JYFL

DEPARTMENT OF PHYSICS • UNIVERSITY OF JYVÄSKYLÄ

annual report 2001

DEPARTMENT OF PHYSICS
UNIVERSITY OF JYVÄSKYLÄ

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Contents

Department of Physics

Rauno Julin

The Department of Physics (JYFL) with its 515 students and 155 employees is one of the largest departments of the University of Jyväskylä. A summary of the JYFL personnel is given in the table on the following page. The number of researchers in the table also includes the graduate students.

The activities in JYFL continued their steady growth in 2001. New records were reached in the number of Master (42) and Doctorate (11) degrees. The number of peer reviewed publications was 131. The total budget of JYFL was 8.22 MEUR with 4.27 MEUR from external sources.

Dr. Päivi Törmä was appointed as the new professor of nanoelectronics. Päivi is the second female professor in physics in Finland. Dr. Jukka Maalampi was appointed as the new professor responsible for the education of physics teachers. His research field is cosmology and neutrino physics. Markku Kataja is the new professor working on industrial physics. Half of his salary is paid by VTT, the Technical Research Centre of Finland.

Research. The year 2001 was for most of the department the second year as the Finnish Centre of Excellence in Nuclear and Materials Physics. The accelerator laboratory continued as an EU Major Research Infrastructure having approximately 200 outside users. The JYFL groups are participating in 20 EU and ESA research projects, in 4 of them as a coordinator.

The JYFL activities in the CERN-ALICE and CERN-ISOLDE projects will form a new Nuclear Matter Programme of the Helsinki Institute of Physics (HIP). The theoretical research on ultrarelativistic heavy ion collisions at JYFL will be a part of the Theoretical Physics Programme at HIP.

The experimental nanophysics group has continued development of X-ray calorimeters and far-infrared to mm-wave bolometers for space based applications, study and development of efficient solid state tunnel junction coolers, research on thermometry with superconducting or normal state tunnel junctions, development of a superconducting charge quantum bit, and research on mesoscopic superconductivity.

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Some statistical data in 2001

Personnel	156	(53)
- professors	13	(11)
- lecturers	4	(3)
- senior assistants	7	(7)
- assistants	7	(7)
- researchers and research assistants	90	(4)
- technicians	30	(17)
- administration	5	(4)
( ) = permanent posts		
Undergraduate students	515	
of which first year students	92	
Graduate students	55	
MSc degrees	42	
PhLic degrees	2	
PhD degrees	11	
Credits (national)	5300	
Number of foreign visitors	225	
Visits abroad	210	
Peer reviewed publications	131	
Invited talks	42	
Other talks	69	
Posters	66	
Seminars given at JYFL	42	
Seminars given outside JYFL	35	
Funding (MEUR) excl. premise costs	8.2	
* University budget	3.9	
* External funding	4.3	
- Academy of Finland	1.5	
- Technology Development Centre	0.3	
- International programmes	0.9	
- Ministry of Education	0.5	
- Contract research	0.7	
- Others	0.4	

The group studying disordered materials has developed a model for earthquakes in tectonic fault zones, models of interface propagation and a new method for using ultrasonics to assess bone quality.

The theory group working on quantum dots found a connection between quantum dots in a strong magnetic field and the rotational states of Bose condensates.

The JYFL cyclotron delivered ion beams for more than 7000 hours mainly for the study of exotic nuclei and reaction mechanisms. Among the key achievements were the determination of the shapes of very neutron-deficient (Po, Rn) and neutron-rich (Zr) isotopes, synthesis of new proton emitters, and structure studies of the heaviest elements.

Thermal properties of semiconductors were studied by ion beam and radiotracer techniques. The broad variety of ion beams available at the accelerator laboratory was utilised in the testing of space electronics, studies of ion stopping powers and ion implantation.

The nuclear theory group develops microscopic nuclear models and applies them to nuclear spectroscopy, and to the description of rare weak decays important for the physics of weak-interactions, neutrinos and dark matter.

In theoretical particle physics and cosmology the main research subjects have been massive neutrinos and the electroweak baryogenesis in the early universe.

Research

Nuclear and accelerator based physics

Summary of the Accelerator laboratory activities

Matti Leino

In the year 2001, the established experimental programs continued together with development work aimed at extending the capabilities to probe even deeper into the physics of exotic nuclei. Two major development projects were started in 2001. The first stage of upgrading the old 6.4 GHz ECR ion source was concluded successfully (see below). Upgrading the IGISOL target area began in the summer and essentially no IGISOL on-line experiments were performed during the second part of the year. The laboratory was authorised by the Finnish Radiation safety Institute to begin the ^{123}I isotope production for MAP Medical Technology. Final preparations to begin the isotope production are underway. Altogether, more than 6000 h of beam on target were delivered. There were more than 200 foreign scientists visiting the laboratory, nearly all of which were cyclotron users. A total of 43 scheduled experiments were performed using the cyclotron.

The laboratory has been operated under the IHRP program of the 5th EU framework (Access to Major Research Infrastructures). It has been active in participating in the FINUPHY round-table activity of the European Research Infrastructures and is coordinating its instrumentation part. The research performed in the laboratory has been an important contribution to the Centre of Excellence in Nuclear and Materials Physics program of the Department of Physics. JYFL groups are coordinating the EU/TMR RTD project EXOTRAPS and the EU/IHP RTD project EXOTAG, and participating in the EU/IHP projects EURISOL, ION CATCHER, and NIPNET. JYFL is also coordinating the National Graduate School in Particle and Nuclear Physics. At the end of the year, the laboratory was chosen as a Marie Curie training site by the European Commission. Two international meetings in nuclear physics were organised by JYFL in 2001. The 3rd International Conference on Exotic Nuclei and Atomic Masses ENAM2001 was held in Hämeenlinna with 275 participants and the Euroschool on Exotic Beams took place at JYFL with 35 young physicists attending. Additionally the EXOTAG working group meeting on 'Electron Spectroscopy' was held in Jyväskylä in February 16-17 in collaboration with the instrumentation groups of the EURISOL project. The Accelerator laboratory's User Meeting was held in October 6th at JYFL with 50 participants attending. In addition, JYFL organized a Scandinavian accelerator meeting, Nordic Ring Meeting, in Jyväskylä during 29th-31st August.

In the following, the main acitivities of the various research groups in the year 2001 are briefly described.

Accelerator facilities

Esko Liukkonen

http://www.phys.jyu.fi/research/accelerator/

Since 1993 the cyclotron has been operated for a grand total of more than 50,000 hours. Since 1996 the annual beam time hours have exceeded 6,000 hours/year, which was our goal, see fig. 1. In 2001 for the second time, the total operating time was 7,411 hours out of which the beam was for 6,064 hours on target. The rest of the total time consists of stand by time caused by the user (762 h) and beam tuning and developing. Protons (23 % of the beam time) were accelerated as H^-. Protons were used for isotope production and proton induced fission (IGISOL). Over 30 different isotopes were accelerated in 2001. Many hours of ^{48}Ca (7 %) beam was delivered to the gas filled recoil separator RITU where the recoil-decay-tagging (RDT) method was used successfully in studies of several isotopes in the No region. Radiation damage tests at RADEF used extensively beam cocktails where a fast change of beams (LET values) is possible.

A beam cocktail consists of ions whose charge-to-mass-ratio is almost the same. The cyclotron can resolve beams when the q/m difference is higher than 0.03 %, while the injection line transports all beams with the same charge-to-mass number-ratio q/A.

During the year 2001 only the new 14 GHz ECR ion source was used as an injector for the K130 cyclotron, since the old 6.4 GHz ECR ion source went through the first major upgrading since it was built. The object of the up-

Esko Liukkonen, professor
Pauli Heikkinen, senior scientist
Hannu Koivisto, scientist
Sami Hahto, graduate student (in USA)
Veikko Nieminen, laboratory engineer
Teuvo Poikolainen, laboratory engineer
Juha Ärje, laboratory engineer
Arto Lassila, engineer
Kimmo Ranttila, engineer
Jani Hyvönen, operator
Anssi Ikonen, operator
Sari Luodes, operator
Hannu Leinonen, technician
Raimo Seppälä, technician

Fig. 2. The upgraded 6.4 GHz ECR ion source.

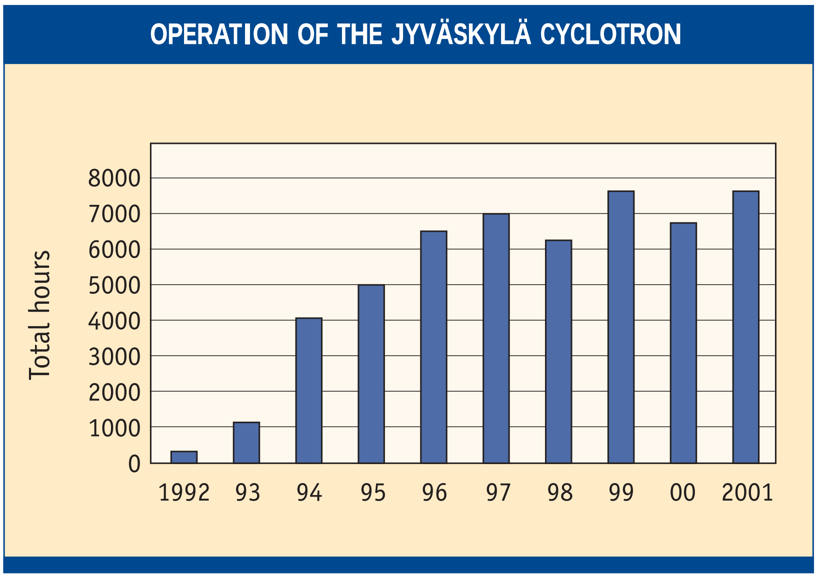

Fig. 1. The K130 cyclotron has been used for over 50,000 hours since 1992.

grade was to optimize the magnetic field configurations for the operation of the source at the microwave frequency of 6.4 GHz. Figure 2 shows the upgraded 6.4 GHz ECR ion source.

The first plasma of the upgraded 6.4 GHz ECR was ignited in August 2001. A significant improvement on the performance of the ion source was achieved as shown in Table 1. The intensity of the O^{7+} ion beam increased approximately by a factor of 40.

The improvement was achieved by redesigning the axial magnetic field configuration of the source. The old coils and power supplies were used. Fig. 3 shows the old and new axial magnetic fields together with the calculated fields on which the redesign was based.

	Original version	Upgraded version	$I_{upgraded}/I_{original}$
O^{4+}	50	234	4.7
O^{5+}	44	225	5.1
O^{6+}	15	202	13.5
O^{7+}	0.8	34	43

Table 1: The best intensities [µA] of different oxygen ion beams before and after the upgrade of the 6.4 GHz ECRIS. The extraction voltage was 10 kV in both cases. The plasma electrode aperture of 10 mm was used with the original and 8 mm with the upgraded version.

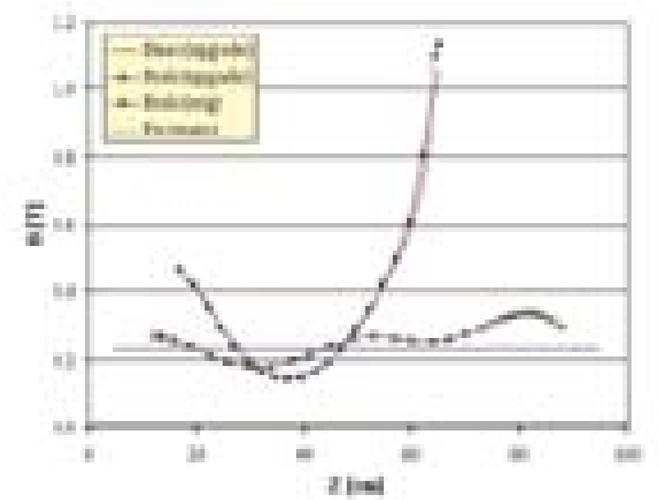

Fig. 3. The axial magnetic field of the original (calculated) and upgraded (measured and calculated) 6.4 GHz ECR ion source.

Exotic nuclei and beams

Juha Äystö and Ari Jokinen

http://www.phys.jyu.fi/research/igisol/

Studies of exotic nuclei, their ground state properties and decays, far from the valley of stability have been performed at two facilities, IGISOL at Jyväskylä and ISOLDE at CERN. A summary of the research done at the IGISOL facility in the past 15 years was published in 2001, see ref. [1]. The year 2001 has been a period of intense research and development of new techniques to manipulate radioactive ions of short-lived nuclei. A major progress was reached in using the cooled and bunched radioactive beams in laser spectroscopy in collaboration with the Manchester and Birmingham Universities. In fact, the original goal of this collaboration, set in 1994, was the study of the ground state properties of neutron-rich Zr isotopes produced in fission. Thanks to the innovative work on cooling and bunching of ion beams, this goal could be reached in the summer 2001 when Zr-measurements extended to ^{102}Zr, the most deformed nucleus in its ground state. The RFQ cooler and buncher will soon be coupled to a JYFL Penning trap which is expected to start its operation in the spring 2001. This work has been carried out in the context of the European EXOTRAPS Collaboration. In 2002, most of our activity in nuclear spectroscopy was done at ISOLDE, CERN, however with important experiments on ^{12}N and ^{62}Ga taking place at IGISOL. Our nuclear physics program at ISOLDE has largely centered on nuclei with nearly equal numbers of protons and neutrons (Z=N nuclei), which provide access to charge dependent effects and other fundamental symmetries: these studies also provide input data to nuclear astrophysics studies. Participation in several development projects at ISOLDE has been an important part of our activity. The work at ISOLDE has been carried out within the Nuclear Matter Project of Helsinki Institute of Physics.

