 14 260 2351

<http://www.jyu.fi/physics>



Contents

## Department of Physics

### Research

#### Nuclear and accelerator based physics

- <sup>09</sup> Centre of Excellence in Nuclear and Accelerator Based Physics
- <sup>12</sup> Accelerator facilities
- <sup>14</sup> Exotic nuclei and beams
- <sup>23</sup> In-beam spectroscopy
- <sup>29</sup> The JYFL gas-filled recoil separator RITU
- <sup>33</sup> Nuclear reactions and ALICE
- <sup>36</sup> Accelerator based materials physics
- <sup>44</sup> Industrial applications
- <sup>49</sup> Nuclear structure, nuclear decays, rare and exotic processes

#### Materials physics

- <sup>54</sup> Nanophysics and nanotechnology
- <sup>65</sup> Nanoelectronics and nanotechnology
- <sup>70</sup> Computational nanosciences
- <sup>75</sup> Soft condensed matter and statistical physics

#### High energy physics

- <sup>79</sup> Ultrarelativistic heavy ion collisions
- <sup>83</sup> Theoretical particle physics and cosmology

<sup>86</sup> Industrial collaboration

<sup>89</sup> Education

<sup>92</sup> Personnel

<sup>94</sup> Boards and committees

<sup>95</sup> Peer reviewed articles

<sup>100</sup> Theses and degrees

<sup>100</sup> Theses

<sup>101</sup> Degrees

# Department of Physics

Jukka Maalampi

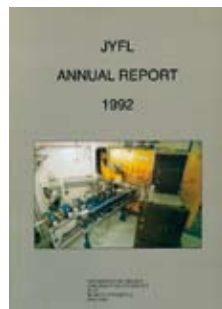
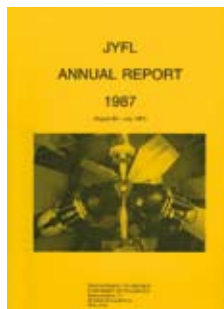
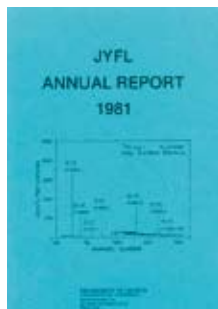
## Preface

The Department of Physics published its first Annual Report in 1976, thirty years ago. Not only has the appearance of the report changed over the past three decades, but also the Department itself is dramatically different from what it was in those pioneering years of the mid-seventies. This applies to both the size and versatility of the Department and to the profile and appreciation of the Department on the national and international scale. The total number of personnel in 1976 was about 40, which should be compared with the present number of 166. The number of doctoral degrees awarded has increased from 2 to 14, and that of refereed scientific

publications from 13 to 136. In 1976 the Department had of the order of 10 foreign visitors, in 2006 this figure rose to more than 200. Only one thing has remained unchanged, namely the number of administrative personnel (4) – and of course the good spirit and unity of the Department.

This annual report describes the activity of the Department of Physics in 2006. Some highlights of the year are collected in this preface, and the future outlook is also considered.





Thirty years of the Annual Report of JYFL. See more on the inside covers...

## Research

The research activity of the Department focuses on three main fields, nuclear and accelerator based physics, materials physics and high-energy physics. In all these fields the Department has good visibility and renowned status on the international level. Evidence of this is provided by the Center of Excellence (CoE) status of our nuclear and accelerator based physics research group awarded for 2006–2011. The other two major research areas were short-listed for 2006 CoE selection (as they were in 2005) but unfortunately they did not receive funding, in spite of excellent reports from the international panels of experts. As a result of the successful University Research Evaluation in 2005, extra annual funding of 60 000 euros for three years has been allocated to the Department by the University. This has allowed us to announce two post doctoral positions for young foreign researchers for 2007–2009.

**Nuclear and accelerator based physics.** One of the highlights of nuclear physics research was the front-page Nature article on detailed spectroscopic measurements of the nobelium isotope  $^{254}\text{No}$  carried out in the accelerator laboratory. Paul Greenlees and Rolf-Dietmar Herzberg (University of Liverpool) were the spokespersons for the experiment. The results of this study allow the location of the so-called island of stability far outside the normal periodic table of elements to be tentatively pinpointed. The result is of extreme value to nuclear theorists who have predicted the existence of such an island but have been unable to localize it.

With regard to theoretical nuclear physics, a piece of excellent news was the funding obtained for professor Jacek Dobaczewski under the Finland Distinguished Professor Programme. His five-year half-time term in the Department will start in 2007. Professor Dobaczewski will found a research group whose main research subject will be physics of exotic nuclei, which nicely fits with



the interests of our experimental nuclear physics groups. A welcome addition to the facilities of the accelerator laboratory was the 1.7 MV Pelletron electrostatic accelerator donated to the Department by the VTT Technical Research Center of Finland. A low-energy accelerator for the needs of materials physics research was on the Department shopping list, but thanks to this arrangement with VTT and to the activity of Professor Harry Whitlow and Senior Assistant Timo Sajavaara, it luckily materialized much sooner and with dramatically less fund-hunting than expected. The Pelletron will strengthen the capabilities of the accelerator laboratory and allow widened activity in nanotechnology and biomedical sciences.

As far as the facilities of the accelerator laboratory are concerned, a further piece of good news was confirmation that the Department will get a new cyclotron as part of the debt conversion program between Russia and Finland. The new cyclotron, which is expected to be ready for operation three years from now, will undertake some of the tasks of the overloaded old cyclotron. Plans also exist to use the new cyclotron for production of medical isotopes. The required space will be built next to the present cyclotron cave. The project has been managed in an exemplary manner by Chief Engineer Pauli Heikkinen.

**Nanoresearch.** Research in nanophysics takes place in the multidisciplinary NanoScience Center, NSC. The NSC is one of the leading nanoresearch units in Finland, which has been evidenced in the excellent success in getting funding from different nationwide funding programs, such as the Research Programme on Nanoscience (FinNano) of the Academy of Finland.

The Faculty will get substantial budget funding for nano research, which has allowed departments to allocate money for new positions in this field. The Department

of Physics and the Department of Chemistry founded a new professorship in computational nanoscience on a fifty-fifty basis, a chair to which Hannu Häkkinen was invited. Häkkinen and his group study the physics and chemistry of nanoscale objects, such as atomic clusters, nanoparticles, nanowires, -bridges and point contacts. In 2007 the Department of Physics will open a new professorship in low-temperature physics with the responsibility of conducting the experimental research in this field at the NSC.

These two new positions will considerably strengthen our research and teaching force in nanophysics.

**High-energy physics.** In high-energy physics a field of growing activity has been ultra-relativistic heavy ion collisions (URHIC), with both our experimentalists and theorists preparing for the ALICE experiment starting in two years' time at the CERN LHC accelerator. Senior Assistant Jan Rak (half of whose salary is paid by the Helsinki Institute of Physics, HIP) has a central role in preparing everything for the forthcoming physics analysis of ALICE data. On the theoretical side, a noteworthy change in personnel took place with the succession of Kari J. Eskola (in 2007) to Vesa Ruuskanen as a professor of theoretical physics. Kari will take full responsibility for the URHIC theory program.

In theoretical particle physics and cosmology, collaboration with the HIP theory program has been close. Senior Assistant Kimmo Kainulainen spent the spring semester in Helsinki as acting professor of cosmology. The HIP theory program will renew its projects in 2008, and we hope that our Department will play an important role in the new projects in order to benefit from the collaboration with HIP in the best possible way.

In 2006, our Department took scientific responsibility for the underground cosmic ray experiment EMMA, un-

Personnel (permanent posts in parentheses)	166 (60)
- professors	12 (12)
- lecturers	5 (5)
- senior assistants	9 (8)
- assistants	5 (4)
- researchers	105 (4)
- technicians	26 (23)
- administration	4 (4)
+ several research assistants (MSc students)	
Undergraduate students	530
of which new students	81
Graduate students	70
MSc degrees	38
PhLic degrees	1
PhD degrees	14
Credits (national)	6687
Median time to complete MSc (years)	5,3
Number of foreign visitors	~290
- in visits	~400
Visits abroad	~255
Peer reviewed publications	137
Other scientific reports	40
Newspaper articles etc.	7
Conference contributions	
- Invited talks	51
- Other talks	94
- Posters	50
Seminars outside JYFL	65
Funding (million €)	11,3
* University budget (incl. premises)	6,3
* External funding	5,0
- Academy of Finland	2,0
- Technology Development Centre	0,5
- International programmes	0,8
- HIP, HUT etc.	0,7
- Contract research	0,8
- Others	0,2

der construction in the Pyhäsalmi mine and managed by the University of Oulu with EU-funding. Senior scientist Wladyslaw Trzaska is in charge of this activity. We consider it to belong to the duties of the accelerator laboratory as a national laboratory to promote and offer its expertise to support this kind of research. The Pyhäsalmi mine has attracted a lot of interest in the European particle and astroparticle physics community as a possible location of the very large underground neutrino experiment which is planned to be built in the distant future.

**Industrial physics.** The Department of Physics serves the general community, not only with basic research and education, but by collaborating with industry and industry-related research institutions. Work in the physics of paper production has a well-established track record in our Department, and we have educated plenty of specialists in this field. To continue such activities and to strengthen the teaching and research of applied physics in the Department a permanent professorship was established and Markku Kataja was nominated to this position. The University has allocated funding for a new senior assistantship in the field of industrial physics to start in 2007.

## Education

In teaching the year 2006 was quite satisfactory. The number of MSc degrees was 38, a little short of the official goal but a good result after the record-breaking previous year. The number of PhD degrees was 14, a new record. It is worth noticing that one of the awarded PhD degrees belonged to the field of physics didactics, a new opening in our doctoral education.



Our Department participates in seven national graduate schools and coordinates two of them, the Graduate Schools in Particle and Nuclear Physics and in Nanoscience.

The decreasing trend in the number of applications and new students enrolled needs attention. With one quarter less applicants and one fifth lower enrollment than in the previous year, the figures for 2006 are worrisome. They may be fluctuations but may also reflect the changes made in the national student matriculation examination, physics being now a test subject of its own. One should believe, on the other hand, that the new matriculation system will guarantee us well motivated and qualified students for the future.

One should also hope that the new nationwide unique candidate's curriculum in nanoscience, currently being planned and expected to start in 2007, will attract a considerable number of new students to the Faculty and the Department. According to the plans, students can apply directly to this multidisciplinary study program when entering the University. A similar arrangement in physics teacher's education has turned out to be quite successful.

## Administration

In recent years, the financial situation of the Department has not been as good as one would have hoped. The deficit of running-cost funds has worsened the conditions of research, particularly in experimental groups. The main reason for the unfortunate developments is the allocation model for budget funding launched by the University in 2004, which has turned out to be unfavo-

orable to our Department in comparison with the previous situation. One must say that the marginal changes made to the model in 2006 did not improve the situation in any essential respect, and therefore we cannot look forward to the future with any great confidence as far as basic funding is concerned.

Transition to the new salary system UPJ took place in 2006 and the transition was quite smooth in our Department. It will take some time to see the possible benefits along with the shortcomings of the new system. Hopefully more benefits than shortcomings will appear.

The www-pages of the Department were renewed in 2006. This project was initiated and organized by Timo Sajavaara and other central persons in the team were Soili Leskinen and Juha Merikoski. Most of the groups renewed or updated their pages during this process.

## Events

On 20th of December Professor Vesa Ruuskanen gave his farewell lecture. Vesa has been one of the cornerstones of the Department from the early seventies. Apart from his contributions in research and administration, his role in teaching and its development has been crucial for the Department. Also two other cornerstones of the Department, Laboratory Engineer Teuvo Poikolainen and Research Technician Erkki Kosola achieved their retirement age. Erkki, Teuvo and Vesa have all serviced the Department in an excellent manner for decades, and one can find the names of all of them in the Annual Report 1976.

# Centre of Excellence in Nuclear and Accelerator Based Physics

Rauno Julin

## Centre of Excellence in Nuclear and Accelerator Based Physics

- 8 Research teams
- 23 PhD level researchers
- 26 Post graduate students
- 9 Technicians

### Facilities

- K130 cyclotron delivering a large variety of low- and high-energy ion beams
- IGISOL facility for low-energy radioactive ion beams, laser systems and ion traps
- Recoil separator with detector systems for tagging experiments
- Experimental facilities for reaction studies and applications
- Pelletron accelerator for materials research

### Scientific Advisory Board of the Centre of Excellence in Nuclear and Accelerator Based Physics

Witold Nazarewicz, professor, University of Tennessee, USA  
William Gelletly, professor, University of Surrey, UK  
Timo Tiihonen, vice-rector, University of Jyväskylä  
Timo Jääskeläinen, professor, Academy of Finland  
Pasi Sihvonen, secretary general, Academy of Finland

### Members of the Programme Advisory Committee of the JYFL Accelerator Laboratory

Christian Beck, Dr, IReS, Stasbourg, France  
Thomas Dossing, Dr., NBI, Copenhagen, Denmark  
Zenon Janas, Dr., University of Warsaw, Poland  
Juhani Keinonen, Prof., University of Helsinki, Finland  
Juergen Kluge, Prof., GSI, Darmstadt, Germany  
John Simpson, Prof., CCLRC, Daresbury, UK (chairman)

The Finnish Centre of Excellence (CoE) in Nuclear and Accelerator Based Physics was nominated by the Academy of Finland for the period of 2006–2011. It involves research carried out by eight teams of JYFL. Most of the teams utilize the large variety of ion beams available at the Accelerator Laboratory of JYFL.

The **accelerator technology team** is responsible for the development of ion beams from the accelerator facility (see “Accelerator Facilities” in the present Annual Report).

The research work of the **IGISOL team** is focused on the decay- and groundstate properties of exotic nuclei by employing novel instrumentation including JYFLTRAP and laser systems (see “Exotic Nuclei and Beams”).

The **heavy element team** uses the upgraded gas-filled recoil separator to investigate the structure of nuclei at the extreme of the nuclear chart (see “The JYFL Gas-filled Separator RITU”).

Several types of tagging methods are used by the **in-beam spectroscopy team** in studies of excited structures in proton drip-line and very heavy nuclei (see “In-beam Spectroscopy”).

The **nuclear reaction team** is responsible for participation in the ALICE experiment at CERN and for the nuclear reaction research at JYFL (see “Alice and Nuclear Reactions”).

Collaboration with the European Space Agency (ESA) and the aviation and space industries on radiation hardness testing along with technological applications are dealt with by the **industrial applications team** (see “Industrial Applications”).

New research directions of ion-beam applications in materials research are the responsibility of the accelerator based **materials physics team**. (see “Accelerator-Based Materials Physics”).

Theoretical support for nuclear structure studies is provided **by the theory team**, which also studies weak interaction, cold dark-matter and neutrino physics (see “Nuclear Structure, Nuclear Decay, Rare and Exotic Processes”).

The JYFL-CoE programme has a strong collaborative international character. Individual research contacts form the backbone of collaborations creating exchange programmes with a significant transfer of scientists and equipment to the Department of Physics.

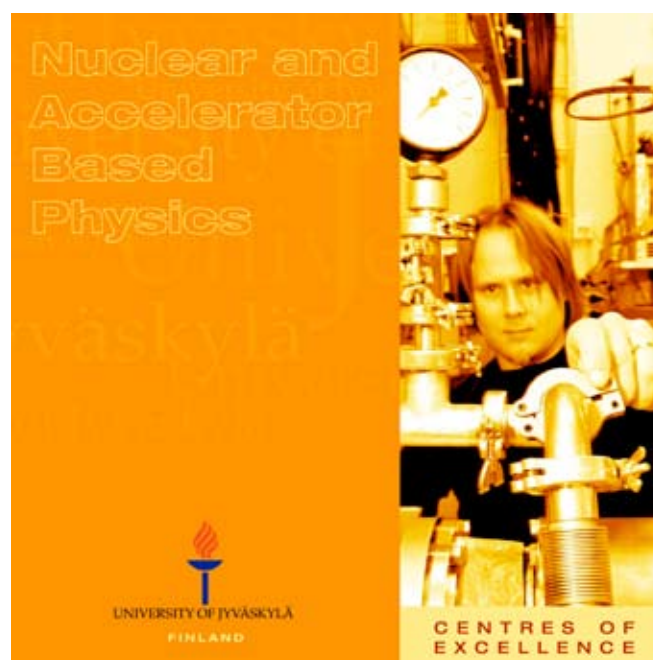
The JYFL-CoE activities at CERN including ISOLDE and ALICE form the Nuclear Matter Programme of the Helsinki Institute of Physics (HIP). The activities in the FAIR project at GSI are also coordinated via HIP. The activities of the JYFL-CoE teams in the HISPEC/DESPEC, LASPEC and MATS projects at the NUSTAR facility will form the major Finnish contribution at FAIR.

The JYFL Accelerator Laboratory is one of the eight major European nuclear physics infrastructures, whose action is concerted through the EU-Integrated Infrastructure Initiative project (EURONS) and it also has the status of an ESA-coordinated irradiation facility. In addition to the Transnational Access Activity (TNA) of EURONS, the JYFL Accelerator Laboratory is a partner in 6 different Joint Research Activities (JRA) of EURONS.

Physicists from the JYFL-CoE participate in different EURISOL-DS tasks dealing with physics and instrumentation, beam intensities and beam preparation issues. The latter task is coordinated by JYFL.

The comprehensive education programme in physics at JYFL and continuous development and construction work by the teams at the Accelerator Laboratory makes the JYFL-CoE an ideal training site for young researchers. PhD education within the JYFL-CoE is an essential part of the national Graduate School in Particle and Nuclear Physics (GRASPANP), which is coordinated by the Department of Physics.

In 2006, the total operating time of the JYFL cyclotron was 7629 hours, which is a new record in the history of the JYFL Accelerator Laboratory. The beam-on-target time was 6200 hours. A total of 31 different isotopes from protons to  $^{136}\text{Xe}$  were accelerated for experiments and applications. The number of scheduled experiments was 60.





The year 2006 was successful in general for the JYFL-CoE. The number of peer reviewed articles in scientific journals was 75, including a Letter report in Nature based on the  $^{254}\text{No}$  experiment at RITU and 12 other Letter reports.

The number of PhD thesis defended within the CoE at JYFL was 7. In addition, several thesis based on the experiments at JYFL were defended in UK universities.

Two issues of Vol.14 of the JYFL Accelerator News were published in 2006.

The annual users meeting for the users of the JYFL Accelerator Laboratory was held on 24–26 April in Saariselkä, Finnish Lapland.

In 2007, commissioning of the 1.7MeV *Pelletron accelerator* at JYFL will open up new possibilities in the research programme of the materials physics team. This accelerator was donated by the Technical Research Centre of Finland (VTT) –Espoo to JYFL in September 2006.

The theory programme will expand when the *new FiDiPro professor*, Jacek Dobaczewski, will start his five-year period in the beginning of 2007.

The first meeting of the Scientific Advisory Board (SAB) of the JYFL-CoE was held on 2 December, 2006.

In total, 40 proposals were evaluated by the Programme Advisory Committee (PAC) of the JYFL Accelerator Laboratory in the meetings on 25 March and 21 October, 2006.

# Accelerator Facilities

Pauli Heikkinen

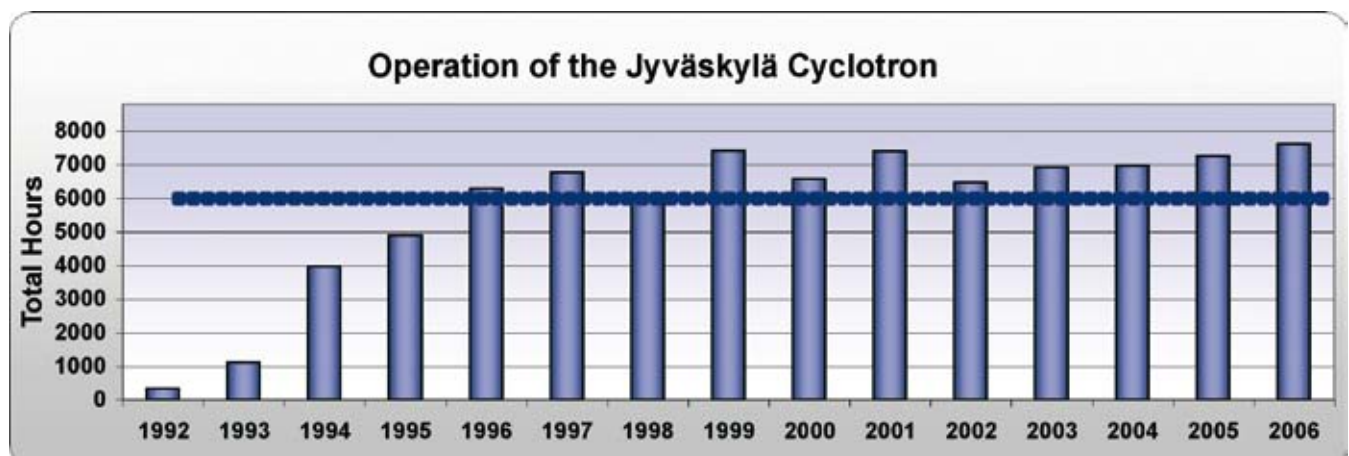
The cyclotron made a new record in total beam time in 2006. The total operating time was 7629 hours, which includes 7255 hours as beam available for experiments and for beam tuning. The beam was on target for 6200 hours.

Protons are still the most used ions, and account for almost 30% of the total due to weekly  $^{123}\text{I}$  production for MAP Medical Technologies and due to IGISOL experiments. Beam cocktails, mainly for space electronics irradiations was the second-most used beam with about 10 % of the beam time and  $^{48}\text{Ca}$  was the next most used beam (7 %). Altogether 31 different isotopes from protons to  $^{136}\text{Xe}$  were accelerated for experiments and applications in 2006.

The Accelerator Laboratory was included in the list of goods and services of Intergovernmental Agreement between Finland and Russia on the partial compensation of the former Soviet Union debt to Finland. One of

Pauli Heikkinen, chief engineer  
 Hannu Koivisto, senior assistant  
 Pekka Suominen, postdoctoral researcher  
 Arto Lassila, laboratory engineer  
 Veikko Nieminen, laboratory engineer  
 Teuvo Poikolainen, laboratory engineer (retired February 1, 2007)  
 Kimmo Ranttila, laboratory engineer  
 Juha Ärje, laboratory engineer  
 Jani Hyvönen, operator  
 Anssi Ikonen, operator  
 Hannu Leinonen, technician  
 Raimo Seppälä, technician  
 Tommi Ropponen, graduate student  
 Juhani Koivumäki, MSc student  
 Tarmo Koponen, MSc student  
 Janne Ropponen, MSc student  
 Markus Savonen, MSc student  
 Ville Toivanen, MSc student

Fig. 1. Operation of the Jyväskylä cyclotron in 1992–2006.



the major items in the list was a 30 MeV  $H^-$  cyclotron for producing medical radioisotopes and to be used in nuclear physics experiments. The final list was approved by the corresponding Ministries of both countries in the beginning of 2007. The contract on the cyclotron was signed in February 2007 by the University of Jyväskylä and Machinoimport together with the D.V. Efremov Scientific Research Institute of Electrophysical Apparatus (FSUE "NIIIEFA"). The cyclotron should arrive in Jyväskylä within 24 months from the signing of the contract and the installation time on site is six months. The cyclotron requires an extension attached to the existing laboratory so that one beam line will be connected to the 123-I production line and one to the IGISOL beam line. Planning of the extension of the laboratory has been started.

Successful tests with the JYFL MMPS plasma chamber have been completed. According to the tests the performance of the 6.4 GHz ECRIS improved by a factor

of 3 with highly charged ions. A remarkable improvement has been obtained in the technology of evaporation ovens. New resistively heated and inductively heated ovens are being developed. In the resistively heated oven a current up to 70 A (500 W) is conducted through the 25  $\mu\text{m}$  Ta foil. The crucible is heated by radiation emitted from the foil. In the experiments a temperature of around 2000°C has been measured from the crucible for a period of days. This makes it possible to produce for example titanium ion beams. A resonant circuit was designed for the inductively heated oven to be used with the signal generator. Up to now, 1800°C has reliably been reached in the crucible. Higher temperature is expected by further development of the resonant circuit. A new concept of an ECR ion source has been designed, built and tested at JYFL during 2006. In this structure a closed B-minimum configuration is produced by using only ying-yang-type coils. The first simple prototype showed its capability of producing highly charged ion beams.



# Exotic Nuclei and Beams

Ari Jokinen, Iain Moore, Heikki Penttilä and Juha Äystö

## Introduction

Our activity in 2006 has followed the well-established path consisting of numerous experiments and R&D instrumentation both at JYFL and at ISOLDE, CERN. The work at ISOLDE is carried out within the Nuclear Matter Program of the Helsinki Institute of Physics (HIP). In addition, our group, with support of HIP, has actively participated in the planning of the experiments for the super fragment separator at the future Facility for Antiproton and Ion Research (FAIR) at GSI.

A major effort has been taken towards the completion of the FURIOS laser ion source, with many technical achievements. Technical developments for JYFLTRAP include a carbon cluster ion source, which will be used to provide an absolute mass standard and development of a considerably accelerated Ramsey excitation purification technique by introducing additional gas cooling. The collaboration with KVI and GSI to develop an ion catcher which is based on either liquid helium or cryogenic helium gas also continued.

The main highlights of the experiments in 2006 included the  $Q_{\text{ec}}$ -value measurements of several superallowed beta decays [1], [2]. The precision mass measurements of neutron rich [3] and, in particular, neutron deficient nuclei [4] with JYFLTRAP continued. JYFLTRAP was also used for producing purified samples of very neutron rich fission products [5] and for proton-induced fission yield



studies [6]. Precision lifetime measurements of excited states of fission products at  $A \approx 110$  employing the triple coincidence method [7] yielded superb physics results. Additionally, a record yield of our reference isotope  $^{112}\text{Rh}$ ,  $\geq 4 \times 10^4$  atoms/ $\mu\text{C}$  produced in 30 MeV p-induced fission, was achieved. Radioactive isotopes produced at IGISOL were used as probe atoms in studying diffusion properties of impurities in solids [8].



Our team has significantly benefited from collaborations with several groups from Europe and the US as well as from EU-funded JRA projects LASER, TRAPSPEC and DLEP, and the Design Study projects EURISOL and DIRAC.

of mass separated  $Y^+$  and corresponding molecules illustrated the time formation sequence of the addition of hydrate molecules to  $YO^+$ , which itself is formed via  $Y^+$ . Data such as these can provide valuable information on the level of impurities within the ion guide.

## Technical Development

### Laser Ion Source [9]

The last year has seen many new developments in the laser ion source programme. By concentrating on an element whose ion survival is very sensitive to the impurities within the buffer gas and surrounding chamber baseline pressure, the laser ion source was used to gain a detailed understanding of the processes at work within the ion guide.

Most importantly, the role of the presence of beam-related plasma within the ion guide was studied, again

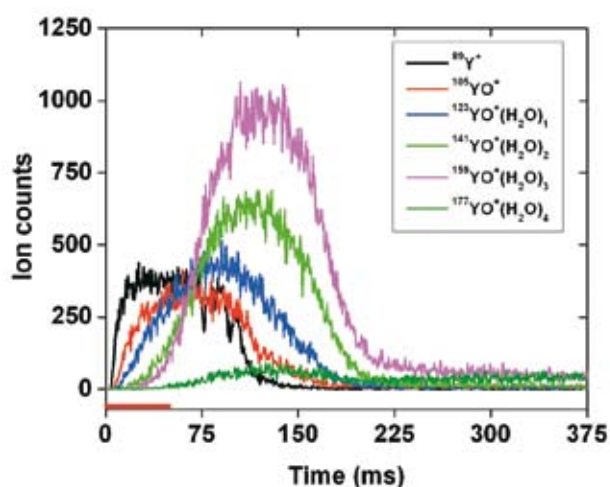


Figure 1 illustrates the role of gas phase chemistry on the yttrium system. Lasers were used to selectively ionize yttrium atoms from a heated filament. Time profiles

Fig 1. Time profiles of yttrium laser ions and corresponding molecules formed during evacuation from the ion guide. The horizontal bar indicates the time period the lasers were on.



Fig 2. A mass scan in the region of  $^{99}\text{Tc}$ . The surface-ionized isotopes  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$  as well as the laser ionized  $^{99}\text{Tc}$  appear in the spectrum. The mass scan was repeated over a narrower range with the lasers off, as indicated by the black line.

using an yttrium filament. Once the creation of  $\text{Y}^+$  was in equilibrium with recombination the addition of the lasers probed the neutral fraction, which was found to be in a rather small volume close to the exit hole of the ion guide. A more recent development has been the first production of a beam of yttrium from the ECR ion source. A 623 MeV  $^{89}\text{Y}^{21+}$  beam of 100 enA intensity was degraded in energy using a rotating nickel target and stopped in the IGISOL ion guide. The ratio of the stopped  $\text{Y}^+$  to  $\text{Y}^{0+}$  mass-separated yield was studied as a function of both helium and argon buffer gas pressure. A saturation level of between 60-70% was achieved, and laser ionization was successfully performed.

In addition to yttrium other elements of interest were studied. In collaboration with the Universities of Manchester and Birmingham, resonance ionization spectroscopy in the ion guide was performed on bismuth. The University of Mainz provided filaments of  $^{99}\text{Tc}$ , which has a half-life of  $2.1 \cdot 10^5$  years. Only  $10^{14}$  atoms of the isotope were used to confirm a three-step ionization scheme and produce the mass scan shown in figure 2.

Towards the development of the laser ion source trap (LIST) technique, extensive studies have been performed off-line to improve the spatial properties of the gas jet exiting the ion guide. This is imperative for a good laser-atom overlap within a sextupole ion beam guide located after the exit nozzle of the gas cell. A Laval-type nozzle, more commonly associated with supersonic jet engines, has been chosen for use in the ion guide. Figure 3 illustrates the ability to visualize the gas jet via the decay of metastable helium atoms excited from a

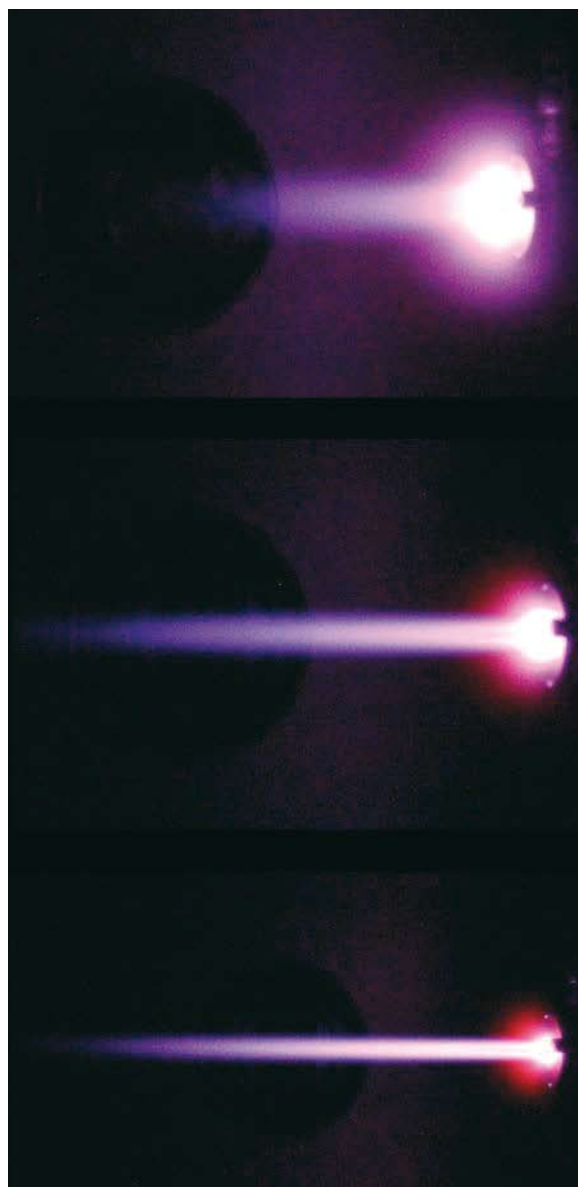
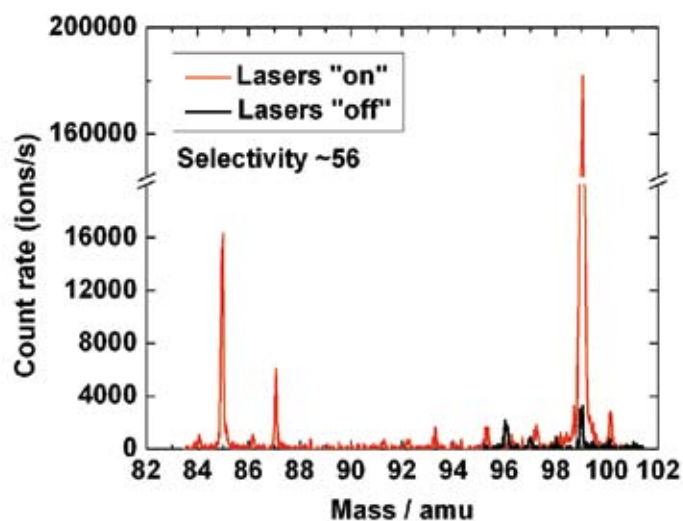


Fig 3. By increasing the helium pressure within the ion guide the visible narrowing of the gas jet is identified in this picture.

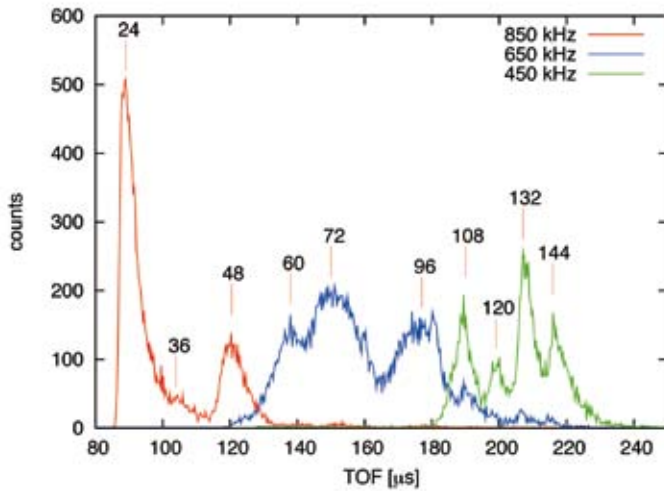


Fig 4. Detected counts vs. time-of-flight for three different RFQ frequencies. For each TOF measurement about ten C-cluster clouds were injected into the RFQ. After cooling, the cluster ions were released through the Penning trap to a MCP detector. Each TOF spectrum shown here is a superposition of 101 such measurements. The count maxima correspond to carbon cluster mass numbers. The figure also illustrates how the RFQ can be used as a mass filter to select a mass range.

DC discharge source. In addition, gas flow simulations have been performed to study the effects of different types of nozzle. The next step will be to laser ionize atoms within the gas jet and directly compare the Laval nozzle with a more standard exit hole.

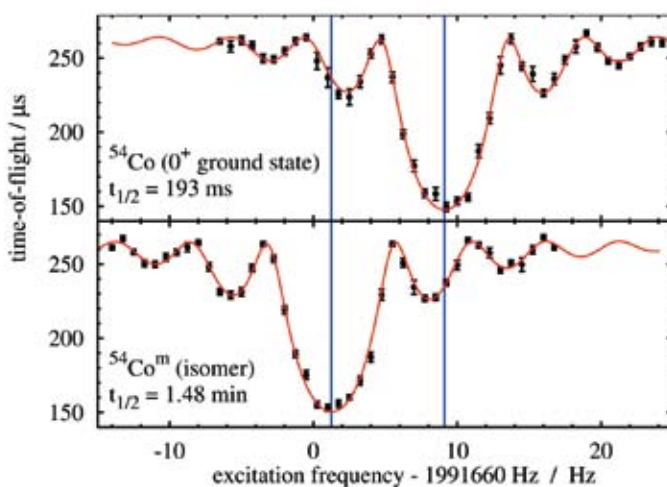


Fig 5. Time-of-flight resonances for the ground and isomeric states of  $^{54}\text{Co}$ . The energy difference is about 197 keV. Cleaning must be rather fast since the interesting ground state has  $T_{1/2} \sim 193$  ms..

## Carbon Cluster Ion Source

A carbon cluster ion source based on laser ablation has been built for the JYFLTRAP. It will be firstly used for systematic studies of the JYFLTRAP setup and, secondly, as a reference ion source for the mass measurements. The carbon cluster ion source is an ideal reference source because it provides ions whose masses are multiples of the atomic mass standard  $^{12}\text{C}$ . Thus far, the controlled production of carbon cluster ions and the capability of the radiofrequency cooler trap (RFQ) to select a size range of clusters have been established (Fig 4.). We wish to proceed to the customary utilisation of C-cluster ions in the near future.

## Dipolar Ramsey Cleaning

JYFLTRAP is a double Penning trap, consisting of a purification trap and a precision trap. The purification trap is used to make a clean sample of ions that is required to perform a proper mass measurement with the precision trap. A typical mass resolution achieved with the purification trap alone is 10 Hz (corresponding to 1 MeV/ $c^2$  for mass  $A = 100$  ions). Unfortunately, in many cases it is not enough to separate contaminating isomers or isobars.

A more refined separation can be attained in the precision trap by using a mass selective dipole excitation to remove the unwanted ions. Conventionally this has been accomplished by driving the unwanted ions to orbits beyond the detection window with a gaussian modulated dipolar excitation. This so called Ramsey excitation method, however, has not been applicable to the most short-lived nuclei. For example, to achieve 5 Hz resolution, about 800 ms in the precision trap is needed. We have succeeded to develop a faster cleaning procedure by employing an additional buffer gas cooling after the

Ramsey excitation. In our method the ions are Ramsey excited in the precision trap and returned to the purification trap for further cooling. The purification is much faster: to reach 5 Hz resolution, only 120 ms is needed for excitation and 60 ms for cooling (Fig 5.).

## Experimental Highlights

### $Q_{EC}$ Values of Superaligned Beta Decays

Several  $Q$ -values were measured during the year 2006. The  $Q$ -values of  $^{26}\text{Al}$ ,  $^{42}\text{Sc}$  and  $^{46}\text{V}$  were published. When the Penning trap value of  $^{46}\text{V}$  appeared to significantly deviate from the previous measurements, as shown also by G. Savard et al. (Phys. Rev. Lett. 95 (2005)102501) it became necessary to remeasure the reaction based  $Q$ -values of  $^{26}\text{Al}$  and  $^{42}\text{Sc}$ . Our new results appeared to be in agreement with the old values. The Conserved Vector Current (CVC) hypothesis holds for all superallowed emitters except  $^{46}\text{V}$ , which seems to hold a small anomaly in its  $Ft$ -value (Fig 6.).

In addition, the  $Q$ -values of  $^{26}\text{Si}$ ,  $^{42}\text{Ti}$ ,  $^{50}\text{Mn}$  and  $^{54}\text{Co}$  were measured. In the experiments aimed to determine the  $Q$ -values of  $^{50}\text{Mn}$  and  $^{54}\text{Co}$ , the Ramsey cleaning method, as discussed in the technical development section, was applied to remove the contaminating isomeric states.

### Mass Measurements for Nuclear Structure and Astrophysics

Extensive program of mass measurements has continued at JYFLTRAP. In 2006, a few more neutron rich isotopes

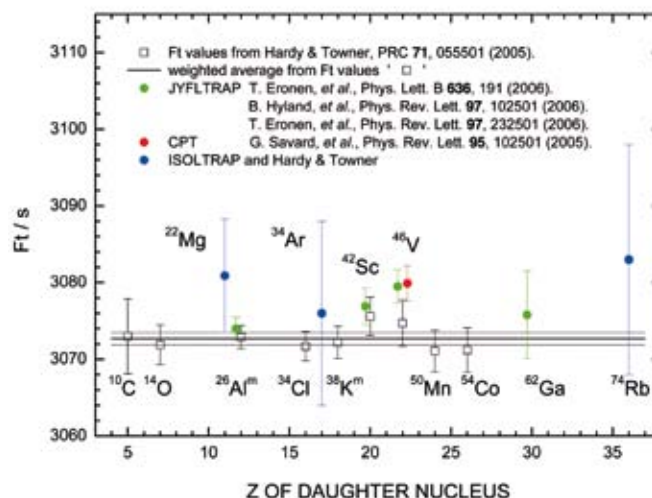


Fig 6. The set of the most precisely known  $Ft$ -values of superallowed beta emitters. The green points are derived from the recent JYFLTRAP  $Q$ -values and the red point from the  $Q$ -value measurement by Savard et al. The large errors of  $^{22}\text{Mg}$ ,  $^{34}\text{Ar}$  and  $^{62}\text{Ga}$   $Ft$ -values are due to the uncertainty of the other factors in  $Ft$  calculation than the  $Q$ -value measurement. The horizontal lines denote the average  $Ft$ -value from 2005. Once the new results are included, the  $Ft$ -value shifts slightly.

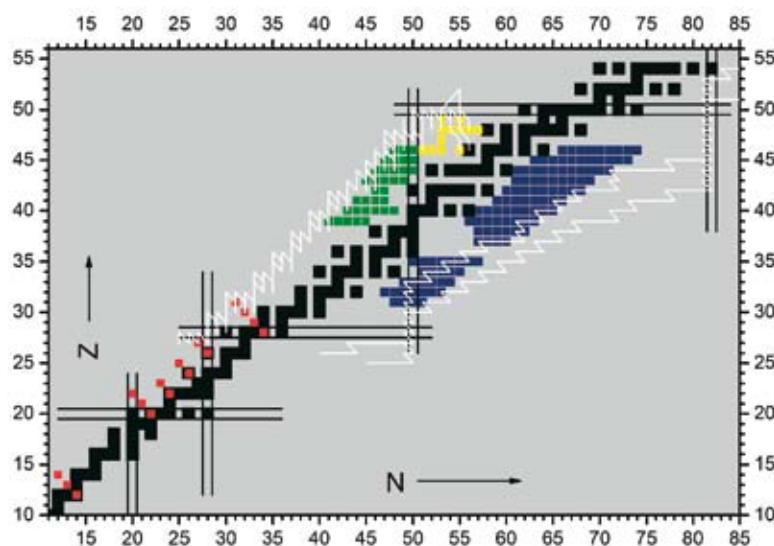


Fig 7. A chart of the nuclides emphasizing the recent mass measurements at JYFLTRAP. Blue squares denote nuclides produced in fission, red squares correspond to the  $Q$ -value determination of super allowed beta decays and green and yellow symbols denote rp-process nuclei produced in heavy ion and light ion fusion evaporation reactions, respectively. White lines illustrate the predicted rp-process and r-process paths.

were studied, though the main progress has occurred in the neutron deficient side of the nuclide chart. Figure 7 summarizes the JYFLTRAP harvest since the project commenced. All in all approximately two hundred atomic masses have been determined. The following two sections summarize the progress for nuclear structure and astrophysics related measurements of atomic masses.

### Masses of Neutron-Rich Light Fission Fragments Close to the N=50 Shell Gap

An interesting region on the neutron-rich side of the nuclide chart is the vicinity of the magic neutron number 50. In recent experiments at JYFLTRAP the masses of over 20 neutron-rich isotopes of Ga, Ge, As and Se were measured with greatly improved precision compared to previously reported values. Some of the masses were measured for the first time. Obtained new mass values provide data for calculating the two-neutron separation energies  $S_{2n}$  with improved precision and for extending the  $S_{2n}$  systematics towards more neutron-rich systems. In figure 8 the  $S_{2n}$  values for even N isotones are plotted as a function of Z. The distance between

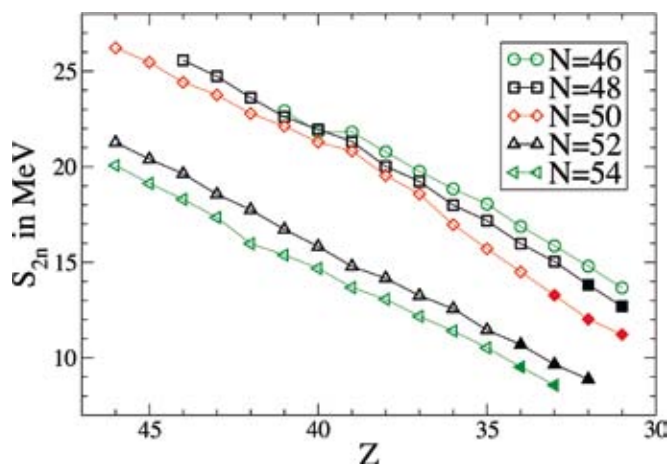


Fig 8.  $S_{2n}$  values for even N isotones as a function of Z. The solid symbols represent the 2006 measurements. The symbol size is larger than the error of the values.

the  $S_{2n}\{N=50\}$  and  $S_{2n}\{N=52\}$  values is proportional to the N = 50 shell gap. This shell gap is widest for nuclei in the vicinity of  $^{90}\text{Zr}$  with magic N = 50 and semimagic Z = 40. At lower Z the shell gap gets narrower. The new precise data exclude the possibility of a constant shell gap within the quoted uncertainty of the  $S_{2n}$  values, thus suggesting the gap may eventually become weaker for highly neutron-rich nuclei.