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Ari Jokinen, academy researcher
Heikki Penttilä, senior assistant
Peter Dendooven, senior scientist -30.9.
Gerard Lhersonneau, senior scientist -30.9.
Jerzy Szerybo, senior scientist
Serguei Zemlyanoi, senior scientist 12.6.-
Wenxue Huang, scientist
Jussi Huikari, graduate student
Anu Kankainen, graduate student
Veli Kolhinen, graduate student
Arto Nieminen, graduate student
Saara Nummela, graduate student -30.6.
Kari Peräjärvi, graduate student -31.5.
Sami Rinta-Antila, graduate student
Youbao Wang, graduate student
Jani Hakala, MSc student
Mikko Lahtinen, laboratory engineer -30.6.
Kari Salomäki, engineer

Technical developments

Wien filter for low-energy radioactive ion beams. In general, it can be stated that the ion guide produces only singly charged ions. However, for some elements an up to a few per cent fraction of doubly charged ions are produced. In special circumstances, like in fission studies in the mass A=70 region where the yield of fission products is orders of magnitude lower than in the A=140 region, the doubly charged ions can create a considerable background. This background can be reduced via charge exhance reactions in the buffer gas of the RFQ cooler, where the amount of doubly charged ions is reduced, and subsequently passing the ion beam through a velocity or Wien filter that separates the now singly charged mass A and 2A species. A Wien filter was built of two Neorem permanent magnets and an iron yoke, which with a 15 mm gap between the magnets provide a 0,66 T magnetic field in the middle of magnets, and two parallel copper electrodes with which an electric field up to 2.1 kV/cm can be created. The tests were performed with singly and doubly charged ^{112}Rh ions, as well as with singly charged ^{72}Cu and simultaneously produced doubly charged ^{144}Ba and ^{144}La ions [2]. A small percentage of N_2 was used in the cooler as charge exchange gas. The results were promising. The background due to ^{144}Ba and ^{144}La could be reduced by a factor of two, even though N_2 is not the most favorable charge exchange medium due to its a little bit too high ionisation potential. Further research to find a proper impurity gas is needed, but the tests showed that the electron capture process of doubly charged ions in the cooler could be controlled.

*The JYFL snowball project** aims at investigating a new approach to transforming a high-energy beam of radioactive ions into a low-energy one. The basic idea is to thermalize the ions in liquid helium and to use electric fields to extract the ions from the liquid and transport them to a high-vacuum region. Advantages of this method are the small size of stopping cell required and the low vapour pressure at low enough temperatures. After thermalization in liquid helium, positive ions will spontaneously form so-called snowballs: clusters of helium atoms which attach themselves to them. The formation and transport of snowballs for radioactive ions has been demonstrated earlier [3]. The manipulation of ions in helium gas and vacuum is also well established. The main new issue in this project is the extraction of the snowballs out of the liquid helium through its surface. First tests were performed using the ~100 keV ^{219}Rn alpha decay recoil ions from an open ^{223}Ra source [4]. A cell was constructed with the ^{223}Ra source at the bottom and an alpha detector at the top. A set of ring electrodes was used to provide the electric field which guides the snowballs/ions from the source onto a foil in front of the detector. This cell was placed inside a cryostat and cooled to 1-2 K. The ^{223}Ra source was covered by about 5 mm of liquid helium preventing alpha particles from the source from reaching the detector. The voltages on the electrodes were tuned in order to optimize the count rate of the ^{219}Rn decay in the alpha detector. The alpha energy spectrum thus obtained at a temperature of 1.47 K is shown in the figure 1. A quantitative investigation of this and similar spectra at other temperatures gives an overall efficiency of about 10^{-4}. This value can be split in 1% snowball formation probability and 1% transport efficiency. In future, some technical changes will be implemented in trying to improve both these processes. *Jyväskylä-Osaka Collaboration

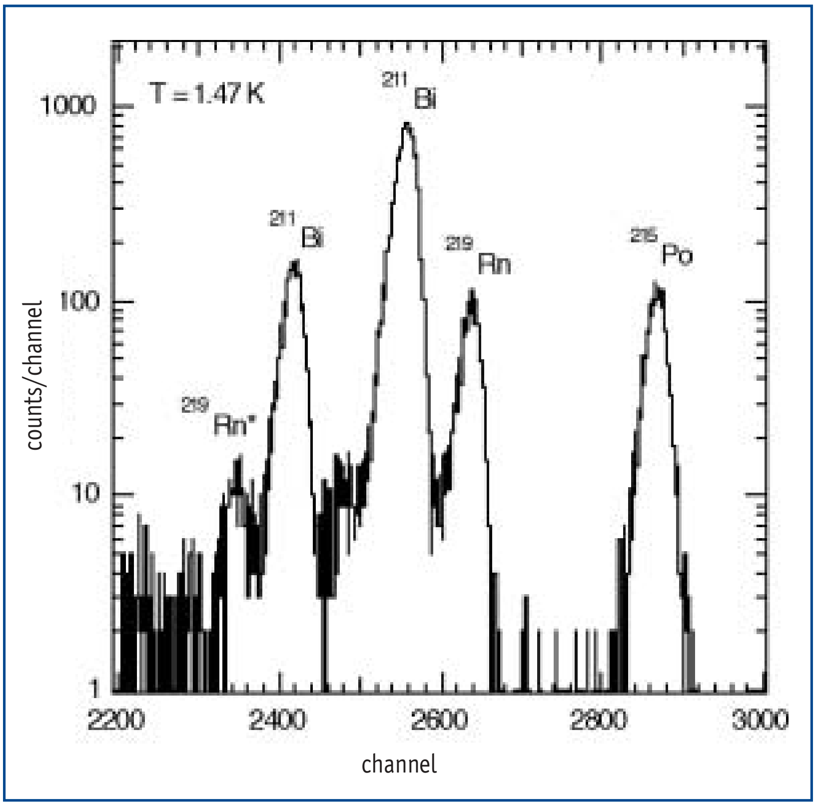

Fig. 1. The understanding of the peaks is based on the measured energy and the calculated energy loss between the place of decay and the detector. The intense peaks result from the decay of ^{219}Rn, ^{215}Po and ^{211}Bi nuclei on the foil in front of the detector. The weak peak (labeled ^{219}Rn*) represents the decay of ^{219}Rn nuclei at the liquid surface.

The ion beam cooler-buncher has been operated routinely in collinear laser spectroscopy experiments with great success [5], see also the section on collinear laser spectroscopy. In addition, the experimental work in characterising the operation of the device was continued in both bunched and DC mode. The bunch width was investigated with a new extraction scheme, where the normally used miniature quadrupole was replaced with a simple end plate. It was demonstrated that bunch widths of the order of 1 µs can be achieved. The transverse emittance of the cooled beam was measured with an emittance meter borrowed from LMU Munich. The measured emittance was 3 π-mm-mrad at 37.5 keV beam energy. This is to be compared to the IGISOL emittance of 12 π-mm-mrad, which was now also measured for the first time.

Collinear laser spectroscopy.* The study of the nuclear shape and size of short-lived radioisotopes in refractory elements has been the long-standing intention of the laser spectroscopy group at the IGISOL. There have been some notable successes in 2001 with the highlights including a series of experiments on the zirconium isotopes and a measurement of a 10ms isomer in ^{130}Ba. These experiments have been made possible through the huge gain in sensitivity that is now routinely achieved with the on-line cooler-buncher [6]. The studies on the zirconium isotopes and isomers included the first measurements of refractory fission fragments. In the same study neutron-deficient isotopes were produced in light-ion fusion reactions. This work provided the nuclear spins, magnetic moments, quadrupole moments and charge radii for zirconium isotopes from A = 87 to 102. Figure 2 shows the measured charge radii compared to both iso-deformation contours from a deformed droplet model and (insert) predictions from relativistic mean-field theory [7]. The results span the N = 50 shell-closure 'kink' and the N = 60 shape change which is clearly seen as a sudden jump in the mean square radius. The measurements are the first optical results to complement the wealth of gamma-ray spectroscopic data on the shape coexistence phenomena in this chain. The observation of hyperfine components of the ^{130}Ba (8^-) isomer were made with an isomer flux of only 150 ion/sec, representing the highest spectral sensitivity achieved to date.

Indications suggest that the structure will be uniquely assignable to one arising from a two-neutron configuration with a smaller prolate deformation than the ground state. Proton-induced fission at the IGISOL gives experimental access to a wide range of exotic nuclear systems, almost all of which cannot be produced at other conventional separator facilities. Studies on these isotopes, and on fusion-produced short-lived isomers, are scheduled to continue at the IGISOL and will be further enhanced by the upgrade of the facility this year.

* Manchester-Birmingham-Jyväskylä Collaboration.

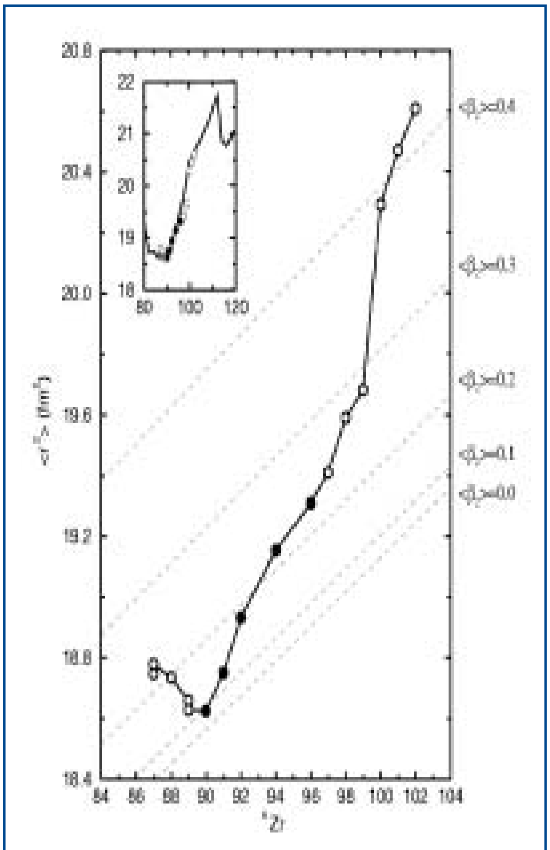

Fig. 2. The Zr mean square charge radii with the open circles indicating the new radioactive measurements. Droplet model iso-deformation contours and (insert) RMF theory predictions [7] are shown for comparison.

JYFLTRAP for isobar purification and mass measurements.* A project for improving the quality of radioactive ion beams produced at IGISOL due to beam handling with ion traps [8] is now in an advanced stage. This is a system of two Penning traps, both placed in one 7 T superconducting magnet. First trap should perform isobaric purification of the beam, second one should serve the precise nuclear mass measurements. In 2001 the following stage was achieved:

- trap vacuum tube was aligned with magnetic field and with the IGISOL beam line,
- trap electrode structure was assembled and inserted into the vacuum tube,
- off-line ion source was mounted into the trap beam line,
- all basic electronic equipment necessary for the trap testing was completed,
- trap control system was prepared for the trap testing,
- first test of the trap at low voltage (1 kV) with the off-line ion source and continuous beam was performed.

Presently the trap system is ready for further tests, which will comprise: capture of a bunched beam, RF-excitation and isobaric purification, tests with the trap at high voltage (40 kV), on-line test with radioactive beam. After successful completion of the purification trap tests, development of the mass measurement trap will be continued.

* EXOTRAPS EU-RTD Collaboration

Highlights from physics experiments

Decay study of ^{12}N at IGISOL.* There is a long history of studies of the decay of ^{12}N and ^{12}B including contributions from Nobel Prize winners Luis Alvarez and Willy Fowler. The attraction to this problem is in the possibility to study a number of important problems in nuclear astrophysics and the nuclear many-body problem in general. In the decay of these nuclei states in ^{12}C are fed which break up into three alpha particles, the inverse of the triple-alpha process forming ^{12}C in the centre of red giant stars. Whereas all previous studies of this problem measured the alpha-particles *in beam* we have succeeded in making an ISOL beam of ^{12}N at IGISOL and measured all three alpha-particles from the decay in coincidence with a modern segmented particle detector set-up [9]. This has brought a dramatic improvement in the possibility to study these important states in ^{12}C, as shown in figure 3. The IGISOL beam line at the Jyväskylä Accelerator Laboratory is the only place worldwide where such beams of ^{12}N and ^{12}B now exist.

*Aarhus-CERN-Gothenburg-Jyväskylä-Madrid-Stockholm Collaboration.

Precision studies of the decay of ^{62}Ga. In these experiments the superallowed $0^+ \rightarrow 0^+$ β-decay of ^{62}Ga has been studied with high precision. The motivation for the experiment comes from testing the electroweak part of the standard model that can be done via the determination of the corrected *Ft* values. They are obtained by half-life β-decay branching ratio and decay energy measurements with high accuracy. From these *Ft* values, the V_{ud} matrix element of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix can be deduced. The standard model states that this matrix should be unitary. However, according to our present knowledge, the unitarity of the CKM matrix is not fulfilled at the 2.5σ level. For these studies, the extracted *ft* values must be corrected for radiative and Coulomb effects, calculated using various theoretical approaches. While these corrections are generally in good agreement with each other for nuclei where experimental data are available, there are considerable differences between the predictions for heavier nuclei. To a large extent, precise measurements of corrected *Ft* values for Fermi superallowed β-decays in heavier nuclei (with T=1) coupled with the previous results will enable us to test the different predictions. In the experiment at the IGISOL ^{62}Ga was produced via ^{64}Zn(p,3n)^{62}Ga fusion-evaporation reactions at about 48 MeV. The detection system consists of a cylindrical plastic scintillator for β detection and three high-efficiency Germanium detectors for γ detection in close geometry around the implantation point (see Fig. 4). The decay of the excited 0^+ state via the 2^+ state has not been observed. Thus, an upper limit of 0.017 % for this decay sequence is deduced. From this non-observation an upper limit of $d_{IM} < 0.093$ for the isospin-mixing matrix element is deduced. A possible Gamow-Teller fed 1^+ state is observed by a decay sequence of a 2225 keV γ-ray in coincidence with the 954 keV line. New higher-intensity measurements of the decay of ^{62}Ga a are planned at IGISOL. In particular, the use of a purification trap should allow significant increase of the precision of the measurements.

*CEN (Bordeaux-Gradignan) - Jyväskylä Collaboration

Decay studies of Z=N nuclei at ISOLDE.* The high-precision studies on superallowed beta decay of ^{74}Rb were continued at ISOLDE providing new data on the role of charge dependent effects, such as Coulomb mixing, in superallowed beta-decay. These, in turn, together with the muon-decay data, give presently the most precise value for the up-down quark mixing matrix element V_{ud} in the Cabibbo-Kobayashi-Maskawa matrix. The main outcome of these experiments, in addition to the half-life and decay energy, was the observation of the feeding of the excited 0^+ state by conversion electron spectroscopy.

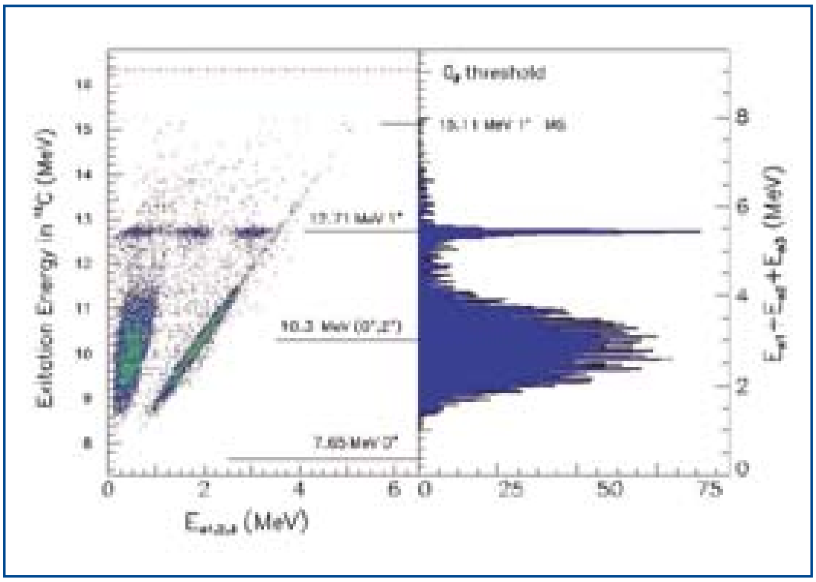

Fig. 3. Triple coincidence data from the β-decay of ^{12}N. The scatter plot shows the total energy of three coincident α particles, plotted against individual α energies. The peaks in the projection on the sum energy axis can be identified as the excited states of ^{12}C.

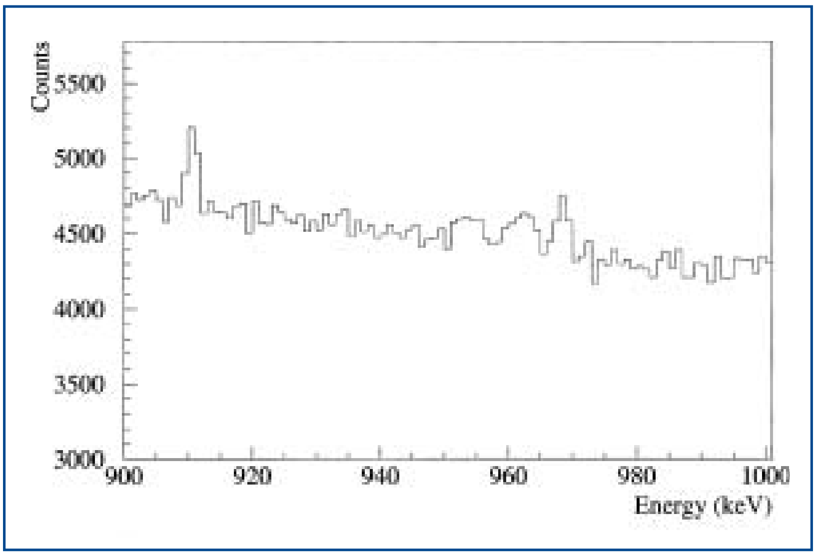

Fig. 4. The γ-ray spectrum from the decay of ^{62}Ga. The peak at 954 keV comes from the decay of the first excited 2^+ state in the daughter nucleus ^{62}Zn. This γ-line decays with the known half-life of ^{62}Ga of about 116 ms. A branching ratio of 0.12(3) % for this γ-transition was deduced, yielding an upper limit of 99.88(3) for the branching ratio of the superallowed Fermi decay of ^{62}Ga.

The magnitude of Coulomb mixing in this state could be estimated for the first time from the measured upper limit of the feeding of the excited 0^+ state in the daughter ^{74}Kr. The obtained result, $d_{IM} < 0.07$ %, emphasizes the importance of the radial mismatch part of the Coulomb correction in the case of ^{74}Rb [11].

Beta decay between mirror nuclei satisfies the selection rules of the Fermi and Gamow-Teller decay. The beta decay between (J,T)=(half-integer,1/2) states are governed by a strong Fermi component which is well known and thus the remaining strength arising from the GT-component can be extracted. The systematics of mirror transitions is well established among the light nuclei up to ^{59}Zn. Recently we have extended this systematics to heavier nuclei, like ^{71}Kr, ^{61}Ga and ^{75}Sr. A selectivity obtained by a combination of laser ionization and on-line mass separation allowed us to perform an accurate decay study of ^{61}Ga [12]. The half-life, decay energy, and beta feeding pattern of ^{61}Ga were studied with an improved accuracy compared to earlier work. The obtained GT-strength distribution compares well with large-scale shell model calculations. The half-life of ^{75}Sr was measured to be 87(3) ms, which exceeds by one order of magnitude the accuracy of the earlier measurement. We have also carefully studied the feeding pattern of the beta decay allowing us to extract the ground state beta feeding [13]. The preliminary analysis shows that the GT-matrix element of the mirror transition is comparable to those obtained among lighter nuclei in the mid fp shell.

R&D work at ISOLDE. Parallel to ongoing research program the JYFL group at ISOLDE has initiated a Si-ball R&D detector project. The Si-ball project aims for high-granularity charged particle detector array for spectroscopic studies of exotic nuclei and their complex decay modes. Presently prototype detectors from different companies are tested providing the basis for selection of detector supplier for the whole detector assembly. In order to continue our research far from stability at ISOLDE we have extensively studied new target materials and forms to optimize the production of exotic nuclei [14]. A special emphasis has presently been in diffusion studies of Kr and Mn isotopes from ZrO_2, Y_2O_3 and $SrZrO_3$ powders. The first two materials were tested also in felt-structure. The obtained data was compared to conventional materials, like Nb, Mo or Zr foils. These studies provide an essential input when selecting target material and form in our forthcoming experiment far from the stability.

* Work carried out at ISOLDE-CERN within the Jyväskylä-CERN-Helsinki-Basel-Strasbourg-Leuven-Madrid-St. Petersburg Collaboration.

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In-beam spectroscopy

Rauno Julin

In-beam spectroscopy. During 2001, a total of 2544 hours of beam time were dedicated to in-beam spectroscopy carried out in collaboration between the JYFL gamma- and RITU groups and the groups from foreign institutes listed at the end of this report. The majority of this time (1848 hours) was taken up by our fourth and final JUROSPHERE + RITU campaign, continuing our successful series of Recoil-Decay Tagging (RDT) experiments. Between 12th February and 19th March four experiments were carried out in the SACRED + RITU campaign and from 14th May to 3rd October a total of twelve experiments were carried out in the JUROSPHERE + RITU campaign. These experiments involved 61 collaborators from 22 institutions.

SACRED + RITU In February, the SACRED electron spectrometer was installed at the target position of RITU for a set of experiments. The SACRED project is led by the University of Liverpool. SACRED is designed to measure cascades of prompt internal conversion electrons produced in the decay of fusion evaporation residues.

A highlight of the SACRED + RITU campaign in 2001 was the study of ^{194}Po using the ^{170}Yb(^{28}Si,4n)^{194}Po reaction [1]. On the basis of level systematics and mixing calculations, an intruding 0$^+$ state should be the first excited state in ^{194}Po at an energy of approximately 250 keV. This would be the lowest such state in any nucleus. This state would be missed in γ-ray experiments and so SACRED was used detect prompt conversion electrons from the possible E0 ($0^+ \rightarrow 0^+$) transition. In figure 1 a candidate electron peak at approximately 120 keV can be observed in the prompt conversion electron spectrum tagged with the ^{194}Po α decay. More experiments are needed to show that this line would be due to such an E0 transition of 220 keV.

In a measurement led by the group from the University of Liverpool, the low-lying structure of ^{226}U was investigated using the ^{208}Pb(^{22}Ne,4n)^{226}U reaction at a bombarding energy of 112 MeV [2]. The singles electron spectrum obtained in the short (approximately 32 hrs) RDT

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measurement is shown in figure 2. The $2^+ \rightarrow 0^+$ transition was clearly identified for the first time, and the data obtained lend support to the level scheme of ^{226}U deduced from an earlier in-beam RDT γ-ray spectroscopic study at JYFL.

In another experiment [3], conversion electrons were measured from the reaction ^{207}Pb(^{48}Ca,2n)^{253}No. A preliminary spectrum of recoil gated electrons is shown in figure 3 (top panel). While the data do not allow detailed interpretations, some preliminary conclusions may be drawn. If it is assumed that the quadrupole moment of ^{253}No is identical to that of ^{254}No, rotational model calculations can be performed to produce a level scheme for

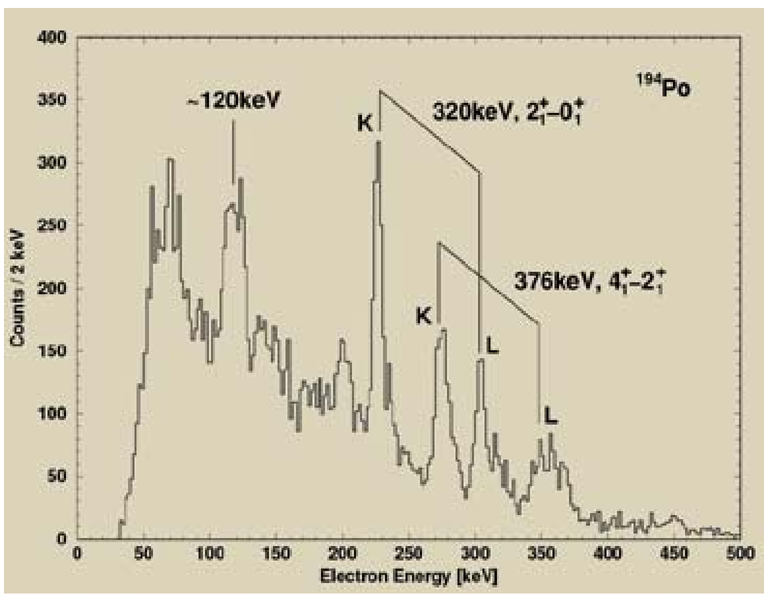


Fig. 1. Prompt conversion electrons tagged with the ^{194}Po decay.