### Masses of rp-Process Nuclei

The rapid proton capture process (rp-process) is a sequence of proton captures and beta decays proceeding along the Z = N line where nuclides on the neutron deficient side of the valley of stability are produced. The process can happen in many different astrophysical sites that have high enough hydrogen density and temperature. These sites can be, for example, supermassive stars, x-ray bursters and supernova outbursts. To study the reaction pathways one needs to know the beta-decay lifetimes, proton capture and photodisintegration rates and the Q-values of the reactions. The JYFLTRAP has successfully been used to study the masses

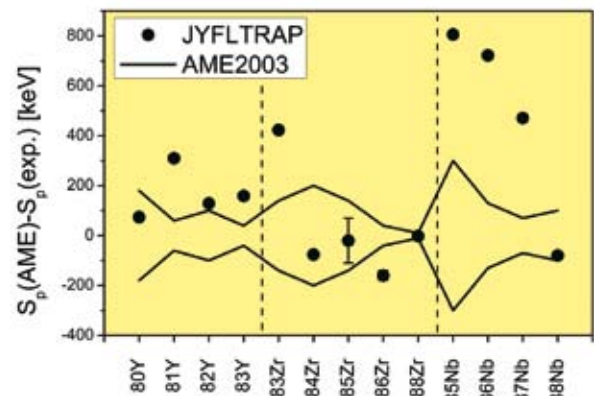
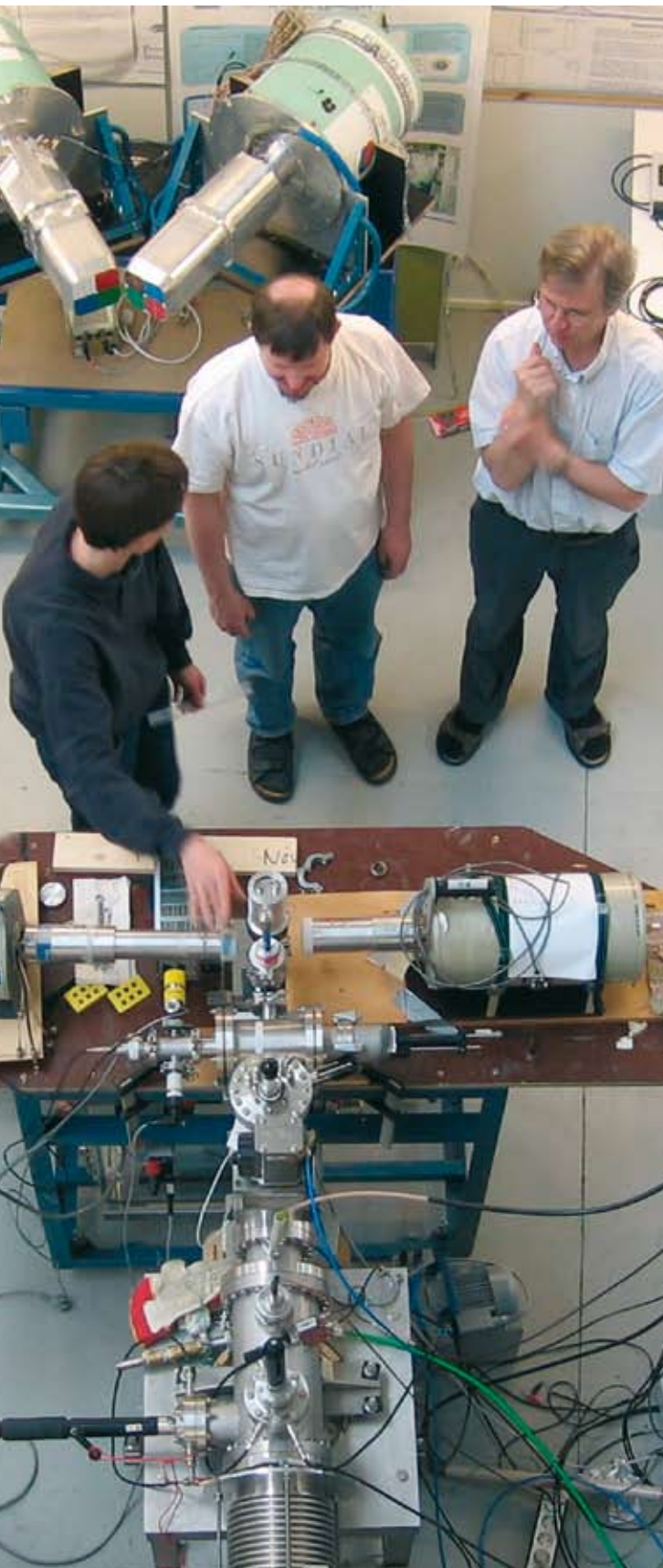


Fig 9. A difference of compiled (AME2003) and experimental proton separation energies for neutron-deficient Y, Zr and Nb-isotopes.



(which lead to the Q-values) of neutron-deficient elements between  $Z \approx 40 - 50$  with uncertainties better than  $\delta m = 10$  keV. This improves considerably the mass values in this region, which were with few exceptions previously obtained from the beta end-point measurements or by estimating the systematic trends in neighboring nuclides. Therefore the mass surface of this region was previously rather poorly determined. Our mass data implies that n-deficient nuclei in the studied mass region are significantly less bound than implied by the newest atomic mass compilation indicates. This may impact the estimated position of the proton drip-line (see figure 9).

### Trap Assisted Spectroscopy

The utilization of the purification trap of the JYFLTRAP facility in spectroscopy experiments has proceeded from the commissioning phase to the standard operation phase. The purification trap is used as a high resolution mass separator to provide clean samples of selected isotopes for beta-gamma decay-spectroscopy experiments. The first experiment exploiting this mode was the decay study of  $^{100,102,104}\text{Zr}$ . The superior purity of the source enabled a determination of absolute gamma intensities and improved decay schemes. Comparison of the experimental Gamow-Teller strength distributions with theoretical calculations suggests a prolate deformation for the studied Zr isotopes. Trap purification was also used in a study of  $^{115}\text{Ru}$  decay [5]. Both studies were carried out with germanium detector setups, with a plastic  $\Delta E$  detector for the beta decay gate. For the total absorption spectroscopy (TAS) technique the clean source is even more essential. The trap assisted TAS at JYFLTRAP is foreseen to be used to study isotopes relevant for nuclear reactor heat production.

## Laser Spectroscopy [10]

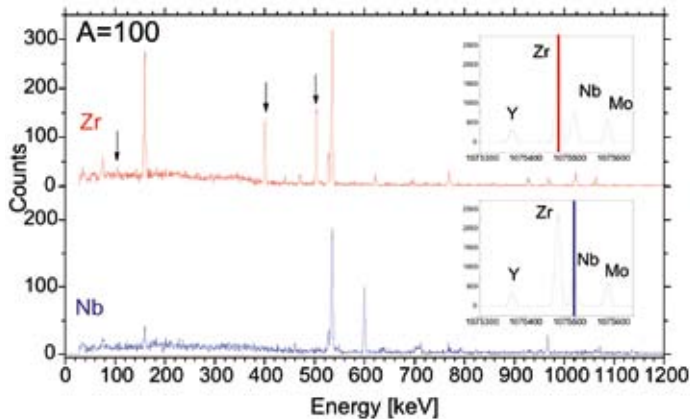


Fig 10. The effect of isobaric purification can be seen from the above gamma spectra. The upper spectrum is collected from a trap purified  $^{100}\text{Zr}$  source and the lower one from a similarly purified  $^{100}\text{Nb}$  source. The gamma peaks identified by arrows are from  $^{100}\text{Zr}$  decay. The 535 keV transition depopulates the lowest  $2^+$  state in  $^{100}\text{Mo}$  and it is seen in both spectra, while the 600 keV transition comes from the  $4^+$  state in  $^{100}\text{Mo}$ . This state is fed only by the decay of the high-spin isomer of  $^{100}\text{Nb}$  and is therefore not seen in the upper spectrum.

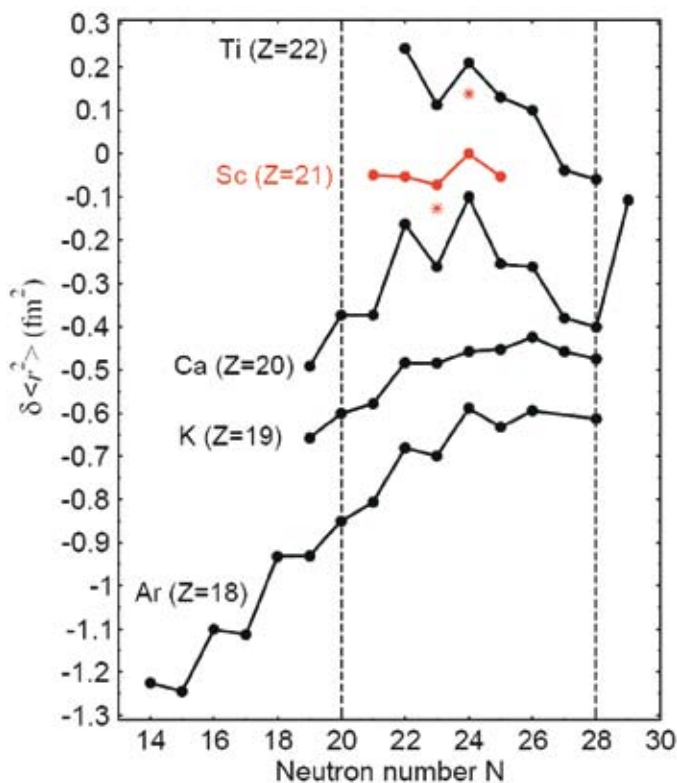


Fig 11. Relative changes in nuclear charge radii in the calcium region. The two asterisks denote  $^{44\text{m}}\text{Sc}$  and  $^{45\text{m}}\text{Sc}$ .

The work of the laser-IGISOL group on the study of proton-rich light nuclei, undertaken in collaboration with JINR Dubna, has been greatly extended by the measurement of a series of scandium isotopes and isomers. In the work, ionic hyperfine structures associated with the nuclear ground states of  $N = Z$   $^{42}\text{Sc}$  to  $^{46}\text{Sc}$  were observed along with isomeric structures from  $^{44\text{m}}\text{Sc}$  and  $^{45\text{m}}\text{Sc}$ .

These optical measurements, the first on radioactive scandium nuclei, are made in a region where the nuclear charge radius displays behaviour quite unlike that observed in any other part of the nuclear chart. Neighbouring isotopic chains around calcium,  $Z = 20$ , as can be seen in figure 11, show nothing of the systematic and smooth isotonic trends displayed by all heavier systems. In contrast, the isotopic chains have charge radii trends very different to those observed in calcium and very different to one another. The differences, which extend to both overall trends and details of odd-even staggering, are believed to arise as the charge radii here on the whole reflect microscopic nuclear properties as opposed to the macroscopic properties that dominate in heavier chains.

Such a possibility can be explored theoretically by comparing the measured charge radii with those predicted by microscopic shell models. Simple shell model approaches, which are rather successful in describing the calcium chain, have been shown by the collaboration to further succeed in describing the changing radius of scandium and particularly the radii of the Sc isomers.

Future work using proton and  $^3\text{He}$  reactions on  $^{40}\text{Ca}$  are planned for 2007. These studies will access both scandium and titanium isotopes at the  $N = 20$  shell closer itself and explore the possibility that diffuse, large, proton structures occur at this closure.

**Manchester University collaboration**

Jonathan Billowes  
 Paul Campbell  
 Bradley Cheal  
 Malamatenina Avgoulea  
 Ben Tordoff  
 Bruce A Marsh  
 Ernesto Mane Junior

**Birmingham University collaboration**

Garry Tungate  
 David Forest  
 Matthew Gardner  
 Mark Bissell  
 Katarzyna Baczynska  
 Mareike Ruffer

**KVI RIASH collaboration**

Peter Dendooven (KVI)  
 Sivaji Purushothaman (KVI)  
 Norioki Takahashi (Osaka)

**Mainz University collaboration**

Klaus Wendt  
 Katja Wies

**Experiment spokespersons and collaborating institutes in 2006**

- [1] T. Eronen, J. Hardy; Texas A&M University, College Station, Texas, USA.
- [2] S. Kopecky, J. Szerypo; University of Munich (LMU), Garching, Germany; Texas A&M University, College Station, Texas, USA.
- [3] A. Jokinen, S. Kopecky; University of Munich (LMU), Garching, Germany; IKS-KU-Leuven, Belgium.
- [4] A. Jokinen, M. Block; GSI, Darmstadt, Germany; PNPI, St. Petersburg, Russia; Giessen, Michigan State University, East Lansing, Michigan, USA.
- [5] J. Kurpeta; University of Warsaw, Warsaw, Poland.
- [6] H. Penttilä, V. Ricciardi; GSI, Darmstadt, Germany; Khlopin Radium Institute, St. Petersburg, Russia.
- [7] H. Mach; University of Uppsala, Nyköping, Sweden; Soltan Institute of Nuclear Studies, Swierk-Otwock, Poland; University of Warsaw, Warsaw, Poland; ILL, Grenoble, France; University of Manchester, U.K.; Oak Ridge NL, Oak Ridge, Tennessee, USA; Yale University, New Haven, USA.
- [8] H.J. Whitlow; Malmö högskola, Malmö, Sweden; Lund University, Lund, Sweden; University of Helsinki, Helsinki, Finland.
- [9] I.D. Moore, K.D.A.Wendt; University of Mainz, Germany; University of Manchester, UK.
- [10] J. Billowes; University of Birmingham, UK; University of Manchester, UK.
- [11] B. Fulton, K. Riisager; CSIC, Madrid, Spain; KVI, Groningen, Netherlands; Aarhus Universitet, Århus, Denmark; CERN, Geneva, Switzerland; University of York, Heslington, UK; Chalmers University of Technology, Göteborg, Sweden.
- [12] S. Sjuve; University of Washington, Seattle, Washington, USA; Argonne NL, Argonne, Illinois, USA.
- [13] K. Peräjärvi; STUK, Helsinki, Finland.
- [14] P. Dendooven; KVI, Groningen, Netherlands; GSI, Darmstadt, Germany; Osaka Gakuin University, Japan; University of Turku, Turku, Finland.
- [15] J. Billowes, J. Lee; McGill University, Montreal, Canada; University of Manchester, UK; University of Birmingham, UK; JINR, Dubna, Russia.

# Nuclear and Accelerator Physics In-Beam Spectroscopy

Paul Greenlees, Pete Jones, Rauno Julin and Sakari Juutinen

Rauno Julin, professor  
Sakari Juutinen, senior assistant  
Pete Jones, senior researcher  
Paul Greenlees, academy researcher  
Tuomas Grahn, graduate student  
Steffen Ketelhut, graduate student  
Markus Nyman, graduate student  
Panu Rahkila, graduate student  
Juha Sorri, graduate student  
Ulpu Leijala, MSc student  
Pauli Peura, MSc student  
Panu Ruotsalainen, MSc student  
Valentin Courtay, visiting MSc student

2006 was a record year for the number of in-beam gamma-ray spectroscopy experiments, with a total of 15 experiments covering 124 days (see the list at the end of this report). These employed the JUROGAM spectrometer coupled to the RITU gas-filled separator and the GREAT focal-plane spectrometer. Although the main theme of the experiments concentrated on Recoil-Decay-Tagging techniques, new approaches were also employed for increased channel-selectivity such as “beta-decay tagging” and the “Coulx plunger”. All campaigns were carried out in close collaboration with the RITU group.

The Gamma and RITU groups out on the town celebrating after Tuomas’ defence.





## JUROGAM Status

Ending 2006, the JUROGAM spectrometer has successfully run three campaigns and totalled over 50 experiments. The array is comprised of 43 EUROGAM Phase I-type Compton-suppressed HPGe detectors supplied from the GAMMAPOOL network and the France-UK detector pool. Situated at the target position of the RITU gas-filled separator, the array is of a flexible design, allowing for standalone experiments, RDT experiments, and also used in conjunction with other target position devices, such as the Köln plunger. JUROGAM has a photo-peak efficiency of approximately 4.2% and combined with the RITU separator, the UK-funded focal plane spectrometer GREAT and associated Total Data Readout (TDR) acquisition system, it forms the world's most powerful spectrometer system for studies of the structure of heavy proton drip-line and transfermium nuclei.

Future plans for in-beam spectroscopy include enhanced target position detectors, such as the UK funded projects SAGE and LISA. In addition design and development work on a larger and more efficient successor to JUROGAM is underway. The GAMMAPOOL network approved the extension of JUROGAM until mid 2008, and also approved thereafter the use of Clover detectors for the upgraded array.

## Status of SAGE

SAGE – a Silicon And GERmanium spectrometer – is a combined electron- and gamma-ray spectrometer especially designed for heavy element research. The project, which is funded by the UK EPSRC is a collaboration of University of Liverpool, Daresbury Laboratory and JYFL. A schematic version of the SAGE spectrometer coupled

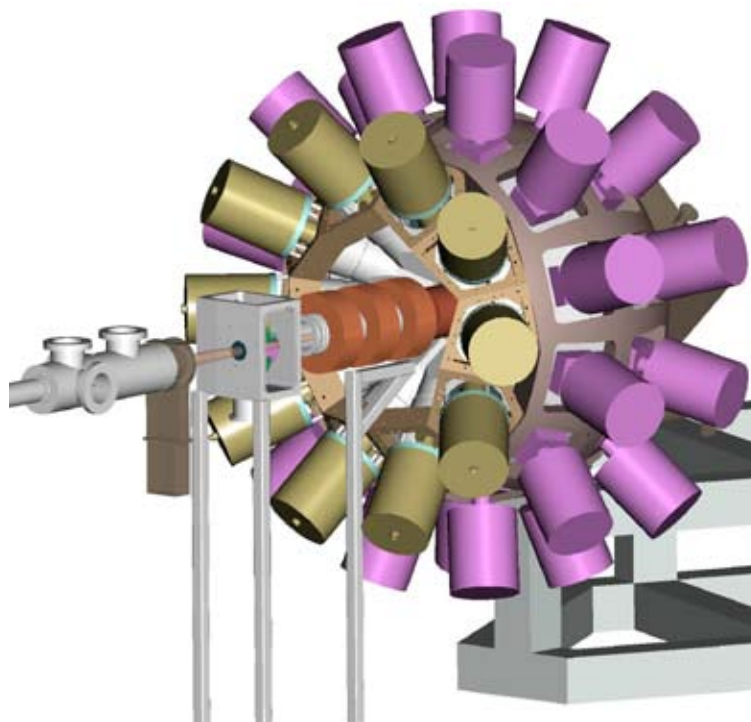


Fig. 1. Schematic drawing of the SAGE spectrometer (Courtesy D. Seddon, University of Liverpool).

to the RITU gas-filled separator is shown in figure 1. During 2006 the SAGE project has made steady progress. A full scale prototype of SAGE was constructed. The functionality and electron transport efficiency were tested successfully. The magnetic field configuration and mechanical design required to combine the solenoid magnets with the JUROGAM array are in their final stage and the infrastructure of the JYFL target hall is prepared for the implementation of SAGE. The development group is confident that the SAGE spectrometer will be operational by the end of the year 2007 and the first experiments will be conducted in early 2008.

## In-beam Spectroscopy of Heavy Elements: $^{253}\text{No}$ , $^{254}\text{No}$ , $^{250}\text{Fm}$

2006 was an exceptional year as far as heavy element spectroscopy is concerned. A clear highlight was the



Fig. 2. Two GSI large-volume Clover germanium detectors installed with the GREAT spectrometer.

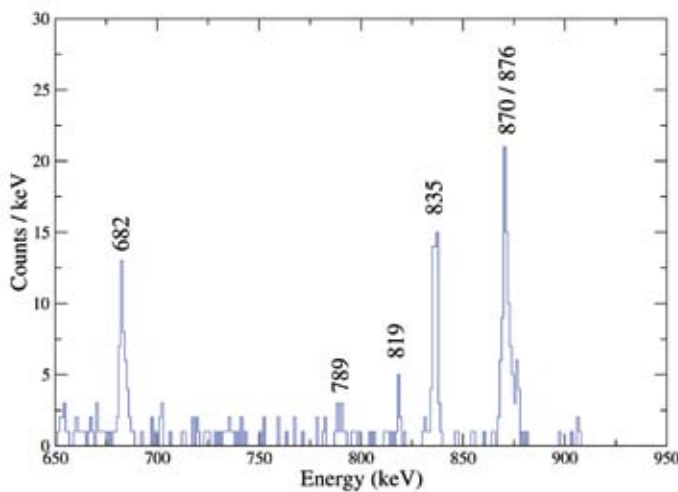
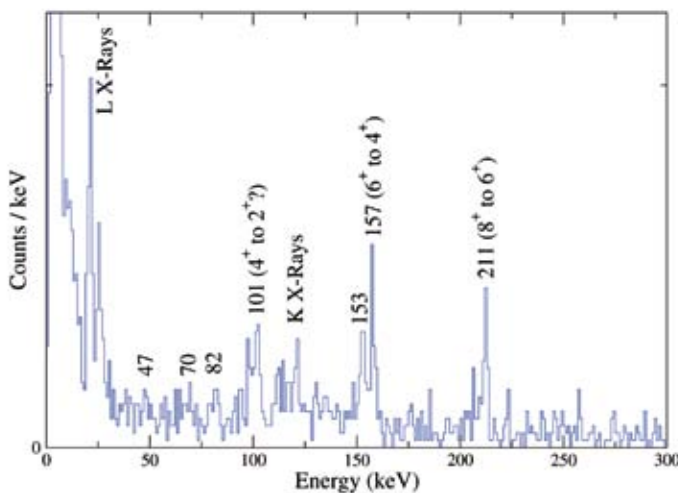


Fig. 3. Gamma-ray spectra of events in coincidence with conversion electrons emitted in the decay of high-K isomer in  $^{250}\text{Fm}$ . Up-panel: Planar Ge spectrum. Lower panel: Clover Ge spectrum.

publication in *Nature* (R.-D. Herzberg et al., *Nature* 442, 896 (2006)) of data obtained in 2005 relating to the decay of isomeric states in  $^{254}\text{No}$ . The high quality spectroscopic data allowed the location of the  $[521]1/2^-$  proton orbital to be unambiguously determined. The location of this orbital has direct consequences for the stability of superheavy elements and will help to constrain theoretical predictions of the properties of the heaviest elements. In particular, the results may help to shed light on the location of the next proton closed shell beyond  $Z=82$ .

The isomer in  $^{254}\text{No}$  was first reported in the 1970's following work carried out at the Lawrence Berkeley Laboratory (Ghiorso et al., *PRC*7, 2032 (1973)). Also reported in the same article was a possible isomer in the alpha-decay daughter of  $^{254}\text{No}$ ;  $^{250}\text{Fm}$ . In order to confirm the existence of this isomer and to obtain more systematic data on the nature of two-quasiparticle states in the region, an experiment was carried out in early 2006. To boost the focal plane sensitivity, two large volume VEGA-type Clover detectors were provided on loan from GSI. A photograph of the Clovers combined with the GREAT spectrometer is shown in figure 2.

The  $^{204}\text{HgS}(^{48}\text{Ca},2n)^{250}\text{Fm}$  reaction was employed to produce the  $^{250}\text{Fm}$  nuclei. As the HgS targets are somewhat fragile, it was necessary to use relatively low beam intensities which allowed both prompt and delayed data to be obtained in a single experiment. The experiment was extremely successful, and the existence of the isomer was quickly confirmed. The high efficiencies of JUROGAM and the focal plane Clover array allowed a preliminary but extensive level scheme to be built up. Analysis is still in progress, but it is speculated the isomeric state is due to a  $K=8^-$  two quasineutron configuration which decays to a  $K=2^-$  octupole band. The prompt data obtained with JUROGAM shows strong evidence for a strongly-coupled rotational structure built upon the

K=8<sup>-</sup> isomer. Example focal plane spectra of gamma-rays in coincidence with conversion electrons emitted in the decay of the isomer are shown in figure 3.

Rounding off the heavy element spectroscopy studies was completion of the analysis of data on <sup>253</sup>No which was obtained in an earlier experiment with JUROGAM. The analysis was presented in the thesis of S. Eeckhaudt (JYFL research report No.8/2006). An earlier study of <sup>253</sup>No carried out at Argonne National Laboratory speculated that the rotational structures observed were based upon the [624]7/2<sup>+</sup> neutron orbital, the 7/2<sup>+</sup> band head being at an energy of 355 keV (Reiter et al., PRL95, 032501 (2005)). The high quality of the data obtained at JYFL allowed the identification of interband M1 transitions, giving a measure of the single-particle g-factor,  $g_{K\pi}$ , from gamma-ray intensity ratios. The result obtained suggests that the rotational structures observed are due to the [734]9/2<sup>-</sup> configuration which is the ground state of <sup>253</sup>No. Several high-energy transitions were also observed in the data, and it was speculated that these may be due to the decay of high-lying three quasiparticle configurations. The spectrum of prompt gamma-rays from <sup>253</sup>No is shown in figure 4. The rotational band transition energies are marked.

Studies of heavy elements at JYFL will be boosted by development of the SAGE spectrometer (discussed above) which will allow a new level of sensitivity to be reached with the improved efficiency of JUROGAM II and the higher throughput afforded by digital electronics.

### Plunger Coulex: Xe

Recently, a new class of dynamical symmetries describing systems undergoing shape-phase transitions have been introduced; the so-called E(5) and X(5) critical point symmetries (F. Iachello, Phys. Rev. Lett. 85, 3580 (2000) and 87, 052501 (2001)). The X(5) symmetry is assumed to be well established (A. Dewald et al., Journal of Physics G, 31 (2005) s1427), while the E(5) symmetry is still an open question. The level scheme of <sup>128</sup>Xe exhibits very promising E(5) features. Therefore, the JUROGAM array was employed in combination with the

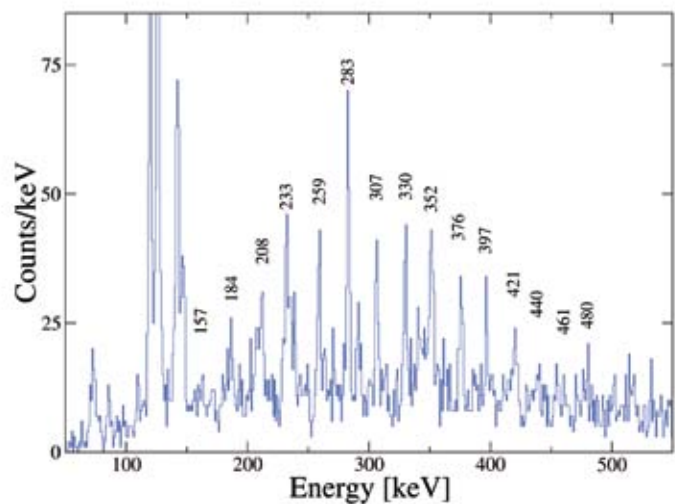


Fig. 4. Recoil-gated singles gamma-ray spectrum from <sup>253</sup>No.

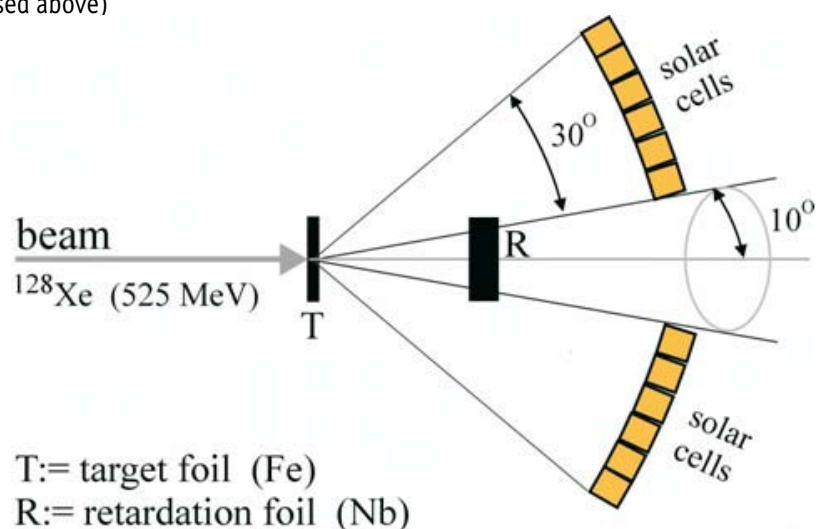


Fig. 5. Sketch of the experimental setup for the Coulex Plunger experiment.

Köln plunger to determine lifetimes in  $^{128}\text{Xe}$  by means of Coulomb excitation and the Recoil Distance Doppler-Shift technique (RDDS) (Figure 5). A 525 MeV  $^{128}\text{Xe}$  beam was Coulomb excited by passing first through a Fe foil serving as the “target”. The excited  $^{128}\text{Xe}$  nuclei were subsequently “retarded” by a Nb foil and then contin-

ued flying into the RITU spectrometer, where they were fully stopped. The scattered Fe nuclei were detected by an array of solar cells. The Nb nuclei were scattered at angles smaller than  $\approx 10^\circ$  and were, therefore, not detected by the solar cells. Particle-gamma coincidences between the Fe nuclei scattered by the Xe beam and the emitted gamma-rays were used to obtain RDDS spectra at 23 plunger distances.

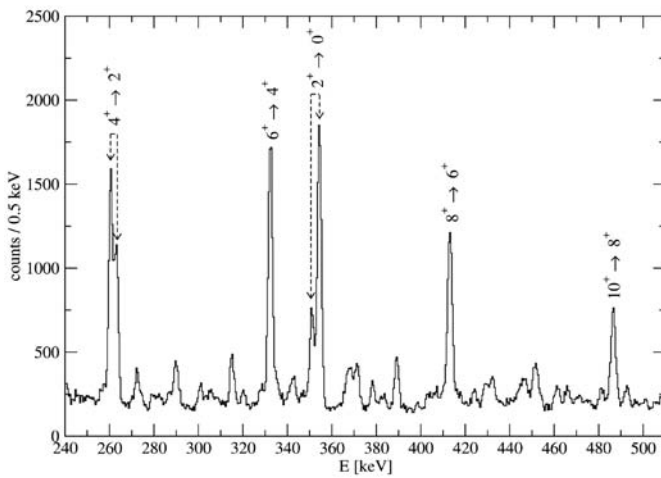


Fig. 6. Recoil-gated gamma-ray spectra from the  $^{86}\text{Kr} + ^{94}\text{Mo}$  reactions. Lines originating from  $^{182}\text{Hg}$  are marked. The target to degrader distance was  $700\mu\text{m}$ .

### RDT Plunger Lifetime Measurements of Oblate and Prolate Yrast States in $^{180,182}\text{Hg}$ and $^{194}\text{Po}$

In earlier RDDS lifetime measurements employing the Köln plunger at RITU the quadrupole collectivity and mixing in mid-neutron shell nuclei close to  $Z = 82$  was probed (PRL 97, 062501, 2006). The results indicated that the collectivity of the prolate yrast bands in  $^{186}\text{Pb}$  and  $^{188}\text{Pb}$  would be higher than that for identical bands in even-mass Hg and Pt nuclei. Therefore, similar life-



time measurements for yrast states in  $^{180}\text{Hg}$  and  $^{182}\text{Hg}$  have been performed, where these bands extend down close to the weakly oblate ground state. A beam of  $^{88}\text{Sr}$  impinging on stretched  $^{94}\text{Mo}$  and  $^{92}\text{Mo}$  targets was used to populate excited states in  $^{180}\text{Hg}$  and  $^{182}\text{Hg}$ , respectively, via 2n- evaporation channels. A 1 mg/cm<sup>2</sup> thick Mg foil served as a degrader foil. In figure 6, a sample recoil-gated gamma-ray spectrum from  $^{182}\text{Hg}$  shows that with this foil the Doppler shift differences are enough for an RDDS analysis, which is in progress.

Earlier lifetime measurements for the first 2<sup>+</sup> and 4<sup>+</sup> states in  $^{194}\text{Po}$  indicate that the contribution of the oblate intruder structure in the ground state on  $^{194}\text{Po}$  is higher than predicted by simple mixing calculations. To shed more light on the onset of collectivity in neutron deficient Po isotopes an RDDS lifetime measurement for  $^{196}\text{Po}$  was performed, where the intruder structures should lie higher in excitation energy. The set-up was similar to the one in the Hg measurement and the  $^{113}\text{Cd}(^{86}\text{Kr},3n)^{196}\text{Po}$  reaction was used.

### Experiments, Spokespersons and Collaborating Institutes for the JUROGAM campaign in 2006

Gamma-ray spectroscopy of  $^{195}\text{At}$ .

H. Kettunen, Jyväskylä, Finland

Search for Magnetic Rotation and Superdeformation in  $^{200}\text{Po}$ .

A. Wilson, Australian National University, Australia

Alpha Decay Tagging Spectroscopy of  $^{110}\text{Xe}$ .

B. Cederwall, KTH- Stockholm, Sweden

Identification of low-lying T = 0,1 states in the N = Z nucleus  $^{78}\text{Y}$ .

S.N.S. Bondili, R. Wadsworth, University of York, UK

The changing structure of the light Re isotopes: Recoil decay tagging of  $^{163}\text{Re}$ .

D. Joss, University of Liverpool, UK

Structure of high -K states in  $^{254}\text{No}$

R.-D. Herzberg, University of Liverpool, UK

P.T. Greenlees, University of Jyväskylä, Finland

Investigation of K-Isomerism in  $^{250}\text{Fm}$ .

P.T. Greenlees, University of Jyväskylä, Finland

R.-D. Herzberg, University of Liverpool, UK

Decay studies of the isomers in the proton emitter  $^{151}\text{Lu}$  and its daughter nucleus  $^{150}\text{Yb}$ .

Z. Liu, University of Liverpool, UK

Gamma spectroscopy of  $^{256}\text{No}$  using a radioactive  $^{238}\text{U}$  target.

B. Gall, IHCP Strasbourg, France

Cross-section measurement for the heavy ion radiative capture reaction  $^{92}\text{Mo}(^{90}\text{Zr},\text{gamma})^{182}\text{Pb}$ : Opening up new possibilities for the study of the light lead nuclei.

D. Jenkins, University of York, UK

Recoil-Decay Tagging Spectroscopy of  $^{172-176}\text{Au}$ .

B. Cederwall, KTH- Stockholm, Sweden

Search for breakdown of T=1/2 mirror symmetry: recoil-beta tagging and decay spectroscopy of  $^{71}\text{Kr}$ .

D. Jenkins, University of York, UK

Probing the onset of collectivity in  $^{196}\text{Po}$  by means of RDDS lifetime measurements.

T. Grahn, University of Liverpool, UK

RDDS lifetime measurements of yrast states in  $^{180,182}\text{Hg}$ .

T. Grahn, University of Liverpool, UK

Coulex-plunger lifetime measurements with Xe beams and test of inverse kinematics for future Coulex-plunger experiments.

S. Harissopoulos, NCSR Demokritos, Greece

# The JYFL Gas-Filled Recoil Separator RITU

Matti Leino and Juha Uusitalo

Matti Leino, professor  
 Juha Uusitalo, senior researcher  
 Catherine Scholey, postdoctoral researcher  
 Sarah Eeckhaudt, graduate student -31.7.06  
 Jan Sarén, graduate student  
 Ulrika Jakobsson, MSc student  
 Erna Kaleva, MSc student  
 Pierrick Favi, visiting MSc student

The activity of the RITU group in 2006 focused, as in recent years, on recoil decay tagging in-beam  $\gamma$ -ray spectroscopy studies of the JUROGAM campaign. The neutron-deficient side of the nuclear chart was widely

probed. Due to the highly efficient focal plane GREAT spectrometer, many of the in-beam experiments also yielded new results on delayed spectroscopy. With the addition of two VEGA detectors at the focal plane (on loan from GSI), isomeric states were used as probes at the proton drip line ( $^{171}\text{Pt}$  [1]) and in the super-heavy element region ( $^{250}\text{Fm}$  [2]).

In the Pb region many nuclei were studied using symmetric reactions. In these studies the lifetimes of lowest excited states were measured utilizing the RDDS plunger technique [3].

## In-beam Study of $^{110}\text{Xe}$

Following the successful study of  $^{106}\text{Te}$  in 2005 [Phys. Rev. C 72, 041303 (2005)], the study of the super-allowed alpha-decaying region above  $^{100}\text{Sn}$  continued in 2006 with the study of  $^{110}\text{Xe}$  [4]. The symmetric reaction of  $^{58}\text{Ni}(^{54}\text{Fe}, 2n)^{110}\text{Xe}$  was employed and RITU successfully separated the beam from recoiling nuclei. The half-life of  $^{110}\text{Xe}$ , 96(3) ms, is rather long for single correlations to be selective enough to unambiguously identify gamma rays from this nucleus using RDT. Thanks to the selectivity of the GREAT spectrometer and the short 70 $\mu\text{s}$  half-life of the daughter nucleus  $^{106}\text{Te}$ , recoil-alpha-alpha correlations were performed to select alpha particles and gamma rays originating from  $^{110}\text{Xe}$ , see fig. 1.

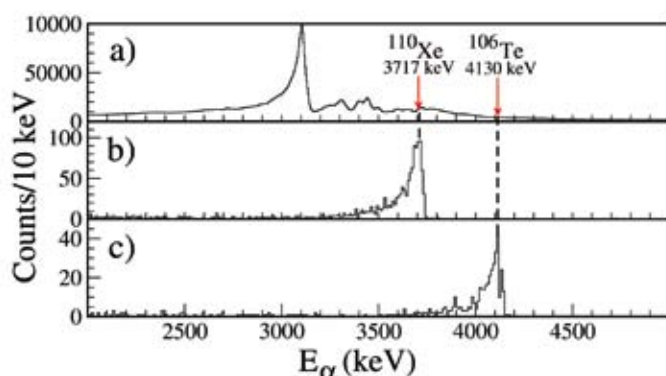


Fig. 1. (a) Recoil-correlated  $\alpha$ -decay energy spectrum for  $^{110}\text{Xe}$ .  
 (b) As in a) with the additional requirement of proper spatial and temporal correlations (220  $\mu\text{s}$ ) with the subsequent  $\alpha$  decay of the daughter nucleus,  $^{106}\text{Te}$ . (c) As in (b) showing the energy spectrum corresponding to the daughter ( $^{106}\text{Te}$ )  $\alpha$  decays.



## Combined In-beam and Focal Plane Study of $^{195}\text{At}$

An in-beam study on the proton-unbound nucleus  $^{195}\text{At}$  was performed using  $^{56}\text{Fe}$  beam on a  $^{141}\text{Pr}$  target [5]. Gamma-ray transitions were identified from the  $1/2^+$  intruder ground state and from the  $7/2^-$  isomeric state. This in-beam study resulted in evidence that there is a significant E3 branch between the isomeric  $7/2^-$  state and the  $1/2^+$  intruder ground state (Fig. 2).

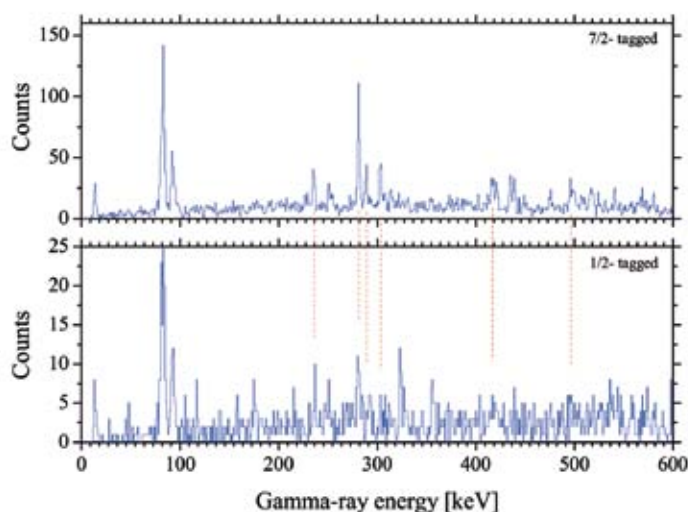


Fig. 2. Energy spectra of recoil-gated prompt  $\gamma$ -rays from the  $^{56}\text{Fe} + ^{141}\text{Pr}$  reactions gated by the  $\alpha$ -particle decays from  $7/2^-$  isomeric and  $1/2^-$  ground states in  $^{195}\text{At}$ .

## Recoil-beta Tagging (RBT)

Recoil-beta tagging (RBT) tests in the mass region  $A = 70 \sim 90$  were continued. In these tests the planar Ge-detector was replaced with a plastic scintillation detector in order to improve the  $\beta$ -particle collection efficiency. Following the RBT-tests, transitions in  $^{74}\text{Rb}$  and in  $^{78}\text{Yb}$  were identified and studied using the symmetric reactions  $^{36}\text{Ar} + ^{40}\text{Ca}$  and  $^{40}\text{Ca} + ^{40}\text{Ca}$ , respectively, at Coulomb barrier energies. In these experiments, the conventional  $300 \mu\text{m}$  thick DSSD

implantation detector was replaced with a 700  $\mu\text{m}$  thick detector [6].

### A Radiative Capture Reaction Test

A heavy ion radiative capture reaction test [7] was performed in September using the combination of a  $^{90}\text{Zr}$  beam on a  $^{92}\text{Mo}$  target. The one neutron evaporation channel was clearly identified although the available beam intensity did not allow an unambiguous identification of the radiative capture channel.

### Proton Unbound Francium Isotopes

One of our main research activities has been to study proton unbound trans-lead nuclei. In November 2006, an experiment in the heavy trans-lead proton unbound region was carried out [8]. The francium isotopes  $^{197,198}\text{Fr}$  were studied using reaction of a  $^{55}\text{Mn}$  beam (a new beam development) on a  $^{144}\text{Sm}$  target. The beam intensity was not enough for a detailed study of  $^{197}\text{Fr}$  and only one event was identified. Development work to produce high intensity beams, to enable experiments in this difficult but fertile field to be performed, is urgently needed.

### The New Vacuum Mode Separator Project

The new vacuum mode separator project which started two years ago has progressed. The quadrupole triplet has been purchased from Danfysik and will be delivered to the laboratory in spring 2007 (Fig. 3). We hope to order the magnetic dipole during 2007. Funding for the most expensive part, the electric deflector, is still an open question. Certain fusion reactions have been simulated more accurately to demonstrate the perform-





ance of the new separator. Web pages for this project have been developed and are located under the RITU web pages [9].

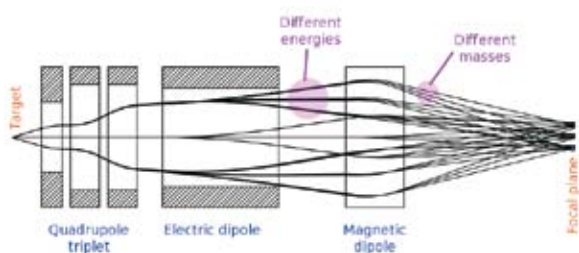


Fig. 3. Ion-optical principle of the new separator (horizontal plane). The energy dispersion from the deflector is cancelled by the magnetic dipole. The mass dispersion from the dipole gives the mass resolving power. The quadrupole triplet is used to achieve point-to-point focusing in both directions.