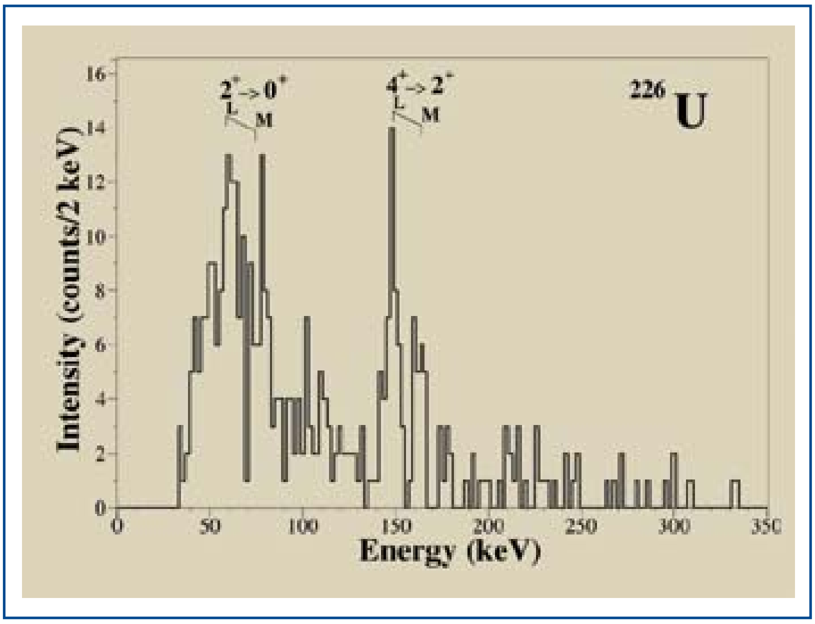
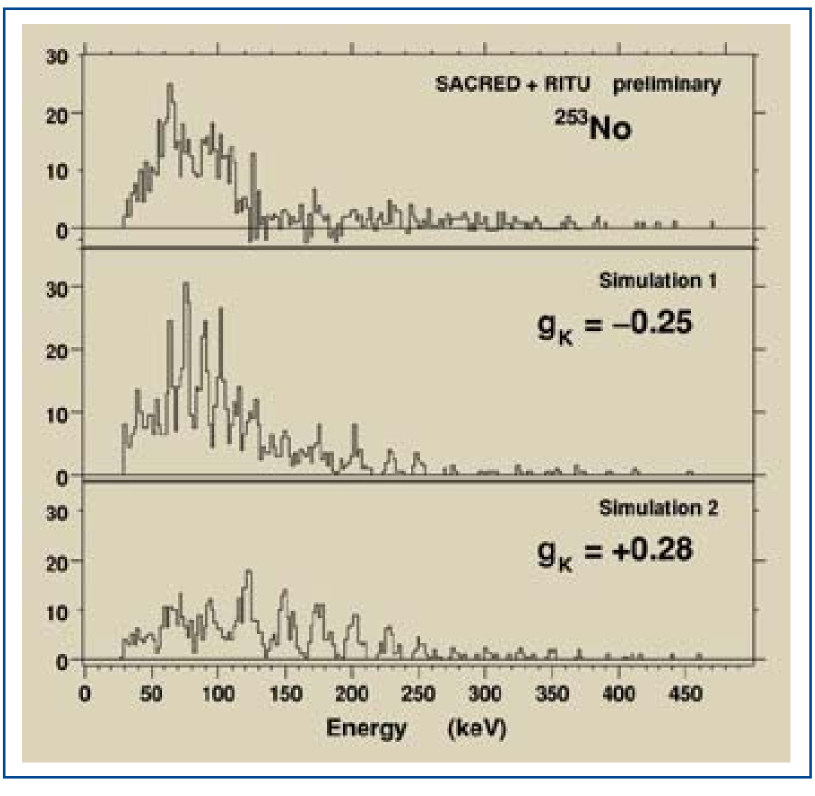


Fig. 2. Prompt conversion electrons tagged with the ^{226}U α decay.

Fig. 3. Measured and calculated spectra of conversion electrons from ^{253}No.



^{253}No. Figure 3 shows the results of simulations based on such a calculation. Negative g_K-values favour M1 intra-band transitions while positive g_K-values enhance the cross-over E2 transitions. The E2 transitions are less converted than the M1 transitions which may allow their observation in a γ-ray investigation. The predicted $^9/_2^-$ [734] ground state leads to the negative g_K value of -0.25. As can be seen from the two simulated spectra in figure 3, the converted M1-transitions from the band based on the $^9/_2^-$ state are in much better qualitative agreement with the experimental data than the transitions from the band based on the expected low-lying $^7/_2^+$ state.

JUROSPHERE + RITU As in previous years, the JUROSPHERE array at the target position consisted of 15 Eurogam Phase I detectors, 7 TESSA detectors and 5 NORDBALL detectors. The total photopeak efficiency of the array was approximately 1.7% at 1.3 MeV. For several experiments 1 to 5 NORDBALL detectors were placed at the focal plane.

One highlight of the JUROSPHERE + RITU campaign was the continuation of the successful programme of in-beam γ-ray spectroscopy on very heavy nuclei with the study of ^{250}Fm using the ^{204}Hg(^{48}Ca,2n)^{250}Fm reaction at 209 MeV laboratory energy [4]. In an excitation function run the production cross section for the main channel (^{250}Fm) was measured to be ~1µb. In the RDT experiment the ground state rotational band was found up to spin 18 and tentative candidates for transitions on top of this band have been identified. A preliminary spectrum gated on ^{250}Fm recoils is shown in figure 4. Early analysis shows a similar rotational behaviour to ^{252,254}No with the moment of inertia very close to that of ^{254}No at low spin and an upbend due to an alignment at higher spin similar to ^{252}No.

Excited states in the N=77 nucleus ^{140}Eu were studied for the first time via the ^{36}Ar + ^{107}Ag reaction in an attempt to determine whether chiral symmetry could be observed in order to validate recent theoretical predictions. A new isomeric state was established built upon the $\nu h_{11/2}$x $\pi h_{11/2}$ configuration with a half-life of 280(20) ns. Both prompt and delayed transitions were observed above and below this state. The analysis is currently ongoing [5].

For the study of very light ^{187}Bi and ^{189}Bi isotopes via the ^{83}Kr + ^{107,109}Ag reactions an array of BGO crystals was placed at the focal plane in order to improve the efficiency. The $^{13}/_2^+$ isomeric state was indentified in ^{187}Bi with a sudden drop of its energy relative to the heavier odd-mass Bi isotopes. This may be due to the oblate-prolate shape change. Prompt gamma-rays were also observed on top of the alpha-decaying $^{1}/_{2}^{+}$ and $^{9}/_{2}^{-}$ states in ^{189}Bi. This is of crucial importance for deducing their origin. The analysis of the data is in progress [6].

Gamma rays from the extremely neutron deficient nucleus ^{171}Au were observed for the first time in an RDT experiment by employing the ^{96}Ru(^{78}Kr,p2n)^{171}Au reaction. In this experiment closely tied in with decay work done by the RITU group we observed that the E = 6996 keV α decay and the E = 1692 keV proton decay originate from the same $^{11}/_{2}^{-}$ level. The γ rays were observed above this level and were found to be in coincidence with both the proton and the α decays, confirming predictions that the $^{11}/_{2}^{-}$ level is predominantly a spherical single particle configuration [7].

The neutron deficient nuclei ^{200,202}Rn were successfully studied via ^{36,40}Ar + ^{166,168}Er reactions. With the use of a detector at the focal plane evidence for µs isomers was found in both nuclei. The extended energy level schemes for these nuclei allow the systematics of the energy levels across the radon isotopes to be extended. There is clear evidence for a parabolic fall in the energies of states with spins >4 which would indicate intruder states becoming more energetically favourable as the mid-shell is approached. The onset of such effects is very similar to that observed in the polonium isotopes indicating that a common mechanism is occurring in both isotopic chains [8].

The extremely neutron deficient nucleus ^{166}Os was successfully studied by bombarding a ^{106}Cd target with a ^{64}Zn beam. Results confirmed the earlier work and extended the known level scheme. At higher spin there is a lowering of the 8^+ and 10^+ excitation energies indicating a rearrangement of the proton orbitals that are occupied [9].

The lightest known odd-mass Pb isotope ^{183}Pb and its decay were studied to learn more about the shape coexistence and ordering of single particle levels far from stability [10]. Gamma rays associated with the decay to both a low spin and a high spin isomer in ^{183}Pb were clearly identified for the first time. Furthermore, it was also possible to obtain detailed information on the α decay of ^{183}Pb to its daughter ^{179}Hg. This new information, in particular the decay pattern and deduced α decay hindrance factors, provide additional support for the recent suggestion of triple shape-coexistence (oblate/prolate/near-spherical) at low excitation in ^{179}Hg .

A high-statistics RDT experiment was carried out for

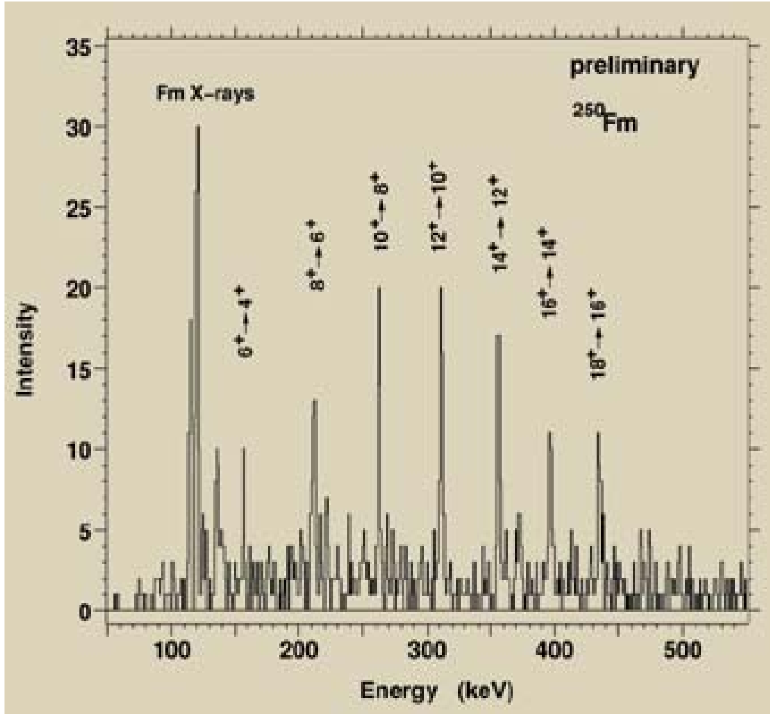


Fig. 4. Singles spectrum of ^{250}Fm gated by recoil nuclei detected in RITU. Unambiguously assigned transitions are labelled.

^{177}Hg. The collected γ-γ coincidence events from the ^{144}Sm + ^{36}Ar reactions tagged with the ^{177}Hg α-decay will enable us to construct the yrast level scheme and thus shed new light on the coupling of the $i_{13/2}$ neutron to the core [11].

The in-beam gamma-ray study of ^{225,227}Th by employing the stand-alone JUROSPHERE array was particularly interesting as α particles (light ions) were used on a radioactive target ^{226}Rn. As a result the level scheme of ^{227}Th has been extended and refined to such an extent that five rotational bands have been assigned spin and parity for the first time. A fresh interpretation of this nucleus based upon K=1/2 coriolis-coupled parity doublet bands has been proposed [12].

Near the end of the campaign, we removed several of the detectors in the array and replaced them with BaF_2 detectors (figure 5). This was a unique set of experiments performed in collaboration with the Studsvik group. The aim was to measure level lifetimes utilising BaF_2 and Ge detectors and combining the RDT technique to unambiguously select the transitions and decay paths. The first reaction used was ^{171}Yb(^{28}Si, xn)^{194,195}Po, the data analysis is ongoing [13]. A further experiment was the study of ^{184}Os for characterising the high spin behaviour by

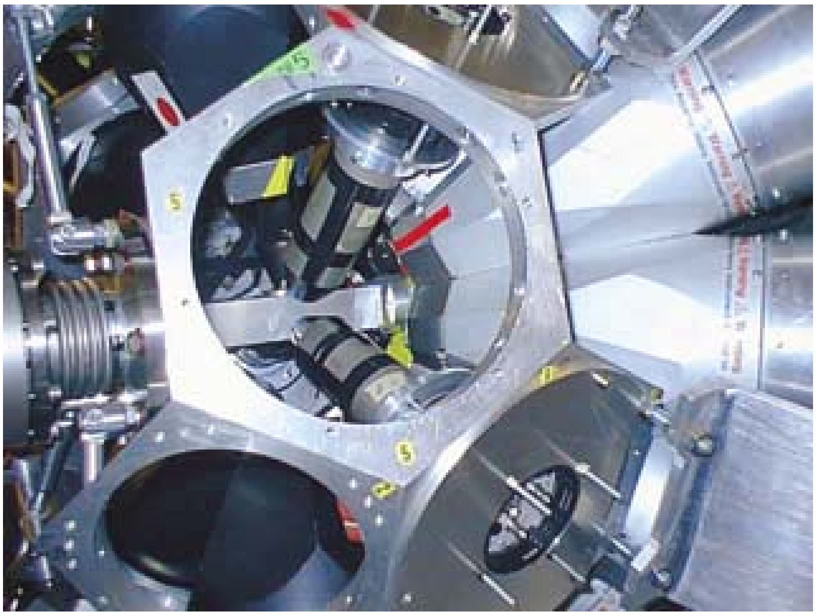


Fig. 5. A view of the BaF_2 detectors with the Ge detectors in the JUROSPHERE array.

distinguishing between intrinsic and rotational levels [14]. This new technique opens up a multitude of possibilities for the study of exotic nuclei.

FUTURE Future plans for the coming year include several SACRED + RITU experiments. The in-beam group will collaborate with the RITU group in the commissioning of the GREAT spectrometer. The GREAT project is led and funded by several UK universities.

We have also received confirmation of a decision by the Euroball Coordination Committee and the UK-France detector pool to bring an array of 45 Eurogam Phase I detectors to JYFL to be combined with RITU to continue the series of Recoil-Decay Tagging (RDT) experiments. This program will be starting in 2003.

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Heavy element studies at RITU

Matti Leino

A series of successful spectroscopy studies has been conducted during the year 2001 using the JYFL gas-filled recoil separator RITU. A considerable part of the activity of the RITU group has been concentrated on in-beam experiments carried out using RITU in conjunction with various spectrometers. This work is described elsewhere in this report. Decay studies have concentrated on the study of very neutron-deficient nuclides in the Au-At region. In addition, the production of Db isotopes was aimed at using the reaction ^{48}Ti + ^{209}Bi [A]. The results of this experiment are under analysis. Highlights from the other experiments will be presented in the following.