### Spokespersons and collaborating institutes:

- [1] B. Cederwall, C. Scholey  
Royal Institute of Technology (Stockholm),  
University of Liverpool, CLRC Daresbury Laboratory
- [2] R. D. Herzberg, P. Greenlees,  
University of Liverpool
- [3] T. Grahn, A. Dewald,  
IKP Köln, TU München
- [4] B. Cederwall, B. Hadinia  
Royal Institute of Technology (Stockholm),  
University of Liverpool, University of York,  
CLRC Daresbury Laboratory
- [5] J. Sarén, M. Nyman, J. Uusitalo,
- [6] D. Jenkins, S. N. S. Bondili, R. Wadsworth,  
University of York
- [7] D. Jenkins,  
University of York
- [8] J. Uusitalo, J. Sarén,
- [9] J. Sarén, J. Uusitalo, M. Leino.



# Nuclear Reactions and ALICE

Jan Rak and Wladyslaw Trzaska

Jan Rak, senior assistant  
Wladyslaw Trzaska, senior scientist  
Mariana Bondila, postdoctoral researcher (HIP/JYFL)  
DongJo Kim, postdoctoral researcher  
Vladimir Lyapin, researcher (HIP/JYFL) -18.6.  
Tomasz Malkiewicz, graduate student  
Sergey Yamaletdinov, graduate student  
Timo Alho, MSc student  
Michal Oledzki, MSc student  
Mikko Sillanpää, MSc student

It was a tragic year for our team. On January 17, as a result of complications after an accident, we have lost Svetlana Tretiakova from JINR Dubna. Svetlana was the world specialist on solid tracking detectors and a key person of two experiments approved for 2006. The second blow came on June 18 with death of Vladimir Lyapin – Technical Coordinator of ALICE T0 detector and renowned expert on fast timing. We also had to endure unwelcome developments in computing and administration. Nevertheless, we were able to fulfil our research plans aided by our outside collaborators who stayed in Jyväskylä for the equivalent of 1290 visitor-days. Our team has carried out 12 in-beam experiments at JYFL that took a total of 60 days (1433 hours of beam on target), conducted a major test at CERN PS and took part in detector developments in Catania.

At low energies a major experimental effort was carried out to study dynamics in binary fragmentation at masses

below  $A=150$ . The two-week experiment involved over 20 scientists from 7 European laboratories. In the other demanding experiment, the shape of the fusion barrier in the reaction of  $^{20}\text{Ne}$  with Sn and Pb isotopes was studied. It involved 3 different registration techniques in two separate setups together with multiple energy changes of the cyclotron beam. We have also continued deep sub-barrier studies of fission and measurements of rainbow scattering. A new method (B-TOF; see Javanainen, et al. in the publication list) for energy loss of charge heavy ions has been invented and intensively utilized in 2006. The year ended with measurement of 110 MeV  $^4\text{He}$  scattered on carbon in an attempt to revive Bose-Einstein condensation properties of the second  $0^+$  state in  $^{12}\text{C}$ .

In 2006, ALICE T0-C and T0-A arrays were built and pre-commissioned as planned, in spite of the shift in installation. According to the new LHC schedule, the arrays will be installed in the cavern in March and July of 2007. The final round of simulations aiming at verifying the role of T0 in trigger and luminosity measurements is well advanced. The work on T0 fast electronics and the integration with readout, slow control, and DAQ have been proceeding as planned, although the unexpected death in June of the Technical Coordinator of T0 (see inset) was a very heavy blow to our team and to our work.

## High-pT Physics

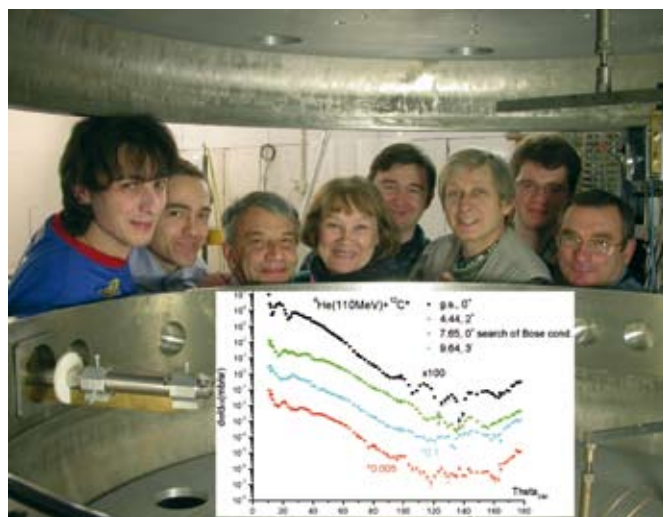
Our group explores partonic properties and their modifications in the excited nuclear medium. Building on the experience from the analysis of RHIC data obtained by the PHENIX collaboration, we have developed various methods of extracting the parton intrinsic transverse momentum  $k_T$  and jet fragmentation transverse momentum  $j_T$  from the two-particle azimuthal correlation function. This activity was aimed at preparing the analysis tools for extraction of these quantities from ALICE data and at testing predictions related to the  $k_T$ -broadening and jet transverse heating.

We were also developing methods for extraction of the fragmentation function from the direct-photon associated distributions and from the particle distributions associated to fully reconstructed jets. These measurements are vital not only for understanding of the processes behind the creation and evolution of QGP but also for exploration of fundamental QCD properties. There is a growing interest even in the string theory field to confront heavy ion data with various predictions emerging from the Maldacena's conjecture of duality between a compactified M/string theory in Anti-deSitter spacetime and large-N conformal theory which provides a connection between string theory and high-temperature QCD.

Further, using decay topology, we have also produced a reconstruction algorithm for charged kaons registered by TPC. In particular, we have addressed the question of whether the identification range achievable in ALICE allows us to use charged kaons – the dominant carriers of strange quarks – to get insight into the properties of the deconfined matter. The results of these studies have formed the basis of the first Finnish Ph. D. thesis on ALICE. The thesis "Detection of charged kaons using

the decay topology in ALICE TPC" was defended by Mariana Bondila on May 22, 2006. The opponent was Prof. Rene Bellwied from Wayne State University in Detroit, Michigan, and the supervisor Doc. W.H.Trzaska.

Since the Tier-1 level data analysis in Nordic countries is coordinated by the Nordic Data Grid Facility, it is natural that we have also started to enhance the connections to the other Nordic ALICE groups. This activity is coherent with the aim to setup modest local computing resources at JYFL and that of relying on the future CSC-located resources for the Finnish LHC-related data analysis. The first step towards including Finland in the ALICE computing grid was taken by installing the AliEn.



## in Memoriam

### Vladimir Lyapin (21.8.1949 – 18.6.2006)

On June 18, 2006 our friend and colleague – Vladimir Lyapin – has passed away. He was overcome by a very violent form of lung cancer that took him away in less than 3 weeks after he was diagnosed.

V. Lyapin's association with the Department of Physics of the University of Jyväskylä and later also with HIP dates back to 1994. At that time a team of physicists from St. Petersburg's Radium Institute, in fulfillment of the bilateral agreement signed in 1992, brought to the new Accelerator Laboratory the first parts of HENDES – High Efficiency Neutron Detection System. Volodia (as he was known to his friends) was in charge of the fast electronics and MCP detectors but his competence included nearly all aspects of experimental nuclear physics. For instance, he has developed an excellent instrument for pulse analysis from fast phototubes, a sophisticated Master Trigger Unit, several generations of fast amplifiers and CFD modules, etc. His devices were used in experiments at CERN, GSI in Darmstadt, ILL in Grenoble, KVI in Groningen, and laboratories in Catania, Legnaro, Dubna and Warsaw.

In 1998 Volodia was part of the consulting team evaluating feasibility of carrying out bonding for ALICE SSD in Finland. Since that time Volodia's involvement in ALICE continued to grow and already in 2000 he became a full-time employee of HIP. At that time he worked on the design and tests of the MCP-based Forward Multiplicity Detector (FMD) for ALICE. Although, the collaboration finally opted for a less sophisticated but cheaper option for FMD, Volodia's expertise and the excellent tim-

ing results achieved in test experiments at CERN have won for HIP the leadership of T0 – the key timing and fast trigger detector in ALICE. Professional know-how and pleasant personality have quickly convinced the collaboration to entrust Volodia with the mandate of Technical Coordinator of T0. In that capacity he was overlooking the work of a dozen of research engineers in 4 institutes. His electronics was adopted in part by other ALICE detectors (V0 and TRD wake-up). Fast timing techniques perfected with Volodia's significant contribution for the needs of the LHC experiment were also used at JYFL. Especially impressive is the impact made by the new picoseconds-timing on TOF-based energy loss measurements of charged ions. Last but certainly not least is Volodia's contribution to teaching. His patience and thoroughness in explaining the fundamentals of electronics and experimental techniques to scores of M.Sc. and Ph.D. students at JYFL were truly exemplary. We all miss him a lot.



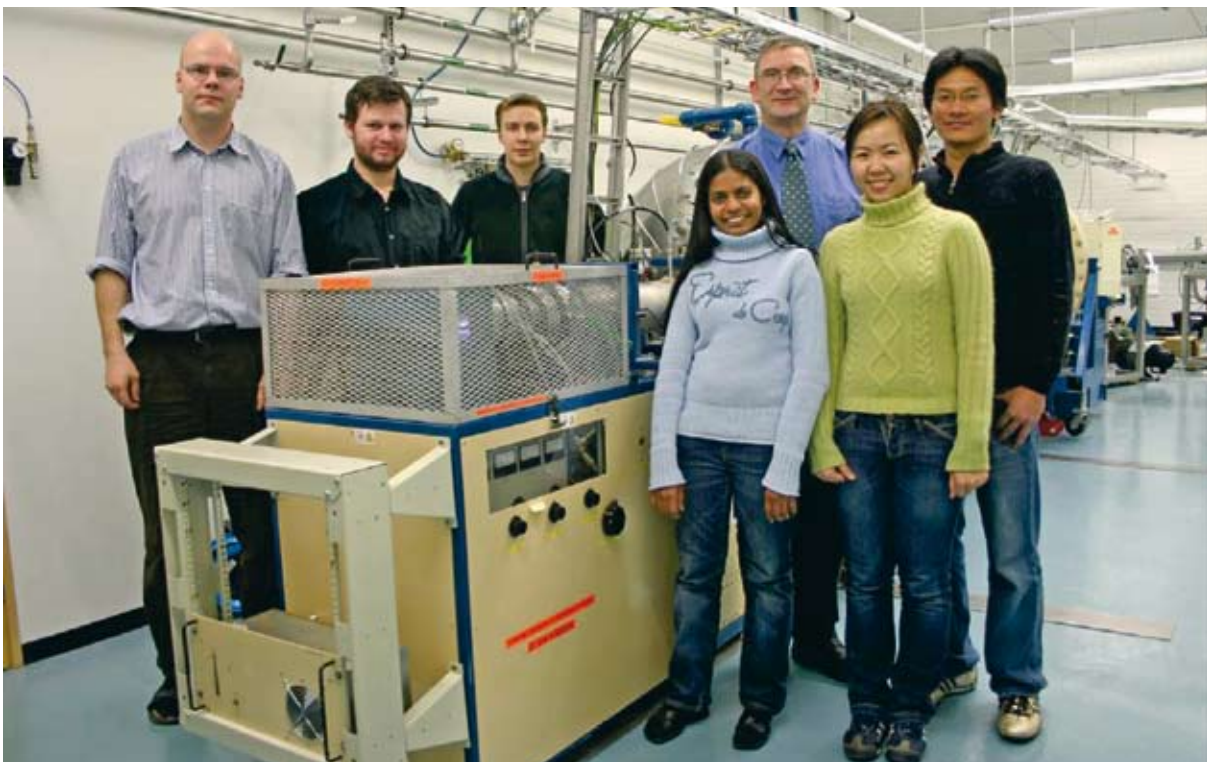
# Accelerator Based Materials Physics

Timo Sajavaara and Harry J. Whitlow

The accelerator-based materials physics group's work has in 2006 become more directed towards biomedical research with ion beams. The areas on which we focus are: (i) the development of MeV ion beam lithography (ii) modification and characterisation of materials with ion beams and (iii) the application of radioactive ion beams from the IGISOL facility.

Group photographed around the Pelletron RF ion source. Left to right Timo Sajavaara, Sergey Gorelick, Mikko Laitinen, Ananda Sagari, Harry Whitlow, Somjai Sangyuenyongpipat, Nitipon Puttaraksa.

Harry J. Whitlow, professor  
Timo Sajavaara, postdoctoral researcher  
Somjai Sangyuenyongpipat, postdoctoral researcher  
Sergey Gorelick, graduate student  
Mikko Laitinen, graduate student  
Ananda Sagari A.R., graduate student  
Elisabeth Wieslander, graduate student, EC-JRC IRMM, Geel, Belgium  
Min Renqin, graduate student, National University of Singapore  
Nitipon Puttaraksa, visiting graduate student, Chiang Mai University, Thailand  
Laura Mättö, MSc student  
Terho Räisänen, MSc student

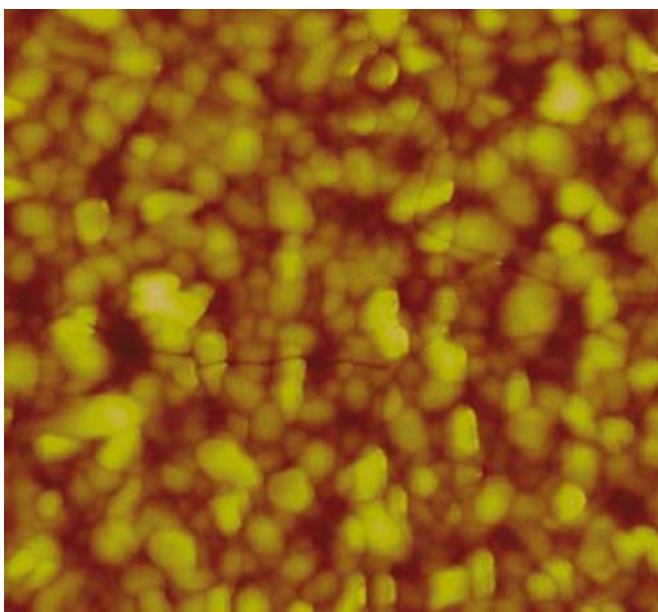


The most significant development has been that the Technical Research Centre of Finland has donated their 1.7 MeV Pelletron accelerator facility to the Accelerator Laboratory. This machine is extremely well suited for materials and thin film research but also it will be able to act as efficient focus for collaboration with commercial entities at local to international levels.

### Deposition of Ca-P-O Films by Means Of Atomic Layer Deposition and Ion Sputtering

Calcium phosphate ceramics such as hydroxyapatite (HA) are one of the most promising implant coating materials due to their good biocompatibility. Two deposition techniques were used to produce thin film coatings: atomic layer deposition (ALD) and ion-beam sputtering.

Fig. 1. Atomic force microscope image of an atomic layer deposited Ca-P-O film on a Si substrate. The film has the correct hydroxyapatite composition as determined by ion beam analysis and it was polycrystalline after annealing. This was confirmed by means of X-ray diffraction and AFM analyses. The scanned area is  $2 \times 2 \mu\text{m}^2$  and z-scale is 100 nm.



The correct stoichiometry could be tailored for atomic layer deposited films and they showed characteristic HA X-ray diffraction peaks when annealed in a moist Ar atmosphere at 800 °C.

Ca-P-O thin films were processed by atomic layer deposition (ALD). The resulting films were analyzed by XRD, XRF, FTIR, TOF-ERDA and AFM to determine film crystallinity, stoichiometry, possible impurities and surface morphology. As-deposited films contained significant amounts of carbonate impurities but the annealing at moist  $\text{N}_2$  flow reduced carbonate content even at 400 °C. The as-deposited Ca-P-O films were amorphous but rapid thermal annealing promoted the formation of the hydroxyapatite phase (Fig. 1). According to the bioactivity studies cell proliferation was enhanced on as deposited ALD-grown Ca-P-O films and greatly enhanced on films annealed at 500 °C in comparison with reference cells cultured on borosilicate glass.

Ion-sputtering was studied as a room temperature deposition technique. Pressed high purity hydroxyapatite targets were bombarded using nitrogen, argon and krypton beams at different acceleration voltages. In order to compensate the P-loss during the sputtering process, a mixture of high purity hydroxyapatite powder and red phosphorus was also used. Comparative theoretical studies to determine the sputtering yield of different elements in the target were done using SRIM simulations. Time-of-flight elastic recoil detection analysis (TOF-ERDA) using a heavy 16 MeV  $^{63}\text{Cu}^{7+}$  ion beam was used to determine the film composition (Fig. 2). The Ca/P atomic ratio for HA is 1.67, the closest Ca/P atomic ratio of 1.6 (approaching to 1.67) was obtained for the film sputtered using Ar as feedstock at 10 kV from a HA + red phosphorus target corresponding to 44 at.% P. The biocompatibility of the films was investigated using osteoblast-like cells. For films deposited under optimal conditions the osteoblasts exhibited dendritic growth,

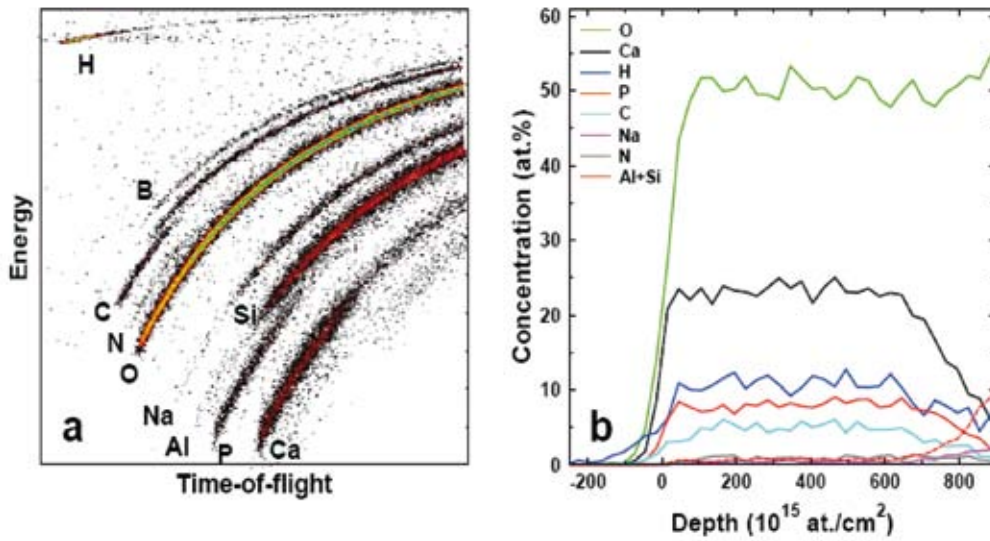


Fig. 2. a) TOF-energy histogram from 100 nm thick film measured with 16 MeV  $^{63}\text{Cu}^{7+}$  ions. The film was sputter-deposited using argon and 6 kV acceleration voltage on a borosilicate substrate. b) The corresponding elemental depth profiles.

indicative of more realistic chemical signalling than for other substratum e.g. polystyrene or plain glass.

teoblast attachment, migration and cytoskeleton organization on these micron and nanometre structures behaved in remarkably different ways (Fig. 3).

### Lithographically Produced Cell growth Substrates

MeV Proton Beam Writing (PBW) has the capability to write extremely high aspect ratio 3D microscale structures with vertical sidewalls and nanometer-scale precision. One of the main applications of PBW is production of 3D structures with geometrically defined nanometer-scale features for biomedical research at the cellular and subcellular-level. Our goal has been to produce and study surfaces with controlled features on a  $\mu\text{m}$  and nm scales to be used as growth substrates for bone cells. Osteoblasts, the cells responsible for bone production, were cultured on lithographically modified surfaces of two materials: SU-8 and PMMA. The PBW system at the National University of Singapore was used to fabricate high aspect ratio structures (in PMMA), while 2-dimensional low aspect ratio structures were fabricated using conventional electron beam lithography and UV lithography in SU-8. It was found that SU-8 can be used as a substrate material for osteoblast cell culture studies if the surface was treated with oxygen plasma. The os-

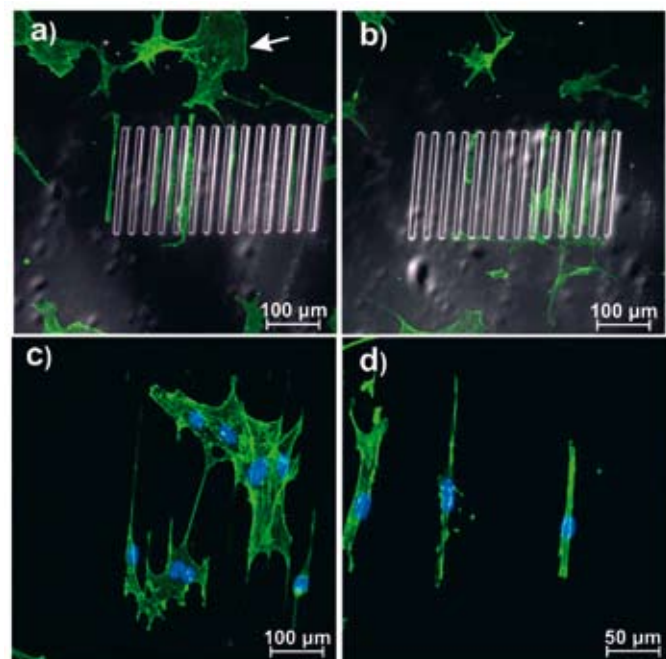


Fig. 3. Fluorescence confocal microscope images of murine osteoblasts cultured on PBW-machined PMMA/sputtered Ca-P-O/glass substrate. a-b) Wide channels (an arrow points at a typical cell growth on smooth PMMA surface). c-d) Narrow channels. Blue denotes cell nuclei.

## Bioimaging with MeV Ions

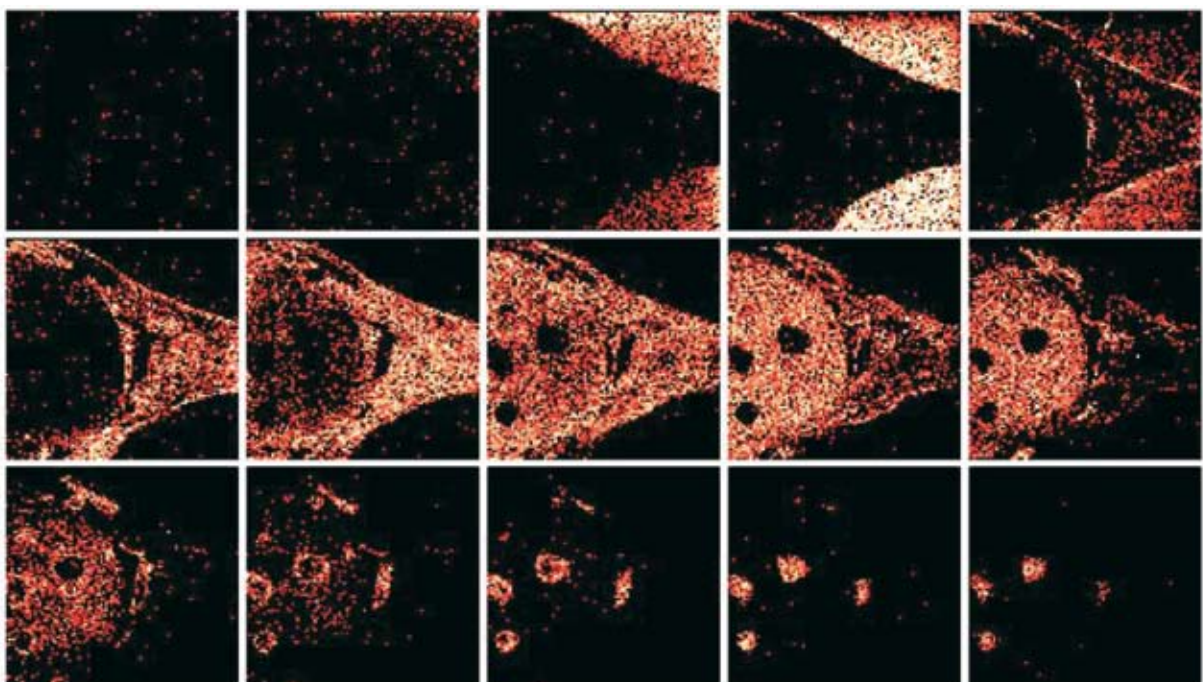
New methods of imaging biological cells and tissue have recently undergone an upsurge of interest. Scanning Transmission Ion Microscopy (STIM) has the capability of structural imaging of biological materials. The energy straggling associated with the ions traversing the tissue growth substrate is the limiting factor for the depth resolution while the attainable beam spot size limited the lateral resolution. Through a combination of directly cultivating the cells on the SiO<sub>2</sub>-passivated surface of a Si p-i-n diode used to determine the energy of transmitted ions and using a 2MeV <sup>4</sup>He<sup>+</sup> beam focused to an 80×90 nm<sup>2</sup> spot size, we were able to demonstrate the imaging of single cells with sub-100 nm spatial resolution. Various representation techniques of the 4-dimensional data were investigated using the BioimageXD software. An example is illustrated in Fig. 4 which presents energy-loss slices through the cell in a way somewhat akin to tomographic imaging. Clearly the organelle structure can be clearly seen with the nucleoli having the greatest energy loss. The nuclear membrane and nucleoli can be clearly discerned and the cell membrane is very sharply delineated.

## Lithography System Development

MeV ion beam lithography system for writing high aspect ratio 3D patterns has been developed at the Jyväskylä accelerator laboratory. The system employs a programmable proximity aperture to define the beam. The proximity aperture is made up of Ta blades with precise straight edges that cut the beam in the horizontal and vertical directions. The blade position and dimensions are set by a pair of high-precision linear-motion positioners. Edge-polishing of a Ta aperture blade with 2000 groove SiC sandpaper followed by diamond paste, resulted in an edge roughness of better than 100 nm peak to valley deviation from straightness over 4 mm, as measured with a profiler.

The sample is mounted in a vacuum chamber on a X-Y-Z stage capable of moving with 100 nm precision steps under computer control. This allows entire pattern elements (horizontal and vertical lines, rectangles, squares)

Fig. 4. 2 MeV <sup>4</sup>He<sup>+</sup> STIM energy-loss sections through a MCF-7 human breast cancer cell cultivated directly on the surface of the STIM detector. The field size is 15 by 15 μm.





with sizes up to  $\sim 500 \mu\text{m}$  to be written in one step (Fig. 5). This approach considerably speeds up the writing time for large patterns compared to writing by scanning a small spot over each pattern element

### Simulation of Slit Scattering

The performance of the PPAL (programmable proximity aperture MeV ion beam lithography) system is primarily governed by the quality of the proximity aperture. Pattern edge sharpness is set by the beam divergence, aperture blade straightness, and secondary and scattered particles from the aperture blade edges (see Fig. 6). The analytical approach for pattern edge sharpness calculations is not straightforward. Therefore Monte Carlo simulations were used. Ray tracing simulations using the object oriented GEANT4 toolkit were performed to investigate the performance of the proximity aperture. The GEANT4 toolkit provides comprehensive detector and physics modelling capabilities, as well as a complete set of functions like ion tracking, material specification and geometry description.

The results indicate that the edge-scattering will not significantly affect the pattern edge sharpness. The predictions will be refined and validated as soon as experimental data becomes available in early 2007.

### Theoretical Studies of Ion-Matter Interactions

Our theoretical activities have focused on maintaining know-how in order to give postgraduate courses at an advanced level and to compliment the experimental program with recent theoretical developments. Many practical applications of MeV ion beam lithography are based on atomic displacement damage. As the attain-

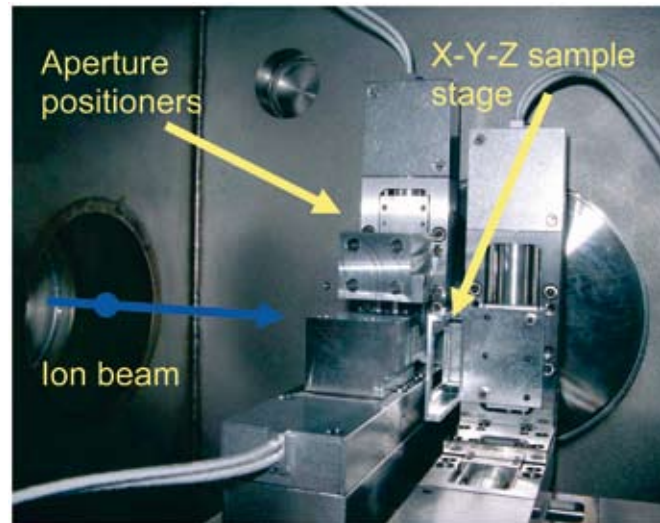


Fig. 5. Photograph of the ion beam lithography system. Two L-shaped aperture blades in close proximity to the sample surface define the shape of the beam spot on the surface. By combining the  $x'$  and  $y'$  movement of the defining aperture with X and Y movement of the target, entire pattern elements can be written in parallel over the  $20 \times 20 \text{ mm}^2$  field.

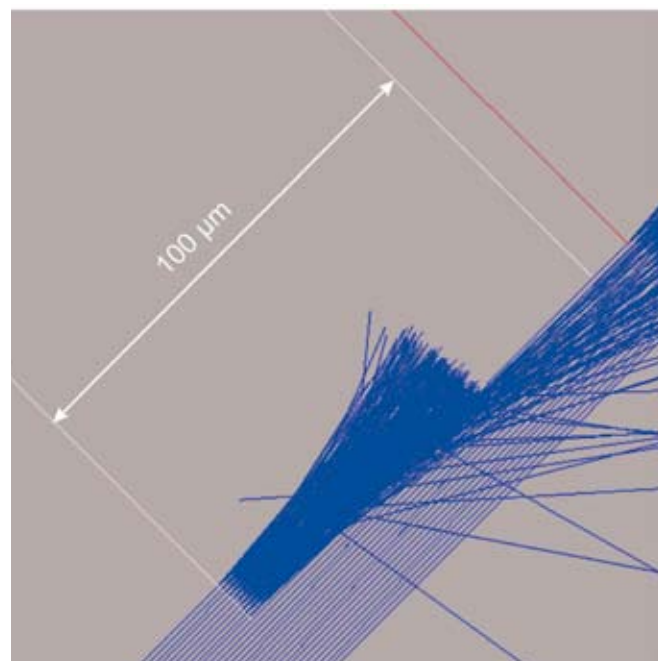


Fig. 6. A parallel beam of 5 MeV protons (proton trajectories are shown in blue) is incident on the edge of a  $100 \mu\text{m}$  thick Ta plate. The protons are scattered in the material, and some of them escape. These protons may hit the sample and affect the pattern edge sharpness.

able beam focus reaches the nanometre region the conventional broad-beam displacement damage approaches are inadequate to describe radial interstitial and vacancy from a nm-scale focused primary beam. We used a hybrid approach where the primary ions are followed using the SRIM binary collision approximation and coupled to molecular dynamics code to follow the recoil cascade via the impulse approximation. Nakagawa's pixel mapping approach was employed to determine the radial defect distribution of defects after the cascade had cooled to room temperature. The results (Fig. 7) showed that al-

though high energy primary knock-on atoms contribute many defects, the low energy primary knock-on atoms give rise to the highest concentration of defects and this is located within 1 nm or so of the ion track.

### Pb diffusion in Glass with Low and High Implantation Fluences

Diffusion studies of ion implanted Pb in glass continued in year 2006. The high fluency study had implantation energy of 50 keV and fluences varied between  $1 \times 10^{14}$  to  $1 \times 10^{16}$  ions  $\text{cm}^{-2}$ . The preliminary results indicate that the activation energy for Pb diffusion in glass is not concentration dependent with high fluences. Diffusion of Pb in very low concentrations was studied using IGISOL-technique. Very low concentrations of radioactive  $^{210}\text{Pb}$  was implanted to the glass substrates, annealing was performed in vacuum, and finally sputtering was used for serial depth sectioning of the sample. Compared to earlier experiment in 2004 the increased number of annealing temperatures and better defined depth profiling gave more coherent results. The data analyses are in progress on both high and low fluence studies and should be concluded in 2007.

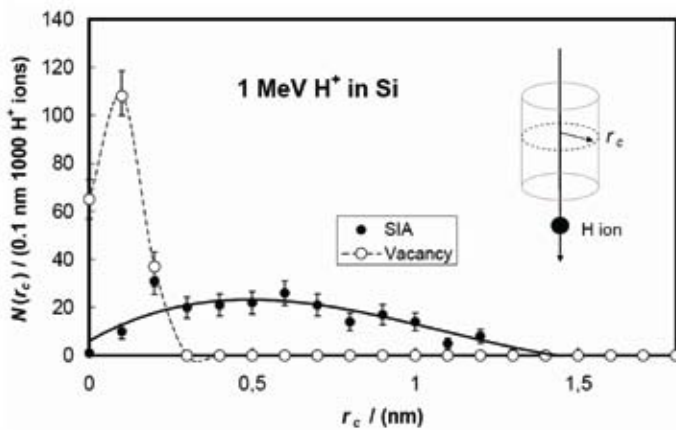


Fig. 7. Radial range distribution of self interstitial atoms (SIA) and vacancies about 1 MeV  $\text{H}^+$  ions incident on  $^{28}\text{Si}$  for primary knock-on atoms with energy less than 40 eV after annealing for 2 ps at 300 K.

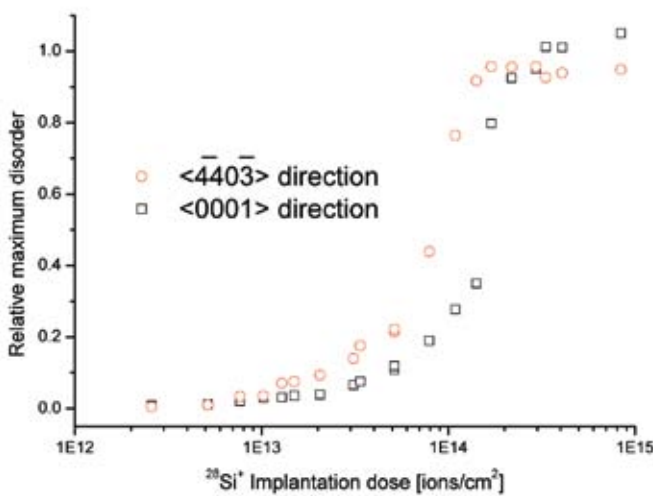


Fig. 8. As implanted relative damage in 4H-SiC. Studied by C-RBS using 2 MeV  $^4\text{He}^+$  ions.

### Damage Recovery of Silicon Carbide

In March 2006 channeling measurements of 4H-SiC were carried out at Pacific Northwest National Laboratory, PNNL, USA. In these studies  $^{28}\text{Si}^+$  ions were implanted at the energy of 550 keV into SiC-crystal at various fluences, and implantation damage and damage recovery due to annealing were measured using channelling-RBS. Channeling spectra were measured from  $\langle 0001 \rangle$  and  $\langle 4403 \rangle$  crystal directions. From measured RBS/C spectra the relative disorder in the damaged region is determined (Fig. 8).

For the 2007 SiC diffusion studies to be done in Jyväskylä, a high temperature oven capable of heating samples in a vacuum at temperatures higher than 1850 °C was designed and built (Fig. 9).

### Development Plan for the New Pelletron Accelerator Facility

The State Technical Research Centre of Finland donated their 1.7 MV Pelletron Accelerator to the Jyväskylä Accelerator Laboratory. The University of Jyväskylä accepted the donation and provided the financial support to cover the necessary building reconstruction costs. The construction of the laboratory was a major work – this was constructed from three adjacent rooms, a 30 cm thick concrete block needed to be cast under the accelerator and magnets, hundreds of meters of stainless steel pipe was required for the cooling water and a major upgrade of the air conditioning and ventilation system in the laboratory was carried out. Despite the extensive work, the first beam could be accelerated and guided to the target a bit more than four months after signing of the contract and the arrival of the accelerator.

The donation is a complete system that allows automated RBS and channelling analysis. One of the terms of the donation is that the Accelerator Laboratory undertakes to provide up to 200 analyses per year without charge. This means circa 1 day per month of beam time.

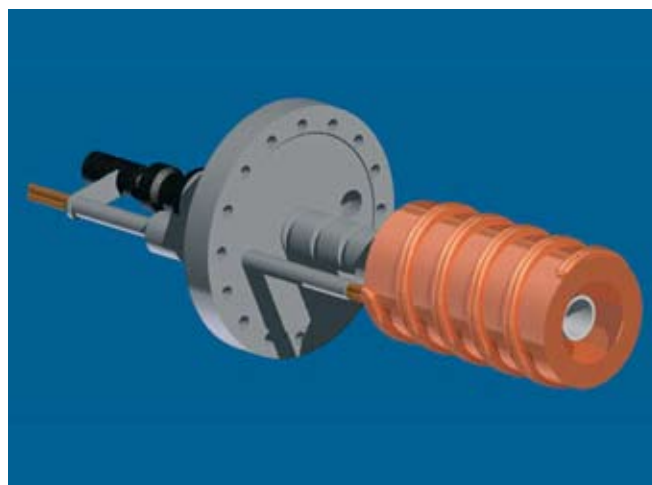


Fig. 9. Oven for the high temperature annealing and its newly designed cooling. The cooling system was designed to extend oven's usable temperature range over the old temperature limit of 1200 °C. When installed, the preliminary test showed that currently oven reaches easily more than 1850 °C without heating the surrounding chamber significantly.

The accelerator is particularly well suited for accelerator-based materials research. This is particularly welcome addition because it will enable us to strengthen our ties to the Nanoscience Centre in Jyväskylä as well as providing a tool that can be used by other research groups and industrial partners. The first step in the development plan is to build an ion beam analysis setup which is capable of depth profiling all the sample ele-

Fig. 10. The 1.7 MV Pelletron installed in the new laboratory in Jyväskylä.



### Main collaboration:

Prof. Frank Watt, Dr. Jeroen van Kan, Dr. Andrew Bettioli, Assoc. Prof. Thomas Osipowicz, National University of Singapore, Singapore.  
Docent Yanwen Zhang, Dr. C.M. Wang, Dr. D.E. McCready, V. Shutthanandan, L. Saraf, B. W. Arey, S. Thevuthasan. Pacific Northwest National Laboratory, Richland, Washington, USA.  
Prof. Johan Helgesson, Dr. Lennart Karlsson, Dr. Jörgen Ekman, Malmö högskola, Sweden  
Prof. Juhani Keinonen, Department of Physical Sciences, University of Helsinki, Finland.  
Prof. Sulin Cheng, Paavo Rakkila, Department of Health Sciences, University of Jyväskylä, Finland.  
Dr. Arno Hahma, Department of Chemistry, University of Jyväskylä, Finland.  
Prof. Ragnar Hellborg, Docent Kristina Stenström, Mariusz Graczyk, C.T. Jönsson, Docent Ivan A. Maximov, Department of Physics, University of Lund, Sweden.  
Dr. T. Weijers, Australian National University, Canberra, Australia.  
Dr. Rainer Grötzschel, Forschungszentrum Dresden-Rossendorf e.V. , Germany.  
Dr. Heiko Timmers, Australian Defence Force Academy, Canberra, Australia.  
Prof. Sachiko Nakagawa, Okayama University of Science, Japan.  
Prof. Wilfried Vandervorst, Bert Brijs, Dr. Kai Arstila, IMEC, Leuven, Belgium.  
Prof. André Vantomme, IKS, K.U.Leuven, Belgium.  
Dr. Kaupo Kukli, Prof. Mikko Ritala, Department of Chemistry, University of Helsinki, Finland.  
Prof. Lauri Niinistö, Dr. Matti Putkonen, Laboratory of Inorganic and Analytical chemistry, Helsinki University of Technology, Finland.  
Docent Mikael Hult, EC-JRC Institute for Reference Materials and Measurements, Geel, Belgium.  
Prof Vilaithong Thiraphat, Assoc. Prof. Somsora Signkarat, Chiang Mai University, Thailand.

ments including hydrogen with better than nanometre depth resolution at the surface. Moreover, this tool will be sensitive enough to measure quantitatively concentrations below 0.1 at.% and ion irradiation sensitive organic materials like polymers. Another high priority development will be the installation of the above described lithography system to one of the Pelletron beam lines.

A longer term plan is to extend the system by building a magnetic focusing system to one of the beam lines and focus the beam to 100 nm or less. In addition to lithography, this will enable biomedical cellular and sub-cellular imaging below the diffraction limit.

# Industrial Applications

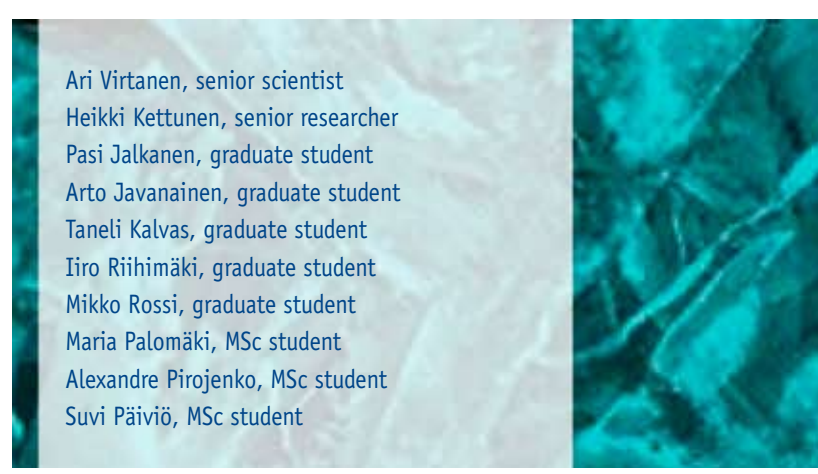
Heikki Kettunen and Ari Virtanen

## Space Related Study

2006 was the first full year, when the RADEF facility was operated as one of ESA's external European Component Irradiation Facilities (ECIF). The following users performed heavy ion and proton tests at RADEF in 2006:

- Alenia Alcatel Space, Toulouse, France
- Comité Européen des Assurances – CEA, Bruyere-le-Chatel, France
- EADS-Space Transportation, Bremen, Germany
- European Space Agency, ESA/ESTEC, Noordwijk, The Netherlands
- Finnish Meteorological Institute
- Helsinki University of Technology, Finland
- Hirex Engineering, Toulouse, France
- Institut für Datentechnik und Kommunikation-snetze – IDA, Braunschweig, Germany
- Instituto Nacional de Tecnica Aeroespacial – INTA, Madrid, Spain
- Oxford Instruments Analytical, Turku, Finland
- Saab Ericsson Space, Gothenburg, Sweden
- Technical University of Denmark – DTU, Copenhagen, Denmark
- University of Helsinki, Finland
- University of Padua, Italy
- Åboa Space Research, Turku, Finland

In figure 1 the distribution of beam time for different users is shown. The total beam time in 2006 was 576



hours, from which 432 hours were used for ESA or non-ESA users. Figure 2 shows the distribution of the use of beam time during the test campaigns.

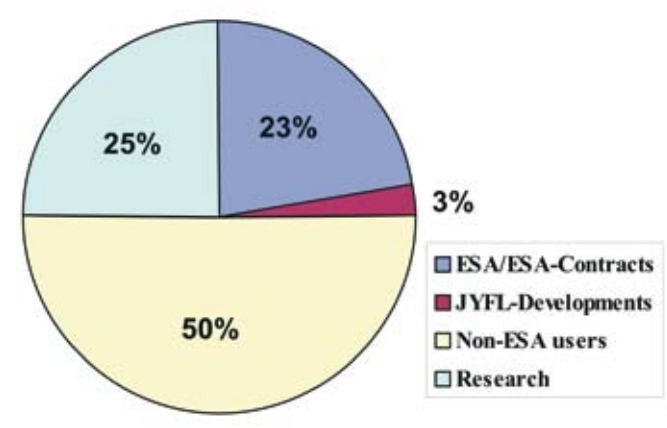


Fig. 1. Relative beam time distribution between ESA- and non-ESA users. In addition, about 30 % of beam time was used for the research or development of the facility. The research means the beam time, which has been allocated via the proposal submitting procedure.