New proton radioactivities. The construction of a time-of-flight and energy loss gas detector, used in combination with the standard position sensitive focal plane detector and a pair of veto detectors to discriminate against beam-related light particles was brought to a conclusion [1]. One of the aims in designing the detector system was to provide clean conditions for the observation of proton radioactivities. Figure 1a) shows the spectrum of mother proton decays of correlated recoil-proton-alpha decay chains from the reaction ^{96}Ru(^{78}Kr,p3n)^{170}Au where the hitherto unobserved proton decay from the $\pi s_{1/2}$ orbital is seen for the first time [B]. Also the previously unknown alpha decay branch from the $\pi h_{11/2}$ orbital was observed as shown in Fig. 1b). In addition, the new proton emitting isotope ^{176}Tl was observed in the reaction ^{78}Kr + ^{102}Pd and the new alpha emitting isotope ^{171}Hg in the Au experiments.

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So far, ^{185}Bi is the heaviest proton emitter known [2]. In heavier elements, ^{189}At and ^{191}At are candidates for the observation of the proton decay branch. An attempt was made to look for the proton decay branch of the unknown isotope ^{191}At. In a 130 hour bombardment of ^{141}Pr with ^{54}Fe, the alpha decay of the new isotope ^{191}At was observed in the 4n evaporation channel on the basis of recoil-α-α correlations with ^{187}Bi. The production cross section was measured to be approximately 250 pb. This value is the lowest reached in RITU experiments so far. No correlated proton events were observed.

Systematics of alpha decay of neutron-deficient At isotopes. Our long term experimental project [3] to study the ground and intruder state systematics of neutron-deficient odd-mass At isotopes ^{191,193,195}At using alpha decay has been successfully completed [C] by the observation of alpha decay of the new isotope ^{191}At. One of the motivations for this study is the predicted onset of nuclear ground state deformation above the Z = 82 proton shell gap and below the neutron shell closure at N = 126 [4].

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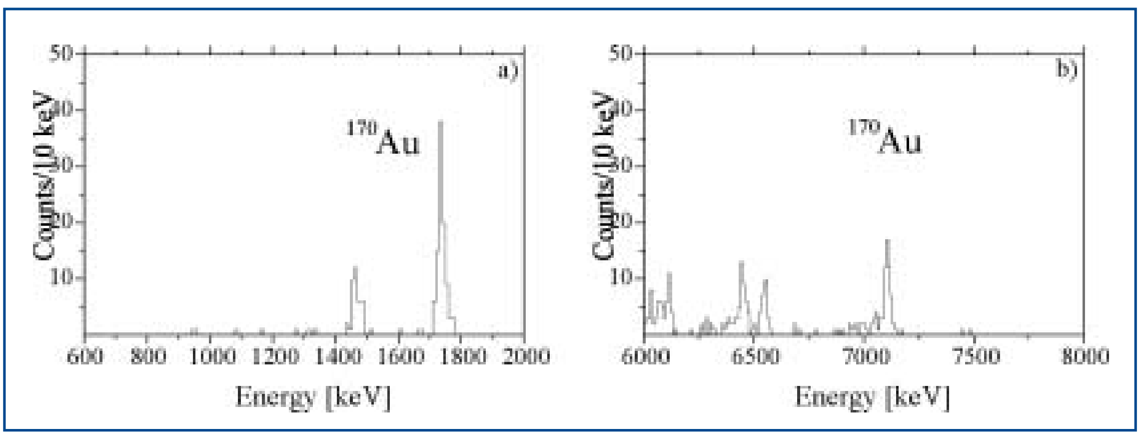
Fig. 1. Proton and alpha particle spectra from the reaction ^{78}Kr+^{96}Ru



For astatine nuclei, the onset of deformation is predicted to occur sharply between ^{199}At and ^{198}At.

These experiments require special care because of summing up of alpha particle energy signals with conversion electron signals in the position sensitive Si detector. This problem has been solved to a large extent by employing Nordball Ge detectors facing the rear side of the Si detector so that α-γ coincidences can be recorded. In this way, the decay of ^{191,193,195}At to levels of ^{187,189,191}Bi has been studied with good statistics using the reactions ^{54,56}Fe + ^{141}Pr and ^{54,56}Fe + ^{142}Nd. Systematics of the excitation energies of $^1/_2^+$, $^7/_2^+$ and $^9/_2^-$ states in At and Bi isotopes have been deduced. Compared with heavier At isotopes, a prominent change in the systematics was discovered indicating a possible change in nuclear shape. New information about low-lying states in ^{187,189,191}Bi was also obtained.

A preparatory experiment aiming at the study of alpha decaying isomeric states in the region just above ^{208}Pb was also conducted [D].

Technical development at RITU. Technical development of the separator system consisted of the installation of a new dipole magnet vacuum chamber and a differential pumping system. In the new vacuum chamber design, special care was taken to reduce the effect of the scattered primary beam at the focal plane, mainly by completely redesigning the beam stop arrangement. In comparing the focal plane background using the reaction ^{56}Fe + ^{141}Pr, a significant improvement was observed. The benefit of using the new chamber is even more pronounced when symmetric reactions are employed. With the new setup, it has been possible to observe fusion products at the focal plane under sufficiently clean conditions for the use of the correlation technique even from reactions such as ^{104}Ru + Mo,Zr. After a development period of several years, RITU can now be used for correlation studies using both symmetric and asymmetric reactions in the heavy element region without significant interference from beam-related heavy particles and without significant losses in transmission. Because of the proton number dependence of the average charge state of fast ions in He gas, which leads to overlap between fusion products and beam or target-like particles, experiments using RITU with symmetric reactions are however not possible below mass number A $\approx$ 120, as a rule. A preliminary investigation for the construction of a new separator which would improve our capabilities to conduct such studies is underway.

The beam window which separates the high vacuum of the beam line from the filling gas of RITU deteriorates rapidly when high intensity beams with high proton number are used. Such beams are needed especially for decay studies in the region of very heavy elements. For these reasons, a differential pumping system was constructed close to the target region to enable irradiations without the gas window. The setup consists of one 1000 m^3/h Roots blower backed by a mechanical pump and a set of diaphragms to reduce the gas consumption. This setup is now in routine use and allows window free operation at He pressures up to 1 mbar with low gas consumption and low loss of primary beam intensity.

An extensive collaboration has been funded in the U. K. to develop a data acquisition and detector system called GREAT [5, E] to be used at the focal plane of the RITU separator. GREAT comprises two Double-sided Silicon Strip Detectors (DSSD) covering an area of 40 mm by 120 mm to be used as a stop detector and 32 PIN diodes for detection of conversion electrons and escaping alpha particles. A segmented planar Ge detector in combination with a large-volume segmented Ge detector, both behind the DSSD detector, will be used for the detection of low- and high-energy γ-rays, respectively. This system provides unsurpassed capability for the detection of γ-γ, α-e$^-$, and also β-γ coincidences. The system is expected to be commissioned in the year 2002. First experiments will concentrate on the study of alpha decay fine structure and isomeric alpha decays as well as γ-rays from high-K isomers in the region around ^{254}No.

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Experiments for spallation reaction cross sections

Timo Enqvist

Due to the importance of spallation reactions in many technical applications, they have recently gained considerable interest. They, for example, could act as an intense neutron source in accelerator-driven subcritical reactors which are proposed to incinerate nuclear waste and/or to produce energy.

Using the fragment separator FRS installed at the heavy-ion synchrotron SIS at GSI in Darmstadt, Germany, nuclide production cross sections of primary residues and their kinetic energies have been experimentally measured in the inverse-kinematics spallation reactions of 1 GeV protons and 2 GeV deuterons with lead [1,2]. The measured production cross sections for fission and fragmentation of ^{208}Pb (1 A GeV) on proton have been summarised in figure 1 on a chart of the nuclides.

Each mentioned reaction produces around 1000 isotopes above 0.1 mbarn. The measured production cross sections and kinetic energies will also greatly help improve the accuracy of the existing spallation models. The status of the models is far from the performance required for technical applications, mainly due to the lack of comprehensive experimental data.

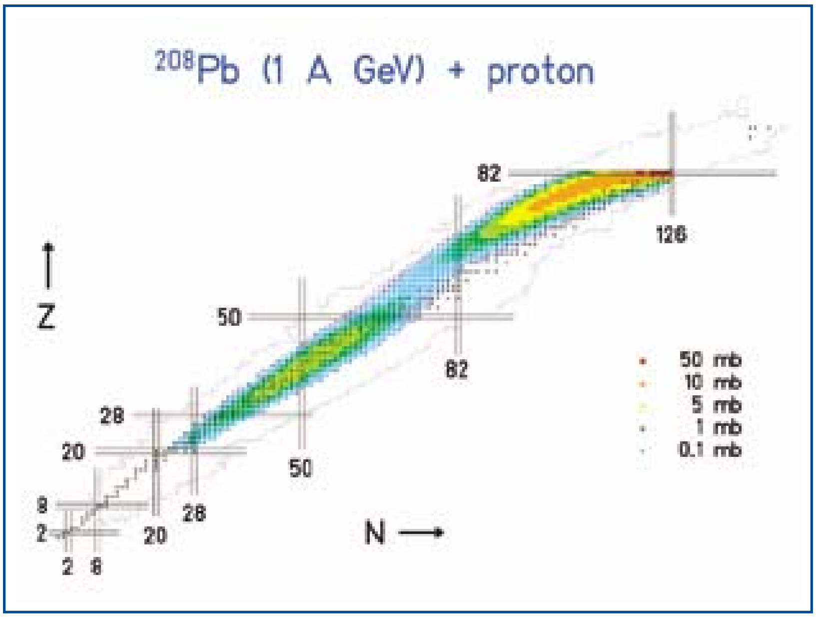

Fig 1. Two-dimensional cluster plot of the isotopic production cross sections of the reaction ^{208}Pb (1 A GeV)+p. Full black squares correspond to the stable isotopes.

References:

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Nuclear reactions

Wladyslaw Trzaska and Valery Rubchenya

http://www.phys.jyu.fi/research/hendes/hendes/

The nuclear reaction group carried out 9 experiments in 2001 totaling about 900 hours of beam time. There were also two runs at facilities outside JYFL but with a substantial contribution of our equipment and know-how. During this year our collaboration has been significantly enlarged. A major improvement in the quality of fission fragment detection came with the installation at JYFL of the CORSET detector developed in Dubna. The efficiency for neutron detection has been enhanced with several DEMON detector modules delivered from Strasbourg. Measurements of the gamma-ray multiplicity in nuclear reactions became possible thanks to the new collaboration with the Cyclotron Institute of Texas A&M University. Finally, the efficiency of light charged particle detection has been increased with the purchase, together

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with the alpha-cluster project, of 40 large area silicon PIN diode detectors.

Superasymmetric nuclear fission. Investigation of the superasymmetric fission mode was continued with the $^{242}Pu(p,f)$ reaction at proton energies up to 55 MeV using HENDES, CORSET and DEMON hardware as well as gamma-ray detectors from Texas A&M University. After the experiment, the same configuration was used in a long measurement of ^{252}Cf spontaneous fission. The quality of the data is very high and the data processing together with theoretical analysis are in progress. Preliminary results indicate the presence of the superasymmetric fission mode in proton induced fission of ^{242}Pu but not in the spontaneous fission of ^{252}Cf.

Fusion-fission reactions. We have continued the studies of the mechanism of heavy ion induced fusion-fission reactions. Special emphasis was placed on the comparison of the fission time scale extracted from different nuclear probes (neutrons, protons and alpha particles). There were also new developments in our study of fine structures (FS) in two-dimensional TKE-E plots for fission fragments using nearly the entire data set collected by the HENDES collaboration over the past years. Manifestation of FS indicates unexpectedly high contribution of low excitation energy fission and overdamped collective motion before scission.

Superheavy nuclear systems. At the turn of the year in our experiment at HENDES the formation and decay of the highly excited superheavy composite system with Z = 118 formed in the reaction $^{86}Kr + {}^{nat}Pb$ was studied. The main goal of the experiment was to determine the relation between the fast fission channels and the formation of a compact compound nucleus. This is an important question in the synthesis of superheavy elements. The double differential distributions of neutrons and of light charged particles (LCP) were measured in correlation with the fragments. The LCP probe provides an additional possibility to determine the time scale of the processes and the neck fragmentation. Important changes in the reaction mechanism with the increase of the nuclear charge were observed for two systems with Z = 110 and 118 respectively. Both measurements were done at JYFL.

Nuclear scattering. The measurement of α-cluster states in ^{22}Ne produced in the $^{18}O + \alpha$ scattering at JYFL was complemented by the study of α-cluster states in the mirror nucleus ^{22}Mg using the same technique and the radioactive ^{18}Ne beam at CRC in Louvain-la-Neuve in Belgium. This pair of measurements is a unique experimental achievement that makes a significant contribution to our understanding of α-cluster states in light nuclei. We have also continued our study of the rainbow phenomena measuring elastic scattering of ^{18}O on a ^{14}C target. We have also prepared for a major upgrade of the Large Scattering Chamber at JYFL to realize our plans to study the mechanism of cluster radioactivity.

Applied research. Our successful collaboration with the Applied Physics group has brought further breakthrough results in the measurements of energy loss of light and heavy ions in thin foils. One of our surprising findings is that the majority of previously measured dE/dx values for HI at energies below 0.5 MeV per nucleon disagree with our latest data. According to our interpretation, the difference is explained by the pulse height defect that was not properly accounted for in the old measurements.

Detection techniques. As usual, a large part of our activity went into the development of detectors, electronics and new experimental techniques. Our work with P. Egelhof's group from GSI on the identification of heavy nuclei using high precision time-of-flight (TOF) and high resolution calorimetric low temperature detectors is a good example. We have also contributed to the EURISOL project by participating in three working groups.