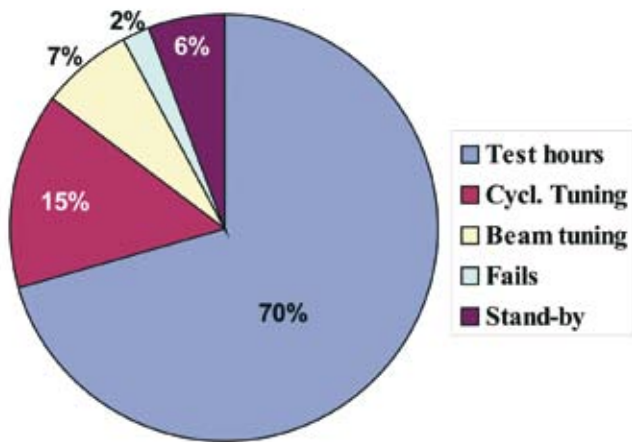
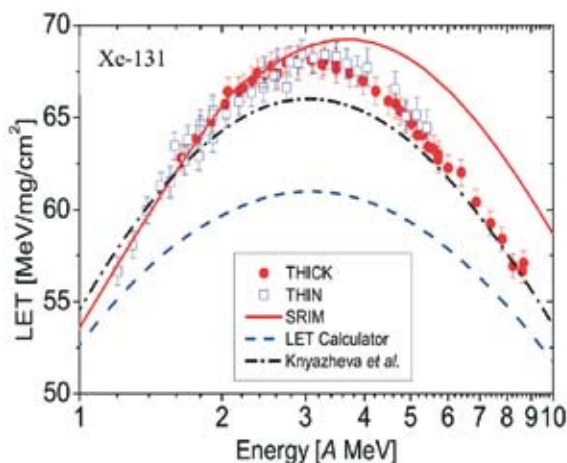


Fig. 2. Relative distribution of the beam time in the campaigns: "Test hours" means the beam-on-DUT time, "cyclotron tuning" corresponds to the time needed to tune the cocktail and the "beam tuning" the time needed for tuning the proper beams. "Fails" are the situations, when the cyclotron tuning or beam tuning have been taken more than four or one hours, respectively. "Stand by" corresponds to the time, when beam has been waiting in a Faraday cup.

Users performing radiation tests at RADEF often rely on semi-empirical prediction codes for determining the linear energy transfer (LET) of ions. However, it is seen that estimations calculated with different codes can have over 10% discrepancies, especially in the case of

Fig. 3. The results of our LET experiment. The points represent our measured data and the lines indicate the results extracted from the well known semiempirical prediction codes.

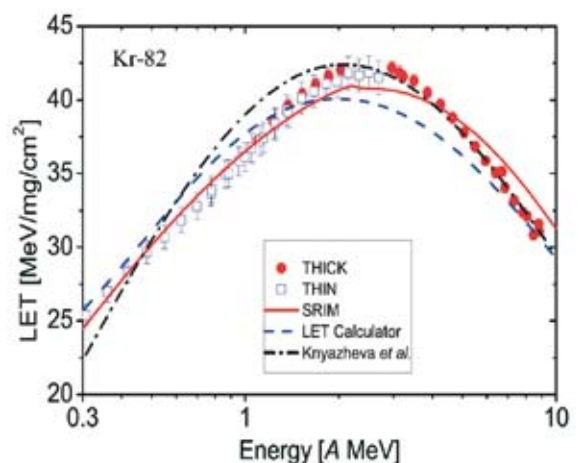


heavy ions with higher LET (e.g. xenon and krypton). As a consequence of the modern component fabrication techniques this has become an important issue when studying the radiation durability of electronics [1].

This LET problem and its consequences for accurate SEE testing were addressed at the 1<sup>st</sup> RADECS Thematic Workshop held in Jyväskylä, May 2005. In order to clarify this inconsistency we measured the LET of <sup>131</sup>Xe and <sup>82</sup>Kr ions in silicon in the energy ranges from 1.25·A to 8.6·A MeV and 0.35·A to 8.8·A MeV, respectively. The high energy ranges have not been previously measured for these ions.

There is a good agreement with measured values and simulations made with SRIM code[2] at low energies. This can be seen in figure 3.

In the case of Xe at high energies the SRIM code seems to overestimate the measured LET values. The LET Calculator [3], on the other hand, seems to underestimate the LET at higher energies for both ions. For krypton the measured LET values follow the SRIM estimates quite well at low energies (i.e. below 1.5·A MeV). The high energy behavior of LET with respect to SRIM estimations can be divided in two parts: in the energy range from 1.5·A to 5·A MeV the measured values are higher than



the SRIM values, and above 5.4 MeV measured LET values are below SRIM values. More details can be found in [4] (accepted to IEEE Trans. Nucl. Sci.).

The results obtained are our first steps towards a more precise way of assigning LET values to SEE data as acquired at ground SEE facilities. The LET of other ions used at the RADEF facility will also be measured and it is hoped that a common LET code can be produced in service of harmonizing LET values and ranges used throughout European Component Irradiation Facilities.

Our group also participated in RADECS2006 Workshop in September, held in Athens. We contributed in three papers; two of them were presented by the group members with one oral and one poster [4, 5, 6].

## Radio-medicine

The high-intensity proton beams, produced from the LIISA ion source, are used weekly in the production of  $^{123}\text{I}$  radioisotope for MAP Medical Technology Ltd. This production covers the needs of radioactive iodine for the 20 largest hospitals in Finland. The  $^{123}\text{I}$  based radio-medicines produced by MAP are mainly used in diagnosing brain-based diseases. They are also delivered for medical research work to many other European countries. During the year 2006 39 production runs were performed with the intensities between 40 to 47 microamperes.

## Ion Beam Applications

In experiments of Al film implantation a new element, Mn, was introduced to wide range of available ion beams of 6.4 Ghz ECR ion source connected to UHV chamber. Superconducting critical temperature  $T_c$  was

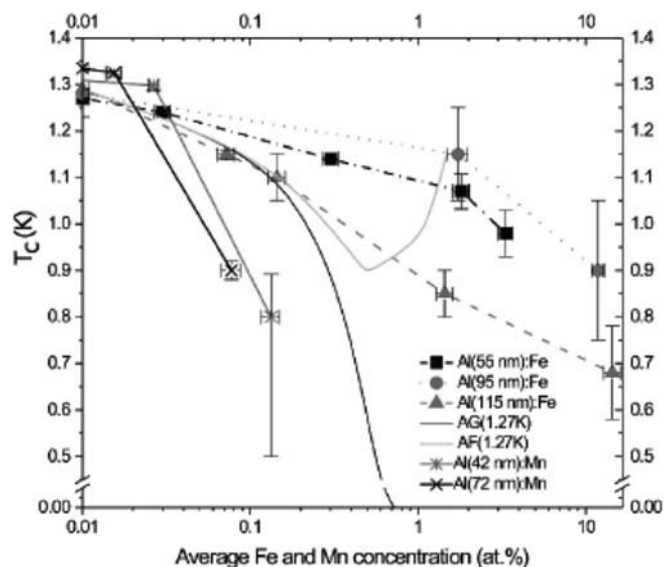


Fig. 4 [8]. Critical  $T_c$  temperature of Al films with respect to ion implanted impurity dose. AG and AF refer to values according Abrikosov and Gor'kov theory for dilute magnetic and antiferromagnetically interacting impurities having same initial suppression rate as ion implanted Fe.

measured in a cryostat in Nano Science Center (NSC). It was found that  $T_c$  is suppressed more efficient by Mn implantation with respect to earlier experiments with Fe [7,8], as is seen in figure 4. Therefore, certain CBT based applications needing  $\sim 10\text{mK}$  range  $T_c$  temperatures can be realized with sequential Mn ion implantation offering competitive and accurate method for  $T_c$  suppression with respect to e.g. chemical vapour or sputter deposition.

## Other Collaborations

With the funding from National Technology Agency, TEKES, a joint project with VTT Processes (Technical Research Centre of Finland) ended in November. It contained studies of different radiation based analyzing techniques of bio-fuels. The results are given in a master of thesis and were also presented to the steering group of the main project with representatives from Tekes, VTT

and eight industrial partners. The group found the results so interesting that it recommended starting a new project with the main focus being on neutron measuring techniques. This is planned to be started together with VTT and in collaboration with the ion source and plasma physics group from Lawrence Berkeley National Laboratory, USA.

One other undergraduate thesis project with a local company and the Cancer Therapy Center of the local hospital was also finalized in 2006.

## Ten Years Industrial Applications

The Industrial applications program of the accelerator laboratory celebrated 10 years of activity in 2006. With funding from 16 research and development projects, 12 research grants and research service the total income has reached 2.7 M€. In honour of this anniversary, the annual service income and revenues passed the 500 k€ milestone in 2006. The increase can be seen in figure 5, where the annual development of funding is shown.

Students have played a very important role in developing the laboratory's industrial applications. The main work has been made by them in their research training and master's or licentiate's theses (29 in total). In summer 2004 a second senior member joined the group, as RADEF started the ESA laboratory upgrade and more permanent technical expertise was needed. Although the main interest has been in industrial applications, the production of scientific publications has been kept at an active level. A total of 39 publications (22 refereed and 17 proceedings) in international journals have been produced in the research and development projects or in different collaborations since 1996. The annual amount of theses and publications are shown in figure 6.

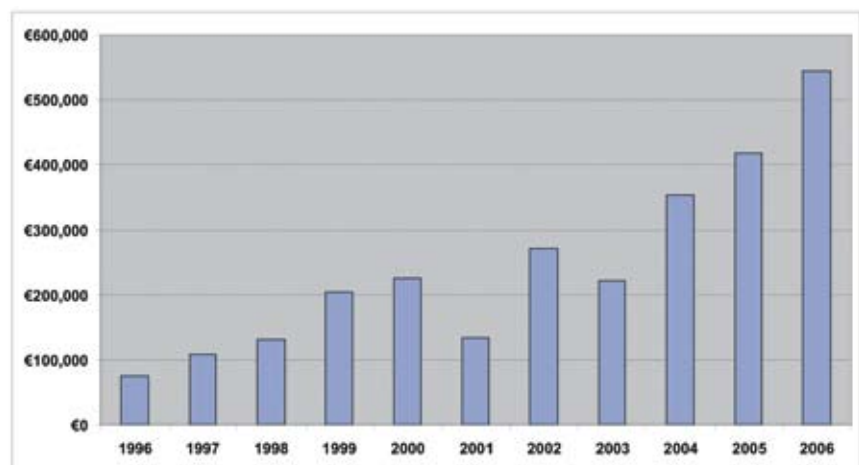


Fig. 5. The annual funding 1996–2006.



## References

- [1] R. Harboe-Sorensen, F. X. Guerre, J. G. Loquet, and C. Tizon, "Heavy-Ion single-event effects testing of lead-on-chip assembled high-density memories," *IEEE Trans. Nucl. Sci.*, vol. 50, no. 6, pp. 2322–2327, 2003.
- [2] J. F. Ziegler, J. P. Biersack, M. Ziegler, D. J. Marwick, G. A. Cuomo, W. A. Porter, and S. A. Harrison, *The Stopping and Range of Ions in Matter*, <http://www.srim.org>.
- [3] TVDG LET Calculator, Brookhaven National Laboratory, <http://www.tvdg.bnl.gov/LETCalc.html>.
- [4] A. Javanainen, T. Malkiewicz, J. Perkowski, W. H. Trzaska, A. Virtanen, G. Berger, W. Hajdas, R. Harboe-Sørensen, H. Kettunen, V. Lyapin, M. Mutterer, A. Pirojenko, I. Riihimäki, T. Sajavaara, G. Tyurin, H. J. Whitlow, *Linear Energy Transfer of Heavy Ions in Silicon* Proc. RADECS 2006 Workshop, 27-29 September, 2006, Athens, Greece
- [5] H. Kettunen, R. Harboe-Sørensen, I. Riihimäki, A. Javanainen, A. Pirojenko, K. Ranttila, A. Virtanen. *Radiation Effects Facility RADEF*, Proc. RADECS 2006 Workshop, 27-29 September, 2006, Athens, Greece
- [6] F. Garcia, K. Kurvinen, R. Orava, J. Heino, A. Virtanen, H. Kettunen and M. Tenhunen, *Radiation Shielding Study of Advanced Data and Power Management Systems (ADPMS) Housing for LEO and MEO Earth Orbits of Carbon Fiber Reinforced Plastic (CFRP) with Wolfram Laminate Using Geant4 Simulations and Experiments*, Proc. RADECS 2006 Workshop, 27-29 September, 2006, Athens, Greece
- [7]. P. Jalkanen, V. Touboltsev, H. Koivisto, P. Suominen, T. Suppala and K. Yu. Arutyunov, J. Räisänen, *JAP* 98, (2005)
- [8] P. Jalkanen, V. Tuboltsev, A. Virtanen and K. Yu. Arutyunov, J. Räisänen, Oleg Lebedev and Gustaaf Van Tendeloo, Submitted to *Solid State Comm.* at Nov. 2006.

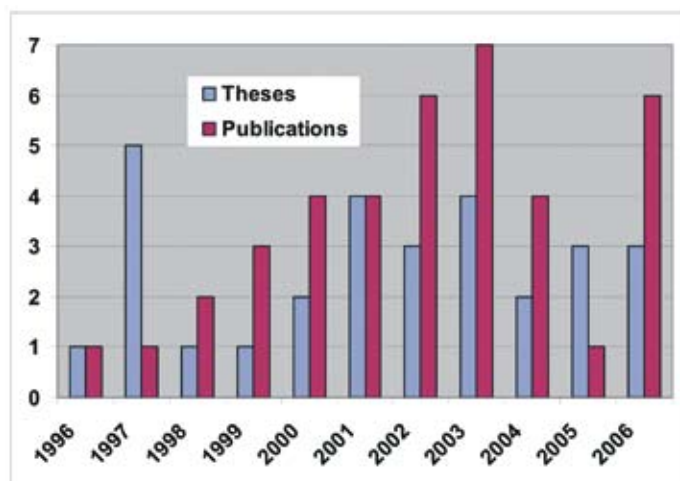


Fig. 6. The annual amount of theses (master or licentiate) and publications made in research and development projects or industrial collaborations during 1996–2006.

# Nuclear Structure, Nuclear Decays, Rare and Exotic Processes

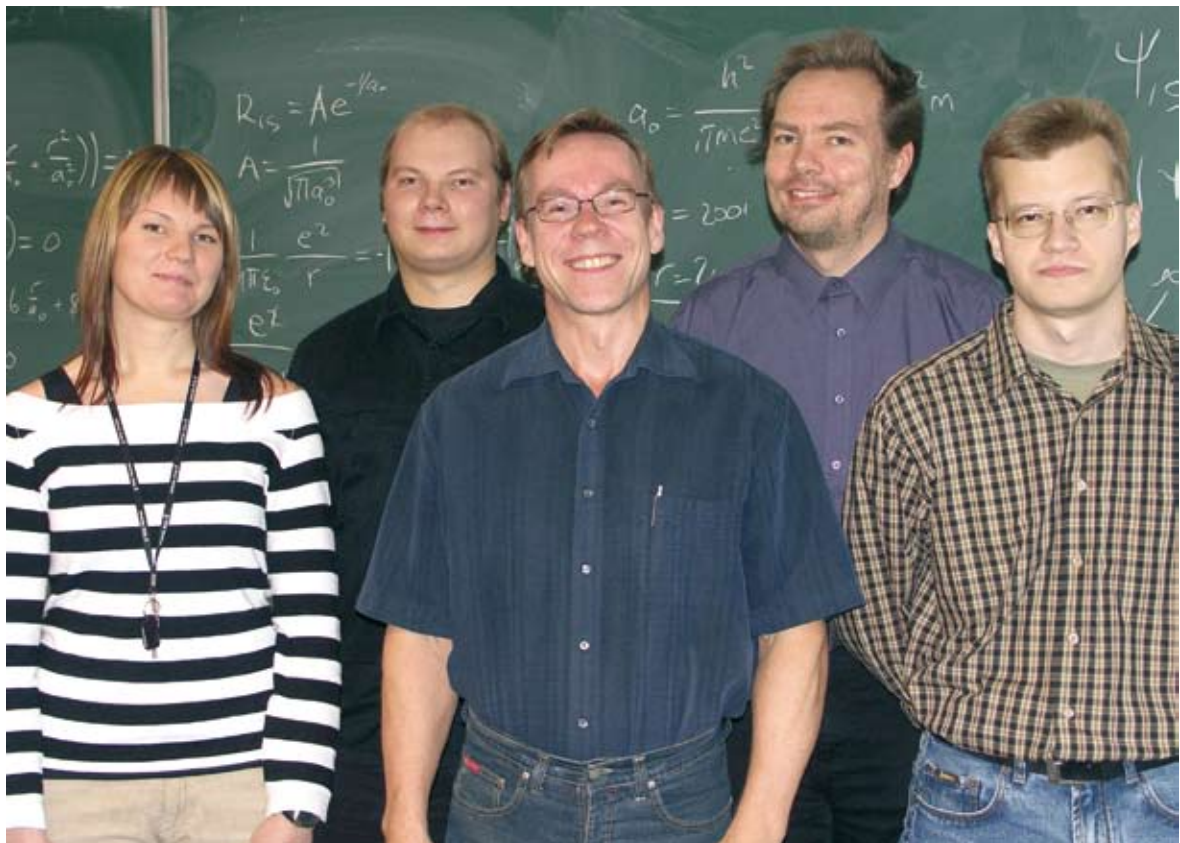
Jouni Suhonen

Jouni Suhonen, professor  
 Jussi Toivanen, assistant  
 Johannes Hopiavuori, docent  
 Markus Kortelainen, postdoctoral researcher  
 Jenni Kotila, graduate student  
 Mika Mustonen, graduate student  
 Sami Peltonen, graduate student  
 Heikki Heiskanen, MSc student -31.8.  
 Pekka Toivanen, MSc student

## Nuclear Matrix Elements Related to Double Beta Decays

Detection of the neutrinoless double beta decay is essential in probing physics beyond the standard model of electroweak and strong interactions. Detection of this decay mode assigns the neutrino to be a Majorana particle. In addition, the related experimental half-lives can be used to access the absolute mass scale of the neutrino. In extraction of the neutrino masses the involved nuclear matrix elements play an essential role:

Group: from the left, first row: Jenni Kotila, Jouni Suhonen, Mika Mustonen, from the left, second row: Markus Kortelainen and Sami Peltonen (out of the group: Johannes Hopiavuori and Jussi Toivanen).



their uncertainties immediately reflect in uncertainties of the extracted neutrino masses.

The transition amplitude of double beta decay consists of virtual single-beta-decay transitions from the ground state of the even-even mother nucleus to the virtual states of the adjacent odd-odd nucleus (the 'left leg'), and from the virtual states further to the states of the even-even daughter nucleus of double beta decay (the 'right leg'). The left and right legs can be tested by using electron-capture and beta-decay data which, unfortunately, are quite scarce. This is why related experiments are urgently called for.

We have suggested recently that the above-described virtual transitions can be probed by experiments measuring muon-capture rates to the involved virtual states. This process involves the capture of a negative muon from the atomic s orbital without emission of a gamma quantum. Muon capture does not probe directly the virtual transitions but rather the wave functions of the virtual states.

In the so-called mass mode of the neutrinoless double beta decay the involved two nucleons exchange a light Majorana neutrino and average value of the exchanged momentum is of the order of 100-200 mega-electronvolts. Thus the involved nucleons are on average at close distance from each other. There is, however, a minimum relative distance after which the two nucleons start to overlap. In nuclear matter this overlapping cannot occur and in the theoretical description of neutrinoless double beta decay one needs to take into account this fact. Based on this it has been argued that special measures have to be taken when performing nuclear-structure calculations using the mean-field picture with residual two-body interactions between the two interacting nucleons. Traditionally these measures boil down to introducing an explicit Jastrow correlation function

into the involved two-body transition matrix elements. This method simply cuts out the close-range part of the relative wave function of the two nucleons and thus violates its normalization. Using the Jastrow method in numerical calculations considerable corrections to the involved Fermi and Gamow-Teller nuclear matrix elements have been reported in the literature.

We have recently studied the effect of short-range correlations by using the more complete new concept of unitary correlation operator method (UCOM). In this method a unitary correlation operator moves a pair of nucleons away from each other whenever they start to overlap. This method also conserves the probability normalization of the relative wave function. We have tested this method against the Jastrow method in the cases of  $^{48}\text{Ca}$  and  $^{76}\text{Ge}$  double beta decays. The nuclear structure part was calculated by using the nuclear shell model for  $^{48}\text{Ca}$  decay and the proton-neutron quasiparticle random-phase approximation for  $^{76}\text{Ge}$  decay. In Fig. 1 we show the multipole decomposition of the matrix element for the  $^{76}\text{Ge}$  decay.

From Fig. 1 and the  $^{48}\text{Ca}$  results one concludes that the Jastrow method cuts off relevant parts of the many-body

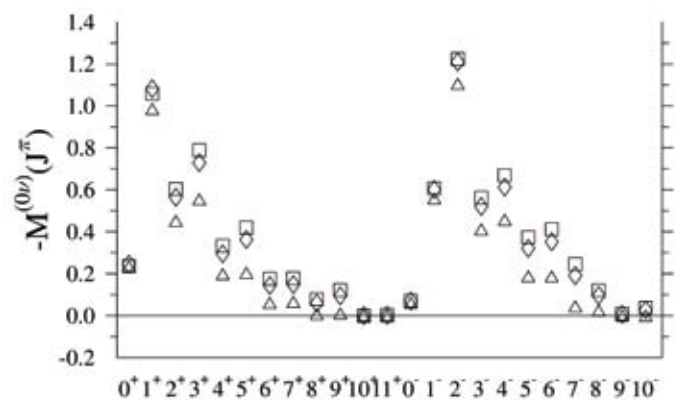


Fig. 1. Multipole decomposition of the nuclear matrix element for  $^{48}\text{Ca}$  decay. The cases are: no short-range correlations included (squares), with Jastrow correlations (triangles) and with UCOM correlations (diamonds).

wave function for high values of angular momentum of the intermediate nuclear states. This leads to excessive reduction in the magnitudes of the nuclear matrix elements. At the same time the UCOM reduces the magnitudes of the matrix elements only moderately, roughly equally for all multipoles. Our results put to question the recent calculations where short-range and tensor correlations cause large effects on the nuclear matrix elements of neutrinoless double beta decay. Study of the effects of the UCOM procedure upon heavier nuclei is in progress.

## Theoretical Rates for Highly-Forbidden Beta Decays

Computer programs have been created to compute rates of highly-forbidden beta-decay transitions. We have used these programs to estimate the decay rates of the fourth-forbidden non-unique beta decays of the odd-mass nuclei  $^{113}\text{Cd}$  and  $^{115}\text{In}$ . The corresponding decay schemes with experimental data have been displayed in Fig. 2.

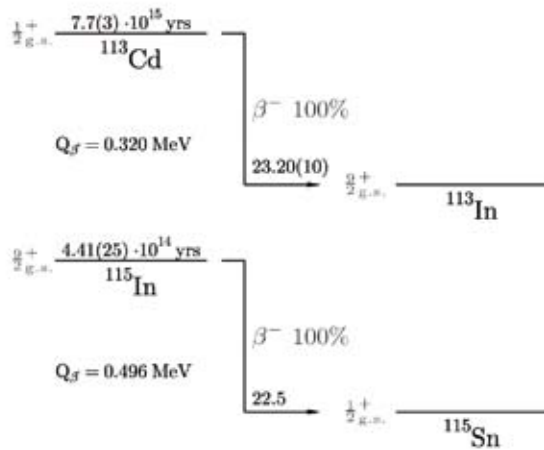


Fig. 2. Experimental data on the fourth-forbidden non-unique beta decays of  $^{113}\text{Cd}$  and  $^{115}\text{In}$ .

The nuclear model employed in the calculations was the microscopic quasiparticle-phonon model (MQPM) where QRPA (quasiparticle random-phase approximation) phonons are combined with BCS quasiparticles to form a non-orthogonal overcomplete basis in which a realistic residual hamiltonian is then diagonalized. The computed half-lives are  $4.95 \times 10^{16}$  years for the decay of  $^{113}\text{Cd}$  and  $1.99 \times 10^{15}$  years for the decay of  $^{115}\text{In}$ . These agree reasonably well with the corresponding experimental values shown in Fig. 2.

We have used the formalism of highly-forbidden beta transitions to investigate the decay transitions of Fig. 3 for the beta decay of  $^{96}\text{Zr}$ .

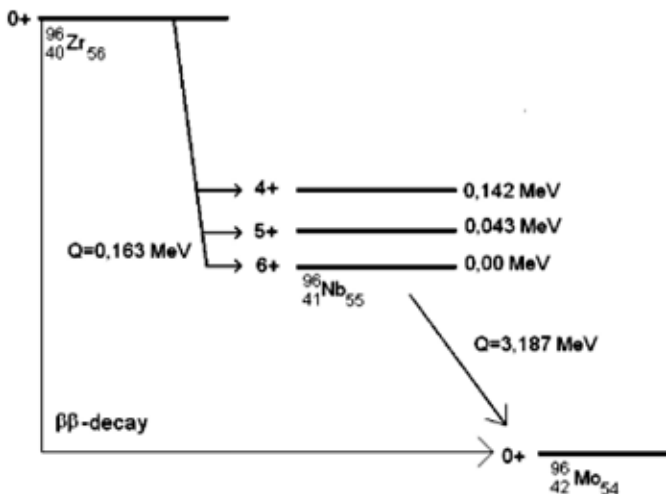


Fig. 3. Single and double beta decays of  $^{96}\text{Zr}$ . Data on the decay Q-values and excitation energies of the first three states of  $^{96}\text{Nb}$  are also indicated.

The involved transitions between the ground state of the mother nucleus  $^{96}\text{Zr}$  and the states of the daughter nucleus  $^{96}\text{Nb}$  are as follows: transition to the  $6^+$  state is sixth-forbidden non-unique, transition to the  $5^+$  state is fourth-forbidden unique, and transition to the  $4^+$  state is fourth-forbidden non-unique. Our calculation shows that the fourth-forbidden unique transition to the  $5^+$  state dominates and the total computed half-life of the decay is  $2.4 \times 10^{20}$  years. There are no measured data on the beta-decay half-life to compare with.

Interestingly enough,  $^{96}\text{Zr}$  decays also via double beta decay with the geochemically measured half-life of

$(3.9 \pm 0.9) \times 10^{19}$  years. Comparing the computed beta-decay half-life with the geochemical double beta half-life indicates that  $^{96}\text{Zr}$  decays principally by double beta decay.

### Detection Rates for Supersymmetric Dark Matter

The lightest supersymmetric particle, LSP, of supersymmetric theories of particle physics is considered to be an important candidate for constituents of cold dark matter (CDM) of the Universe. Nucleus-LSP elastic scattering can be used for direct detection of the LSP and that is why it is of great interest to chart the possible detector nuclei and their sensitivity to the LSP detection.

We have calculated the structure of the ground states of the  $^{23}\text{Na}$ ,  $^{71}\text{Ga}$ ,  $^{73}\text{Ge}$ ,  $^{127}\text{I}$  and  $^{133}\text{Cs}$  detector nuclei by using the nuclear shell model. Since the scattering rate of the LSPs is spin dependent for the used odd-mass detector nuclei, the description of the magnetic moments of the ground states of these nuclei is extremely important. Our shell-model results reproduce the measured magnetic moments quite well. We were able to summarize our results in a way that enables evaluation of the LSP detection rates independently of the used parametrizations of supersymmetric models. Studies of the inelastic channels of LSP detection, e.g. for  $^{83}\text{Kr}$ ,  $^{73}\text{Ge}$  and  $^{127}\text{I}$  are in progress.

### Systematics of Alpha-Decay Hindrance Factors for Rotational States

We have used a simple model to explain the alpha-decay fine structure in rotational nuclei. We have used a coupled-channels formalism to estimate decay widths and a double-folding procedure to compute the interac-

tion between the decay daughter and the alpha particle. The simple rotational model is able to explain very well the total half-lives and decay widths to the first  $2^+$  states. Our analysis reveals that the effective nucleon-nucleon interaction is influenced by alpha clustering and this dependence changes with the mass of the decaying nucleus. Hence, alpha-decay fine structure is in a position to improve our knowledge about how the effective nucleon-nucleon potential changes in the presence of alpha clustering.

Our results for decays to the first  $4^+$  states have not the same quality as the results for the  $2^+$  states, but nevertheless are in fair agreement with the data for decay widths and half-lives. Interestingly, our results for the intensity of decay to a rotational state depends on the deformation of this state. This pattern is, however, not in agreement with part of the data on decays to the  $4^+$  states. The reason for this deviation is still unclear.

### Gamma and Beta Decays Involving Two-Phonon Structures

We have developed the Microscopic Anharmonic Vibrator Approach (MAVA) for microscopic description of low-lying two-phonon states in even-even nuclei. The building blocks of the two-phonon states are the quasiparticle random-phase approximation (QRPA) phonons. A realistic microscopic nuclear Hamiltonian is diagonalized in a basis containing one-phonon and two-phonon components yielding a dynamical mixing of these two degrees of freedom. We have used MAVA to describe energetics and gamma decays of low-lying collective states in chains of even-even Cd, Ru and Mo isotopes.

We have extended the MAVA to describe states of odd-odd nuclei and their beta decay to the adjacent even-even nuclei. This model, coined as the proton-neutron

MAVA (pnMAVA), has been applied to describe beta-decay feeding of the low-lying collective states in the  $^{106}\text{Pd}$  and  $^{108}\text{Pd}$  nuclei. The results have been published and are encouraging. The pnMAVA is currently being applied to the Cd, Ru and Mo chains of isotopes. Since the  $3(N-Z)$  sum rule, i.e. the Ikeda sum rule, is quite accurately satisfied by the pnMAVA, it can also be used to predict strength functions of charge-exchange reactions. In a similar vein we can apply the pnMAVA to describe double beta decays in medium-heavy and heavy nuclear systems.

### New Extension of the MQPM: The pnMQPM for Beta Decays of Odd-Mass Nuclei

We are currently on the way to extend the formalism of the microscopic quasiparticle-phonon model, MQPM, to its proton-neutron sister model, the pnMQPM (proton-neutron MQPM). In the MQPM a BCS quasiparticle was coupled with a QRPA (quasiparticle random-phase approximation) phonon to create a three-quasiparticle state. Then the residual hamiltonian was diagonalized in a basis consisting of these three-quasiparticle states and all the one-quasiparticle states. In this way the wave functions of states of an odd-mass nucleus were created by using the adjacent even-even nucleus as a reference.

As in the MQPM, also in the pnMQPM the residual hamiltonian is diagonalized in the basis of one- and three-quasiparticle states, but the three-quasiparticle states are based on pnQRPA (proton-neutron QRPA) phonons instead of QRPA phonons. One thus generates the wave

functions of the states of an odd-mass nucleus by using the neighboring odd-odd nucleus as a reference. This change in the construction of the basis states is better suited for description of beta-decay transitions in odd-mass nuclear systems since the pnQRPA formalism satisfies the Ikeda sum rule for the reference nucleus. Development and applications of the pnMQPM formalism is in progress.

### Large-Scale Computing with the Program 'Eicode'

The shell-model code EICODE has been under constant development and use during the year 2006. A new method that speeds up j-scheme nuclear shell-model calculations has been developed. The method allows the low-spin states of a nucleus to be calculated up to a hundred times faster than with the previously available j-scheme methods. The new method has been implemented into the shell-model code EICODE. Shell-model calculations for various nuclei involved in the cold dark matter search, such as  $^{83}\text{Kr}$  and  $^{133}\text{Cs}$ , have been made using the new method.

Other improvements of EICODE are the introduction of seniority truncations, as in the shell-model code NATHAN, and a center-of-mass quantum number truncation scheme for no-core shell model type calculations. The new speedup method also allows an efficient compression of the used density matrix element data, thus making it possible to more easily perform large shell-model calculations that require very large amounts of density matrix elements.

# Nanophysics and Nanotechnology

Markus Ahlskog, Konstantin Arutyunov, Ilari Maasilta and Sorin Paraoanu

The Nanophysics group is mainly dedicated to experimental research in some of the key issues in nanoscale or mesoscopic physics. Main activities are mesoscopic superconductivity, thermal effects in mesoscopic devices, and the fundamentals of solid state quantum computing. In addition, we do research on the physical properties of single carbon nanotubes.

## Thermal Properties of Nanostructures and Radiation Detector Development

Ilari Maasilta

The main research direction of the thermal nanostructure research team led by Dr. Maasilta is to (a) understand energy flow mechanisms in low-dimensional geometries, and (b) utilize this knowledge in the development of ultrasensitive thermal and radiation sensors (bolometry).

Markus Ahlskog, professor  
Konstantin Arutyunov, senior researcher  
Shadyar Farhangfar, senior researcher  
Ilari Maasilta, academy researcher  
Sorin Paraoanu, academy researcher  
Andreas Johansson, postdoctoral researcher (also with Nanoelectronics group)  
Lasse Taskinen, postdoctoral researcher  
Asaf Avnon, graduate student  
Khattiya Chalapat, graduate student 1.4.-  
Terhi Hongisto, graduate student  
Jenni Karvonen, graduate student  
Kimmo Kinnunen, graduate student  
Panu Koppinen, graduate student  
Jian Li, graduate student 1.8.-  
Jarkko Lievonen, graduate student  
Minna Nevala, graduate student  
Maciej Zgirski, graduate student  
Hannu-Pekka Auraneva, MSc student  
Ville Haaksluoto, MSc student  
Olli Herranen, MSc student  
Tero Isotalo, MSc student  
Henri Jaakkola, MSc student  
Jaakko Leppäniemi, MSc student  
Davie Mtsuko, MSc student  
Mikael Pajunen, MSc student  
Harri Pitkänen, MSc student  
Kari-Pekka Riikonen, MSc student  
Lasse Väistö, MSc student  
Sami Ylinen, MSc student

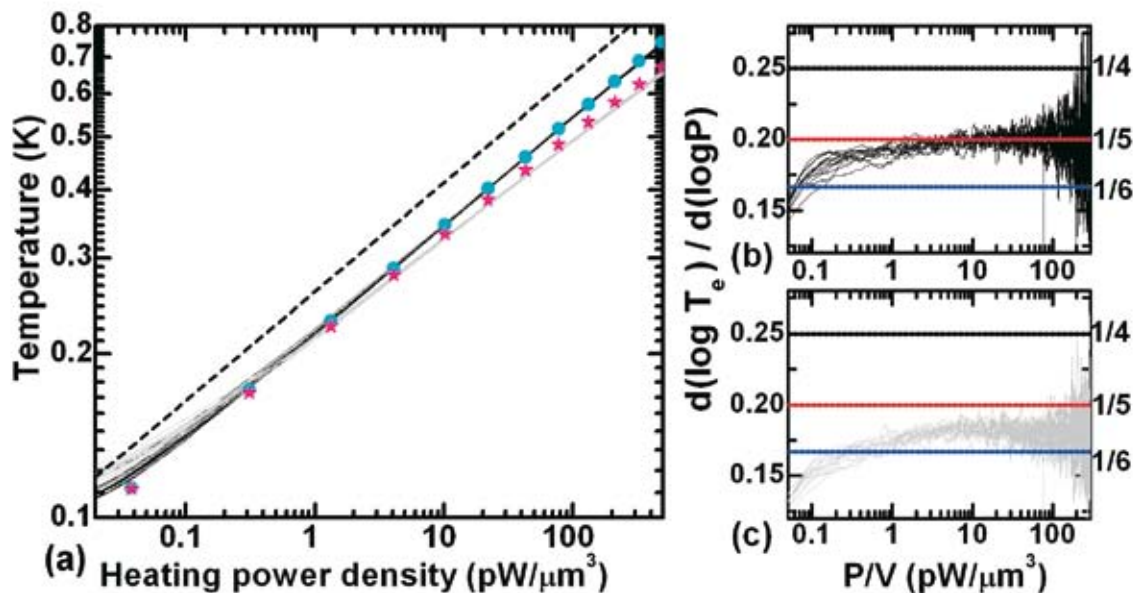


## Electron-Phonon Interaction in Nanostructures

Group: From the left, first row: Jenni Karvonen and Minna Nevala, second row: Kimmo Kinnunen, Panu Koppinen, Ilari Maasilta, Tero Isotalo and Henri Jaakkola

We have continued to utilize normal-metal-superconductor tunnel junctions (NIS) for ultrasensitive thermometry in sub-Kelvin temperature range. NIS-junctions can be used to characterize the electron-phonon (e-p) interaction in metals very accurately.

Fig. 1. (a) Solid: Temperature of a Cu wire vs. Joule heating power at two different locations. (b) and (c) The measured temperature vs power dependencies are not the same at those two locations.





The main results achieved in 2006 are: (a) Measurement of the e-p interaction in the Kondo alloy Aluminum doped with Manganese for several Mn concentrations. We have shown that by using this material, the sensitivity of a sub-Kelvin bolometer can be improved by a factor of 5 compared to typical materials. This is because the strength of the e-p interaction varies significantly with the concentration of the Mn impurities. Our results will be applied in the next generation bolometers developed for NASA and observatory applications by the National Institute for Standards and Technology (NIST) in Boulder CO. (b) We have discovered that significant temperature gradients develop quite easily even in good conductors such as Cu and Au at sub-Kelvin temperatures. This affects the design of solid state coolers and bolometers, and is critical for the correct interpretation of e-p interaction measurements, but can be understood with the help of e-p interaction theory and electronic thermal conduction by diffusion.

### Thermal Transport in Insulating Nanostructures

Theoretical and experimental work on phonon transport in low-dimensional structures is also a focus field. We have started an experimental project to study phonon transport in novel insulating materials, such as SiC and AlN. High quality piezoelectric AlN for this purpose is processed by reactive sputtering in collaboration with Uppsala University. We have developed new lithographic techniques to fabricate complex suspended AlN structures with tunnel junction thermometers integrated. These structures will be used to study the multitude of interesting thermal phenomena associated with low dimensional piezoelectric phonons, which carry EM fields with them. Numerical FEM modelling of phonon trans-



Fig. 2. A suspended mesoscopic AlN structure.

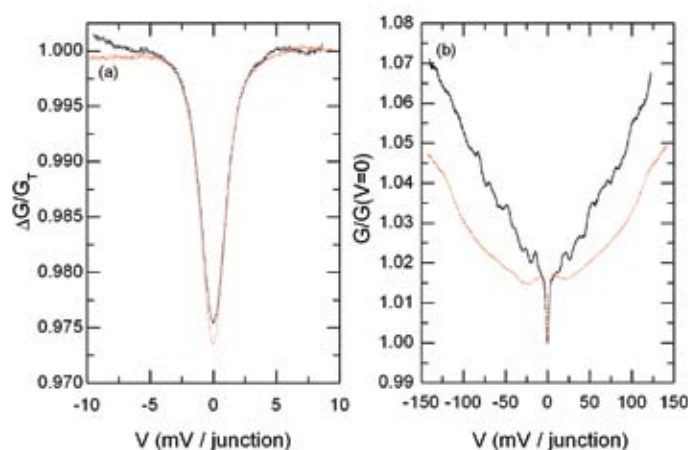


Fig. 3. The differential conductance of a Al/AlO<sub>x</sub>/Al tunnel junction device at 4.2 K before (black) and after (red) annealing at 400 C. (a) the Coulomb blockade feature near zero bias shows that the charging energy increases and (b) the resonances caused by impurities disappear with the annealing.

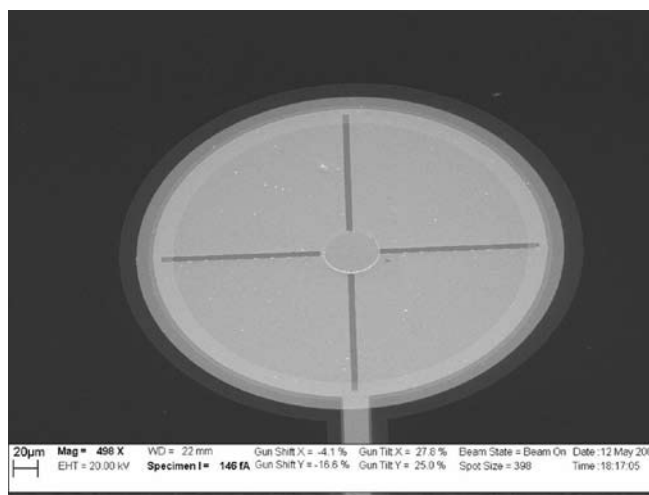


Fig. 4. A novel TES sensor design with low noise.

port in complex boundary geometries is performed in collaboration with mathematicians at the St. Petersburg State University.

### Development of Tunnel Junctions

As tunnel junctions are of critical importance in our applications, we have also managed to show how their characteristics can be improved. With our home-built vacuum annealing system we have demonstrated that by annealing Al- $\text{AlO}_x$ -Al tunnel junctions between 350–450 degrees C their characteristics can be improved quite significantly. They become completely stable with time (no aging) and many negative properties of the  $\text{AlO}_x$  barrier disappear (such as unwanted resonances). The change in the measured properties can be explained with the barrier thickness and height both increasing with annealing. This technique appears to have wide relevance in applications such as quantum bit readouts and sensitive measurements of current noise.

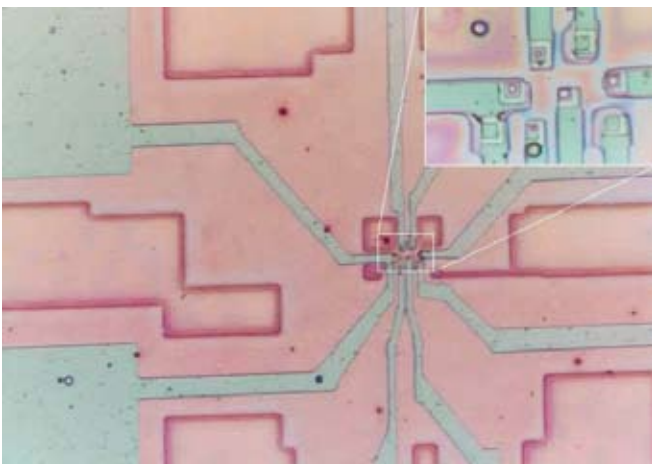


Fig. 5. A sample with 8 NbN/TaN/NbN SNS Josephson junctions.

### Superconducting Transition Edge Sensors (TES) for X-ray calorimetry

Superconducting transition edge microcalorimeter development continued with a project funded by the European Space Agency, in collaboration with Oxford Instruments Analytical Oy. The long term goal for ESA is to develop a cryogenic imaging spectrometer in the 0.1–10 keV band with a few eV resolution, to be installed onboard a satellite (XEUS). We have shown that using novel geometric designs, the noise properties of the TES sensors can be improved, predicting clear improvements on the detector energy resolution. In addition, we have calculated how to optimally operate TES sensors, when their heat dissipation is limited by a ballistic phonon flow in 2D membranes (has shown to be a realistic situation).

### NbN/TaN/NbN SNS Josephson Junction Development for Superconducting Digital Electronics

The superconducting Rapid-single-flux-quantum (RSFQ) logic is the technology with highest speeds of any digital electronics family. It is based on non-hysteretic Josephson junctions, which are traditionally made with tunnel junctions and external shunt resistors. However, in recent years interest has grown on using naturally non-hysteretic SNS Josephson junctions. We have started the development of high quality SNS junctions from top quality epitaxial NbN/TaN/NbN trilayers, fabricated by pulsed laser ablation by our collaborators at the Indian Institute of Technology, Kanpur. The NbN films have critical temperatures ranging up to 17 K, allowing for the possibility that the RSFQ logic can be supported by simple closed cycle coolers operating at around 10 K.

## Flux Penetration Avalanches in Ultrahigh Quality Niobium Nitride

We have continued the collaborative project between NSC, Indian Institute of Technology Kanpur and University of Oslo, where the goal is to study the thermomagnetic instabilities occurring with flux penetration into epitaxial NbN films. Images are obtained with the magneto-optical technique (measurements performed in Oslo). Fig. 6. shows how the flux penetration develops with increasing magnetic field. The flux forms sophisticated dendritic avalanche patterns and can have a fractal dimension.

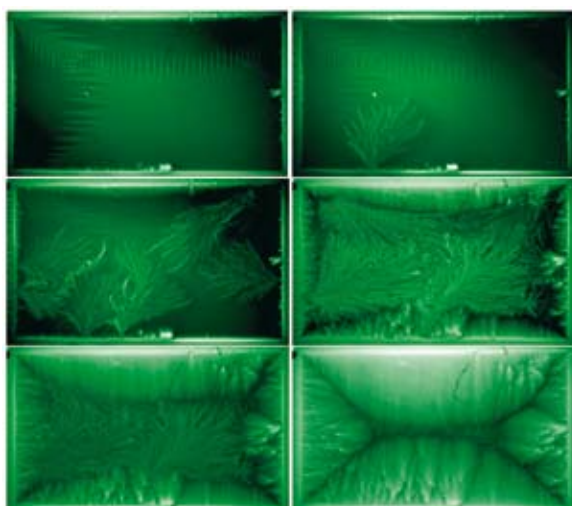


Fig. 6. Flux penetration into an epitaxial NbN film as a function of applied magnetic field, measured by magneto-optical imaging. Image courtesy of T. Johansen, Oslo University.

## Mesoscopic Superconductivity

Konstantin Arutyunov



Fig.7. Mesoscopic superconductivity group inside electromagnetically shielded room constructed specially for precision ultra-low-temperature measurements using  $^3\text{He}/^4\text{He}$  Kelvinox-400 dilution refrigerator. Acknowledging extreme accuracy in designing the measuring set-up for their flagship product *Oxford Instrument Superconductivity* assigned an honorable "Reference" tag to our site.

## Nanotechnology

We have refined our method of progressive reduction of pre-fabricated nanostructures by low-energy ion bombardment. Fig. 8. demonstrates evolution of aluminum nanowire after a sequence of  $\text{Ar}^+$  sputterings. Very precise adjustment of ion sputtering parameters enables us to trace evolution of size phenomena on a same nanowire from 100 nm down to 10 nm with accuracy  $\sim 1$  nm (Fig. 9a). In collaboration with VTT patent application FIN-20060719 has been filed in August 2006.

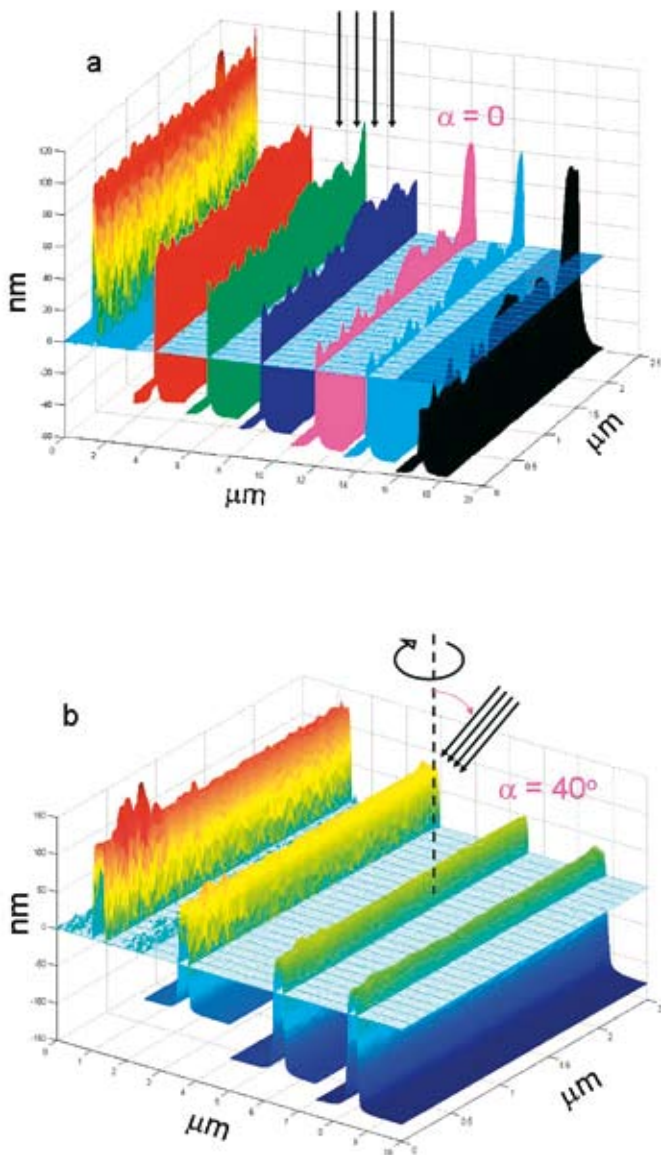


Fig. 8. SPM pictures illustrating evolution of the same aluminum nanowire after sessions of ion beam sputtering. Arrows illustrate the direction of bombardment with 1keV Ar<sup>+</sup> ions. a) Constant angle perpendicular to the plane of the structure. Note progressive development of structural inhomogeneity. b) Sputtering of a similar nanowire at 40° while rotating the substrate. Note the 'polishing' effect removing the original sample roughness. In both cases silicon substrate is sputtered faster than aluminum. Plane with grating (height = 0) separates silicon from aluminum.

## Electron Transport in One-dimensional Superconductors

Progressive reduction of the effective diameter of a nanowire has been applied to trace evolution of the shape of superconducting transition  $R(T)$  in quasi-one-dimen-

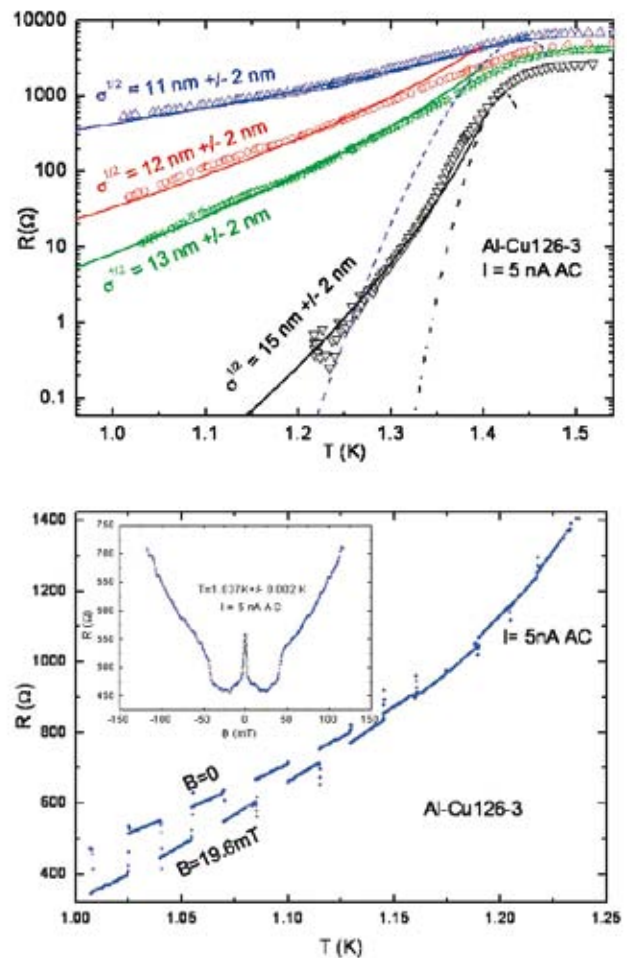


Fig. 9. a) Resistance vs temperature for the thinnest samples obtained by progressive reduction of the diameter of the same aluminum nanowire Al-Cu126-3. Note dramatic changes in slope of the  $R(T)$  dependence when effective diameter is changed by +/- 1 nm. Fitting using 'orthodox' thermal fluctuation model is shown with dashed lines for 11 and 15 nm samples. Fitting using quantum phase tunneling model is shown with solid lines. b) Slowly recorded (~ 1 hour) resistance vs temperature dependence for 11 nm sample from Fig. 9a. While sweeping the temperature few times perpendicular magnetic field  $B = 19.6$  mT was switched on and off. Top branch corresponds to zero field, while the lower one - to field 'on'. Inset: resistance vs perpendicular magnetic field for the same sample measured at constant temperature and small AC current.

sional aluminum structures. In nanowires with effective diameter  $<15$  nm the  $R(T)$  dependencies are much wider than predicted by the model of thermally activated phase slips (Fig. 9a). The effect can be accounted for quantum fluctuations of the order parameter. Negative magnetoresistance is observed in the thinnest samples (Fig. 9b). Experimental results are in reasonable agreement with existing theoretical models. The effect should have a universal validity indicating breakdown of zero resistance state in a superconductor below a certain scale. The work is done in tight collaboration with theoretical group from Institute for Nanotechnology, Forschungszentrum Karlsruhe, Germany.

It has been observed that critical temperature of superconducting nanowires systematically varies with reduction of the wire cross section (Fig. 10). In collaboration with theoretical group of University of Antwerp, Belgium it was shown that the effect originates from size-dependent resonances in the superconducting density of states. The results are published in *Physical Review B* 74, 052502 (2006).

### Tunneling Spectroscopy of Persistent Currents in Superconducting Microrings

Our recent pioneering results on solid state interferometry [K. Arutyunov and T.T. Hongisto, *Phys. Rev. B* 70, 064514 (2004)] triggered an intensive collaboration with theorists. In collaboration with groups from Institute for Physics of Microstructures, Russian Academy of Sciences and University of Antwerp, Belgium it has been shown that apart from observation of a novel

Fig. 11. a) Experimentally observed magnetic field modulation of a tunnel current in NIS structure with superconducting electrode in the shape of  $25 \mu\text{m} \times 25 \mu\text{m}$  loop. The inset shows variation of the period of the oscillations. b) Calculated corresponding dependence of the current density and jumps of vorticity  $\Delta L$  (inset).

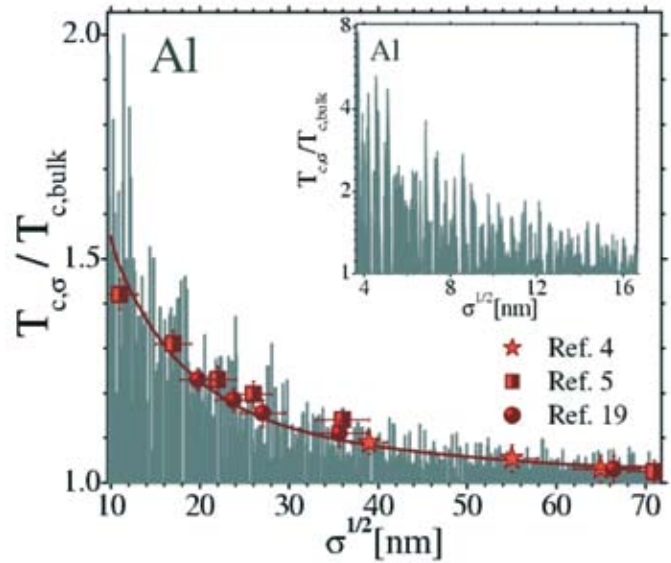
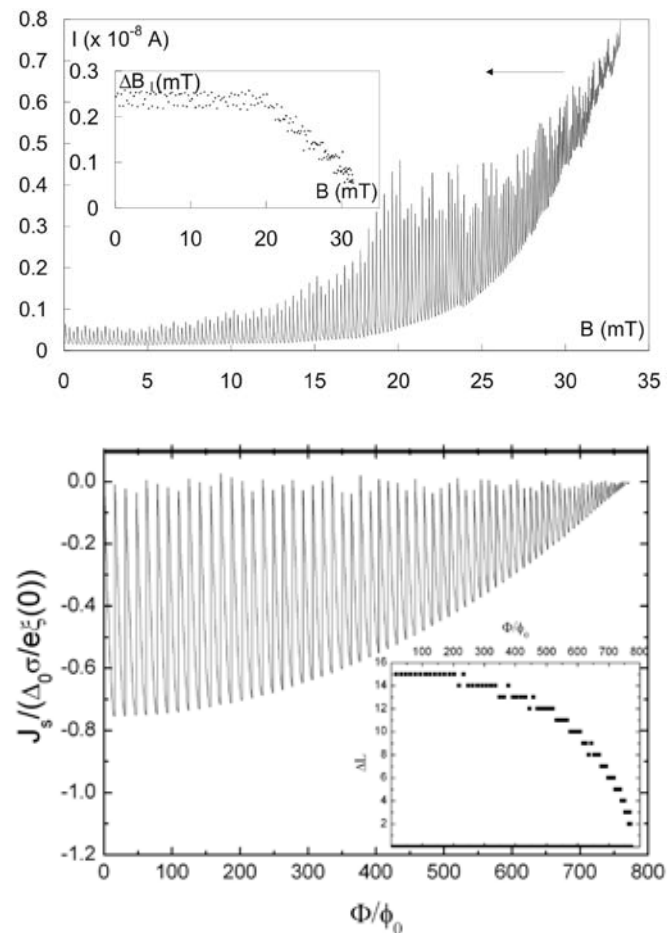


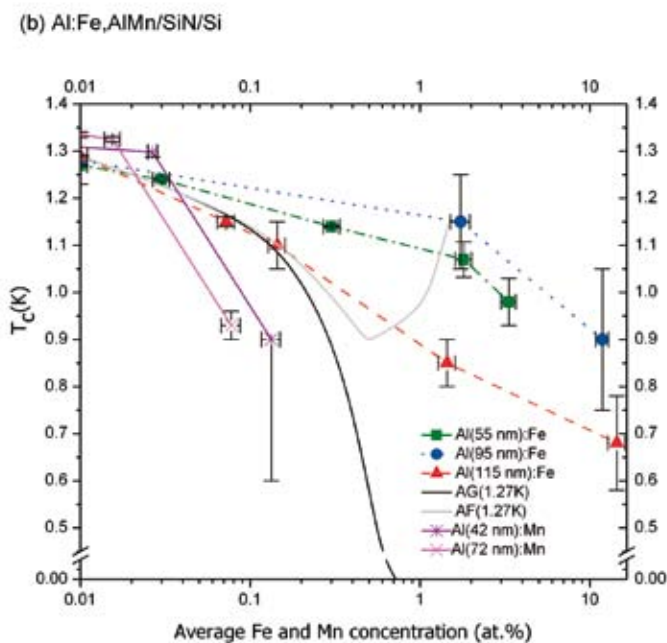
Fig. 10. Critical temperature  $T_{c,\sigma}/T_{c,bulk}$  versus the square root of the cross section  $\sigma$  of a cylindrical Al nanowire. Symbols are experimental data from our own results and from literature, the solid curve is a guide to the eye and indicates the general trend of the experimental results. Inset: the same dependence but in the small- $\sigma$  region.



physical effect, the method enables probing of persistent currents in superconducting nanorings (Fig. 11). The results are published in *Europhys. Lett.* 75, 315 (2006). This approach opens wide horizons in experimental study of quantum coherent phenomena in various micro- and nanostructures.

## Spin Doping of Low Dimensional Superconductors

Recently there appeared a number of publications predicting unusual behavior of low dimensional superconductors with low concentration of residual magnetic impurities.



In collaboration with the material science group from JYFL cyclotron lab (Dr. A. Virtanen) ion implantation of Fe and Mn into Al thin films was used for effective modification of Al superconductive properties. Critical temperature of the transition to superconducting state was found to decrease gradually with implanted Fe concentration. It was found that suppression by Mn implantation is much stronger compared to Fe. At low concentrations of implanted ions, suppression of the critical temperature can be described with reasonable accuracy by existing models, while at concentrations above 0.1 at. % a pronounced discrepancy between the models and experiments is observed. Å-resolution TEM analysis (Fig. 12b) has been done in collaboration with EMAT group of University of Antwerp, Belgium. Results will be published in *Sol. St. Comm.*, (2007).

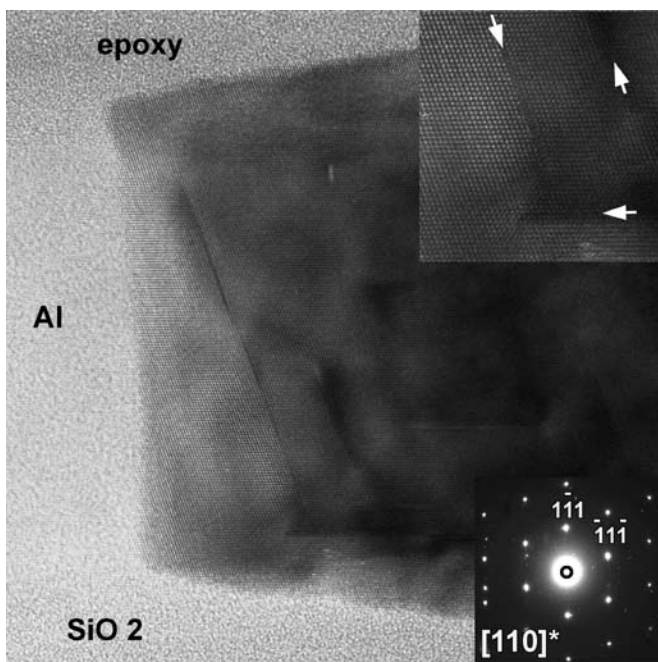


Fig. 12. a) Dependence of critical temperature in Al films grown on SiN/Si substrates and subsequently implanted with Fe and Mn. Lines stand for theoretical predictions of the Abrikosov- Gor'kov (AG) model and the one assuming impurity atoms interacting antiferromagnetically (AF). b) High resolution electron microscopy (HREM) image along the [110] zone of an individual Al grain of a structure implanted with Mn with dose  $5 \cdot 10^{14}$  1/cm<sup>2</sup>. Dislocations and associated stacking faults along {111} planes are marked by white arrows. Inset: electron diffraction (ED) pattern taken in [110] direction reveals undeformed cubic Fm-3m lattice for the Al grain. Note absence of any inclusions in HREM and distortion of ED pattern due to Mn implantation.

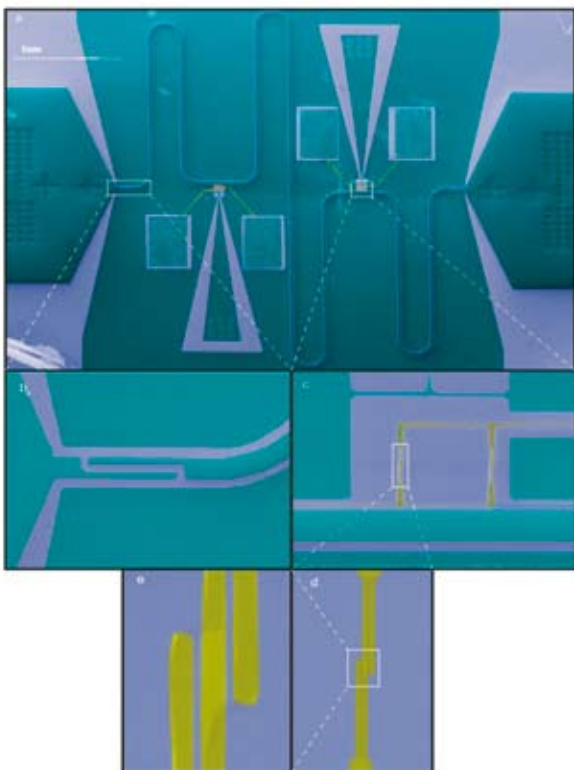
# Quantum Engineering

Sorin Paraoanu

In 2006, the Quantum Engineering (QE) unit of the NanoPhysics group has consisted of the following researchers: S. Paraoanu, K. Chalapat, J. Li, S. Ylinen, and V. Haaksuoto. This unit is doing research on the microwave properties of nano-structured materials and on quantum coherence effects in superconducting devices based on the Josephson effect.

## Superconducting Microwave Resonators

In 2006 we have fabricated and tested on-chip CPW superconducting resonators (Fig. 13) and microwave resonant cavities. Testing of these systems at frequencies up to 40 GHz, as well as more in-depth studying of qubit-resonator phenomena, will continue in 2007.



## Microwave-induced Coupling of Superconducting Qubits

We have investigated the quantum dynamics of a system of two capacitively coupled qantronium circuits under microwave irradiation (Fig. 14). A qantronium circuit (also called charge-flux qubit) is a split Cooper pair box shunted by a relatively large Josephson junction used for read-out. We find that, with the boxes operated at the charge co-degeneracy point, the quantum evolution of the system can be described by a new effective Hamiltonian which takes the form of two qubits with tunable coupling between them (G. S. Paraoanu, *Microwave-induced coupling of superconducting qubits*, Phys. Rev. B 74 (2006) 140504 (R)). This Hamiltonian can be used for experimental tests on macroscopic entanglement and for implementing quantum gates.

## Interaction-Free Measurement with Superconducting Circuits

We have proposed an interaction-free measurement protocol for a quantum circuit consisting of a superconducting qubit and a read-out Josephson junction. By measuring the state of the qubit one can ascertain the presence of a small pulse of electric current without any disturbance due to energy exchange with the continuum of states outside the washboard potential well in which the qubit is localized. An experiment of this type would constitute a test, at the macroscopic level, of a strongly nonclassical consequence of quantum mechanics. Two fundamental physical processes, interferometry and tunneling, are combined here to demon-

Fig. 13. Colored SEM picture of a micro-resonator (a) fabricated on a Si chip, connected to a  $50\Omega$  transmission line through on-chip interdigitated capacitors (b), and coupled to SQUID structures (c,d,e).

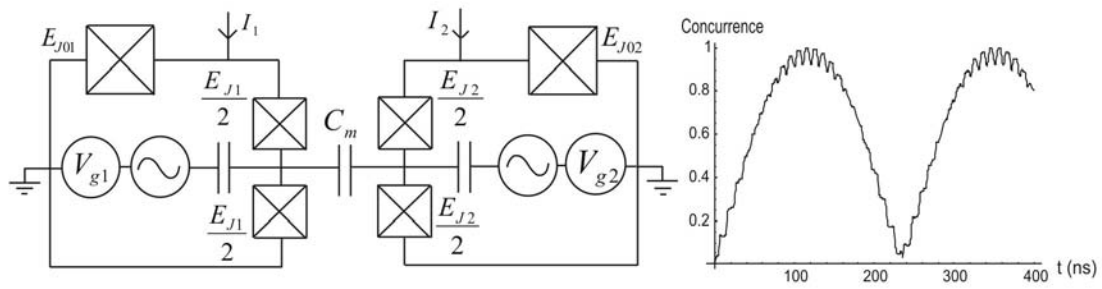


Fig. 14. Left: schematic of the capacitive coupling between two charge-flux qubits. Right: a graph showing the concurrence for the case of relatively large equal-amplitude microwave coupling to each of the qubits, proving that the qubits become entangled.

strate the equivalent of the optical Mach-Zender interaction-free detection scheme for this superconducting quantum circuit (Fig. 15). (G. S. Paroanu, *Interaction-free measurements with superconducting qubits*, Phys. Rev. Lett. 97 (2006) 180406; G. S. Paroanu, *How do Schrödinger cats die?*, J. Low Temp. Phys. 146 (2007) 263). The crossover between standard interference effects (such as the shift in the interference pattern due to phase difference accumulated) and the interaction-free phenomenon is also discussed.

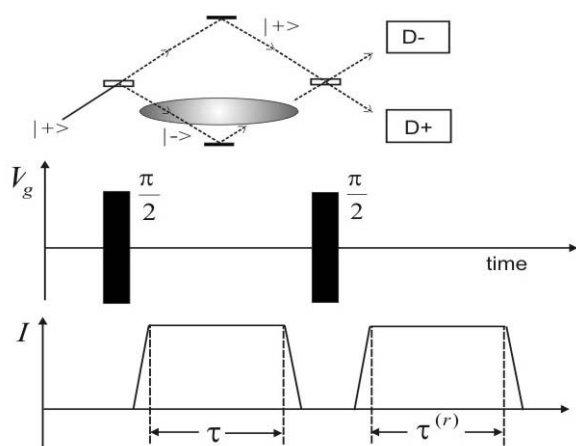


Fig. 15. Mach-Zehnder interferometric setup (upper schematic) and the quantonium pulse sequence (graphs below) with the axes of the flux graph slightly displaced for clarity.

## Molecular Technology

Markus Ahlskog

The Molecular Technology group studies electronic and mechanical properties of macromolecular particles and devices that are based on them. The main focus is on carbon nanotubes (CNT), while conducting polymers and viral particles are under consideration as well.

Carbon nanotubes are seen as one of the main components in future nanotechnology and already today as a superb system in which the phenomena of nanoscale physics can be investigated. The carbon nanotube consists of one or multiple concentric shells of seamless graphite sheets. A single wall nanotube (SWNT) has a diameter of 1–3 nm while the multiwalled nanotube (MWNT) may have any diameter in the range of 2–50 nm. Depending on the wrapping angle of the graphite sheet (chirality), an individual nanotube can be either metallic or semiconducting. A fact of fundamental importance is that the charge carriers in nanotubes of all sizes are truly delocalized. Ballistic conduction over  $\mu\text{m}$ -sized distances have been measured in carbon nanotubes. The axial Young's modulus of an individual nanotube sheet is approximated by the in-plane modulus of graphite ( $\cong 1 \text{ TPa}$ ), which makes the carbon nanotube one of the stiffest material that exists. A single carbon nanotube is thus an excellent free-standing electrical conductor.



In a project funded by Tekes (The Finnish Technology Development Center) we investigate the use of single CNTs as memory elements in digital nanoelectronic circuits. Figure 16 shows the conductance of a field effect transistor (FET) based on single CNTs as a function of gate voltage, swept in both directions between negative and positive polarity. A very robust hysteresis of the gate dependent conductance, due to charge trapping in the backgate oxide, emerges which can be utilized to define non-volatile memory states of the transistor.

Atomic Force Microscopy (AFM) is most crucial to much of the experimental research in nanotechnology. In the standard type of AFM, the tip responds to the local topography of the surface via (normally) attractive long-range Van der Waals forces and repulsive close-range forces. Normally the AFM is operated in ambient conditions, that is, in air and the humidity that comes with it. To obtain true atomic resolution operation in UHV (ultra high vacuum) conditions is often required. A type of AFM that lies between the ambient and UHV-type instruments is the so called environmental-AFM (env-AFM) which is operated inside a chamber as the UHV-AFM, but has a more modest level of vacuum (down to  $10^{-6}$  mbar vs. the  $10^{-9}$  mbar of the UHV), and therefore is more practical to use. In addition to vacuum the env-AFM has the possibility to operate in different gaseous atmospheres, full control of humidity, and also temperature control above and below room temperature, and therefore offers many functionalities otherwise not possible in AFM work. We have constructed an environmental chamber for a standard commercial AFM, shown in Fig. 17. Our design differs from earlier reported schemes especially in that the instrument can be efficiently operated inside the chamber and yet be easily reconfigured into the original setup.

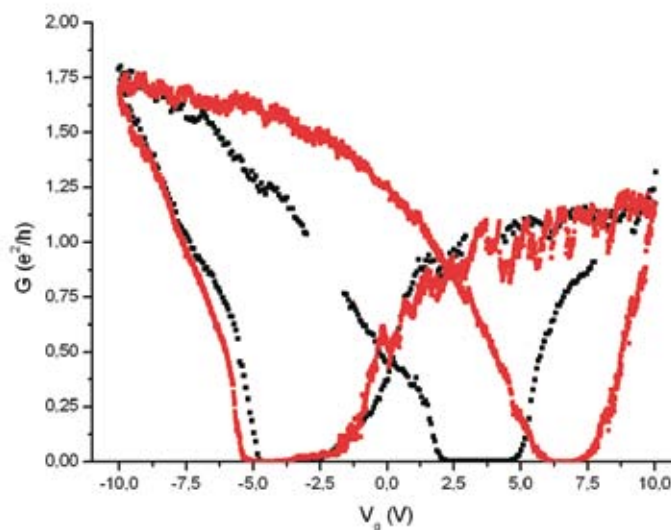


Fig. 16. Gate dependent conductance of a carbon nanotube based FET, exhibiting hysteretic behaviour between voltage sweeps taken in opposite directions. The effect is very stable as can be seen from the two different curves taken a long time apart.



Fig. 17. A commercial AFM (PSIA XE-100) placed inside an environmental chamber.

# Nanoelectronics and Nanotechnology

Päivi Törmä

Päivi Törmä, professor  
Kari Loberg, lecturer  
Jussi Toppari, senior researcher  
Lars Melwyn Jensen, postdoctoral researcher  
Andreas Johansson, postdoctoral researcher (also with Nanophysics group)  
Tommi Hakala, graduate student  
Jami Kinnunen, graduate student  
Timo Koponen, graduate student  
Anton Kuzyk, graduate student  
Mikko Leskinen, graduate student  
Marcus Rinkiö, graduate student  
Sampo Tuukkanen, graduate student  
Ville Kotimäki, MSc student  
Heli Lehtivuori, MSc student  
Veikko Linko, MSc student  
Weilu Liu, MSc student  
Joni Pasanen, MSc student  
Marina Zavodchikova, MSc student

The group belongs to the Nanoscience Center (NSC) of University of Jyväskylä.

offered by the Fermi gases continues to give rise to important experimental results also relevant to high -  $T_c$  superconductors, nuclear collision physics, physics of neutron and compact stars, quantum information and quantum computing.

In late 2005 and during 2006 a number of experiments on polarized (unequal number of spin up and spin down fermions) Fermi gases launched a vigorous study on the different phases of the superfluid Fermi gas, including the possible realizations and observations of BCS - (Bardeen, Cooper, Schrieffer), BP - (breached pairing), FFLO - states (Fulde, Ferrell, Larkin, Ovchinnikov), and deformed Fermi surface states (DFS). We have continued and extended our studies of the imbalanced gases in various geometries.

Increasingly more precise measurements on imbalanced Fermi gases appeared during 2006 leading to several suggestions for the spatial structure of the imbalanced condensates. The suggested phases range from phase separation into a superfluid droplet surrounded by a normal gas to more exotic superfluid states characterized by coexistence of magnetic and superfluid order. The imbalanced Fermi gases were studied in traps with particular focus on the possibility of observing the non-standard magnetically polarized superfluid pairing states with oscillating order parameter found in our theoretical calculations. Moreover, it was suggested that the nature of the order parameter could be probed by using recently developed RF spectroscopy.

## Ultracold Atomic Fermi Gases

During 2005 and 2006 the observation of vortex lattice states in rotating gases presented the so far strongest case for superfluidity in the atomic Fermi gases along the whole crossover region from weakly interacting fermions to weakly interacting bosonic molecules of fermions. The unprecedented control of interactions, internal and external degrees of freedom, and thermodynamics



Fig. 1. The group

Fermions in optical lattices made of crossing laser beams present new exciting possibilities and a promise of technological applications especially in the areas of quantum metrology, and precision spectroscopy. Optical lattices also make direct simulations of tailor-made quantum Hamiltonians possible. We have extended our earlier work on three-dimensional optical lattice to the case of imbalanced gases and have found that while in the literature the zero-temperature phase diagram of a free imbalanced gas is dominated by the phase-separated state and the FFLO area is negligibly small, in a lattice the two phases are equally visible.

Three-component Fermi gases are also experimentally realistic in the very near future and have until now received only scant attention. For this reason, we studied a homogeneous three-component Fermi gas, where the components are different alkali atoms. We generalized the well-known two-component BCS-theory into the three-component BCS-theory.

Current crossover experiments are all conducted with broad Feshbach resonance taking place over a large region of magnetic field values and which is equivalent to the case of a weak coupling of the fermions to the closed molecular channel. However, there is an experimental effort to also drive the crossover with the experimentally observed narrow resonances. In this connection we have extended the Leggett crossover model to also cover the case of narrow resonances and subsequently studied the effect of the width of the resonance on several physical quantities in the crossover regime.

### Dielectrophoresis and Polarizability of DNA Molecules

Dielectrophoresis (DEP), i.e., movement of a polarizable particle induced by a nonhomogeneous electric field, is an electrical analogue of the optical tweezers. The dielectrophoretic force is determined by the gradient of the electric field square and the polarizability of a particle ( $F_{\text{DEP}} = \nabla(E^2)$ ). We have shown that the dielec-

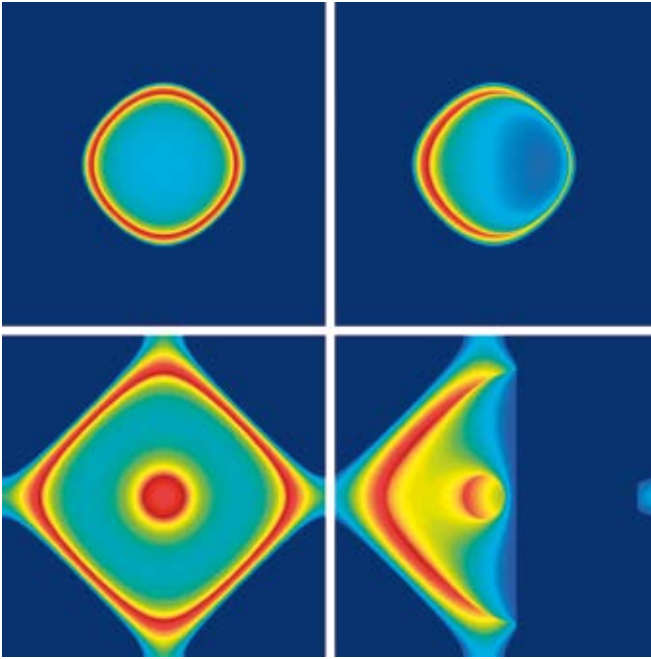


Fig. 2. Differences in the momentum distributions of the two species of Fermions with a population imbalance in an optical lattice with average densities of 0.05 (top row) and 0.2 (bottom row) atoms / lattice site. The figures on the left show the breached pairing (BP) phase with a symmetric breach around the Fermi surface and the ones on the right show the asymmetric breach of the Fulde-Ferrel-Larkin-Ovchinnikov (FFLO) phase.

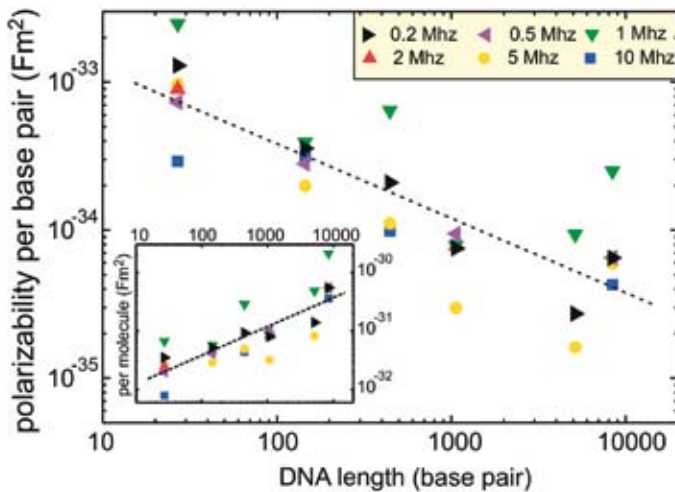


Fig. 3. Polarizability of DNA fragments as a function of a length of the molecules. It was observed that the polarizability per base pair increases with a decrease of the molecule length, which is an indication of a counter-ion cloud polarization.

trophoretic trapping combined with a thiol-based (-SH) immobilization is an efficient method for positioning of nanoscale DNA molecules to lithographically fabricated electrodes. The DEP trapping and the thiol-based immobilization was intensively studied using *in situ* confocal microscopy. Dependency of the trapping efficiency on a DNA length, varying from 27 to 8461 base pairs, and a frequency of the applied AC-signal were studied. The immobilization of DNA modified with different linkers, i.e. hexanethiol and dithiol phosphoramidite (DTPA), was studied with a theoretical support from density functional theory calculations performed by Hannu Häkkinen.

Finite element method simulations were used in conjunction with the analysis of the data obtained from the DEP experiments performed using confocal microscopy. In addition to the DEP efficiency, these studies revealed information about the DNA polarizability. Especially the dependency of the polarizability on the length of the DNA fragment and the frequency of the applied AC-signal (See Fig. 3) was clarified.

For nanoscale objects, such as short DNA molecules, the Brownian motion poses a challenge due to an increase in the thermal drag force as the dimensions of the trapped particle decrease. To further extend the DEP-based method to nanoscale, we have replaced one of the lithographically fabricated fingertip-style electrodes by a carbon nanotube (CNT), which has a smaller diameter than a lithographically fabricated electrode and thus generates higher gradients to the induced electric field. Therefore, it offers higher DEP forces even by using relatively low trapping voltages. It was observed that CNT indeed functions as a more efficient DEP trap for nanoscale DNA if compared to the lithographically fabricated nanoelectrodes (See Fig. 4).

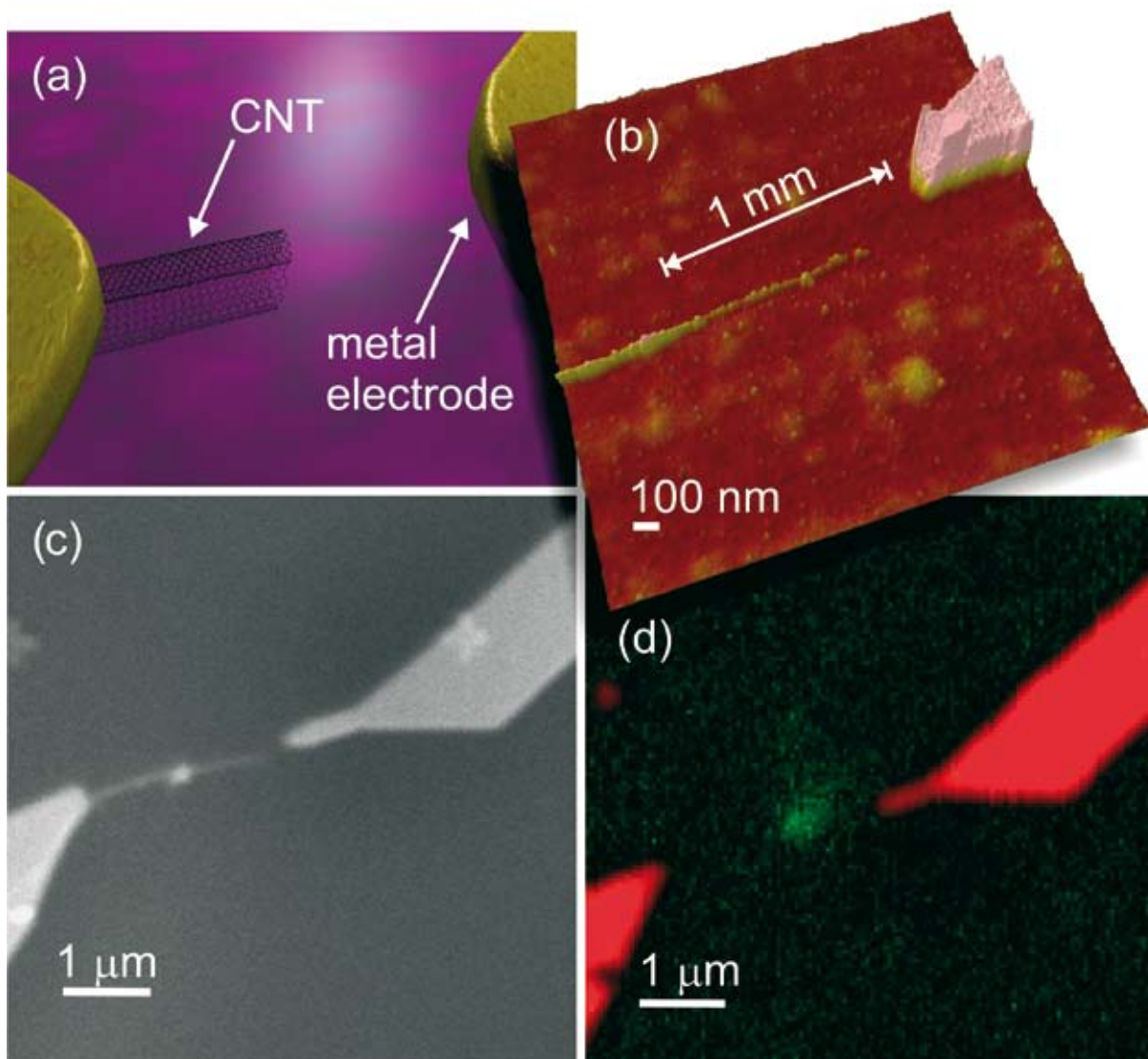


Fig. 4. Use of a carbon nanotube (CNT) as an electrode for the dielectrophoretic trapping of DNA. (a) A schematic view, (b) AFM image and (c) SEM image of the sample. (d) In the confocal microscope image one can see a fluorescence spot (i.e. fluorescently labelled DNA, green) at the end of the multi-walled CNT, whereas there is no DNA observed in the end of the metal-electrode.

This work has been done in collaboration with chemists and biologists at NSC (V. Hytönen, T. Ihalainen, E. Niskanen and M. Vihinen-Ranta).

### Molecular Scale Memory Elements

Due to fundamental physical limitations, the scaling down of current designs in silicon-based microelectronics is causing them to function unreliably. Molecular electronics can, in principle, overcome these limitations and especially single walled carbon nanotubes (CNTs) are an attractive material due to their unique electronic, mechanical, and chemical properties. Depending on the diameter and the chirality of the CNT, it behaves as one-dimensional metal or semiconductor. These properties together with their great mechanical toughness and chemical inertness make them promis-

ing material for creating reliable high-density arrays of molecular-level devices.

One of the interesting applications of nanotubes would be to utilize their exceptional properties to fabricate high density memory elements. We are studying the possibilities to create such a memory element by utilizing a semiconducting single walled CNT in combination with a carefully chosen nanometer thin dielectric layer. In Fig. 5, we show an atomic force micrograph of one of our typical nanotube devices. It is made on top of a highly

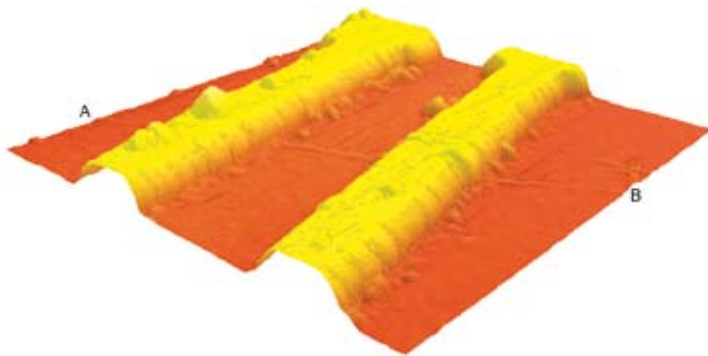
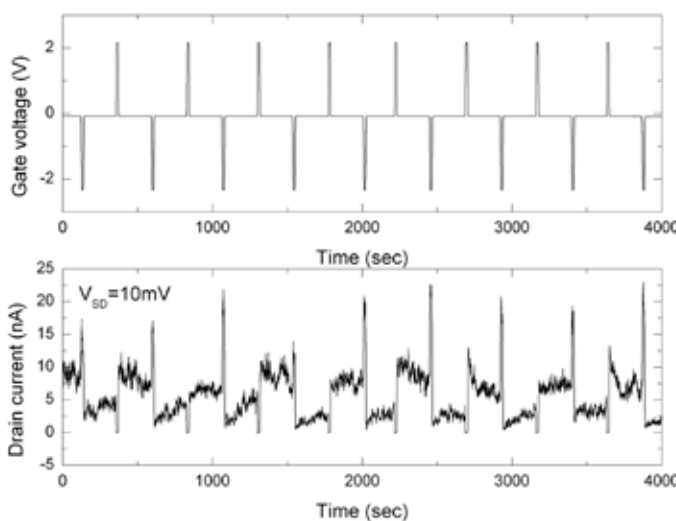


Fig. 5. An atomic force micrograph of a typical nanotube device.



doped Si substrate covered with the thin dielectric layer. The highly doped Si substrate beneath the dielectric layer is used as a back gate. We have observed hysteresis which makes the device a poor FET, but instead an excellent memory device with two different conductance states at zero gate voltage. The memory effect is highly reproducible and has been seen in the majority of our devices, with a yield of more than 90 %.

In order to demonstrate the memory application of the above device, we show in Fig. 6 its conductance response as it is addressed by voltage pulses applied to its back gate, displayed in the upper pane as a function of time. In the lower pane, the conductance response of the nanotube device is displayed. The conductance is switching between two different states, depending on whether the preceding voltage pulse is positive or negative. A positive voltage pulse switches the conductance to its higher value, while a negative voltage pulse reduces the conductance with a factor of 10. Thus the nanotube memory device has well resolved ON and OFF states. Note that these measurements were made at room temperature, further stressing that CNTs may provide solutions to everyday electronics products.