Ion beam based materials physics and applications

Jyrki Räisänen and Ari Virtanen

The previously launched research topics have been continued and their scope widened. Also some new projects have been initiated. The present research programme consists of the following main topics:

Diffusion of impurity atoms and self-diffusion in compound semiconductors studied by radiotracers. The material of main interest in the diffusion studies has been silicon-germanium alloy. Si-Ge alloys grown epitaxially on Si substrates have recently become the subject of scientific and technological interest primarily because of the enormous potential for fabricating novel devices compatible with the existing Si-based processing technology. For the diffusion studies we employ the sophisticated modified radiotracer technique. Radioactive beams at Jyväskylä/IGISOL, CERN/ISOLDE and University of Bonn have been used for sample implantation. The depth-concentration profiles have been determined by sputtering based serial sectioning.

The experiments of the ^{71}Ge self-diffusion studies in Si_{1-y}-Ge_y alloys as a function of composition y carried out in collaboration with the University of Stuttgart and Max-Planck-Institut für Metallforschung (CERN/ISOLDE collaboration) have been completed. The motivation for such studies has been to test the prediction that in these alloys the self-diffusion mechanism changes from interstitialcy-type on the silicon side to vacancy-type on the germanium side. In this comprehensive study we covered the full range of Si_{1-x}-Ge_x materials, from x=0 to x=1.

The first diffusion experiments ever with radioactive ^{31}Si ($t_{1/2}$=2.6 h) beams were carried out successfully at the IGISOL facility in collaboration with the Stuttgart and IGISOL groups. The study aimed at the verification of the validity of substituting silicon tracers by germanium tracers in self-diffusion studies since so far ^{71}Ge has been used for "simulating" the Si behaviour. In the first experiments data for $Si_{0.5}Ge_{0.5}$, $Si_{0.2}Ge_{0.8}$ and pure germanium materials have been deduced.

Also new projects related to diffusion of several dopant elements in Si-Ge alloys have been initiated during 2001.

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Grigori Tiourine, laboratory engineer

Structural and thermal properties of Er implanted $Si_{1-x}Ge_x$ alloys. Optical properties of Er atoms incorporated into semiconductors have been given a great deal of attention over the last decade. Among a variety of semiconductor hosts, Si is of particular interest for optoelectronics as Er in its trivalent state shows characteristic luminescence around 1.54 μm corresponding to the minimum absorption of silica based fibres. Er incorporation into Si based chips should allow realisation of optoelectronic integrated circuits and should improve their performance considerably.

However, the low solid solubility of optically active Er in Si based materials and the long radiative lifetime result in a luminescence yield that is moderate at low temperatures. This implies that Er:Si devices produced by thermal equilibrium methods (e.g. doping during MBE growth) have insufficient emission when operating at room temperature. The band gap energy of the host semiconductor is known to be an important parameter if one wants to change the energy transfer efficiency. In a $Si_{1-x}Ge_x$ based host the energy band gap and, thus the energy transfer can reach acceptable levels by changing the Ge concentration x. $Si_{1-x}Ge_x$ can also be integrated easily with Si. Therefore, $Si_{1-x}Ge_x$ alloys form a promising material for fabrication of the next generation optoelectronic devices with high integrability in conventional silicon technology. Nevertheless, very little work has been done on erbium in silicon-germanium. In order to reach a technological application level, a better understanding of both the structural and optical properties of Er doped $Si_{1-x}Ge_x$ is needed.

Since ion implantation is by its nature a non-equilibrium process, concentrations of optically active Er atoms implanted into $Si_{1-x}Ge_x$ alloys can be extended well beyond

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the equilibrium solid solubility limit. This makes ion implantation attractive for doping of $Si_{1-x}Ge_x$ with Er. On the other hand, with the use of ion implantation the quality of the host crystal will be impaired and several kinds of radiation defects are generated. Both the optical and the annealing properties of the defects still have to be studied.

In the project we have tried to identify experimentally and by simulations the lattice location of Er atoms implanted into silicon-germanium matrix (presumably optically active). Their thermal behaviour during post-implantation annealing that is typically used in semiconductor technology for dopant activation and radiation damage recovery as well as for matrix recrystallization by the solid phase epitaxy has been studied. Er-implanted $Si_{1-x}Ge_x$ samples with different Ge concentrations have been prepared in the new UHV chamber shown in the figure recently completed and attached to the 6.4 GHz ECR ion source at JYFL. The analysis of the samples has been carried out in Ørsted Laboratory, Niels Bohr Institute, Denmark. By means of Rutherford Backscattering Spectrometry complemented with channelling ability (RBS/channelling) we were able to identify lattice location of implanted Er in $Si_{1-x}Ge_x$ lattice on the basis of computer simulation of experimental channelling spectra. Thermal behaviour of the implanted ultra-shallow Er layers (40-50 nm thick) upon annealing was found to depend strongly on the stoichiometry of the alloys (Ge concentration) that is of importance for micro- and nano-devices fabrication because of constantly shrinking characteristic dimensions in large scale integrated circuits.

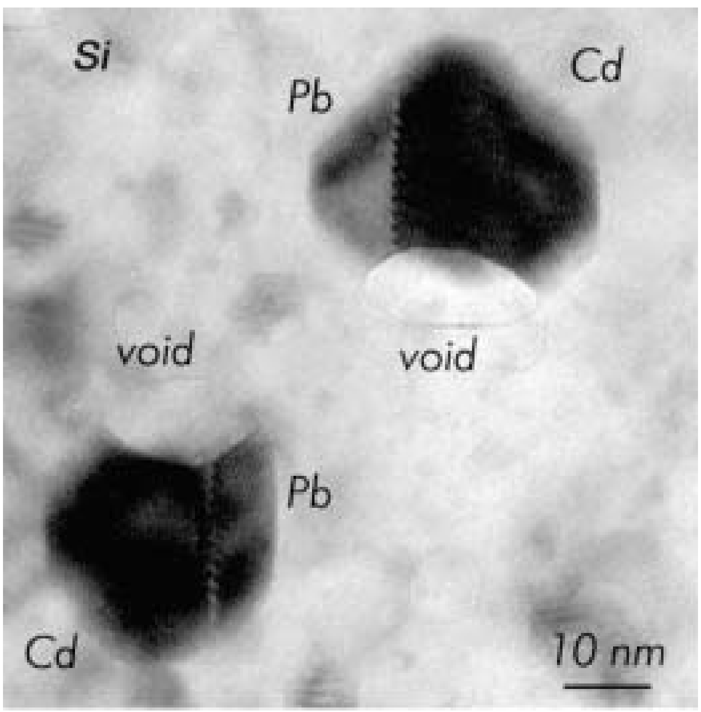
Nanoscale Lead-Cadmium Alloy Inclusions Formed in Silicon by Ion Implantation. Nanocrystalline inclusions embedded into a crystalline matrix, which can be considered as embedded nanoscale laboratories (from 1 to 100 nm), show unique and non-trivial size-dependent properties different as compared with those for a bulk material (e.g. anomalous phase transformations, non-equilibrium crystal structures etc.).

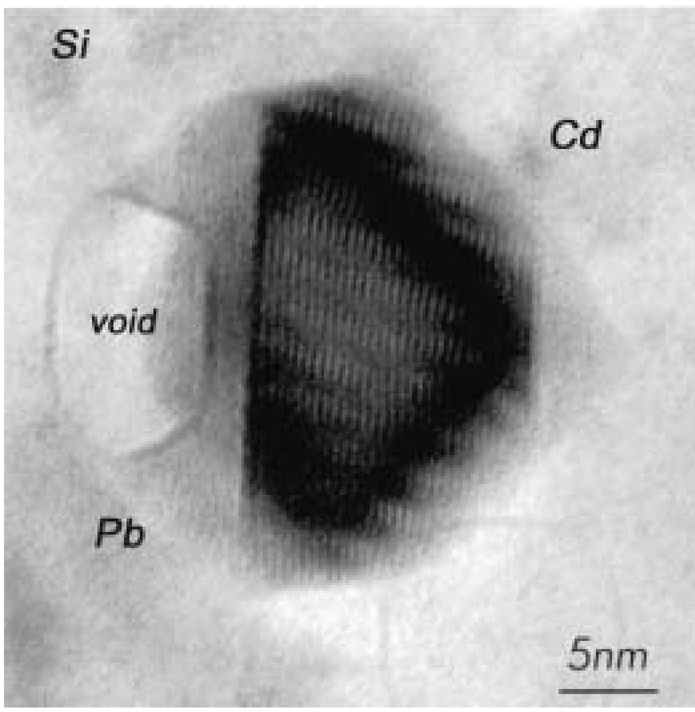
In the other collaboration project with Niels Bohr Institute cadmium-rich nanoscale lead-cadmium alloy inclusions have been made in silicon by sequential ion implantation and subsequently analysed by transmission electron microscopy (TEM) and Rutherford backscattering/channelling analysis (RBS). To ensure crystallinity of the silicon matrix the implantations were carried out at 600°C. This is well above the melting point of both lead and cadmium, and the inclusions were therefore liquid during their formation and growth. The overall shape of the inclusions is shown in the figure to be cuboctachedral and they have a two-phase microstructure consisting of nearly pure segments of lead and cadmium attached along internal {001} and {011} planar interfaces. The lead segments tend to grow in parallel cube alignment with the silicon matrix while the orientation of the cadmium segments is varied. Due to shrinkage of the inclusions during initial cooling and solidification in the rigid silicon matrix, the alloy inclusions also contain voids. They are faceted both externally towards the silicon matrix and internally towards the metals. The voids tend to have well-defined location with respect to the inclusion/matrix interface, and in this respect the voids can be considered as a third "phase" with a shape defined by surface energies rather than interface energies.

During in-situ heating and cooling experiments with TEM and RBS analysis, the melting and solidification of the inclusions can be followed directly. The inclusions melt in a two-stage process where eutectic melting is followed by melting of the excess cadmium. This is accompanied by shrinkage of the voids, which eventually disappear at 675°C. Upon cooling the voids reappear while the inclusions are still liquid. Solidification of the inclusions into a three-phase structure – cadmium, lead and void – takes place in a two-stage process that is reversed in comparison with melting.

Stopping powers of energetic heavy ions in solids. The aim of the programme is to obtain new, previously poorly known data for heavy ion stopping powers for important classes of materials.

A novel micro channel plate based time of flight technique developed by the JYFL Nuclear Reactions group has been employed in several joint collaboration studies related to stopping power determinations of compounds as well as pure elements. This technique allows measurements of continuous stopping power curves in a very broad energy range and is especially suited to be used with cyclotrons. It has been employed successfully, for example, in the stopping power determinations of gold, nickel, carbon, polycarbonate and havar alloy for 0.2-11 MeV/u ^{40}Ar, ^{28}Si, ^{16}O, ^{4}He and ^{1}H ions. A procedure to extract simultaneously continuous stopping power curves for several ions and materials over a wide energy range has been shown feasible. The procedure combines the novel method mentioned above with the capability of our cyclotron and ECR ion source to produce the so-called ion cocktails. In the first experiments a 6 MeV/u cocktail consisting of $^{16}O^{4+}$, $^{28}Si^{7+}$ and $^{40}Ar^{10+}$ ions was employed.





The measurements for obtaining stopping powers of havar and polycarbonate for protons and alpha particles have been completed. The data is being analysed in terms of modified Bethe-Bloch theory for the purpose of extracting values of the dominant parameters of the formalism employed. The work is carried out in collaboration with Washington State University. Traditional transmission technique measurements have been used in the stopping power determinations of polycarbonate, mylar and havar for ^{40}Ar ions in the energy range of 1.0-3.25 MeV/u.
A new project related to cancer treatment by proton therapy was initiated aiming at stopping power determinations of several materials for 60 MeV protons.

Irradiation tests in RADEF facility. Royal Institute of Technology and Swedish Space Corporation performed two SEE and RadHard tests of commercial-off-the-shelf memory DRAM's selected for the European satellite SMART-1. Since the satellite is equipped with a slow propulsion engine, the spacecraft will be exposed to radiation during 400 days when passing the radiation belts of the Earth. The satellite will leave the belts by the beginning of the year 2004 and continues towards the Moon. The tests were done according to ESA's specifications (ESA/SCC No. 251000) and the results were within the requirements set for SMART-1. Due to the short range in the relevant energy region the DRAM circuit has to be decapsulated, see Figure 1. In front of the silicon die a metal structure is revealed, complicating heavy ion tests since a part of the sensitive area is shielded.

European Space Agency, ESA, and a french company HIREX Engineering, performed three SEE tests in RADEF. In addition to the component testing one goal of ESA was to evaluate the RADEF facility and the capability of the new ECR ion source to offer higher penetration beams and beam cocktails, which are of growing interest to the space community. The reason is, that modern advanced semiconductor devices are assembled like shown in Figure 1 and, for the complete SEE assessment, the shielding requires backward irradiation with high penetration ions.

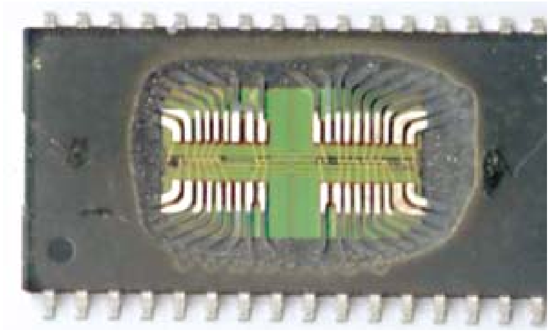


Fig. 1. The open DRAM chip. The comb shaped metal structure in front of the silicon die is visible.