The project is done in collaboration with M. Ahlskog's and K. Rissanen's groups at JYU and E. Kauppinen's group at HUT as well as Nokia Oyj, Planar Inc and Vaisala Oyj.

Fig. 6. A nanotube device is addressed by voltage pulses applied to its back gate, displayed in the upper pane as a function of time. The lower pane shows the conductance response to the voltage pulses. The conductance is switching between two different states, depending on whether the preceding voltage pulse is positive or negative.

# Computational Nanosciences

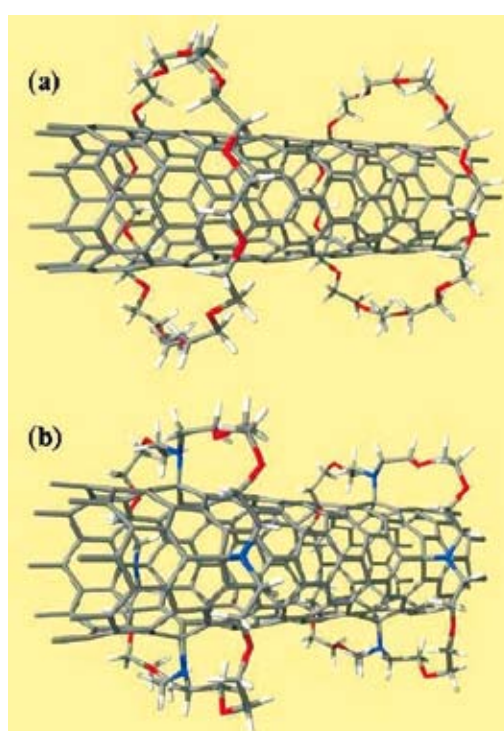
Hannu Häkkinen, Matti Manninen

## Electronic Structure of Carbon Nanotube Based Rotaxane Complexes

Jaakko Akola, Kari Rytönen  
and Matti Manninen

We have studied the geometry and electronic structure of pristine and chemically functionalized single-walled carbon nanotubes (SWNT's). This is done by applying the density functional theory (DFT) of electronic structure which is based on quantum mechanics. The possibility to tune and control the electronic properties of the SWNT's by threading them inside cyclic crown ether (CE) and  $\beta$ -cyclodextrin macromolecules have been investigated. The noncovalent interaction between the nanotube and the macromolecule in this kind of a rotaxane complex can be changed to covalent bonding by cross-linking them chemically. This can be done by substituting some CE oxygen with a nitrogen or by an oxygen abstraction in the  $\beta$ -cyclodextrin. It is found that SWNT's maintain their electronic properties upon the noncovalent complexation, whereas the cross-linking introduces new features in the electronic band structure.

Fig. 1. Geometry of SWNT-CE complex (a) before and (b) after substitution of four ether oxygens (red) with trifunctional nitrogen (blue).



The results show that it is possible to form polyrotaxane systems from SWNT's and cyclic supermolecules (see Figure 1) where the electronic properties of the nanotube are preserved. This might enable size-selectivity and separation of SWNT's. Furthermore, it is possible to tune the conductivity of the SWNT significantly by chemical cross-linking. The conductivity change suggests also that properly activated SWNT-rotaxanes could be used as chemical sensors, where the presence of the macrocycle enables a more specific binding site for the target molecule than in the case of a pristine nanotube.

## Rotating Fermions and Bosons In A Harmonic Trap

Matti Manninen

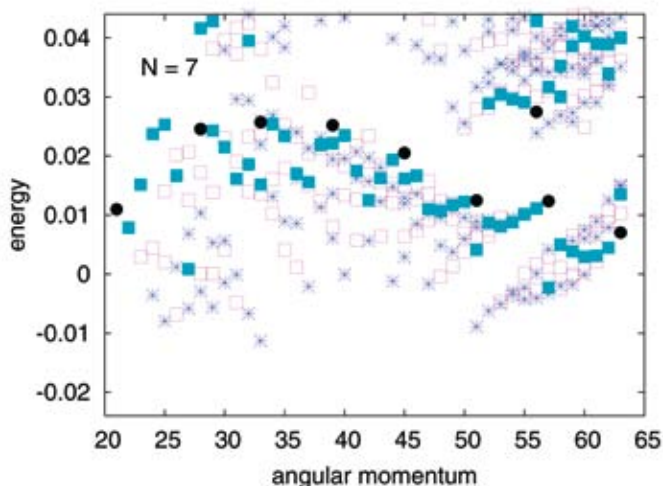
Electrons in quantum dots and weakly interacting fermionic and bosonic atoms in harmonic traps form related many-particle systems. We have studied theoretically the rotational states in such systems and observed strikingly similar vortex formation for both bosons and

fermions. Moreover, the rotational spectrum is rather insensitive to the interparticle interaction. For spinless bosons and fermions the vortices are the dominating low energy excitations at small angular momentum, while at large angular momentum the rapid rotation causes particle localization (Reimann et al, *New J. Phys.* 8, 59 (2006)).

We have shown that, at large angular momentum, the whole many-particle spectrum can be described with rigid rotations accompanied with vibrational modes (Nikkarila and Manninen, *Solid State Commun.* 141, 209 (2007)). The allowed combinations of angular momentum and vibrational modes are determined by the symmetry group of the localized positions and the statistics of the particles in question.

The rotational states of bosons and fermions are closely related as indicated by Ruuska and Manninen (*Phys. Rev. B* 72, 153309 (2005)). We have further studied this similarity by converting the exact boson state to the corresponding fermion state and computing the overlap between that and the exact fermion state. The overlaps of corresponding states are in general large (typically 80 %) and the pair correlation functions are very similar to the two types of particles.

In the case of fermions we have also studied the effect of spin to the rotational spectrum. In this case there are many other low energy excitations than vortices and the spectrum becomes very intriguing as seen in Fig. 2 which shows the spectrum for seven electrons. The figure shows the different spin states with different symbols ( $S=7/2$  with black dots,  $5/2$  with blue squares,  $3/2$  with open circles and  $1/2$  with blue stars). We can see a large energy gap above the black dots. This is caused by the localization of the electrons. In the rich spectrum shown in Figure 2 this gap is due to spin excitations, which include spin waves and domain formation.





# Magnetism of Fermionic Atoms in Optical Lattices

Matti Manninen

We have used a density functional mean field model to study spontaneous magnetism of fermionic atoms trapped in a two-dimensional optical lattice. Especially we are interested in situations where more than one atom occupies each lattice site. It turns out that the magnetism follows closely the shell structure in the individual lattice wells, emerging as there is an excess of one spin species in a single lattice site. The situation is in fact analogous to the behavior of quantum dot lattices in semiconductors, where the magnetism is governed by the shell structure of the single-dot components (Koskinen et al, Phys. Rev. Lett. 90, 66802 (2003)).

The results show that two-component cold fermionic atoms in an optical lattice establish a rich magnetic phase diagram, and can show analogous effects to the electrons in magnetic solids. The magnetism in the optical lattice is determined by the number of atoms per lattice site, and the depth of the lattice. If the lattice is shallow, for strong inter-site tunneling the lattice does not show any magnetism. For deeper lattices, where the tunneling is small, the total spin of the atoms at a single site is determined by the shell structure in the lattice minima.

For closed shells (so-called “magic numbers” with 2, 6, 10 or 12 atoms per site) the single-wells are non-magnetic. For contact-interacting repulsive fermions, Hund’s first rule applies in a particularly dramatic way, removing the interaction between the same atom species. Antiferromagnetic ordering of the single-site spins was found when a gap at the Fermi level could open

up. This was the case at mid shell, with 1, 4, 8, or 11 particles per lattice site. Ferromagnetism occurred at the beginning and the end of a shell.

Figure 3 shows the magnetic phase diagram for a square lattice with 1 to 12 atoms per lattice site, showing the nonmagnetic and magnetic regions for each atom number as a function of the well depth of the lattice.

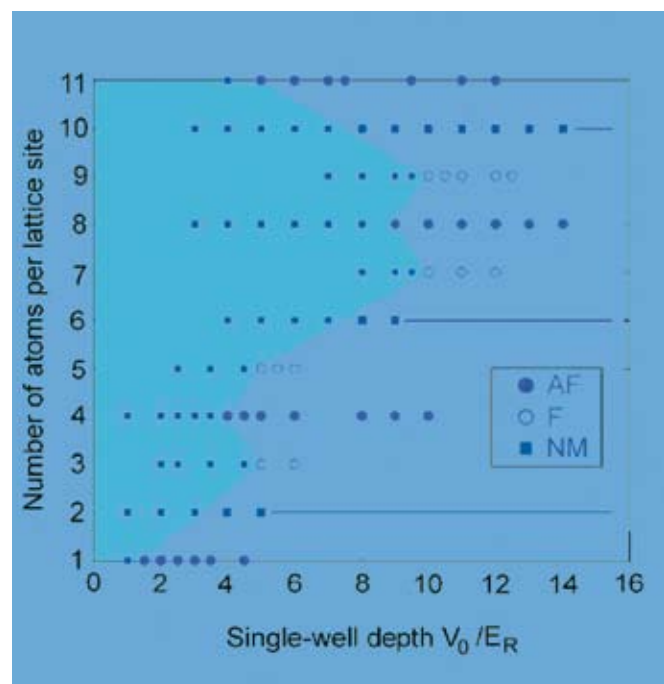


Figure 3.

# Divide and Protect: Capping Gold Nanoclusters with Molecular Gold-Thiolate Rings

Hannu Häkkinen and Michael Walter

Synthesis, characterization, and functionalization of size-controlled, ligand-stabilized gold nanoparticles are long-standing issues in the chemistry of nanomaterials. Ligand-protected gold nanoparticles offer an intriguing possibility to economically fabricate building blocks for potential applications in catalysis, sensing, photonics, biolabeling, and molecular electronics. These building

blocks are expected to have unique size-dependent physical and chemical properties that have been documented in studies of size-selected gold clusters in the gas phase. Collective efforts by several groups have established a series of Au core sizes in 1–3 nm range that are predominantly formed in the process of reducing gold from metal salt in the presence of phosphines (P-R<sub>3</sub>) or thiols (HS-R). A profound understanding of the growth mechanism or of the physical reasons for the observed “magic” core sizes is, however, still lacking due to the complexity of the growth process and the heavy numerical burden of modeling the ligated gold clusters by state-of-the-art electronic structure calculations. Additional complication is brought by the fact that ligand-exchange reactions involving phosphines and thiolates (S-R) have been shown to modify the growth pattern and to lead to stabilization of core sizes different from that of the original compound. Moreover, high sulfur-to-gold ratios result in etching of the gold core. These experimental facts point to the drastically different nature of the gold/phosphine and gold/thiolate interfaces.

We have performed large-scale density functional theory calculations for Au<sub>39</sub>(PH<sub>3</sub>)<sub>14</sub>Cl<sub>6</sub> (1) and Au<sub>38</sub>(SCH<sub>3</sub>)<sub>24</sub> (2) (J. Phys. Chem. B 110, 9927 (2006), Figure 4). The explored systems have core sizes of about 1.1 nm and are chemical homologues to experimentally isolated cluster compounds. The calculations reveal a novel form of gold core protection, namely, by gold-thiolate tetraunits (AuSCH<sub>3</sub>)<sub>4</sub>; thus, compound 2 can be written as Au<sub>14</sub>[(AuSCH<sub>3</sub>)<sub>4</sub>]<sub>6</sub>. (2a) This structure is energetically competitive with the one where the gold core is dis-

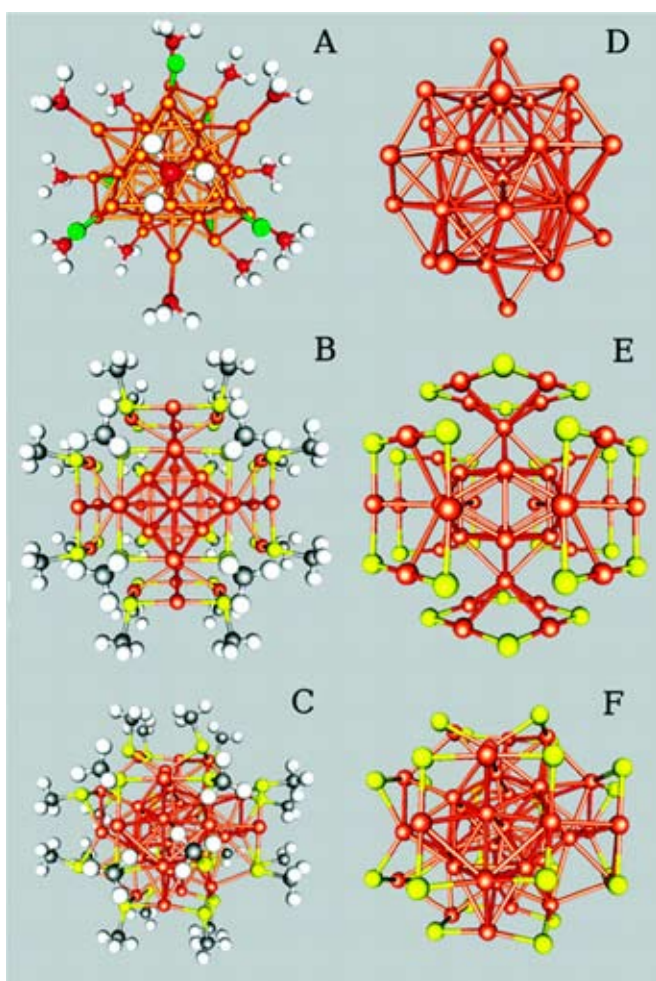


Fig. 4. A to C: Structures of clusters (1), (2a) and (2b). D: Au core of (1), shown by a 90 degree rotation about the horizontal axis on the left; E: Au-S framework of (2a), with 45 degree rotation about the vertical axis on the left; and F: Au-S framework of (2b). Au: orange-brown, S: yellow, P: red, Cl: green, C: dark grey, H: white.

ordered and the number of metal bonds is maximized (structure (2b) in Fig. 4). The interaction between  $(\text{AuSCH}_3)_4$  and the remaining  $\text{Au}_{14}$  core in 2a is comparable to the phosphine-Au bond strength in 1, which is suggested to have important consequences for the understanding of ligand-exchange reactions involving phosphines and thiolates. We also discuss the implications of different structure motifs regarding optical spectra of these species.

The density functional theory was used to explore structural, energetic, vibrational, and optical properties of fully thiolated gold clusters  $(\text{MeSAu})_\chi$  with  $\chi = 2-12$  (J. Am. Chem. Soc. 128, 10269 (2006)). Clusters up to

$(\text{MeSAu})_4$  adopt Au-S ring conformations, and crownlike structures are formed for larger sizes. The clusters are essentially polymeric and show convergence in structural and energetic properties at  $(\text{MeSAu})_4$ . The nature of the Au-S bond is polar covalent with a degree of cyclic electron delocalization. Vibrational analysis reveals characteristic Au-S stretch vibrations at  $\sim 300 \text{ cm}^{-1}$ . Effects of ligand substitution are studied in the case of the tetramer by comparing the results for methylthiolate with hexylthiolate, benzenethiolate, and glutathionate (GS). The choice of ligand has clear effects on electronic properties. For example, the optical gap is  $\sim 1.5 \text{ eV}$  lower for  $(\text{GSAu})_4$  than for  $(\text{MeSAu})_4$ .



# Soft Condensed Matter and Statistical Physics

Markku Kataja, Juha Merikoski and Jussi Timonen

Jussi Timonen, professor  
 Markku Kataja, professor  
 Juha Merikoski, lecturer  
 Andrei Rybin, docent  
 Jari Hyväluoma, postdoctoral researcher  
 Pekka Kekäläinen, postdoctoral researcher (part time)  
 Petro Moilanen, postdoctoral researcher  
 Markko Myllys, postdoctoral researcher  
 Pasi Raiskinmäki, postdoctoral researcher (part time) -31.5.  
 Janne Juntunen, graduate student  
 Ari Jäsberg, graduate student  
 Janne Kauttonen, graduate student  
 Tomi Kempainen, graduate student  
 Viivi Koivu, graduate student  
 Keijo Mattila, graduate student (Mathematical Information  
 Technology)  
 Lasse Miettinen, graduate student  
 Otto Pulkkinen, graduate student  
 Marko Rasi, graduate student  
 Esa Rehn, graduate student  
 Tuomas Tallinen, graduate student  
 Tuomas Turpeinen, graduate student (Mathematical Information  
 Technology)  
 Juha Vinnurva, graduate student  
 Mikko Voutilainen, graduate student  
 Tuomas Airaksinen, MSc student  
 Jarkko Alaraudanjoki, MSc student  
 Vantte Kilappa, MSc student  
 Arto Lähteelä, MSc student  
 Eeva Metsälä, MSc student  
 Tuomas Nuorento, MSc student

## Statistical Physics

### Fragmentation and Elasticity

The previously introduced generic model for elastic material in which mass points are connected by massless elastic beams was further developed so as to reliably describe situations in which large or even plastic deformations appear. This model was implemented numerically such that it can describe crumpling and folding of thin elastic sheets. In collaboration with a research group at MIT, such crumpling and folding processes were simulated under various geometrical constraints and compression rates. Related experiments were done at MIT.



Fig. 1. Microfractures in a sapphire crystal.

Microfracturing that appears in sapphire crystals under point-force loading can be accurately measured by detecting at very low temperatures the temperature pulses which follow from breaking only a few hundred covalent bonds. Such data produced when testing the CRESST dark matter detection system were further analyzed for their statistical and correlation properties (large international collaboration). We have found previously that the energy distribution of fracture events follows a power law similar to that for earthquake magnitudes. We analyzed further the waiting time ( $\tau$ ) distribution that also appears to display power-law behaviour at small  $\tau$ . Possible precursors preceding large events were as well analyzed.

### Stochastic Systems

When analyzing the dynamics of slow-combustion fronts, it became evident that related heat transfer processes need to be better understood if the pinning behaviour of such fronts is considered. We have therefore developed a new method to measure the heat diffusion coefficient of any solid material by recording the time-dependent temperature field under appropriate boundary conditions. The measured temperature evolution is fitted by a theoretical expression, in which the convective transfer of heat away from the sample is included, and in which the heat diffusion coefficient is the fitted quantity. If the specific heat of the material is known, the conductivity coefficient of heat can also be determined. The method developed was calibrated with samples made of pure silicon and pure copper.

We continued our research on theory of interacting particle systems. For zero-range processes in random media, we gave a complete characterization of the stationary distribution in the boundary driven case, and calculated in the thermodynamic limit certain expectations for

the motion of a tagged particle. We also studied polymer systems where coupling of stochastic processes produces directed transport. For this purpose, we extended numerical density-matrix renormalization-group techniques for problems including time-dependent potentials. As another example of coupled processes, we analyzed stationary and time-dependent properties of two interacting interfaces.

## Soft Condensed Matter Physics

### Transport Properties of Porous Materials

We used high-resolution X-ray microtomographic reconstructions of paper and granular materials as samples in *ab initio* fluid-flow simulations by the lattice-Boltzmann method, by which the fluid transport properties of these materials were determined. We analyzed in particular the penetration under external pressure of a non-wetting liquid in a tomographic reconstruction of a sample of paper board (collaboration with the University of Minnesota). The simulated intrusion curve corresponded almost exactly to the one measured by mercury intrusion porosimetry (MIP) on the same sample, provided that the simulation result was interpreted the same way as the MIP result using the Washburn equation. Using image analysis of the tomographic reconstruction, we could however conclude that the MIP result cannot be reliably converted to a pore-size distribution because there are large pores and pore throats shielded by smaller ones. This 'ink-bottle' effect was further analyzed by constructing a numerical invasion percolation model which was applied on the same tomographic reconstruction. We thereby determined the 'access function'

of the sample, which describes the fraction the liquid actually invades of the pore space that it could invade with the given external pressure. The ink-bottle effect was found to be significant. Similar simulations of the

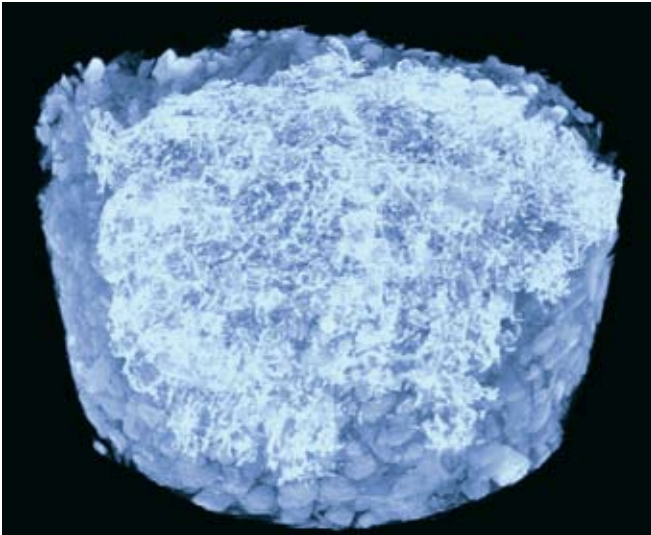


Fig. 2. Three-dimensional distribution of KI inside a granular compound as measured by tomographic imaging.

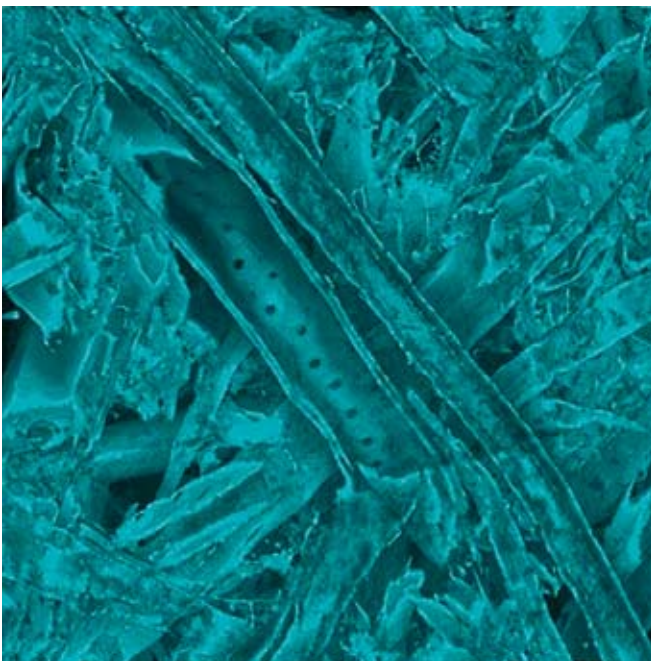


Fig. 3. X-ray tomographic reconstruction of a sample of paper board with 0.7  $\mu\text{m}$  resolution.

permeability of paper as a function of compression were as well carried out.

## Rheology of Liquid-Particle Suspensions

We completed an extensive research project 'Rheological materials in process industry (ReoMaT)' funded mainly by Tekes and carried out jointly with VTT, Tampere University of Technology and Åbo Akademi University during the years 2003–2006. The research included three main topical areas: experimental rheology, development of experimental techniques and numerical analysis. In addition to conventional methods, the projected research utilized several novel techniques, both experimental and numerical, that have only recently become available in other disciplines of materials science and flow mechanics. It led to several new innovations in experimental techniques for finding the relevant material properties of liquid-particle suspensions, methods based on ultrasound Doppler velocimetry in particular. The lattice-Boltzmann numerical method was utilized in order to study mesoscopic mechanisms leading to observable rheological behaviour of liquid-particle suspensions, including shear thickening, strain hardening and wall slip. A new improved semiempirical correlation model and a related measurement technique for estimating losses in fibre-suspension flows was also developed. In addition, the rheology of consolidating fibre network under large deformations was studied in the context of modelling filtration of liquid-fibre suspensions.

## High-Resolution Computed X-Ray Tomography

X-ray tomographic imaging was used to analyze the three-dimensional structure of paper, compressed layers of mineral pigments, and granitic rock. Both an in-

house table-top device with a resolution of about a micrometer, and the synchrotron radiation facility at ESRF in Grenoble (large international collaboration) with a resolution of  $0.7 \mu\text{m}$ , were used. In order to improve image quality, new methods for noise reduction were developed, and for analysis purposes new methods for segmentation were constructed. In the case of paper we analyzed how the properties of coating colour and coating process influence the structure of the coating layer in printing paper, structural reasons for gloss variations in printed paper (collaboration with Universities of Joensuu and Oulu), and change of porosity and pore-size distribution under compression. In layers of mineral pigments we analyzed the effect of pigment shape and compression pressure on the pore-size distribution (collaboration with Åbo Akademi University and University of Helsinki), and in granitic rock the three-dimensional structure of fractures together with mineral distributions (collaboration with University of Helsinki).

### Assessment of Bone by Ultrasonic Guided Waves

A numerical bone model was developed in collaboration with Laboratoire d'Imagerie Paramétrique (CNRS and Université de Paris 6). Realistic macroscopic geometry of the virtual bone developed was extracted from x-ray tomographic reconstructions of the same human radius bone samples which were previously measured by ultrasound in Jyväskylä. Propagation of ultrasound was simulated in two and three dimensions by using a finite-difference method. Simulated and measured ultrasound velocities were in close agreement, which indicated that variability in bone geometry alone explained

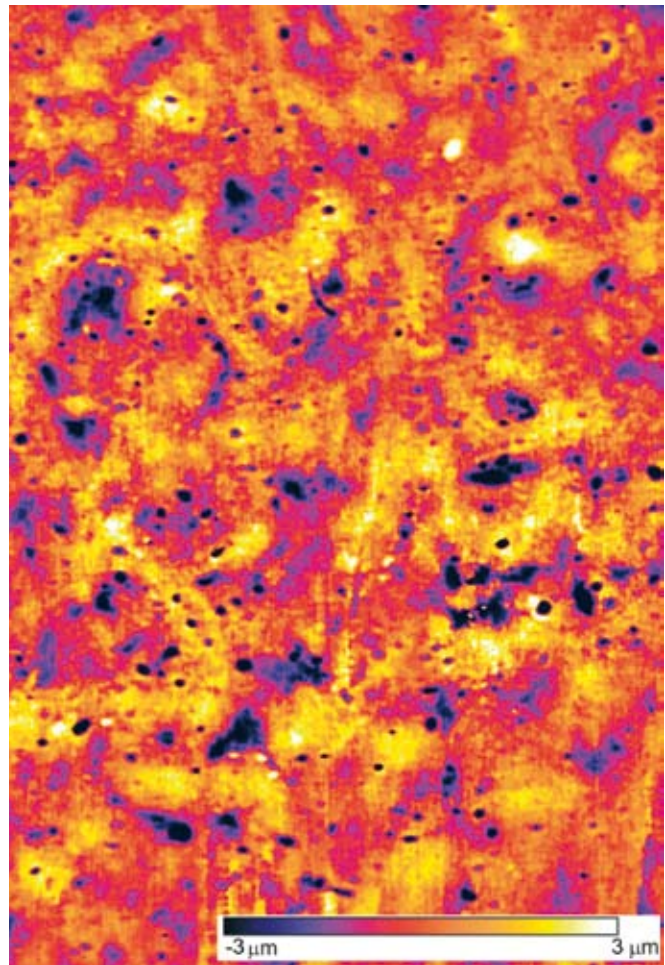


Fig. 4. Surface topography of printed paper.

most of the variability in recorded ultrasound velocity. A particular aim of numerical modelling is to explain the impact of overlying soft tissue, which is difficult to model analytically. Clinical studies in large subject populations were performed to estimate the ability of ultrasound method to diagnose and monitor the quality of bone. A new measurement set-up was also designed and is being constructed with novel, custom-made array transducers.

# Ultrarelativistic Heavy Ion Collisions

Kari J. Eskola and Vesa Ruuskanen

Vesa Ruuskanen, professor  
 Kari J. Eskola, senior assistant -9/06, lecturer 10/06-  
 Kimmo Tuominen, assistant  
 Thorsten Renk, postdoctoral researcher (HIP)  
 Vesa Kolhinen, postdoctoral researcher  
 Sami Räsänen, assistant -7/06  
 Harri Niemi, graduate student  
 Hannu Paukkunen, graduate student (HIP)  
 Topi Kähärä, graduate student (HIP)  
 Suvi Laitinen, MSc student  
 Jussi Auvinen, MSc student  
 Matti Heikinheimo, MSc student  
 Tuomas Karavirta, MSc student  
 Petri Kiuru, MSc student  
 Perttu Mäkinen, MSc student

The primary goal of ultrarelativistic heavy ion collisions (URHIC) is to study strongly interacting elementary particle matter, Quark Gluon Plasma (QGP), and its transition to a gas of hadrons. In URHIC theory, along with trying to understand the QCD matter properties and QCD dynamics, we aim at solid predictions for various observables measurable soon in the ALICE experiment at CERN-LHC, currently in the BNL-RHIC and previously in the CERN-SPS experiments. Our basic computational tools are QCD perturbation theory (pQCD), relativistic hydrodynamics and effective field theories at finite temperature.

Fig. 1. The URHIC theory group in November 2006.





Our research is financially supported by the Academy of Finland (SA). We have participated in the proposals for the *SA Center of Excellence in Theoretical Physics Research* (prof. Enqvist, Helsinki), proceeding to the shortest list again. Together with prof. Kajantie's group in Helsinki, we form the *URHIC* theory project lead by Eskola at Helsinki Institute of Physics in 2002-7. We are also in a close contact with prof. Rummukainen in Oulu and with the ALICE group at JYFL. Our collaborators abroad come from, e.g., CERN, Rome, Frankfurt, NBI, Odense, Heidelberg, LBNL, U. Virginia, Duke U., McGill U. and Nagoya. We participate in international meetings such as *Quark Matter* and the *Hard Probes*, and run an active visitor program. The *Lecture Week on the Physics of Hadrons and URHIC* at Hyytiälä in 9/06, which we organized with prof. Hoyer (Helsinki), was part of the Giessen-Copenhagen-Helsinki-Jyväskylä-Torino collaboration in the *European Graduate School of Complex Systems in Hadrons and Nuclei*. With the local ALICE group, we are organizing an international workshop *High- $p_T$  physics at LHC* in 3/07 at JYFL.

### Parton Distributions of Bound and Free Nucleons

Specific QGP signals in URHIC are examined against reference cross sections of inclusive hard processes, such as direct photon and large- $p_T$  hadron production. These can be computed through the QCD factorization theorem, provided that *nuclear* parton distribution functions (nPDFs) are known. Previously, we have pioneered a global analysis, where the QCD-evolving nPDFs are extracted from hard process data in nuclear collisions and conservation laws. Our *EKS98* parameterization is in a worldwide use and a standard reference in the field. We are now, after extensive further work, ready to publish a statistical error analysis for the obtained nPDFs. Further data constraints will, however, be needed for

nuclear gluons: current RHIC data from d+Au collisions and charm production in e+Au collisions possible in the future are being investigated for this purpose. Next-to-leading-order and nonlinear scale evolutions are on our work-list. We have also suggested that the anomalously large value of the weak-mixing angle observed by NuTeV in Fermilab in (anti)neutrino+Fe scatterings, could be explained by suitable nuclear modifications of the valence quark distributions in iron.

### High- $p_T$ Hadron Spectra as Tomographic Tool for QCD Matter?

One of the most striking QGP signals observed so far is that the single inclusive high transverse-momentum hadron spectrum in central Au+Au collisions at RHIC is suppressed by a factor 5 relative to p+p collisions. Earlier, pQCD cross sections folded with nPDFs, fragmentation functions and eikonized energy loss probabilities, and accounting for simplest production geometry, we have predicted the amount of the suppression for central Pb+Pb collisions at the LHC and also at higher  $p_T$  at RHIC. Now we have included both the production geometry and QCD matter evolution in detail, by studying inelastic energy losses of high- $p_T$  partons traversing a 3-dimensionally expanding hydrodynamic system. In particular, we have investigated prospects of doing medium tomography, i.e. obtaining information of the (dynamic) QCD matter density distribution through the energy losses. Our RHIC results suggest that high- $p_T$  hadron-hadron (see Fig. 2) and photon-hadron correlations indeed serve as tomographic tools, once the information from single high- $p_T$  hadron spectra is used to determine the quenching power of the QCD-medium. LHC predictions are in preparation. A Monte Carlo simulation of elastic energy losses is being developed.

Also the angular distribution of low- $p_T$  hadrons bal-

ancing a high- $p_T$  trigger hadron in Au+Au collisions at RHIC has been observed to be quite different from p+p collisions. A much debated question is whether this new structure is a Mach shock wave phenomenon caused by supersonic energy-losing partons traversing the QCD matter, and what is the underlying dynamical energy transfer mechanism to the matter, especially to

its flow. Also we have launched studies on this exciting question, demonstrating the importance of both transverse and longitudinal flow in the interpretation of the RHIC data.

### Hydrodynamic Modelling of Nuclear Collisions with Minijet Initial Conditions

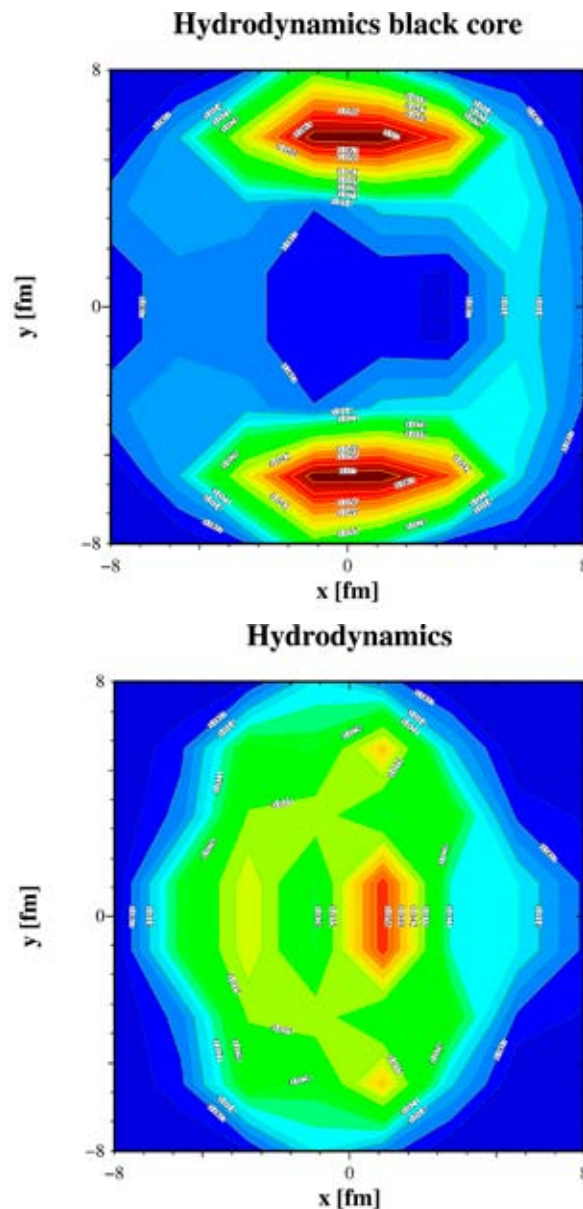


Fig. 2. Vertex distribution of those back-to-back partons, whose hadronic products fulfill the high- $p_T$  trigger conditions in central Au+Au collisions at RHIC. Two different energy loss set-ups reproducing the single-hadron data are shown. The transverse plane coordinates are  $x$  and  $y$  and the trigger parton propagates to the left.

Relativistic hydrodynamics provides an appealing method to study the evolution of a locally thermalized expanding system and phenomena like electromagnetic emission during the expansion stage. Strong features in its favour are the implementation of conservation laws and the QCD phase transition through the equation of state. In addition to the hydrodynamic modelling itself, one of our pioneering specialities is the calculation of the QGP initial densities in a (nearly) closed framework of pQCD minijet production and gluon saturation. In fact, we have been among the few groups in the position of making hydrodynamic predictions for future colliders, e.g. on hadron multiplicities and  $p_T$ -spectra. Recently, we have shown that the low- $p_T$  parts of the dominant hadron spectra measured in central Au+Au collisions at RHIC are reproduced well by the hydrodynamically computed spectra and resonance decays, when a single, rather high, decoupling temperature is used. Based on the successful tests at RHIC, we have predicted the low- $p_T$  hadron spectra, multiplicities and net-proton number in central Pb+Pb collisions at the LHC. In addition, we have also compared the hydrodynamical spectra with the nonthermal high- $p_T$  spectra (see below). Work in progress includes dynamical improvements of the decoupling criterion, studies of the correlation between the final transverse flow and initial transverse profiles of matter, and predicting the amount of elliptic flow for Pb+Pb collisions at the LHC. An extensive invited review of various hydrodynamical results was completed and published.

## Electromagnetic Probes

A new precision measurement of dimuon emission from In+In collisions has been performed by the NA60 collaboration at the CERN-SPS. This dataset allows to study double differential observables for the first time and hence poses strong constraints and challenges to theory. We have, based on experience in modelling Pb+Pb collisions at the same energy, developed a model description of the fireball created in the In+In collisions which successfully describes the collective expansion of the system and allows to disentangle medium evolution and in-medium changes of vector mesons. Some features, such as the hardening of the  $p_T$  spectra in the rho-like mass region and the softening at higher mass were successfully predicted by this framework. Using the constraints provided by the double differential data, we have given strong arguments that a phase with a temperature larger than the phase transition temperature seen on the lattice contributes to the observed dilepton radiation. In the hydrodynamical framework, computation of electromagnetic emission at RHIC and LHC, and studies of partonic jet-to-photon conversion will be carried on.

## Effective Theories for QCD and Electroweak Symmetry Breaking

In earlier work, we have constructed effective theories for QCD at finite temperature and explained how deconfinement and chiral symmetry restoration intertwine into a single phase transition as observed in the lattice measurements. Currently we are extending these results to finite chemical potentials, and in the future we will include also the diquark condensation phenomenon. We will study the consequences of various nuclear and quark matter equations of state for the phenomenology of compact stars.

Investigations of the dynamics of various strongly interacting theories have far reaching consequences also beyond hadron physics: The electroweak symmetry breaking may be driven by a new kind of strong interaction termed Technicolor. This scenario had severe problems regarding the electroweak precision measurements, and was thought already ruled out. Using cutting edge techniques developed for supersymmetric Yang-Mills theories we have introduced new Technicolor theories and shown that these are compatible with the current precision measurements, see Fig. 3. The Higgs particle in this model is expected to be light, with a mass of 150 GeV and well within reach at the LHC. These theories have interesting consequences for cosmology since they feature particles which could serve as dark matter. We have studied this possibility and reported our findings. Study of the detailed collider phenomenology of these theories is currently in progress.

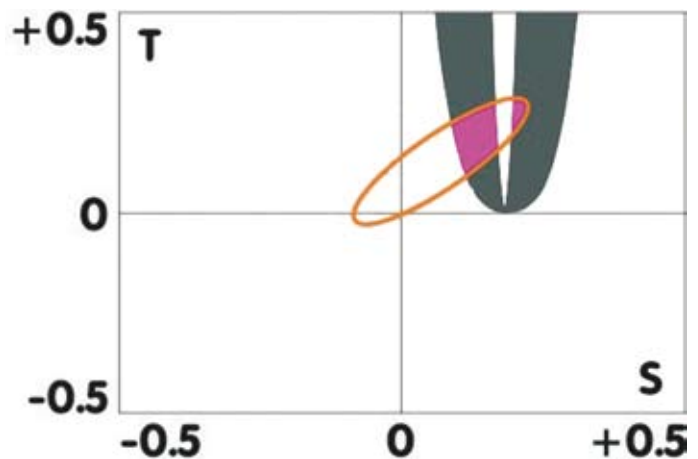


Fig. 3. The electroweak precision data is often presented in terms of parameters called  $S$  and  $T$ . Once the Technicolor gauge group is fixed, our model has two free parameters. The shaded parabola shows  $S$  and  $T$  obtained from the model as the two free parameters are varied. The ellipse is the confidence curve corresponding to one standard deviation of the most up-to-date global fit to the data.

# Theoretical Particle Physics and Cosmology

Kimmo Kainulainen, Markku Lehto and Jukka Maalampi

Jukka Maalampi, professor  
 Kimmo Kainulainen, senior assistant  
 Markku Lehto, senior assistant  
 Maxim Dvornikov, postdoctoral researcher 28.8.-  
 Petteri Keränen, postdoctoral researcher -31.7.  
 Matti Herranen, graduate student  
 Diego Meschini, graduate student  
 Minja Myyryläinen, graduate student  
 Ari Peltola, graduate student  
 Johanna Piilonen, graduate student  
 Pyy Rahkila, graduate student  
 Vappu Reijonen, graduate student (University of Helsinki)  
 Janne Riittinen, graduate student  
 Daniel Sunhede, graduate student  
 Jussi Virkajärvi, graduate student  
 Risto Hautala, MSc student  
 Tuomo Puumalainen, MSc student  
 Essi Silokunnas, MSc student

## Neutrino physics

Jukka Maalampi

The recent activity in theoretical particle physics has been concerned mainly with neutrinos, in particular astrophysical neutrino phenomena. We have studied the effects and observational signals of the possible sterile neutrinos in astrophysical environments. Sterile neutrinos have no interactions with matter, except that they can mix quantum mechanically with the ordinary active neutrinos and form as a result a part of the propagating neutrinos that have a definite mass. They are predicted by many theoretical models, and they may have an important role in neutrino mass and mixing mechanism. Most recently we have investigated these issues in connection to supernova explosions, where neutrinos encounter the effects of the matter of the star envelope they traverse. We have created a code that numerically solves the six-dimensional density matrix equation and gives the evolution of the neutrino states in the envelope. This has also lead us to study a more general question of level crossing, so called multilevel Landau-Zener problem, in the case of non-linearly varying Hamiltonians.



The group of theoretical particle physics and cosmology. Standing (from left) Jussi Virkajärvi, Minja Myyryläinen, Janne Riittinen, Daniel Sunhede, Matti Herranen, Johanna Piilonen and Pyy Rahkila. Sitting Kimmo Kainulainen (left) and Jukka Maalampi.

Our group have also studied neutrino oscillation from a more formal point of view, namely by formulating the problem using relativistic quantum mechanism. Using this formalism, we have investigated for example the spin-flavor oscillations in rapidly varying magnetic fields, as well as interactions of mixed fermions with classical sources.

## Cosmology

Kimmo Kainulainen

### Extended Gravity and Dark Energy

One of the greatest mysteries of the modern cosmology concerns the observed accelerated expansion of the universe – the simplest explanation for which postulates that the universe is filled with a substance called “dark energy” (DE), carrying a negative pressure. An alternative solution is that the Newtons and Einsteins theories for gravity need to be modified at large distances. Our group has studied large dimensions motivated scalar-tensor theories as well as phenomenologically motivated  $f(R)$ -gravity extensions of the classical Einstein-Hilbert-theory. Our current activities concentrate on studying the constraints on these extensions arising from precision measurements in the Solar system. We are also studying the formulation of the extended gravity theories in the context of the Palatini-variational principle. Our group has a strong collaboration effect with the cosmology group in Helsinki and we are currently developing collaborative efforts in  $f(R)$ -theories with the cosmology group in Turku.