In Figure 2 the preliminary test results of the evaluation are shown. With the same devices tested at both the RADEF and the ESA coordinated test site, HIF, at UCL, Louvain-La-Neuve, Belgium, using the same tester, test set-up and test programs, allows for a direct correlation between obtained SEU results. As can be seen in comparison, a fairly good agreement between the two curves exists. However, these preliminary results need to be analyzed further and corrected for possible stuck bits and other run deficiencies.

In Table 1 an example of a high penetration cocktail is expressed. Before the test, all beam components were extracted and identified, but in the actual irradiation, the production of krypton beam did not succeed. This indicates, that more attention to the beam development and to the reliability has to be paid in the future.

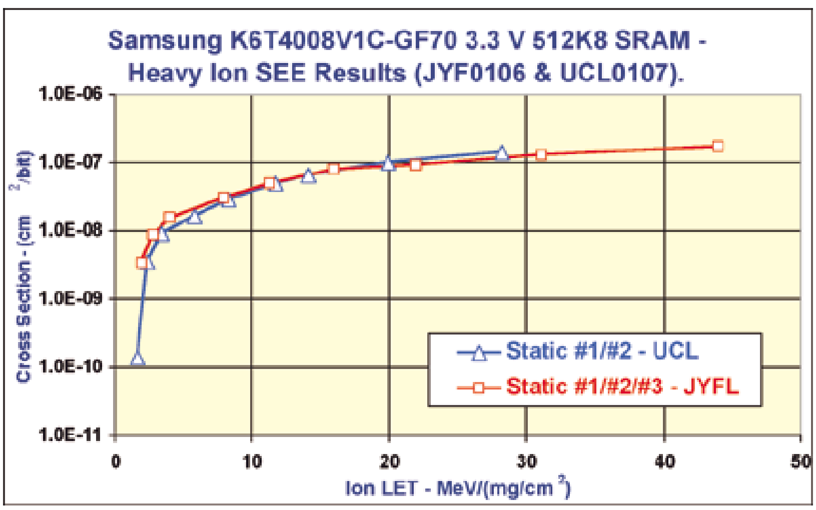


Fig. 2. Preliminary SEU test results measured at RADEF (JYFL) and at HIF (UCL).

Also, Helsinki Institute of Physics, HIP, performed a detector test in the RADEF station The purpose was to study the radiation tolerance of silicon used for detector material in high-energy physics experiments. The samples were irradiated with 15 MeV protons and three different doses were used: $6*10^{12}$, $5*10^{13}$ and $1*10^{14}$ protons/cm^2. The highest dose corresponds to the radiation levels of about 10 years in the inner parts of the CERN LHC experiment. The leakage current of the diodes irradiated with the highest dose showed an increase of three orders of magnitude. In addition, the results indicate that an inversion in conductivity from n-type to p-type takes place already after the irradiation with the lowest dose.

Radiotherapy project. Last year also a new radiotherapy technology project was commenced. The project started from a need of radiotherapy hospitals to measure on-line the dynamic photon fields of the modern radiotherapy accelerators. As the solution the advanced PSAC (Position Sensitive Avalanche Counter) multiwire detector, aimed originally for the detection of particle radiation, was developed (see Fig. 3). The monitoring of the high energy photons was done by detecting collimated photonuclear reaction products followed by the disintegrations in the uranium converter. The position of the disintegration was defined by using the delay-line technique. The functionality tests were performed in actual environments with the accelerators of Tampere University Hospital (Department of Oncology) and Central Finland Health Care District (Radiotherapy Hospital).

Ion	LET [MeV/(mg/cm^2)]	Range [µm]	Energy [MeV]
N^{4+}	2	208	140
Si^{8+}	7	133	280
Fe^{15+}	18	103	523
Kr^{22+}	29	99	766

Table 1. The high energy beam cocktail produced by the new ECR ion source (A/Q~3.8, E/u ~9.3 MeV/u)

Major foreign collaborators for ion beam based materials physics research:

- W. Frank, A. Strohm, T. Voss. Universität Stuttgart and Max-Planck-Institut für Metallforschung, Stuttgart, Germany
- CERN/ISOLDE collaboration, Geneva, Switzerland
- E. Johnson, A. Johansen, L. Sarholt, Ørsted Laboratory, Niels Bohr Institute, Copenhagen, Denmark
- L. E. Porter, Washington State University, Pullman, Washington, USA

Major foreign collaborators for applications:

- R. Harboe-Sørensen, European Space Agency, ESA, Noordwijk, The Netherlands
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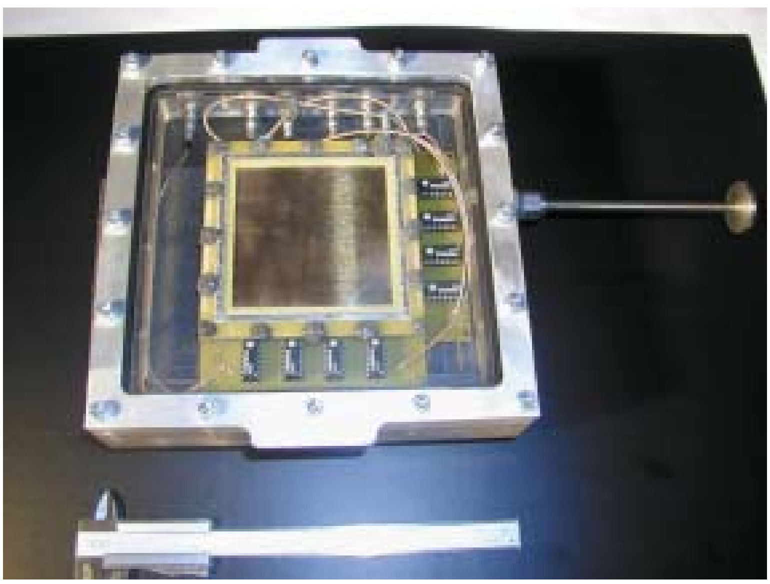

Fig 3. A photo from the PSAC detector equipped with the converter and delay-line components. The wires of the uppermost cathode, meant for background subtraction, can barely be seen. The brown plate is the U-converter. The hose on right is for the gas feeding system.

Nuclear structure models and reactions

Jouni Suhonen

http://www.phys.jyu.fi/research/nuclear_theory/

The theoretical nuclear physics group develops microscopic nuclear models and applies them to nuclei of current interest for both the traditional nuclear spectroscopy and for processes involving connections to modern particle-physics theories. The nuclear spectroscopy side includes studies of structure of the nuclei and their decays via alpha, beta and gamma emission. The particle-physics side involves processes connected to modern nuclear astrophysics, neutrino astrophysics, dark-matter search, weak-interaction physics and physics of massive neutrinos. In the following we highlight some special topics currently studied by the group.

One of the recent key issues on the nuclear spectroscopy side has been studies of α-like resonances and α-decay. Description of α-like resonances, a sub-group of quasi-molecular resonances, has been a long-standing problem in theoretical nuclear physics investigating four-particle correlations in nuclei. No really microscopic nuclear-structure theory exists for quantitative description of these experimentally observed complex resonances. We have developed the first fully microscopic description of α-like resonances [1] using as basic building blocks the Gamow-type of single-particle states in continuum. The four-particle correlations are treated by the multi-step shell model. We have found that the unbound single-particle resonance states in continuum play a decisive role in quantitative description of the α-like states. Especially for the $\alpha+^{40}Ca$ quasimolecular resonances a proper inclusion of the continuum produces a spectacular improvement over the previously used more phenomenological theoretical approaches [2].

The same can be said about calculations of alpha-decay fine structure in decays to excited states of the final nucleus. Some preliminary attempts have been made to account for the huge variation of the alpha-decay hindrance factors from one nucleus to the other. The problem becomes more interesting when considering that large sums of money are being invested presently to measure more and more accurately a wider selection of nuclei to produce systematics of the values of the hindrance factors. Extensive theoretical calculations are called for to study the variations of the hindrance factors and to explain them on a microscopic nuclear-structure level. Just recently we have started a fully microscopic

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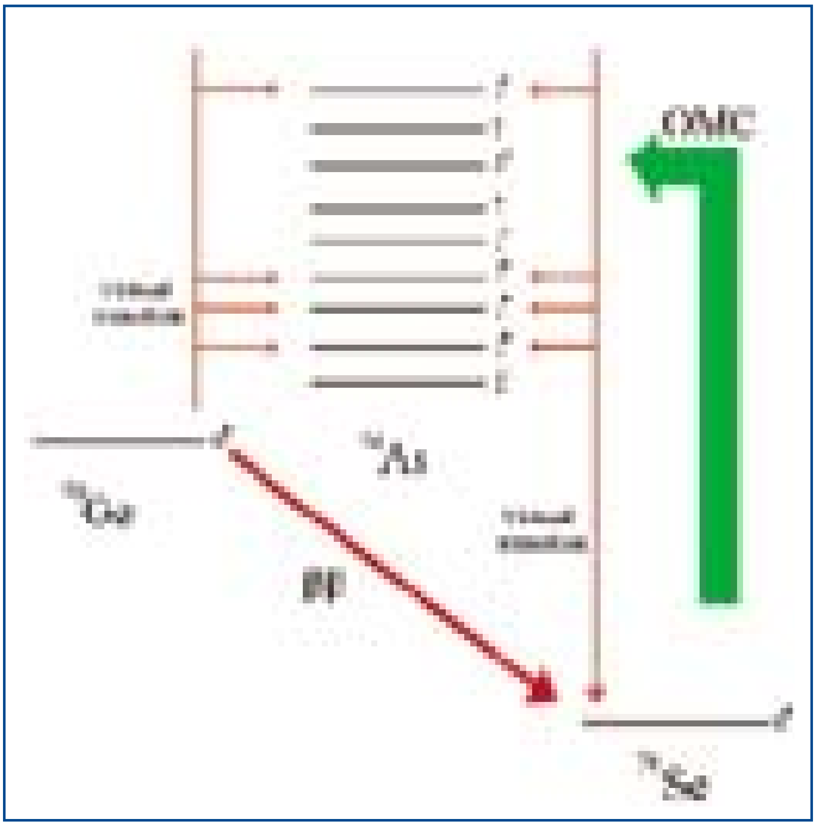
calculation of hindrance factors of alpha decay to excited 2^+ states in spherical nuclei, and nuclei with signs of coexistence of spherical and deformed degrees of freedom. The basic nuclear-structure framework concists of the use of the BCS method to create two-quasiparticle excitations and the use of the quasiparticle random-phase approximation (QRPA) to take into account collective degrees of freedom in the α-decay daughter nucleus. In the case of the 2^+ states, we have started the studies of the α-decay hindrance factors and first results have been already published for the decays of $^{198-204}Rn$ [3]. The hindrance-factor analysis is at the present being extended to decays to 0^+ excited states. This analysis will be carried out for nuclei close to the Z=82 magic shell (decays of Rn, Po, Pb and Hg nuclei). The interesting feature in these decays is the possibility to study the shape coexistence near the Z=82 magic shell, ie. the interference between the normal excitations and the 0^+ two-particle-two-hole excitations.

Related to the weak-interaction physics, we have studied lately the exotic muon-to-electron conversion in ^{27}Al [4] and the two-neutrino double beta decay of ^{106}Cd to excited states of ^{106}Pd [5]. Furthermore, we are currently studying neutrinoless double beta decay to excited 0^+ states with the aim of finding promising candidates to probe sub-eV neutrino masses in modern underground experiments using huge active-mass detectors. In the work [6] it was found that the two-phonon-type of 0^+ states are only very weakly populated by this decay, thus escaping detection, but in the work [7] it was speculated that a massive source made of ^{96}Zr could yield to majorana-neutrino masses below 0.1eV when presently planned underground installations could be used for tracking measurements combined with gamma-coincidence methods. This unofficial proposal for an experiment has been coined "ZORRO" (Zirconium ORiented

Rare-events Observatory) in the NANP'01 Conference (see Ref. [8]). A further analysis of the 0^+ decays has been performed for the ^{100}Mo decay in [9] using the spectroscopic information obtained in [10].

The capture of negatively charged muons by the atomic nuclei can be used as a probe of different types of weak-interaction-induced processes. The ordinary muon capture (OMC) is a process similar to the nuclear electron capture, except that the large mass of the muon, relative to the mass of an electron, causes that the so-called induced weak-interaction currents, mostly the induced pseudoscalar current, can be detectable in muon-capture processes. We have been able to constrain the structure of the weak-interaction currents by muon-capture-rate calculations using renormalized shell-model operators and realistic effective nucleon-nucleon interactions. In these works we have investigated the renormalization of the weak hadronic current in the semileptonic reactions, in particular the role of the induced pseudoscalar coupling. The latest study of this sort has been reported in [11]. Furthermore, in collaboration with experimental groups in France, Belgium, Switzerland, and Russia we have managed to obtain new constraints for the genuine, non-induced scalar component of the fundamental weak-interaction current in the very recent experiments carried out at the PSI (Paul-Sherrer Institute) in Switzerland [12].