### Quantum Transport Problem and Electroweak Baryogenesis

Another intriguing problem in modern cosmology concerns the origin of the baryon asymmetry, excess of matter over the antimatter, in the Universe (BAU). Our group has studied the creation of BAU in the electroweak phase transition (EWPT). A proper treatment of electroweak baryogenesis calls for the use and development of the quantum transport equations (QTE) in non-equilibrium plasmas and in spatially changing backgrounds. The QTE's for EWBG were first derived by us in the WKB approximation. We then have explored the more fundamental derivation of QTE's in the context of the Schwinger-Keldysh closed time path (CTP) formalism, and the WKB-limit was recovered in the limit of slowly varying backgrounds and weak interactions through controlled expansions in gradients and in coupling constants. We have recently extended the quantum transport formalism to include non-local quantum coherence effects (reflection) and we are developing a numerical code to solve for the momentum dependent diffusion of the CP-even and -odd currents in realistic

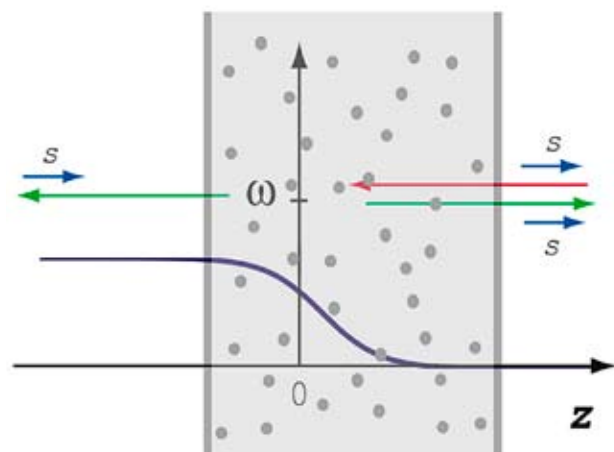


Fig. 1. In the electroweak baryogenesis problem fermions are reflecting off a phase transition wall under the influence of decohering collisions. This phenomenon can now be treated accurately by use of a quantum transport equation derived by our group using the CTP-formalism.

situations both in the WKB- and in the thin wall limits. Among our main goals in this work is to compute the BAU in the context of the minimal supersymmetric standard model including also the CP-violating currents from the neutralino sector.

## Time, Space, Gravitation, and Quantum physics

Markku Lehto

### Physics of Time

Originally inspired in the problem of quantum gravity, our group was led to the physical analysis of the concept of time.

We have approached the problem of physical time from two perspectives. The first concerns a metageometric analysis of time based on experiments involving preparation of quantum-mechanical systems; this time is apt to explain the origin of the classical concept of external parameter time. The second approach involves a geometric analysis of time based on measurements, which provides the physical foundation for classical, special-



relativistic, and general-relativistic spacetime. The two approaches are envisaged to converge in the emergence of metageometric correlations.

Our sought-for metageometric, physical things were found by looking at the process of quantum-mechanical preparation (exemplified by a Stern-Gerlach experimental setup for the observable spin). From it, the theoretical concepts of metageometric premeasurement and transition things were developed.

Details on this research will appear in a forthcoming doctoral thesis of Diego Meschini.

### Physics of Black Holes

There are good reasons to believe that the quantum-mechanical degrees of freedom of the black hole are due to the microscopic structure of spacetime at the event horizon. Therefore, one is led to probe the microscopic properties of the event horizon. It is possible, for example, to construct the horizon from microscopically small black holes such that the correct (statistical) entropy is produced. This result found by our group is encouraging as it has been proposed that microscopic black holes might have something to do with the structure of spacetime at the Planck-length scale. We have also argued that the concept of entropy may be associated with other horizons of spacetime as well and, at least to some extent, even with any spacelike two-surface of spacetime. One believes that these entropies also stem from the microscopic structure of spacetime. An understanding of the nature of black-hole radiation may therefore give valuable insights into the microscopic theory of spacetime itself.

Details on this research will appear in a forthcoming doctoral thesis of Ari Peltola.

# Industrial Collaboration

Jussi Timonen, Päivi Törmä and Ari Virtanen

The Department has numerous contacts with domestic and foreign industry and research laboratories.

The important milestone of 10 years of *industrial applications in accelerator laboratory* was achieved in 2006. Putting the period into nutshell, a total of 2.7 million euros, 29 MSc or licentiate theses and 39 international publications have been produced in the group during these years. These have been made in 16 R&D projects, 12 research grants and in commercial service activity for international and national industrial companies.

Fifteen users performed irradiation tests at the RADEF facility last year. From those 10 users were international. Users were mainly private companies, but Instituto Nacional de Tecnica Aeroespacial, INTA, from Madrid and Comité Européen des Assurances, CEA, from Bruyerele-Chatel, France, were performing satellite component tests in RADEF for the first time. In addition, two new universities (Technical University of Denmark from Copenhagen and University of Padua from Italy), carried out their test campaigns here. The total RADEF beam time in 2006 was 576 hours, from which 432 hours were used for ESA or non-ESA users.

Another important branch of our industrial collaboration is related to the medical applications. The Iodine-123 production for MAP Medical Technologies was continued at a constant level during 2006. A total of 39 production runs were performed, in which the beam current was 40-50  $\mu\text{A}$ . Another medical project was continued

in collaboration with Gammapro Ltd. and Jyväskylä Radiotherapy Hospital. This produced one MSc thesis by the end of 2006.

Co-operation with Doseco Ltd. continued in terms of one MSc project, which was done with the national Radiation and Nuclear Safety Authority including a neutron detection study for Nuclear Power Plant of Loviisa. Collaboration of the group with paper and paper machine industry continued also actively with Metso Paper Corporation. This project started as an MSc project, where the radiation was employed for studying formation profiles in paper. A new type of energy controlled  $\beta$ -radiography device was built for the use in the company's research laboratory. This project turned to be so fruitful, that the decision to continue it as a PhD project was made. Another project, performed with the Technical Research Centre, VTT, also produced one MSc thesis. The work was done in collaboration with VTT Processes, Jyväskylä, and eight private companies. The aim was to study controlling possibilities of biomass flow used in fuel peat power plants. This brought up a new idea about the application of neutrons in the study of humidity and inorganic impurities in wood logs and peat. A decision to start a PhD project from this subject with VTT Processes during the spring 2007 was made. The idea is to do this study in collaboration with Plasma and Ion Source group from Berkeley National Laboratory, USA.

The *nanophysics* and *nanotechnology* group has well es-



tablished collaboration with a few companies in Finland. For about three years ultrasensitive radiation detectors based on calorimetry and bolometric sensing for x-rays and IR-radiation have been developed in collaboration with Oxford Instruments Analytical company from Espoo (formerly Metorex International). At the first stage the work has been motivated by the need of on-chip integrable ultrasensitive sensors in space research, and collaborative projects are continuing, funded by the European Space Agency. In addition, a TEKES funded project in collaboration with VTT Information technology and VTT Millilab has continued to develop superconducting bolometers in the sub-millimeter band.

The *nanoelectronics and nanotechnology group* has established contacts with industry. The professorship in electronics has been sponsored by local municipalities and industry. The nanoelectronics group was funded

by Tekes within the ELMO (“Miniaturization of Electronics”) research programme. The project focused on micro- and nanosensors and was in collaboration with the companies Enermet, Metso Drives, Nanoway and JSP (Jyväskylä Science Park). A patenting process has been started as a result of the project. The industry collaboration is continued under new projects and including companies interested in nanotechnology such as Nokia, Planar and Vaisala, with funding from the FinNano Nanotechnology Programme of Tekes. The Nanoelectronics Education and Investment programme took place during the years 2002–2004 in collaboration with several companies such as Enermet, Nokia, JSP, Nanoway, Aplicom. The programme was mainly funded by EU via the regional government and partly by companies. The programme allowed developing the teaching in electronics and investments to equipment essential for research in nanoelectronics and nanotechnology. The Nanoscience



Center research infrastructure programme 2004–2006, also funded by EU via the regional government and partly by companies (now about ten participating), is also an important platform for industry collaboration. Through this programme, companies can have a so called “Window to Nanotechnology” to follow the rapid development of the field.

*The soft condensed matter and statistical physics group* continued its established collaboration with a number of companies in several branches of industry.

X-ray computed microtomography was used in several applied and industrial research projects for studying e.g. the structure of paper and pigment coating layers, paper-making fabrics, minerals, mineral wool and biological samples. In this work an in-house table-top x-ray scanner was used together with the synchrotron radiation based tomography facility at ESRF. Work at ESRF involved large international collaboration with more than ten research groups in Europe and the USA. Related to the tomographic techniques used, noise-reduction algorithms for improved image quality and segmentation algorithms for improved structural analysis were developed. Flow simulations based on the lattice-Boltzmann method were also carried out with tomographic images of paper and pigment layers in order to gain better understanding of the transport properties of these materials.

The research group continued participation in four large national research consortia funded by Tekes and industry, and in one funded by the Ministry of Trade and Commerce. These projects focused on developing new

experimental and numerical techniques for flow in porous media, on basic and applied research on the rheological properties and dynamics of fibre suspensions, on tomographic imaging of paper-like materials and pigment layers, and on ultrasound methods in assessment and monitoring of the quality of bone.

Several other projects involving direct collaboration with industry were carried out. These projects included experimental research, numerical simulation and modelling of processes such as transport of fluid in paper, matrix diffusion, rheological properties of pigment suspensions and structural properties of paper and mineral wool.

Industrial collaborators included Metso Paper, Stora Enso, UPM, M-real, ABB, Sulzer Pumps Finland, Kemira, Omya Finland, Specialty Minerals Nordic, Hansaprint, Ciba Specialty Chemicals, Tamfelt, KCL, Top Analytica, Next Wave, Numerola, Paroc and Posiva.



# Education

## Education

Jukka Maalampi and Juha Merikoski



Jukka Maalampi, professor  
Juha Merikoski, lecturer  
Inkeri Halkosaari, graduate student  
Jussi Helaakoski, graduate student  
Niina Nurkka, graduate student  
Tero Alakurtti, MSc student  
Otso Jarva, MSc student  
Jarmo Jääskeläinen, MSc student  
Joonas Ketonen, MSc student  
Laura Ketonen, MSc student  
Maarit Lappalainen, MSc student  
Pasi Nieminen, MSc student

The Department of Physics offers an internationally competitive study program at all academic levels. During the years 2004–2006 the Department was a national high-quality education unit, the only such unit in exact natural sciences. A particular strength, together with the diversity of choices of specialization in experimental and theoretical approaches in various fields of physics or teacher education, is that teaching at all stages of studies is closely connected with present-day research. Physics students get involved in laboratory work and other research as well as teaching and student recruitment, and they are strongly present at the Department in all its activities.

In 2006 the number of master's degrees taken at the Department was 38, of whom 9 obtained teacher qualification. The Department produced 14 PhD degrees, which is

an all-time high. The employment of the newly graduated students has continued to be good. According to recent very comprehensive surveys, the employment among the graduates of the years 2000–2005 is 98%.

### Students

In 2006 there were 406 applicants for physics studies, with 255 indicating physics as their first choice. As a whole, 81 undergraduate students enrolled in 2006. The majority, 96 % of students were admitted based on their high school record and national maturity test result. In addition, a traditional entrance examination was organized together with universities of Helsinki, Kuopio, Oulu and Turku. Only one fifth of the applicants and enrolled students were women, which stands as a great challenge for the student recruitment in future. Direct enrollment to teacher education has quickly become popular and 16 students chose it this year.

In 2006 there were about 530 undergraduate students at the Department. The new students first aim at the degree of Bachelor of Science and then continue to the degree of Master of Science. Some 30 students, many of them with a polytechnic engineering background, studied in the master programs for industrial physics, nanoelectronics and renewable energy. The number of post-graduate students aiming at the degree of Doctor of Philosophy was about 70.

## Teacher Education

The trilateral co-operation between the Departments of the Faculty, the Department of teacher education and the Teacher training school has been close and inspiring in recent years. This is reflected e.g. in the co-operation of supervising MSc thesis projects which are now more often than before concerned with typical research questions of didactics. Further education for personnel involved in various stages of teacher education are arranged on a regular basis.

The Department participates in the *Finnish graduate school of mathematics, physics, and chemistry education*, with five students working on a degree of doctor or licentiate of philosophy in physics education. Niina Nurkka defended successfully her thesis on the subject *Developing and evaluating a research-based teaching-learning sequence on the moment of force* in 2006.

## Teaching Development

The first-year crash course *Flying start*, one of the trademarks of the Department, was given for the sixth time. A major improvement this year was to have well-performed and enthusiastic physics students act as tutors. The research-oriented approach of the *Flying start* of the previous years was now combined with more effort to provide a good start for regular studies beginning after the *Flying start*, which was well received by the students. Also, the program was rearranged to better allow participation in the other activities arranged by the University for the incomers.

According to the Licentiate thesis study *Physics education at JYFL: Improving interactions and research-oriented learning*, completed in 2006 by Inkeri Halkosaari, the effects of the *Flying start* have been very positive in improving students' motivation to complete their stud-





ies. The annual number and standard of graduates at the Department remains high, while the common trend in many places has been declining. As indicated also by this thesis, tutoring had probably been the weakest

link of the *Flying start* in the past years and improvements really needed.

A continuing challenge is to further develop the teaching practices of other courses to better correspond to the requirements of the physics profession in practice, also in line with the aims of the Bologna process. In this, promoting team work and taking advantage of the highly international profile of the Department are key elements. The Department has expanded its summer student program so that the number of paid students in summer 2006 was 45.

### Other Education Activities

In addition to its regular teaching program, the Department has continued the co-operation with the Open University supplementary-education program for teacher qualification. The Department was active in the 16<sup>th</sup> Jyväskylä International Summer School. Physics was also strongly present and obtained very positive response in the Science fair of the University.

The Department has continued co-operation with schools in the Central Finland district. Physics students frequently visit high schools to increase interest in studies in natural sciences. The Department collaborates with schools within the CERN network by organizing training lectures prior to the CERN visits of student groups. The Accelerator laboratory and the Nanoscience center remain popular excursion destinations for school students.

Email addresses:  
forename.surname@phys.jyu.fi  
Note: ä=a, ö=o, å=a

## Head of the Department

Jukka Maalampi, prof.

## Vice-Head of the Department

Rauno Julin, prof.

## Professors

Markus Ahlskog  
Rauno Julin  
Markku Kataja  
Matti Leino  
Jukka Maalampi  
Matti Manninen  
Vesa Ruuskanen  
Jouni Suhonen  
Jussi Timonen  
Päivi Törmä (on leave)  
Harry J. Whitlow  
Juha Äystö (on leave 1.8.-)

## Research professor

Päivi Törmä (EURYI award)

## Lecturers

Kari J. Eskola 1.10.- (JYFL/HIP)  
Ari Jokinen 1.10.-  
Kari Loberg  
Juha Merikoski  
Matti Piiparinen

## Senior assistants

Konstantin Arutyunov  
Kari J. Eskola -30.9. (JYFL/HIP)

Hannu Häkkinen  
Sakari Juutinen  
Kimmo Kainulainen  
Hannu Koivisto  
Markku Lehto  
Jan Rak (JYFL/HIP)  
Timo Sajavaara (on leave)  
Jussi Toppari

## Assistants

Vesa Apaja 1.8.-  
Tommi Hakala (on leave 1.8.-)  
Anu Kankainen (on leave 1.8.-)  
Heikki Kettunen -31.7.  
Sami Räsänen -31.7.  
Jussi Toivanen  
Kimmo Tuominen (JYFL/HIP)

## Academy research fellows and scientists

Paul Greenlees  
Ilari Maasilta  
Gheorghe-Sorin Paraoanu  
Heikki Penttilä  
Juha Äystö 1.8.-

## PhD scientists

Jaakko Akola  
Vesa Apaja -31.7.  
Mariana Bondila (HIP/JYFL) 1.9.-  
Maxim Dvornikov 28.2.-  
Shadyar Farhangfar  
Lars Melwyn Fjelsted  
Tuomas Grahn 1.6.-  
Pauli Heikkinen  
Karoliina Honkala -31.7.  
Jari Hyväluoma 1.7.-

Andreas Johansson  
Ari Jokinen -30.9.  
Pete Jones  
Pekka Kekäläinen (part time)  
Petteri Keränen -31.7.  
Heikki Kettunen 1.8.-  
DongJo Kim 1.6.-  
Vesa Kolhinen (HIP/JYFL)  
Markus Kortelainen 1.6.-  
Matti Koskinen 1.3.-  
Daniela Koudela 15.9.-  
Olga Lopeza 1.8.-  
Petro Moilanen 1.10.-  
Iain Moore  
Markko Myllys  
Kari Peräjärvi -30.4. (HIP/JYFL)  
Saidur Rahaman  
Pasi Raiskinmäki (part time) -31.5.  
Thorsten Renk (HIP/JYFL)  
Valery Rubtchenya  
Kari Rytönen 1.11.-  
Timo Sajavaara  
Somjai Sangyuenongpipat 15.8.-  
Catherine Scholey  
Tetsu Sonoda  
Pekka Suominen 1.7.-  
Lasse Taskinen 1.7.-  
Wladyslaw Trzaska  
Vladimir Tuboltsev -30.6.  
Juha Uusitalo  
Michael Walter  
Christine Weber 1.5.-  
Ari Virtanen

## MSc scientists

Asaf Avnon 1.9.-  
Mariana Bondila (HIP/JYFL) -31.8.

Khattiya Chalapat 1.4.-  
Viki-Veikko Elomaa  
Tommi Eronen  
Sarah Eeckhautd -31.7.  
Pentti Frondelius 1.2.-  
Sergey Gorelick  
Tuomas Grahn -31.5.  
Ulrike Hager  
Jani Hakala  
Heikki Heiskanen 1.9.-  
Jussi Helaakoski  
Matti Herranen  
Terhi Hongisto  
Jari Hyväluoma -30.6.  
Pasi Jalkanen  
Arto Javanainen  
Janne Juntunen  
Ari Jäsberg  
Katarzyna Kacprzak (on leave 9.5.-)  
Anu Kankainen -30.4.  
Jenni Karvonen  
Pasi Karvonen  
Tomi Kemppinen  
Thomas Kessler  
Steffen Ketelhut 1.3.-  
Jami Kinnunen  
Kimmo Kinnunen  
Viivi Koivu  
Timo Koponen  
Panu Koppinen  
Markus Kortelainen -31.5.  
Jenni Kotila  
Anton Kuzyk  
Thomas Kühn  
Topi Kähärä 1.8.-  
Mikko Laitinen  
Mikko Leskinen  
Jian Li 1.9.-  
Jarkko Lievonen 1.9.-  
Tomasz Malkiewicz  
Sami Malola 1.9.-  
Keijo Mattila  
Diego Meschini

Lasse Miettinen  
Mika Mustonen  
Minja Myyryläinen  
Minna Nevala  
Harri Niemi (HIP/JYFL)  
Juha-Pekka Nikkarila 1.3.-  
Markus Nyman  
Hannu Paukkunen  
Ari Peltola  
Sami Peltonen  
Johanna Piilonen  
Otto Pulkkinen  
Nitipon Puttaraksa 1.11.-  
Panu Rahkila  
Pyy Rahkila  
Esa Rehn  
Iiro Riihimäki  
Janne Riittinen  
Marcus Rinkiö  
Sami Rinta-Anttila  
Juho Rissanen  
Janne Ronkainen  
Tommi Ropponen  
Mikko Rossi 1.9.-  
Kari Rytönen -31.10.  
Antti Saastamoinen  
Ananda Sagari A.R.  
Jan Sarén  
Juha Sorri  
Daniel Sunhede  
Pekka Suominen -30.6.  
Olli Tarvainen -7.4.  
Tuomas Tallinen  
Lasse Taskinen -30.6.  
Benjamin Tordoff -31.8.  
Tuomas Turpeinen  
Sampo Tuukkanen  
Juha Vinnurva  
Jussi Virkajärvi  
Mikko Voutilainen  
Sergey Yamaletdinov  
Maciej Zgirski

*MSc students are listed in research reports.*

## Computer systems

Nikola Ciprich 1.5.-  
Vera Hansper  
Janne Kulju  
Hannu Laru

## Laboratory engineers

Väinö Hänninen  
Arto Lassila  
Veikko Nieminen  
Einari Periäinen  
Teuvo Poikolainen  
Kimmo Ranttila  
Antti Nuottajärvi  
Tarmo Suppala  
Juha Ärje

## Operators

Jani Hyvönen  
Anssi Ikonen

## Other technical staff

Martti Hytönen  
Atte Kauppinen  
Erkki Kosola -30.4.  
Hannu Leinonen  
Esa Liimatainen  
Erkki Pesu  
Hannu Pohjanheimo  
Kai Porras  
Marko Puskala  
Raimo Seppälä  
Yrjö Stenman  
Markku Särkkä

## Administration

Anna-Liisa Blå  
Marjut Hilska  
Soili Leskinen  
Ritva Väyrynen

# Boards and Committees

## Departmental Council

1.8.2005-31.7.2008

Jukka Maalampi, professor (chairman)

Markus Ahlskog, professor

Matti Leino, professor

Jouni Suhonen, professor

Jussi Timonen, professor

Hannu Laru, computer support

Juha Merikoski, lecturer

Kimmo Tuominen, assistant

Tero Mononen, student

Perttu Mäkinen, student

Jouko Perkkiö, student

## Scientific Advisory Board of the Centre of Excellence in Nuclear and Accelerator Based Physics

Witold Nazarewicz, professor, University of Tennessee, USA

William Gelletly, professor, University of Surrey, UK

Timo Tiihonen, vice-rector, University of Jyväskylä

Timo Jääskeläinen, professor, Academy of Finland

Pasi Sihvonen, secretary general, Academy of Finland

## Programme Advisory Committee of the JYFL Accelerator Laboratory

Christian Beck, Dr., IReS, Stasbourg, France

Thomas Dossing, Dr., NBI, Copenhagen, Denmark

Zenon Janas, Dr., University of Warsaw, Poland

Juhani Keinonen, Prof., University of Helsinki, Finland

Juergen Kluge, Prof., GSI, Darmstadt, Germany

John Simpson, Prof., CCLRC, Daresbury, UK (chairman)

# Peer Reviewed Articles

## Accelerator Facilities

G. Ciavola, S. Gammino, L. Celona, Passarello, L. Ando, L. Torrisi, M. Cavenago, A. Galata, P. Spaedtke, K. Tinschert, R. Lang, R. Iannucci, R. Leroy, C. Barue, D. Hitz, H. Koivisto, P. Suominen, O. Tarvainen, H. Beijers, S. Bradenburg, D. Van Rooyen, C. Hill, D. Kuchler, H. Homeyer, J. Röhrich, L. Schachte and S. Dobrescu

MS-ECRIS, the European Roadmap to 3<sup>rd</sup> Generation ECR Ion Sources  
Rev. Sci. Instrum. 77 (2006) 03A303

O. Tarvainen, P. Suominen, T. Ropponen and H. Koivisto  
Emittance and plasma potential measurements in double frequency heating mode with the JYFL 14 GHz ECRIS  
Rev. Sci. Instrum. 77 (2006) 03A309

H. Koivisto, P. Suominen, O. Tarvainen, A. Virtanen and A. Parkkinen  
Electron cyclotron resonance ion source related development work for the heavy ion irradiation tests  
Rev. Sci. Instrum. 77 (2006) 03A316

T. Thuillier, H. Koivisto, T. Lamy, P. Sortais, P. Suominen and O. Tarvainen  
A-Phoenix, a new ECR ion source for the Spiral II Facility  
Rev. Sci. Instrum. 77 (2006) 03A323

Y. Kawai, G. D. Alton, Y. Liu and H. Koivisto  
Effect of broadband microwave radiation on the performance of a conventional b-minimum geometry ECR ion source  
Rev. Sci. Instrum. 77 (2006) 03A331

P. Suominen, O. Tarvainen and H. Koivisto  
First Results with a modified multipole structure electron cyclotron resonance ion source  
Rev. Sci. Instrum. 77 (2006) 03A332

## Exotic Nuclei and Beams

Y. Wang, P. Dendooven, J. Huikari, A. Jokinen, V. S. Kolhinen, G. Lhersonneau, A. Nieminen, S. Nummela, H. Penttilä, K. Peräjärvi, S. Rinta-Antila, J. Szerypo, J. C. Wang and J. Äystö  
New levels in <sup>118</sup>Pd observed in the  $\beta$  decay of very neutron-rich <sup>118</sup>Rh isotope  
Chinese Physics Letters 23 (2006) 808

A. Kankainen, T. Eronen, S. P. Fox, H. O. U. Fynbo, U. Hager, J. Hakala, J. Huikari, D. G. Jenkins, A. Jokinen, S. Kopecky, I. Moore, A. Nieminen, H. Penttilä, S. Rinta-Antila, O. Tengblad, Y. Wang and J. Äystö  
Excited states in <sup>31</sup>S studied via beta decay of <sup>31</sup>Cl  
Eur. Phys. J. A 27 (2006) 67

D. G. Jenkins, C. J. Lister, R. V. F. Janssens, T. L. Khoo, E. F. Moore, K. E. Rehm, D. Seweryniak, A. H. Wuosmaa, T. Davinson, P. J. Woods, A. Jokinen, H. Penttilä, G. Martinez-Pinedo and J. Jose  
Re-evaluating reaction rates relevant to nova nucleosynthesis from a nuclear structure perspective  
Eur. Phys. J. A 27 (2006) 117

N. L. Achouri, F. De Oliveira Santos, M. Lewitowicz, B. Blank, J. Äystö, G. Canchel, S. Czajkowski, P. Dendooven, A. Emsallem, J. Giovinazzo, N. Guillet, A. Jokinen, A. M. Laird, C. Longour, A. Ostrowski, K. Peräjärvi, N. Smirnova, M. Stanoiu and J.-C. Thomas  
The beta -decay of <sup>22</sup>Al  
Eur. Phys. J. A 27 (2006) 287

A. Kankainen, L. Batist, S. A. Eliseev, V.-V. Elomaa, T. Eronen, U. Hager, J. Hakala, A. Jokinen, I. Moore, Yu. N. Novikov, H. Penttilä, K. Peräjärvi, A. V. Popov, S. Rahaman, S. Rinta-Antila, P. Ronkanen, A. Saastamoinen, D. M. Seliverstov, T. Sonoda, G. K. Vorobjev and J. Äystö  
Mass measurements of neutron-deficient nuclides close to A=80 with a Penning trap  
Eur. Phys. J. A 29 (2006) 271

A. Herlert, S. Baruah, K. Blaum, P. Delahaye, M. Dworschak, S. George, C. Guénaut, U. Hager, F. Herfurth, A. Kellerbauer, M. Marie-Jeanne, S. Schwarz, L. Schweikhard and C. Yazdijan  
Towards high-accuracy mass spectrometry of highly charged short-lived ions at ISOLTRAP  
Int. J. Mass Spectrometry 251 (2006) 131

A. Jokinen, T. Eronen, U. Hager, I. Moore, H. Penttilä, S. Rinta-Antila and J. Äystö  
Precision experiments on exotic nuclei at IGISOL  
Int. J. Mass Spectrometry 251 (2006) 204

J. Äystö  
Odd couple decays  
NATURE 439 (2006) 279

J. Ekman, J. Helgesson, L. B. Karsson, M. Mohsenpour, I. Riihimäki, V. Touboltsev, P. Jalkanen, A. Virtanen, H. Kettunen, J. Huikari, I. Moore, A. Nieminen, H. Penttilä, K. Arstila, J. Äystö, J. Räsänen and H. J. Whitlow  
Retention of Pb isotopes in glass surfaces for retrospective assessment of radon exposure  
Nucl. Instr. Meth. B. 249 (2006) 544

B. Tordoff, T. Eronen, V.-V. Elomaa, S. Gullick, U. Hager, P. Karvonen, T. Kessler, J. Lee, I. Moore, A. Popov, S. Rahaman, S. Rinta-Antila, T. Sonoda and J. Äystö  
An ion guide for the production of a low energy ion beam of daughter products of alpha-emitters  
Nucl. Instr. Meth. B 252 (2006) 347

D. Rodriguez, G. Audi, J. Äystö, D. Beck, K. Blaum, G. Bollen, F. Herfurth, A. Jokinen, A. Kellerbauer, H.-J. Kluge, V. S. Kolhinen, M. Oinonen, E. Sauvan and S. Schwarz  
Accurate mass measurements on neutron-deficient krypton isotopes  
Nucl. Phys. A 769 (2006) 1

T. Eronen, B. Blank, G. Canchel, V. Elomaa, U. Hager, J. Hakala, A. Jokinen, I. Moore, H. Penttilä, S. Rahaman, S. Rinta-Antila, A. Saastamoinen, T. Sonoda and J. Äystö  
High precision measurement of the Q-value of the superallowed decay of <sup>62</sup>Ga  
Phys. Lett. B 636 (2006) 191

D. G. Jenkins, A. Meadowcroft, C. J. Lister, M.P. Carpenter, P. Chowdhury, N.J. Hammond, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, D. Seweryniak, T. Davinson, P. J. Woods, A. Jokinen, H. Penttilä, G. Martinez-Pinedo and J. Jose  
Re-evaluation of <sup>30</sup>P(p, $\gamma$ )<sup>31</sup>S astrophysical reaction rate from a study of the T=1/2 mirror nuclei, <sup>31</sup>S and <sup>31</sup>P  
Phys. Rev. C 73 (2006) 065802

F. Perrot, F. Marechal, C. Jollet, Ph. Dessagne, J.-C. Angélique, G. Ban, P. Baumann, F. Benrachi, U. Bergmann, C. Borcea, A. Buta, J. Cederkall, S. Courtin, J.-M. Daugas, L.M. Fraile, S. Grevy, A. Jokinen, F. R. Lecolley, E. Lienard, G. LeScornet, V. Meot, Ch. Miede, F. Negoita, N. A. Orr, S. Pietri, E. Poirier, M. Ramdhane, O. Roig, I. Stefan, and Y. Wang  
Beta decay studies of neutron-rich K isotopes  
Phys. Rev. C 74 (2006) 014313

M. L. Bissel, K. Baczyńska, J. Billowes, P. Campbell, B. Cheal, T. Eronen, D. H. Forest, M. D. Gardner, I. D. Moore, B. W. Tordoff, G. Tungate and J. Äystö  
Model independent determination of the spin of the <sup>180</sup>Ta naturally occurring isomer from second order perturbed hyperfine structure  
Phys. Rev. C 74 (2006) 047301

U. Hager, T. Eronen, J. Hakala, A. Jokinen, S. Kopecky, I. Moore, A. Nieminen, S. Rinta-Antila, J. Äystö, V. S. Kolhinen, J. Szerypo and M. Oinonen  
First precision mass measurements of refractory fission fragments  
Phys. Rev. Lett. 96 (2006) 042504

T. Eronen, V. Elomaa, U. Hager, J. Hakala, A. Jokinen, A. Kankainen, I. Moore, H. Penttilä, S. Rahaman, J. Rissanen, A. Saastamoinen, T. Sonoda and J. Äystö  
Q-values of the superallowed  $\beta$  eEmitters <sup>26</sup>Al<sup>m</sup>, <sup>42</sup>Sc and <sup>46</sup>V and their impact on  $V_{ud}$  and the unitarity of the CKM matrix  
Phys. Rev. Lett. 97 (2006) 232501



## In-beam Spectroscopy

R. D. Herzberg, P. T. Greenlees, P. A. Butler, G. D. Jones, M. Venhart, I. G. Darby, S. Eeckhauudt, K. Eskola, T. Grahn, C. Gray-Jones, F. P. Hessberger, P. Jones, R. Julin, S. Juutinen, S. Ketelhut, W. Korten, M. Leino, A.-P. Leppänen, S. Moon, M. Nyman, R. D. Page, J. Pakarinen, A. Pritchard, P. Rahkila, J. Saren, C. Scholey, A. Steer, Y. Sun, Ch. Theisen and J. Uusitalo Nuclear isomers in superheavy elements as stepping stones towards the island of stability  
 Nature (London) 442 (2006) 896

A. N. Steer, D. G. Jenkins, R. Glover, B. S. Nara Singh, N. S. Pattabiraman, R. Wadsworth, S. Eeckhauudt, T. Grahn, P. T. Greenlees, P. Jones, R. Julin, S. Juutinen, M. Leino, M. Nyman, J. Pakarinen, P. Rahkila, J. Saren, C. Scholey, J. Sorri, J. Uusitalo, P. A. Butler, I. G. Darby, R.-D. Herzberg, D. T. Joss, R. D. Page, J. Thomson, R. Lemmon, J. Simpson and B. Blank Recoil-beta tagging: A novel technique for studying proton-drip-line nuclei  
 Nucl. Instr. Meth. A 565 (2006) 630

F. Becker, A. Petrovici, J. Iwanicki, N. Amzal, W. Korten, K. Hauschild, A. Hurstel, Ch. Theisen, P.A. Butler, R.A. Cunningham, T. Czosnyka, G.de France, J. Gerl, P. Greenlees, K. Helariutta, R.-D. Herzberg, P. Jones, R. Julin, S. Juutinen, H. Kankaanpää, M. Muikku, P. Nieminen, O. Radu, P. Rahkila and Ch.Schlegel Coulomb excitation of  $^{78}\text{Kr}$   
 Nucl. Phys. A 770 (2006) 107

T. Grahn, A. Dewald, O. Möller, R. Julin, C. W. Beausang, S. Christen, I. G. Darby, S. Eeckhauudt, P. T. Greenlees, A. Gorgen, K. Helariutta, J. Jolie, P. Jones, S. Juutinen, H. Kettunen, T. Kröll, R. Krücken, Y. Le Coz, M. Leino, A.-P. Leppänen, P. Maierbeck, D. A. Meyer, B. Melon, P. Nieminen, M. Nyman, R. D. Page, J. Pakarinen, P. Petkov, P. Rahkila, B. Saha, M. Sandzelius, J. Sarén, C. Scholey and J. Uusitalo Collectivity and configuration mixing in  $^{186,188}\text{Pb}$  and  $^{194}\text{Po}$   
 Phys. Rev. Lett. 97 (2006) 062501

I. E. Bastin, R.-D. Herzberg, P. A. Butler, G.D. Jones, R. D. Page, D. G. Jenkins, N. Amzal, P. M. T. Brew, N. J. Hammond, R. D. Humphreys, P. J. C. Ikin, T. Page, P. T. Greenlees, P. M. Jones, R. Julin, S. Juutinen, H. Kankaanpää, A. Keenan, H. Kettunen, P. Kuusiniemi, M. Leino, A. P. Leppänen, M. Muikku, P. Nieminen, P. Rahkila, C. Scholey, J. Uusitalo, E. Bouchez, A. Chatillon, A. Hurstel, W. Korten, Y. Le Coz, Ch.Theisen, D. Ackermann, J. Gerl, K. Helariutta, F. P. Hessberger, Ch. Schlegel, H. J. Wollersheim, M. Lach, A. Maj, W. Meczynski, J. Styczen, T. L. Khoo, C. J. Lister, A. V. Afanasjev, H. J. Maier, P. Reiter, P. Bednarczyk, K. Eskola and K. Hauschild In-beam gamma ray and conversion electron study of  $^{250}\text{Fm}$   
 Phys. Rev. C 73 (2006) 024308

D. T. Joss, J. Simpson, D. E. Appelbe, C. J. Barton, D. D. Warner, K. Lagergren, B. Cederwall, B. Hadinia, S. Eeckhauudt, T. Grahn, P. T. Greenlees, P. M. Jones, R. Julin, S. Juutinen, H. Kettunen, M. Leino, A.-P. Leppänen, P. Nieminen, J. Pakarinen, J. Perkowski, P. Rahkila, C. Scholey, J. Uusitalo, K. Van de Vel, R. D. Page, E. S. Paul, D. R. Wiseman and M. A.Riley Yrast states and band crossings in the neutron-deficient platinum isotopes  $^{169-173}\text{Pt}$   
 Phys. Rev. C 74, (2006) 014302

## The JYFL Gas Filled Recoil Separator RITU

A.-P. Leppänen, J. Uusitalo, P. T. Greenlees, R.-D. Herzberg, N. Amzal, F. Becker, P. A. Butler, A. J. C. Chewter, J. F. C. Cocks, O. Dorvaux, S. Eeckhauudt, K. Eskola, J. Gerl, T. Grahn, N. J. Hammond, K. Hauschild, K. Helariutta, F. P. Hessberger, M. Houry, G. D. Jones, P. M. Jones, R. Julin, S. Juutinen, H. Kankaanpää, H. Kettunen, T. L. Khoo, W. Korten, P. Kuusiniemi, Y. Le Coz, M. Leino, C. J. Lister, R. Lucas, M. Muikku, P. Nieminen, M. Nyman, R. D. Page, J. Pakarinen, P. Rahkila, P. Reiter, J. Saren, Ch. Schlegel, C. Scholey, O. Stezowski, Ch. Theisen, W. H. Trzaska and H. J. Wollersheim Recoil-fission tagging of the transfermium nucleus  $^{252}\text{No}$   
 Eur. Phys.J. A 28 (2006) 301

F. P. Heßberger, S. Hofmann, D. Ackermann, S. Antalic, B. Kindler, I. Kojouharov, P. Kuusiniemi, M. Leino, B. Lommel, R. Mann, K. Nishio, A. G. Popeko, B. Sulignano, S. Saro, B. Streicher, M. Venhart and A.V. Yeremin Alpha-gamma decay studies of  $^{255}\text{No}$   
 Eur. Phys. J. A 29 (2006) 165

A. Chatillon, Ch. Theisen, P. T. Greenlees, G. Auger, J. E. Bastin, E. Bouchez, B. Bouriquet, J. M. Casandjian, R. Cee, E. Clement, R. Dayras, G. de France, R. de Tourreil, S. Eeckhauudt, A. Gorgen, T. Grahn, S. Grevy, K. Hauschild, R.-D. Herzberg, P. J. C. Ikin, G. D. Jones, P. Jones, R. Julin, S. Juutinen, H. Kettunen, A. Korichi, W. Korten, Y. Le Coz, M. Leino, A. Lopez-Martens, S. M. Lukyanov, Yu. E. Penionzhkevich, J. Perkowski, A. Pritchard, P. Rahkila, M. Rejmund, J. Saren, C. Scholey, S. Siem, M. G. Saint-Laurent, C. Simenel, Yu. G.Sobolev, Ch. Stodel, J. Uusitalo, A. Villari, M. Bender, P. Bonche and P.-H. Heenen Spectroscopy and single-particle structure of the odd-Z heavy elements  $^{255}\text{Lr}$ ,  $^{251}\text{Md}$  and  $^{247}\text{Es}$   
 Eur. Phys. J. A 30 (2006) 397

F. P. Heßberger, S. Hofmann, D. Ackermann, S. Antalic, B. Kindler, I. Kojouharov, P. Kuusiniemi, M. Leino, B. Lommel, R. Mann, K. Nishio, A. G. Popeko, B. Sulignano, S. Saro, B. Streicher, M. Venhart and A.V. Yeremin Alpha-gamma decay studies of  $^{255}\text{Rf}$ ,  $^{251}\text{No}$  and  $^{247}\text{Fm}$   
 Eur. Phys. J. A 30 (2006) 561

D. T. Joss, I. G. Darby, R. D. Page, J. Uusitalo, S. Eeckhauudt, T. Grahn, P. T. Greenlees, P. M. Jones, R. Julin, S. Juutinen, S. Ketelhut, M. Leino, A.-P. Leppänen, M. Nyman, J. Pakarinen, P. Rahkila, J. Saren, C. Scholey, A. Steer, A. J. Cannon, P. D. Stevenson, J. S. Al-Khalili, S. Erturk, M. Venhart, B. Gall, B. Hadinia and J. Simpson Probing the limit of nuclear existence: Proton emission from  $^{159}\text{Re}$   
 Phys. Lett. B 641 (2006) 34

K. Lagergren, D. T. Joss, R. Wyss, B. Cederwall, C. J. Barton, S. Eeckhauudt, T. Grahn, P. T. Greenlees, B. Hadinia, P. M. Jones, R. Julin, S. Juutinen, D. Karlgren, H. Kettunen, M. Leino, A.-P. Leppänen, P. Nieminen, M. Nyman, R. D. Page, J. Pakarinen, E. S. Paul, P. Rahkila, C. Scholey, J. Simpson, J. Uusitalo and D. R. Wiseman High-spin states in the proton-unbound nucleus  $^{161}\text{Re}$   
 Phys. Rev. C 74 (2006) 024316

## ALICE and Nuclear Reactions

G. V. Rogachev, A. Aprahamian, F. D.Becchetti, P. Boutachkov, Y. Chen, G. Chubarian, P. A. DeYong, A. Formichev, V. Z. Goldberg, M. S. Golovkov, J. J. Kolata, Yu. Ts. Oganessian, G. F. Peaslee, M. Quinn, A. Rodin, B. B. Skorodumov, R. S. Slepnev, G. Ter-Akopian, W. H. Trzaska, A. Wotr and R. Wolski Isobaric analog states as a tool for spectroscopy of exotic nuclei  
 Nucl. Instr. Meth. B 241 (2005) 977

J. Perkowski, J. Andrzejewski, A. Climent-Font, G. Knyazheva, V. Lyapin, T. Malkiewicz, A. Munoz-Martin and W. H. Trzaska Stopping power measurement of  $^{48}\text{Ca}$  in solid absorbers in broad energy range  
 Nucl. Instr. Meth. B 249 (2006) 55

G. N. Knyazheva, S. V. Khlebnikov, E. M. Kozulin, T. E. Kuzmina, V. G. Lyapin, M. Mutterer and W. H. Trzaska Energy losses of  $^{252}\text{Cf}$  fission fragments in thin foils  
 Nucl. Instr. Meth. B. 248 (2006) 7

V. A. Rubchenya, A. A. Alexandrov, S. V. Khlebnikov, V. G. Lyapin, V. A. Maslov, Yu. E. Penionzhkevich, G. Prete, Yu. G. Sobolev, G. P. Tyurin, W. H. Trzaska, D. N. Vakhtin and E. Vardaci Light particle accompanied quasifission in superheavy composite systems, Physics of Atomic Nuclei Vol. 69 No. 8 (2006) 1388

ALICE Collaboration ALICE: Physics Performance Review  
 Phys. J. G 32 (2006) 1295

PHENIX Collaboration Nuclear Modification of Single Electron Spectra and Implications for Heavy Quark Energy Loss in Au + Au Collisions at  $\sqrt{s_{NN}} = 200\text{ GeV}$   
 Phys. Rev. Lett. 96 (2006) 032301

#### PHENIX Collaboration

Common suppression pattern of  $\epsilon$  and  $\pi 0$  mesons at high transverse momentum in Au + Au collisions at  $s(NN)^{1/2} = 200$ -GeV  
Phys. Rev. Lett. 96 (2006) 202301

#### PHENIX Collaboration

Azimuthal angle correlations for rapidity separated hadron pairs in d + Au collisions at  $s(NN)^{1/2} = 200$ -GeV  
Phys. Rev. Lett. 96 (2006) 222301

#### PHENIX Collaboration

Measurement of high-p(T) single electrons from heavy-flavor decays in p + p collisions at  $s^{1/2} = 200$ -GeV  
Phys. Rev. Lett. 97 (2006) 252002

#### PHENIX Collaboration

Measurement of direct photon production in p + p collisions at  $s^{1/2} = 200$ -GeV  
Phys. Rev. Lett. 98 (2007) 012002

#### PHENIX Collaboration.

Nuclear effects on hadron production in d + Au and p + p collisions at  $s(NN)^{1/2} = 200$ -GeV  
Phys. Rev. C 74 (2006) 024904

#### PHENIX Collaboration

Improved measurement of double helicity asymmetry in inclusive midrapidity  $\pi 0$  production for polarized p + p collisions at  $s^{1/2} = 1200$ -GeV  
Phys. Rev. D 73 (2006) 091102

#### PHENIX Collaboration

Jet properties from dihadron correlations in p + p collisions at  $s^{1/2} = 200$ -GeV  
Phys. Rev. D 74 (2006) 072002

M. Brenner, M. Lattuada, M. Gulino, S. V. Khlebnikov, Li Chengbo, G. Prete, W. H. Trzaska, M. Zadro and S. E. Belov  
Alpha-particle transfer from  $^6\text{Li}$  to  $^{28}\text{Si}$  leading to high excitation of  $^{32}\text{S}$   
Physica Scripta 74 (2006) 692

V. A. Grigoriev, F. F. Guber, V. A. Kaplin, A. I. Karakash, T. A. Karavicheva, N. V. Kondratieva, A. B. Kurepin, V. A. Loginov, V. G. Lyapin, V. N. Lukianov, T. Malkievicz, A. I. Reshetin, L. P. Shusterman and W. H. Trzaska  
Studies of gain and timing properties of Russian fine-mesh phototubes FEU-187  
Pribory i tekhnika experimenta 5 (2006) 93

## Accelerator Based Materials Physics

F. Iacopi, Y. Travaly, B. Eyckens, C. Waldfried, T. Abell, E.P. Guyer, D.M. Gage, R.H. Dauskardt, T. Sajavaara, K. Houthoofd, P. Grobet, P. Jacobs and K. Maex  
Short-ranged structural rearrangement and enhancement of mechanical properties of organosilicate glasses induced by Ultraviolet radiation  
J. Appl. Phys. 99 (2006) 053511

A. Martin Hoyas, Y. Travaly, J. Schuhmacher, T. Sajavaara, C. M. Whelan, B. Eyckens, O. Richard, S. Giangrandi, B. Brijs, W. Vandervorst, K. Maex, J. P. Celis, A. M. Jonas and A. Vantomme

The impact of the density and type of reactive sites on the characteristics of the atomic layer deposited WNC films  
J. Appl. Phys. 99 (2006) 063515

S. Gasiorok, P. K. Sahoo, K. P. Lieb, S. Dhar, T. Sajavaara and J. Keinonen

Solid phase epitaxy of Na-ion irradiated alpha-quartz: Cathodoluminescence, kinetics and surface morphology  
Journal of Non-Crystalline Solids 352 (2006) 2986

J. P. Coad, J. Likonen, M. Rubel, E. Vainonen-Ahlgren, D. E. Hole, T. Sajavaara, T. Renvall, G.F. Matthews and JET EFDA Contributors

Overview of material re-deposition and fuel retention studies at JET with the Gas Box divertor  
Nucl. Fusion 46 (2006) 350

Y. Zhang, D. E. McCready, C. M. Wang, J. Young, M. I. McKinley, W. J. Weber, H. J. Whitlow, A. Razpet, G. Possnert, T. Zhang and Y. Wu

Formation of silicide films by ion beam deposition  
Nucl. Instr. Meth. B 242 (2006) 602

H. J. Whitlow, Y. Zhang, C. M. Wang, D. E. McCready, T. Zhang and Y. Wu

Formation of cobalt silicide from filter metal vacuum arc deposited films  
Nucl. Instr. Meth. B 247 (2006) 271

S. Giangrandi, B. Brijs, T. Sajavaara, K. Arstila, A. Vantomme and W. Vandervorst

Irradiation-induced damage in porous low-k materials during low-energy heavy-ion Elastic Recoil Detection Analysis  
Nucl. Instr. Meth. B 249 (2006) 189

B. Brijs, T. Sajavaara, S. Giangrandi, T. Janssens, T. Conard, K. Arstila, K. Nakajima, K. Kimura, A. Bergmaier, G. Dollinger, A. Vantomme and W. Vandervorst

The analysis of a thin  $\text{SiO}_2/\text{Si}_3\text{N}_4/\text{SiO}_2$  stack: A comparative study of low-energy heavy ion elastic recoil detection, high-resolution Rutherford backscattering and secondary ion mass spectrometry  
Nucl. Instr. Meth. B 249 (2006) 247

T. Sajavaara, B. Brijs, S. Giangrandi, K. Arstila, A. Vantomme and W. Vandervorst

Analysis of thin high-k and silicide films by means of heavy ion time-of-flight forward-scattering spectrometry  
Nucl. Instr. Meth. B 249 (2006) 292

C. T. Joensson, I. A. Maximov, H. J. Whitlow, M. Shutthanandan, L. Saraf, D. E. McCready, B.W. Arey, Y. Zhang and S. Thevuthasan

Synthesis and characterisation of cobalt silicide films on silicon  
Nucl. Instr. Meth. B 249 (2006) 532

T. D. M. Weijers-Dall, H. Timmers, K. Stenström, P. Persson, A. Pergjegaj, X. Wang, M. Graczyk, T. Osipowicz, M. Q. Ren, D. J. O'Connor and H. J. Whitlow

Measurements of the stopping forces for heavy ions in Ge, Ag and Au using novel 'polka-dot' detectors  
Nucl. Instr. Methods B 251 (2006) 352

I. Jogi, J. Aarik, M. Laan, J. Lu, K. Kukli, H. Kämbre, T. Sajavaara and T. Uustare

Effect of preparation conditions on properties of ALD-grown  $\text{TiO}_2$  films in  $\text{Mo}/\text{TiO}_2/\text{Al}$  stacks  
Thin Solid Films 510 (2006) 39

See also Exotic Nuclei and Beams: Nucl. Instr. Meth. B. 249 (2006) 544

## Industrial Applications

A. Virtanen

The use of particle accelerators for space projects  
J. Phys. 41 (2006) 101

E. Tuovinen, J. Härkönen, P. Luukka, E. Tuominen, E. Verbitskaya, V. Eremin, I. Ilyashenko, A. Pirojenko, I. Riihimäki, A. Virtanen and K. Leinonen

Czocharalski silicon detectors irradiated with 24 GeV/c and 10 MeV protons  
Nucl. Instr. Meth. A 568 (2006) 83

J. Ekman, J. Helgesson, L. B. Karlsson, M. Mohsenpour, I. Riihimäki, V. Touboltsev, P. Jalkanen, A. Virtanen, H. Kettunen, J. Huikari, A. Nieminen, I. Moore, H. Penttilä, K. Arstila, J. Äystö, J. Räisänen and H. J. Whitlow  
Retention of Pb isotopes in glass surfaces for retrospective assessment of radon exposure  
Nucl. Instr. Meth. B 249 (2006) 544

T. Kalvas, S. K. Hahto, F. Gicquel, M. King, J. H. Vainionpää, J. Reijonen, K. N. Leung and T. G. Miller

Fast slit-beam extraction and chopping for neutron generator  
Rev. Sci. Instrum. 77 (2006) 03B904

See also: Accelerator Facilities: Rev. Sci. Instrum. 77 (2006) 03A316

## Nuclear Structure, Nuclear decays, Rare and Exotic Processes

O. Civitarese and J. Suhonen

Neutrinoless double beta decay and the electron neutrino mass  
Czech. J. Phys. 56 (2006) 447

M. Kortelainen, J. Suhonen, J. Toivanen and T. S. Kosmas

Theoretical LSP detection rates for dark-matter detectors  
Czech. J. Phys. 56 (2006) 467

J. Kotila, J. Suhonen and D. S. Delion

Study of the low-lying collective states using a microscopic anharmonic vibrator approach,  
Czech. J. Phys. 56 (2006) 473

*J. Suhonen*

Beta decays and muon capture as probes of double beta matrix elements  
 Czech. J. Phys. 56 (2006) 511

*J. Suhonen and M. Kortelainen*

Muon-capture rates and their relation with the double beta decay  
 Czech. J. Phys. 56 (2006) 519

*J. Kotila, J. Suhonen and D. S. Delion*

Study of the low-lying collective states in  $^{94}\text{Mo}$ - $^{100}\text{Mo}$  isotopes using the MAVIA  
 Nucl. Phys. A 765 (2006) 354

*M. Kortelainen, T. S. Kosmas, J. Suhonen and J. Toivanen*

Event rates for CDM detectors from large-scale shell-model calculations  
 Phys. Lett. B 632 (2006) 226

*D. S. Delion, S. Peltonen and J. Suhonen*

Systematics of the alpha decay to rotational states  
 Phys. Rev. C 73 (2006) 014315

*M. T. Mustonen, M. Aunola and J. Suhonen*

Theoretical description of the fourth-forbidden non-unique beta decays of  $^{113}\text{Cd}$  and  $^{115}\text{In}$   
 Phys. Rev. C 73 (2006) 054301

## Nanophysics and Nanotechnology

*L. J. Taskinen and I. J. Maasilta*

Improving the performance of hot-electron bolometers and solid state coolers with disordered alloys  
 Appl. Phys. Lett. 89 (2006) 143511

*D. V. Vodolazov, F. M. Peters, T. T. Hongisto and K. Yu. Arutyunov*

Microscopic analysis of multiple flux transitions in mesoscopic superconducting loops  
 Europhys. Lett., 75 (2), (2006) 315

*L. J. Taskinen, J. T. Karvonen and I. J. Maasilta*

Electron-phonon interaction in a thin Al-Mn film  
 Nucl. Instr. Meth. A 559 (2006) 639

*I. J. Maasilta*

Optimizing the operating temperature of a transition edge sensor  
 Nucl. Instr. Meth. A 559 (2006) 706

*T. Kühn and I. J. Maasilta*

Ballistic phonon transport in dielectric membranes  
 Nucl. Instr. Meth. A 559 (2006) 724

*G. S. Paraoanu*

Interaction-free measurements with superconducting qubits  
 Phys. Rev. Lett. 97 (2006) 180406

*A. A. Shanenko, M. D. Croitoru, M. Zgirski, F. M. Peters and K. Arutyunov*

Size dependent enhancement of superconductivity in nanowires  
 Phys. Rev. B. 74 (2006) 052502

*G. S. Paraoanu*

Microwave-induced coupling of superconducting qubits  
 Phys. Rev. B 74 (2006) 140504 (R)

*M. Zgirski, K.-P. Riikonen, T. Holmqvist, M. Savolainen, V. Touboltsev, and K. Arutyunov*

Phase slip phenomena in ultra-thin superconducting wires, in Quantum Computation in Solid State Systems edited by B. Rugiero, P. Delsing, C. Granata, Y. Pashkin, P. Silvestrini  
 Springer (2006) 70

*I. J. Maasilta, K. M. Kinnunen, A. K. Nuottajärvi, J. Leppäniemi and A. Luukanen*

Operation of TES sensors with excess thermal noise  
 Supercond. Sci. and Technol. 19 (2006) S242

## Nanoelectronics and Nanotechnology

*S. Tuukkanen, J. J. Toppari, A. Kuzyk, L. Hirviniemi, V. P. Hytönen, T. Ihalainen and P. Törmä*

Carbon nanotubes as electrodes for dielectrophoresis of DNA  
 Nano Lett. 6 (2006) 1339

*T. Koponen, J. Kinnunen, J.-P. Martikainen, L. M. Jensen and P. Törmä*

Fermion pairing with spin-density imbalance in an optical lattice  
 New J. Phys. 8 (2006) 179

*J. Kinnunen and P. Törmä*

Beyond linear response spectroscopy of ultracold Fermi gases  
 Phys. Rev. Lett. 96 (2006) 070402

*J. Kinnunen, L. M. Jensen and P. Törmä*

Strongly interacting Fermi gases with density imbalance  
 Phys. Rev. Lett. 96 (2006) 110403

*T. Koponen, J.-P. Martikainen, J. Kinnunen and P. Törmä*

Sound velocity and dimensional crossover in a superfluid Fermi gas in an optical lattice  
 Phys. Rev. A 73 (2006) 033620

*L. M. Jensen, H. M. Nilsen and G. Watanabe*

BCS-BEC crossover in atomic Fermi gases with a narrow resonance  
 Phys. Rev. A 74 (2006) 043608

*T. Paananen, J.-P. Martikainen and P. Törmä*

Pairing in a three component Fermi gas  
 Phys. Rev. A 73 (2006) 053606

## Computational Nanosciences

*K. Manninen H. Häkkinen and M. Manninen*

Ab initio simulation of Na-59(+) and Na-93(+)  
 Comput. Mat. Sci. 35 (2006) 158

*H. Häkkinen and M. Moseler*

55-atom clusters of silver and gold: Symmetry breaking by relativistic effects  
 Comput. Mater. Sci. 35 (2006) 332

*B. Huber, H. Häkkinen, U. Landman and M. Moseler*

Oxidation of small gas phase Pd clusters: A density functional study  
 Comput. Mater. Sci. 35 (2006) 371

*H. Grönbeck, M. Walter and H. Häkkinen*

Theoretical characterization of cyclic thiolated gold clusters  
 J. Am. Chem. Soc. 128 (2006) 10269

*R. van Harrevelt, K. Honkala, J. K. Nørskov and U. Manthe*

The effect of surface relaxations on the  $\text{N}_2$  dissociation rate on stepped Ru: transition state theory studies  
 J. Chem. Phys. 124 (2006) 026102

*C. Diaz, J. K. Vincent, G. P. Krishnamohan, R. A. Olsen, K. Honkala, J. K. Nørskov and G. J. Kroes*

Reactive and nonreactive scattering of N-2 from Ru(0001): A six-dimensional adiabatic study  
 J. Chem. Phys. 125 (2006) 114706

*J. Akola, K. Rytönen and M. Manninen*

Electronic properties of single-walled carbon nanotubes inside cyclic supermolecules  
 J. Phys. Chem. B 110 (2006) 5186

*J. Akola and R.O. Jones*

Density functional calculations of ATP systems I: Crystalline ATP hydrates and related molecules  
 J. Phys. Chem. B 110 (2006) 8110

*J. Akola and R.O. Jones*

Density functional calculations of ATP systems II: ATP hydrolysis at the active site of actin  
 J. Phys. Chem. B 110 (2006) 8121

*H. Häkkinen, M. Walter and H. Grönbeck*

Divide and pProtect: Capping gold nanoclusters with molecular gold-thiolate rings  
 J. Phys. Chem. B 110 (2006) 9927

*A. Hellman, M. Biczysko, T. Bligaard, D. C. Clary, S. Dahl, R. van Harrevelt, K. Honkala, H. Jonsson, M. Luppi, E.J. Baerends, G. J. Kroes, U. Mathe, J. K. Nørskov, R. A. Olsen, E. Skulason, C. S. Tautermann, A. J. C. Varandas and J. K. Vincent*

Predicting Catalysis: Understanding ammonia synthesis from first principles calculations  
 J. Phys. Chem B 110 (2006) 17719

*M. Toreblad, Y. Yu, S. M. Reimann, M. Koskinen and M. Manninen*

Finite boson and fermion systems under extreme rotation: Edge reconstruction and vortex formation  
 J. Phys. B 39 (2006) 2721

*J. R. Götz, M. Walter and J. S. Briggs*

Cross-sections for (e,3e) collisions on helium: the DS6C wavefunction  
 J. Phys. B 39 (2006) 4365

*P. Singha Deo and M. Manninen*

Importance of individual scattering matrix elements at Fano resonances  
 J. Phys. Cond. Mat. 18 (2006) 5313

B. Huber, P. Koskinen, H. Häkkinen and M. Moseler  
Oxidation of Pd-clusters on magnesia leads to the ultimate limit of epitaxy with a catalytic function  
Nature Materials 5 (2006) 44

P. Koskinen, H. Häkkinen, G. Seifert, S. Sanna, Th. Frauenheim and M. Moseler  
Density-functional based tight-binding study of small gold clusters  
New Journal of Physics 8 (2006) 9

S. M. Reimann, M. Koskinen, Y. Yu and M. Manninen  
Rotating quantum liquids crystallize  
New Journal of Physics 8 (2006) 59

M. Walter and H. Häkkinen  
A hollow tetrahedral cage of hexadecagold dianion provides a robust backbone for a sub-nanometer oxidation and reduction agent via endohedral doping  
Phys. Chem. Chem. Phys. 8 (2006) 5407

S. M. Reimann, M. Koskinen, Y. Yu and M. Manninen  
Vortex localization in rotating clouds of bosons and fermions  
Phys. Rev. A 74 (2006) 043603

J. S. Briggs and M. Walter  
Nodes of entangled N-particle wavefunctions  
Phys. Rev. A 74 (2006) 062108

J. Akola and H. Häkkinen  
Ab initio study of the adsorption of gold atoms and clusters on graphite (0001) with defects  
Phys. Rev. B 74 (2006) 165404

C. Diaz, J. K. Vincent, G. P. Krishnamohan, R. A. Olsen, K. Honkala, J. K. Norskov and G. J. Kroes  
Multidimensional effects on dissociation of  $N_2$  on Ru(0001)  
Phys. Rev. Lett. 96 (2006) 096102

J.-P. Nikkarila and M. Manninen  
Rotating electrons in quantum dots: Classical limit  
Solid State Commun. 14 (2007) 209

R. Vang, K. Honkala, S. Dahl, E. K. Vestergaard, J. Schnadt, E. Laegsgaard, B. S. Clausen, J. K. Norskov and F. Besenbacher  
Ethylene dissociation on flat and stepped Ni(111): A combined STM and DFT study  
Surf. Sci. 600 (2006) 66

A. Hellman, K. Honkala, I. N. Remediakis, A. Logadottir, A. Carlsson, S. Dahl, C. H. Christensen and J. K. Norskov  
Insights into the ammonia synthesis from first-principles  
Surf. Sci. 600 (2006) 4264

## Soft Condensed Matter and Statistical Physics

J. Åström, F. Pröbst, P. C. F. DiStefano, L. Stodolsky, J. Timonen et al.  
Fracture processes studied in CRESST  
Nucl. Instr. Meth. A 559 (2006) 754

J. Åström, F. Pröbst, P. C. F. DiStefano, L. Stodolsky, J. Timonen et al.  
Fracture processes observed with a cryogenic detector  
Phys. Lett. A 356 (2006) 262

J. Hyväluoma, P. Raiskinmäki, A. Jäsberg, A. Koponen, M. Kataja and J. Timonen  
Simulation of liquid penetration in paper  
Phys. Rev. E 73 (2006) 036705

P. Moilanen, P. H. F. Nicholson, V. Kilappa, S. Cheng and J. Timonen  
Measuring guided waves in long bones: modeling and experiments in free and immersed plates  
Ultrasound Med. Biol. 32 (2006) 709

## Ultrarelativistic Heavy ion Collisions

P. Huovinen and P. V. Ruuskanen  
Hydrodynamic models for heavy ion collisions  
Ann. Rev. Nucl. Part. Sci., vol 56 (2006) 163

K. J. Eskola and H. Paukunen  
NuTeV  $\sin^2\Theta_w$  anomaly and nuclear parton distributions revisited  
JHEP 0606 (2006) 008

K. J. Eskola, H. Honkanen, H. Niemi, P. V. Ruuskanen and S. S. Räsänen  
Transverse spectra of hadrons in central A A collisions at RHIC and LHC from pQCD + saturation + hydrodynamics and from pQCD + energy losses  
Nucl. Phys. A 774 (2006) 805

T. Renk, S. A. Bass and D. K. Srivastava  
Dynamics of the Landau-Pomeranchuk-Migdal effect in Au + Au collisions at 200-AGeV  
Phys. Lett. B 632 (2006) 632

T. Renk and J. Ruppert  
Mach cones in an evolving medium  
Phys. Rev. C 73 (2006) 011901

J. Ruppert, Th. Renk and B. Muller  
Mass and width of the  $\rho$  meson in a nuclear medium from Brown-Rho scaling and QCD sum rules  
Phys. Rev. C 73 (2006) 034907

T. Renk  
Through the blackness: High p(T) hadrons probing the central region of 200-AGeV Au - Au collisions  
Phys. Rev. C 74 (2006) 024903

T. Renk  
Towards jet tomography: gamma-hadron correlations  
Phys. Rev. C 74 (2006) 034906

D. D. Dietrich, F. Sannino and K. Tuominen  
Light composite Higgs and precision electroweak measurements on the Z resonance: An update  
Phys. Rev. D 73 (2006) 037701

## Theoretical Particle Physics and Cosmology

M. Dvornikov  
Evolution of coupled fermions under the influence of an external axial-vector field.  
Eur. Phys. J.C 47 (2006) 437

D. Meschini and M. Lehto  
Is empty spacetime a physical thing?  
Foundations of Physics, 36 (2006) 1193

A. Peltola and J. Mäkelä  
Radiation of the inner horizon of the Reissner-Nordström black hole  
Int. J. Mod. Phys. D 15 (2006) 817

M. Dvornikov  
Neutrino spin oscillations in gravitational fields  
Int. J. Mod. Phys. D 15 (2006) 1017

T.-F. Feng, X.-Q. Li and J. Maalampi  
Mixing among the neutral Higgs bosons and rare B decays in the CP violating MSSM  
Phys. Rev. D 73 (2006) 035011

K. Kainulainen and D. Sunhede  
Dark energy from large extra dimensions  
Phys. Rev. D 73 (2006) 083510

T.-F. Feng, X.-Q. Li, L. Lin, J. Maalampi and H.-S. Song  
The two-loop supersymmetric corrections to lepton anomalous magnetic and electric dipole moments  
Phys. Rev. D 73 (2006) 116001

## Other Books and Reports

J. Maalampi  
MaaIlmanviiva. Albert Einstein ja moderni fysiikka.  
Ursa (2006), 221, ISBN 952-5329-51-8

In four decades of subatomic physics. Essays in Honour of Professor of Theoretical Physics Pentti Vesa Ruuskanen on the Occasion of His Retirement 21 December 2006  
Ed. Kari J. Eskola and Kimmo Kainulainen, JYFL Research Report No. 15/2006

## Theses

### MSc Theses

(Alphabetical order)

Tuomas Airaksinen, Numeerista virtauslaskentaa hila-Boltzmann-simulointimenetelmällä

Tero Alakurtti, CSEM-sähkömagnetismitesti

Asaf Avnon, Dielectrophoretic trapping of carbon nanotubes and electropolymerization of conducting polypyrrole

Eric Blair, Solution phase fabrication of quantum dots: microfluidic methods

Lasse Elomaa, Akustisen sadeanturin tyypikalibrointi laboratoriossa

Essi Förström, Metrinen geometria ja kosmologia

Mohamed Rabie Hassan, On-chip microwave generation and detection in Josephson circuits

Heikki Heiskanen, Beta minus decay of  $^{96}\text{Zirkonium}$  to  $6^+$ ,  $5^+$  and  $4^+$  states of niobium using the BCS and pnQRPA methods

Lasse Hirviniemi, Hiilinanoputket elektrodeina dielektriforesissa

Otso Jarva, Avoimet laboratoriotyöt yliopisto-opetuksessa

Han Jie, Technical background, applications and implementation of quartz crystal microbalance systems

Jarmo Jääskeläinen, Luokanopettajiksi opiskelevien käsityksiä voimasta

Timo Kallinen, Teridian 71M6513-pohjaisen kWh-mittarin suunnittelu ja toteutus

Joonas Ketonen, Tippuminen on energiaa – luokanopettajaopiskelijoiden käsityksiä energiasta

Laura Ketonen, Tippuminen on energiaa – luokanopettajaopiskelijoiden käsityksiä energiasta

Pilvi-Helinä Kivelä, Puristinhuovan permeabiliteettimitaukset

Joonas Koivisto,  $^{124}\text{Ag}$ :n beetahajoaminen  $^{124}\text{Cd}$ :n viritystiloille

Topi Kähärä, Kahden kevyen kvarkkimaun kvanttiväriydynamiikan termodynamiikka lineaarisessa sigmamallissa

Suvi Laitinen, Lumo-kvarkkituotto syvässä epäelastisessa elektroni-protoni-sironnassa vapaan sekä ytimeen sitoutuneen protonin gluonijakauman tutkimisessa

Maarit Lappalainen, Kokeellisuus fysiikan ja kemian opetuksessa alaluokilla

Heli Lehtivuori, Nanometriluokan DNA-molekyylien kytkentäryhmän vaikutus elektrodi-DNA-elektrodi -rakenteen sähköjohtavuuteen

Jani Leskinen, JUROGAM II pohjatyö: nelikiteinen Clover-germanium-ilmaisimien gammaspektrometrina

Jarkko Lievonen, Moniseinäisten hiilinanoputkien elastisuus

Weilu Liu, Guiding macromolecules by using magnetic tweezers

Mikko Lommi, Stirling-perustaisen mikro-CHP-laitteiston prosessilaskenta ja lämmönvaihtimen mitoitus

Arto Lähteelä, Röntgenmikrotomografian käyttö päällystetyn paperin tutkimisessa

Ma Zhibin, Strategies of fault detection for power quality improvement – a project in Baotou Power Supply Bureau, China

Sami Malola, Kultapintojen kuvaaminen tiheysfunktio-naaliteoriaan perustuvan tiukan sidoksen menetelmän avulla

Pasi Nieminen, Esitysmuotojen hallinnan koherenssin arviointi

Harri Niiranen, Elektronien ja kaksikulotteisten fononien välisen energiasiirtotehon mittaaminen

Juha-Pekka Nikkarila, Kvanttipisteiden elektronien energiaspektrin tulkinta klassisten rotaatioiden ja värähtelyjen avulla

Maria Palomäki, Intensiteettimuokattua sädehoitokenttää mittaavan ilmaisimen kehittäminen

Alexandre Pirojenko, RADEF-aseman ohjaus- ja tiedonkeruujärjestelmä

Suvi Päiviö, Radiometristen mittausmenetelmien soveltuvuus biopolttoaineen epäpuhtauksien havaitsemiseen

Erkki Sulkala, Kiinteiden biopolttoaineiden pyrolyysikaasujen analyysi FTIR-menetelmällä

Ismo Talka, Pienpolton hiukkasten sähköinen suodattaminen

Tuomas Tallinen, Tomografiaan perustuva paperin huokosrakenteen analyysi

Heidi Tarvainen, <sup>83</sup>Kr-ytimen viritystilarakenne ja MQPM-malli

Topi Tikkala, Fixed sample magnetometer (FSM)

Outi Virtanen, Radioaktiivisuuden tuotto ydinreaktioissa

Lasse Väistö, Tunneliliitosten ominaisuuksien parantaminen lämpökäsittelyllä

## PhLic Theses

Inkeri Kähärä, Physics education at JYFL: Improving interactions and research-oriented learning, JYFL Laboratory Report 1/2006

## PhD Theses

*(Chronological order)*

Raimo Lohikoski, Dynamic modeling of DNA  
JYFL Research report 1/2006

Markus Kortelainen, Muon capture and its use as a probe of double beta decays  
JYFL Research report 2/2006

Tuomas Grahn, Lifetimes of intruder states in <sup>186,188</sup>Pb and <sup>194</sup>Po  
JYFL Research report 3/2006

Mariana Bondila, Detection of charged kaons using the decay topology in ALICE TPC  
JYFL Research report 4/2006

Lasse Taskinen, Thermal properties of mesoscopic wires and tunnel junctions  
JYFL Research report 5/2006

Pekka Suominen, Modified multipole structure for electron cyclotron resonance ion sources  
JYFL Research report 6/2006

Jari Hyväluoma, Application of the lattice-Boltzmann method to multiphase flows  
JYFL Research Report No 7/2006

Sarah Eeckhaudt, Spectroscopy in the transfermium region: probing rotational, non-yrast and isomeric structures in <sup>253,254</sup>No  
JYFL Research Report No 8/2006

Anu Kankainen, Studies of exotic nuclei of astrophysical interest near the N=Z line  
JYFL Research Report No 9/2006

Niina Nurkka, *Voiman momentin tutkimusperustaisen opetusjakson kehittäminen ja arviointi*  
JYFL Research Report No 10/2006

Kari Rytönen, Electronic and structural studies of free and supported metal clusters and molecules  
JYFL Research Report No 11/2006

Jami Kinnunen, Radio-frequency spectroscopy of superfluid Fermi gas  
JYFL Research Report No 12/2006

Sampo Tuukkanen, Dielectrophoresis as a tool for on-chip positioning of DNA and electrical characterization of nanoscale DNA  
JYFL Research Report 13/2006

Sami Rinta-Antila, Development of trap-assisted spectroscopy and its application to beta decay of neutron-rich zirconium isotopes  
JYFL Research Report No 14/2006

## Degrees

*(alphabetical order)*

### BSc Degrees

*(main subject)*

Heinonen, Henri (physics)  
Jääskeläinen, Jarmo (physics)  
Kärnä, Aarno (physics)  
Mäkelä, Aaro (physics)  
Pollari, Terhi (physics)

### MSc Degrees

*(main subject)*

\* = MSc includes teachers pedagogical studies

Airaksinen, Tuomas (physics)  
Alakurtti, Tero (physics)\*  
Kivelä, Pilvi-Helinä (physics)  
Avnon, Asaf (physics)  
Blair, Eric (physics)  
Elomaa, Lasse (electronics)  
Laitinen, Suvi (theor. physics)

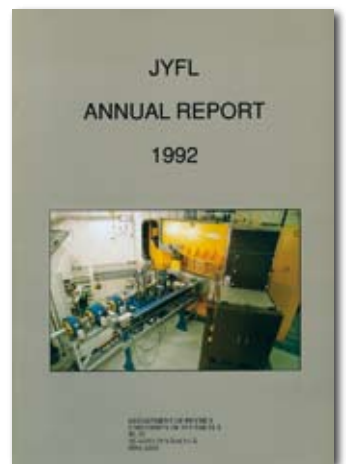
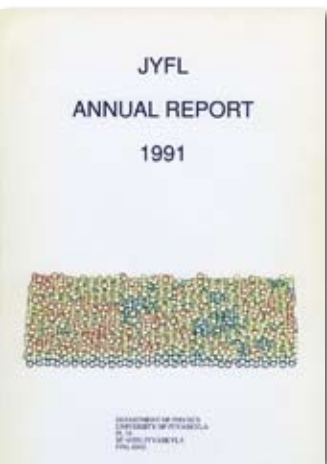
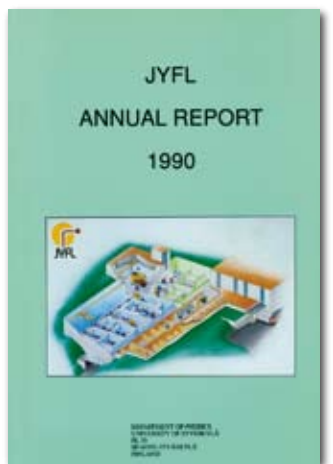
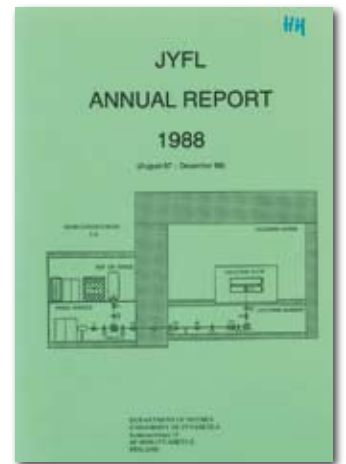
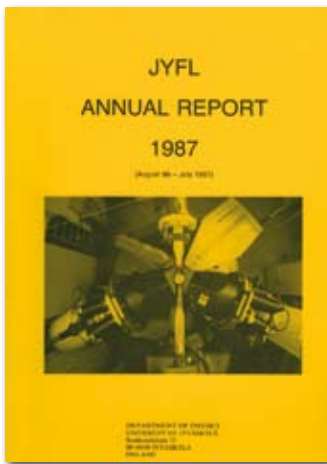
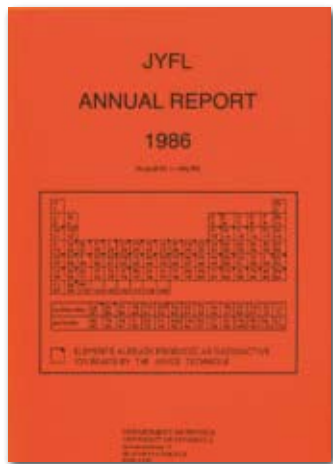
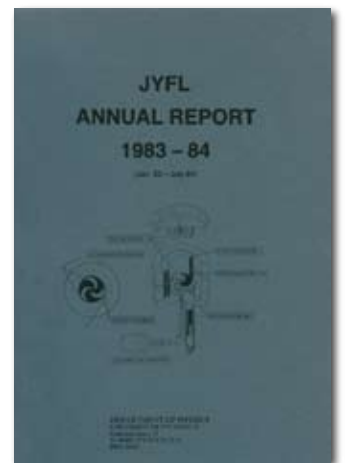
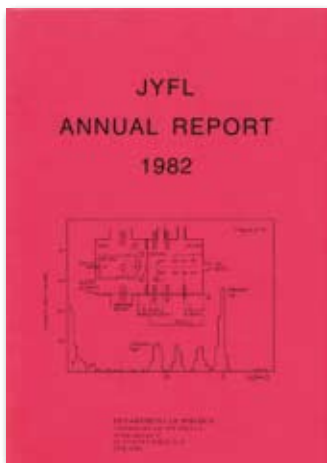
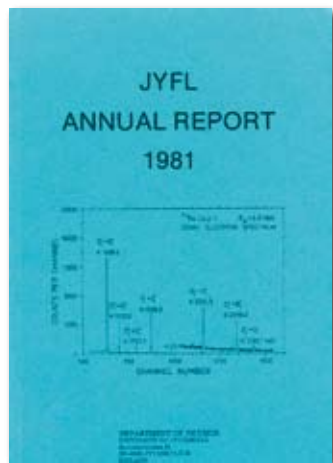
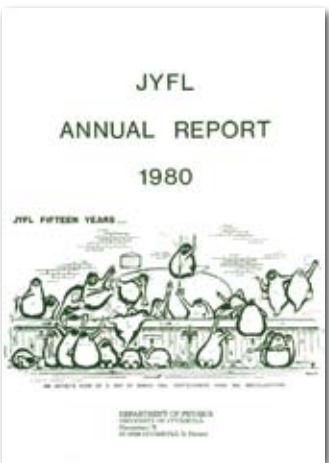
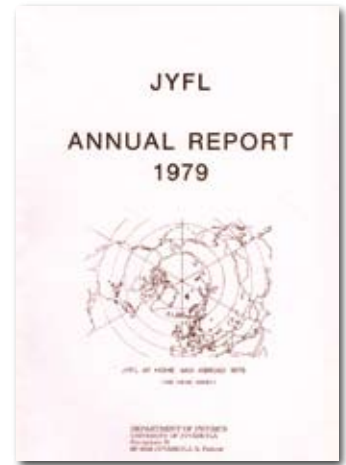
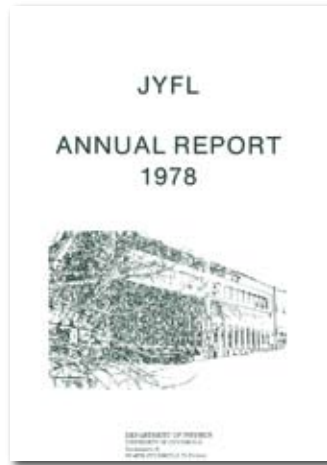
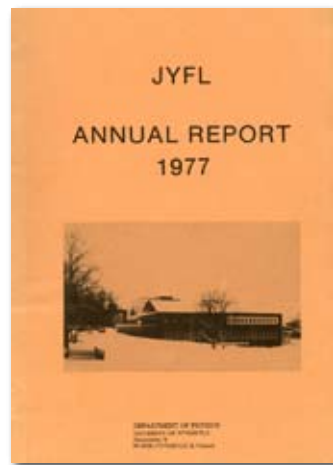
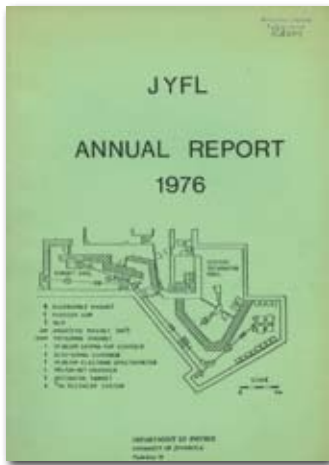
Han, Jie (electronics)  
 Hassan, Mohamed (physics)  
 Lievonen, Jarkko (appl. physics)  
 Heiskanen, Heikki (theor. physics)  
 Jarva, Otso (physics)\*  
 Jääskeläinen, Jarmo (physics)\*  
 Ketonen, Joonas (physics)\*  
 Ketonen, Laura (physics)\*  
 Koivisto, Antti (physics)  
 Kähärä, Topi (theor. physics)  
 Lappalainen, Maarit (physics)\*  
 Lehtivuori, Heli (physics)  
 Leskinen, Jani (physics)  
 Liu, Weilu (electronics)  
 Lommi, Mikko (appl. physics)  
 Lähteela, Arto (physics)  
 Ma, Zhibin (electronics)  
 Malola, Sami (physics)  
 Nieminen, Pasi (physics)\*  
 Niiranen, Harri (appl. physics)\*  
 Nikkarila, Juha-Pekka (physics)  
 Palomäki, Maria (appl. physics)  
 Päiviö, Suvi (appl. physics)  
 Silokunnas (former Förström), Essi (theor. physics)  
 Sulkala, Juha (physics)  
 Talka, Ismo (appl. physics)  
 Tallinen, Tuomas (physics)  
 Hirviniemi, Lasse (electronics)  
 Tarvainen, Heidi (theor. physics)  
 Virtanen, Outi (physics)\*  
 Väistö, Lasse (appl. physics)

## PhLic Degrees

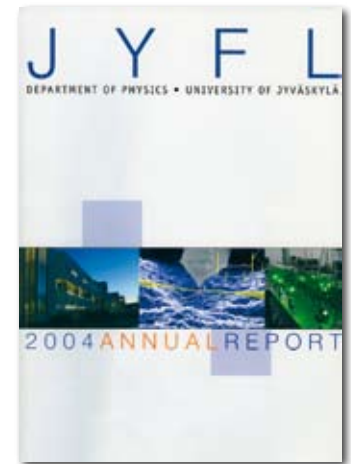
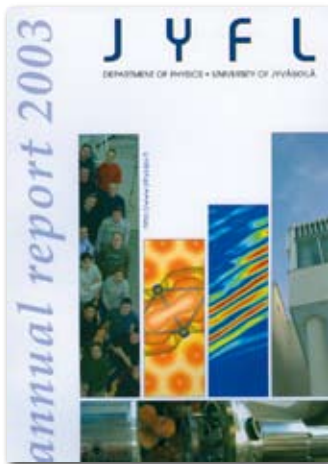
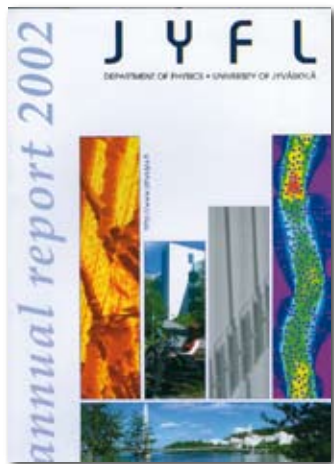
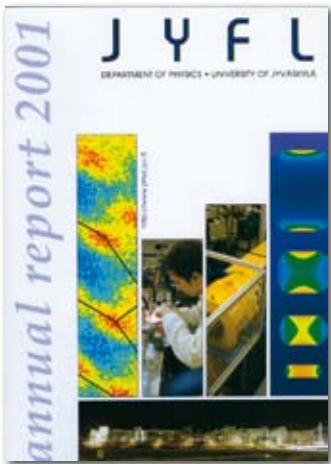
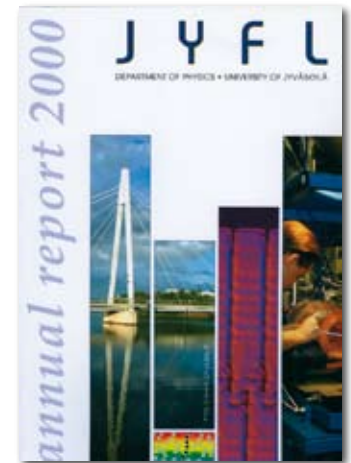
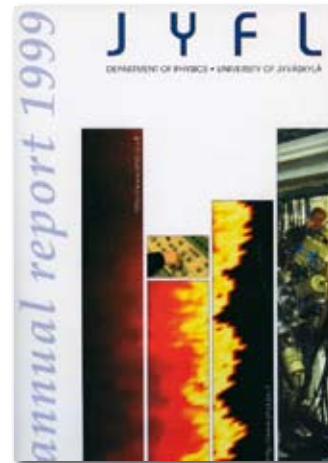
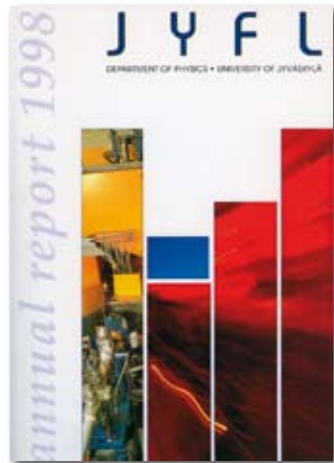
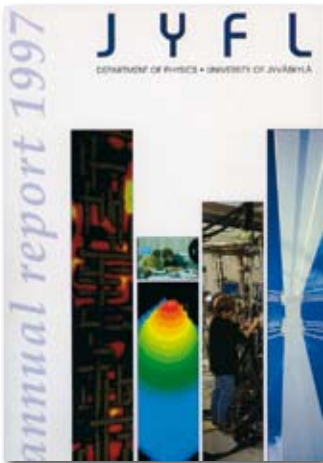
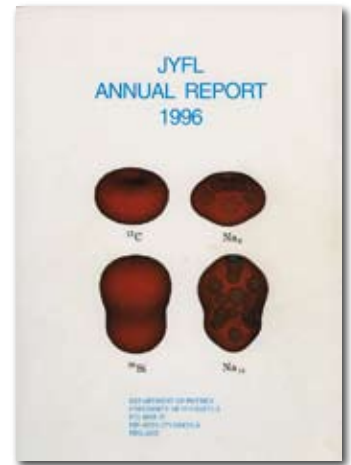
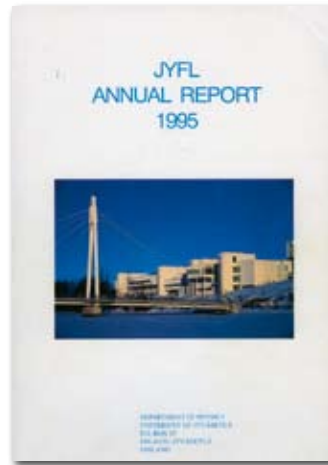
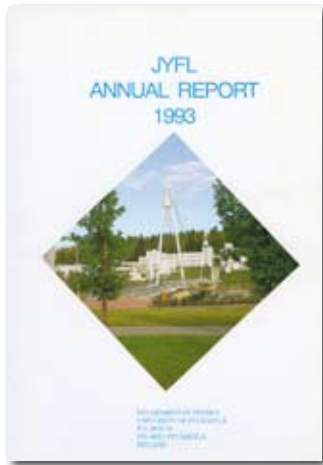
Kähärä, Inkeri (physics)

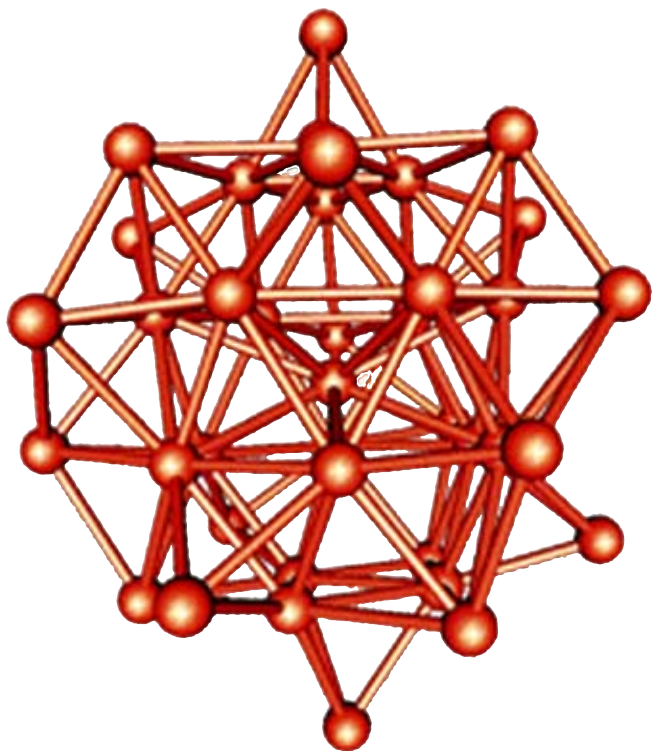
## PhD Degrees

Bondila, Mariana (physics)  
 Eeckhautd, Sarah (physics)  
 Grahn, Tuomas (physics)  
 Hyväluoma, Jari (appl. physics)  
 Kankainen, Anu (physics)  
 Kinnunen, Jami (theor. physics)  
 Kortelainen, Erno (theor. physics)  
 Lohikoski, Raimo (physics)  
 Nurkka, Niina (physics)  
 Rinta-Anttila, Sami (physics)  
 Rytkönen, Kari (physics)  
 Suominen, Pekka (physics)  
 Taskinen, Lasse (appl. physics)  
 Tuukkanen, Sampo (appl. physics)









2006

ANNUAL REPORT

JYFL  
DEPARTMENT OF PHYSICS  
UNIVERSITY OF JYVÄSKYLÄ

B.O. Box 35  
FI-40014 UNIVERSITY OF JYVÄSKYLÄ  
FINLAND

Tel +358 14 260 2350

Fax +358 14 260 2351

<http://www.jyu.fi/physics>