A very new idea about using of the OMC rates as a probe of the virtual transition of the double beta decay has been advocated in [13]. This idea has been collecting experimental interest to the extent that an experimental proposal to the PSI has been submitted [14]. This idea has been presented in figure below for the $2\nu\beta\beta$ decay of ^{76}Ge. As is well known, a reliable theoretical description of double-beta-decay processes needs a possibility to test the involved virtual transitions against experimental data. Unfortunately, only the lowest virtual transition can be probed by the traditional electron-capture or β-decay experiments. We now propose that calculated amplitudes for many virtual transitions can be probed by experiments measuring rates of the OMC to the relevant intermediate states (in figure below to the states of ^{76}As). The first results from such experiments are expected to appear soon. As examples we have discussed in [13] the $\beta\beta$ decays of ^{76}Ge and ^{106}Cd and the corresponding OMC for the ^{76}Se and ^{106}Cd nuclei in the framework of the proton-neutron QRPA with realistic interactions. It was found that the OMC observables, just like the $2\nu\beta\beta$-decay amplitudes, strongly depend on the strength of the particle-particle part of the proton-neutron interaction.



Our theory group is also interested in the physics of solar and supernova neutrinos and dark matter. The supernova explosions are a way to generate elements of various masses in a nucleosynthesis of exotic nuclei far from the beta-stability line. The excess energy of the supernova is converted to supernova neutrinos detectable by experimental facilities on the Earth. To understand the luminosity of the supernova and the related nuclear reactions involving neutrino-nucleus scatterings, one has to perform theoretical calculations of the neutrino-nucleus scattering cross sections, beta-decay and electron-capture probabilities etc. At the same time it is interesting to calculate neutrino-nucleus cross sections for potential neutrino detectors of solar neutrinos to help in solving the rather long-standing 'solar-neutrino problem', where a strong discrepancy between the measured and the solar-model predicted neutrino flux on the Earth has been recorded. To start with, we intend to calculate neutrino-^{127}I scattering cross sections in relation with the detection of the solar neutrinos. This work is based on our recently finished calculations on the spectroscopy of ^{127}I and its neighboring nuclei [15].

Finally, the study of the cold dark matter of the Universe is one of the key issues of the present-day astrophysics, astro-particle physics, neutrino-physics, neutrino-cosmology, etc. Recent particle-physics theories seem to favour light supersymmetric particles (LSP) as constituents of this matter. To shed light to this problem one should need reliable estimates of the LSP-nucleus scattering cross sections for possible destection of this component of the dark matter. Needles to say that discovering the nature of the dark matter helps in understanding the past, present and future evolution of the Universe in a much more accurate way. Recently we have started the LSP-nucleus cross section calculations for ^{27}Al, a proposed candidate for detection of the LSPs.

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Materials physics

Physics of nanostructures and nanotechnology

Jukka Pekola

SINIS On-chip cooling

Next generation of space borne science missions studying the evolution of the universe, extra solar planets, and black holes require radiation detectors operated at deep cryogenic temperatures below 100 mK. In year 2001 we completed a three year long study of superconductor-insulator-normal metal–insulator–superconductor (SINIS) tunnel junction coolers. These devices are capable of cooling microscopic samples, such as the above mentioned detectors from 0.3 K to about 0.1 K. In the project, a successful demonstration of cooling of electron gas from 0.3 K to 0.1 K was demonstrated, and cooling of lattice from 0.2 K to 0.1 K.

The encouraging results from the experiments justify further study of the idea. Especially, the novel experiment where highly doped silicon is used instead of a normal metal seems promising. The main focus of future work will be on the increase of net cooling power in order to enable cooling of macroscopic samples.

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http://www.phys.jyu.fi/research/nanotech/

X-ray microcalorimeter development

A potential follow-up mission to the presently flying *XMM-Newton* telescope of the European Space Agency, the *X*-ray *E*volving *U*niverse *S*pectroscopy (*XEUS)* –mission is under study by the Agency. The *XEUS* will study the hot matter of the Universe, formation of first Galaxies and black holes, among a variety of other subjects. The other of *XEUS*'s main instruments will be a cryogenic imaging spectrometer, capable of eV –class resolution of 5.9 keV X-rays. At present, the most promising technology is based on transition-edge microcalorimeters (TES), operated at temperatures close to 100 mK. In 2001 an ESA funded study was completed, where a resolution of 9.1 eV was obtained for 5.9 keV X-rays. In the beginning of 2002, a follow-up activity is anticipated to start, focusing on the further study of detector physics. Presently, all groups working with TES's seem to have excess

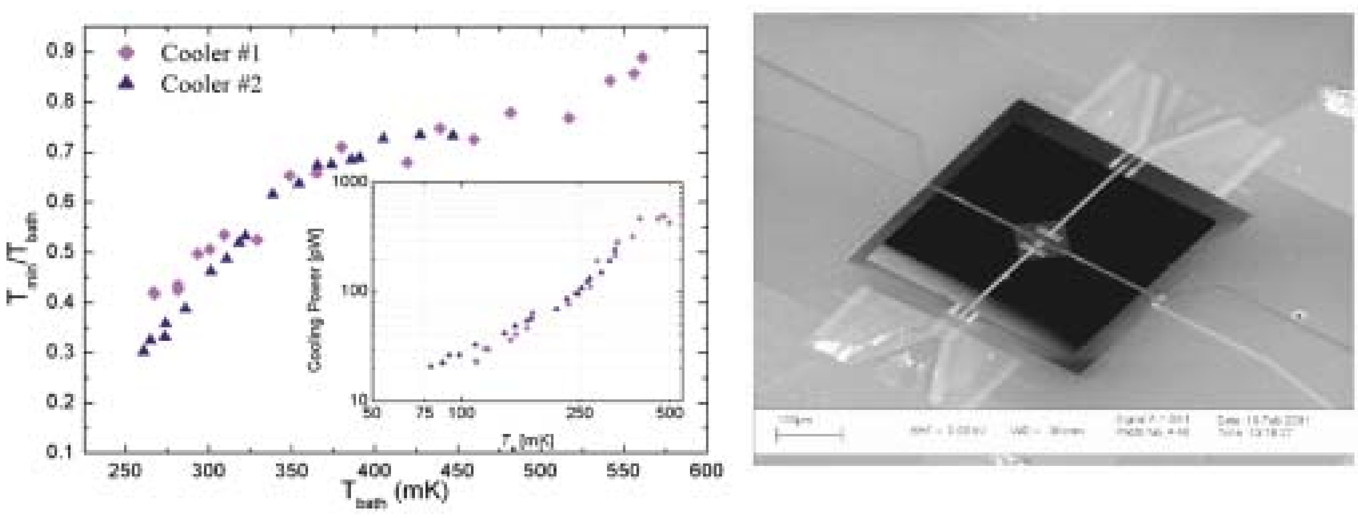


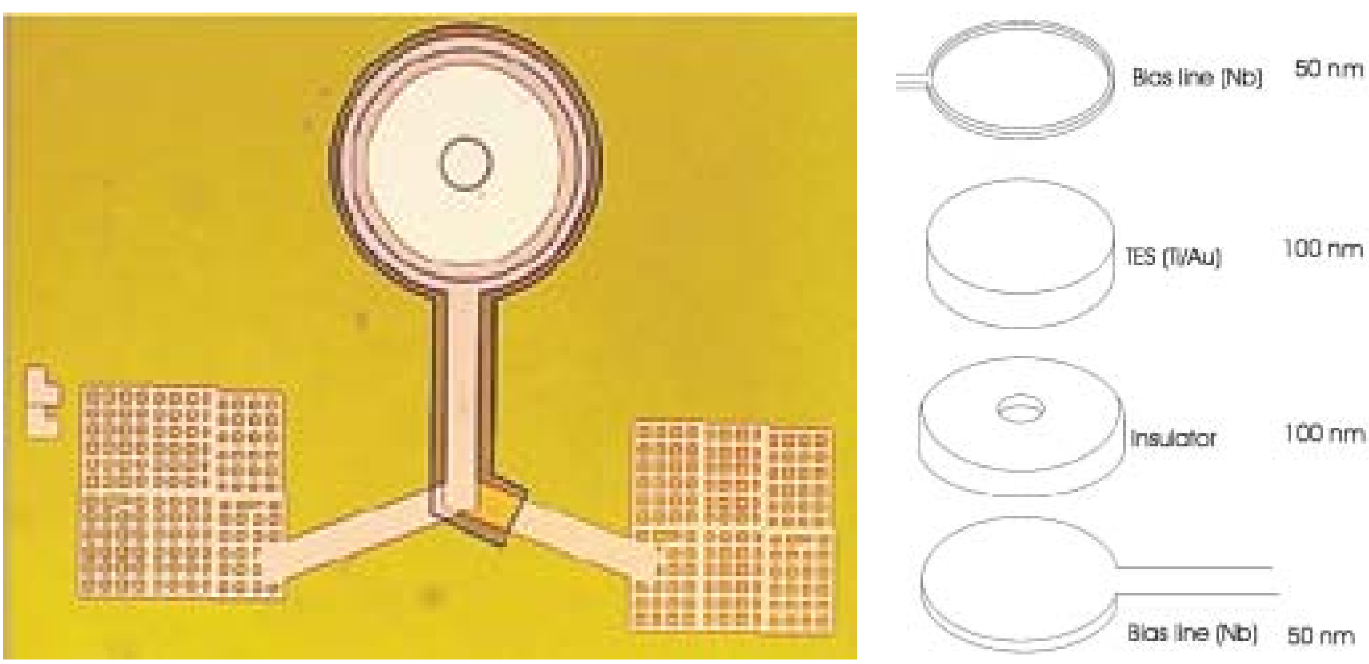
Fig. 1. (Left) Cooling performance of an electronic cooler. (Right) A SEM image of a phonon cooler with large area junctions.

noise within the device, whose origin is not known. To study this, we have developed a novel device geometry which excludes possible edge effects, present in earlier microcalorimeter geometries. The principal idea in the design is a radial current distribution, where the current is fed via a superconducting central contact through a toroidal TES, and collected at a superconducting guard ring on the outer perimeter of the titanium-gold TES. The processing is challenging because an additional insulator layer is needed between the TES and the superconducting ground plane.

Superconducting Hot-spot microbolometers

A principal idea in the operation of transition-edge microcalorimeters is the concept of electro-thermal feedback. This effect arises from the fact that, when a thermally insulated superconducting film is biased with a voltage bias, the power dissipated in the film equals $V^2/R(T)$. If the substrate is cooled below the critical temperature of the film (T_c), the film can be maintained

Fig. 2. (Left) An optical microscope image of a CORTES (Corbino disk TES). The TES detector is located as a toroidal ring around the central superconducting contact and the darker outer contact. (Right) A diagram showing the order of metallisation layers in the CORTES.



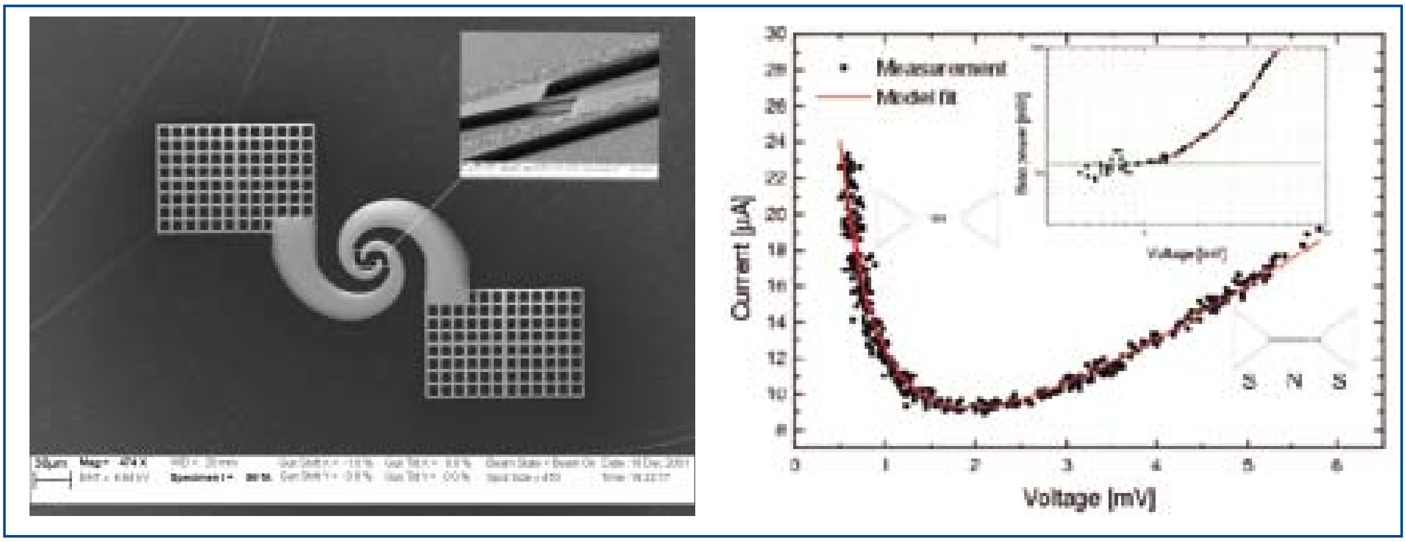


Fig. 3. (left) A SEM image showing the log-spiral antenna, coupled to a Nb airbridge (inset). (Right) The I-V characteristics of the bridge, measured with a SQUID. The agreement with a hot-spot model is remarkably good. The inset in the graph shows the bias power leveling off to a constant.

in normal state if a current larger than the critical current passes through the film. As the voltage bias is reduced, also the current is reduced until to the point where parts of the film go superconducting, the resistance is decreased, and thus the bias dissipation is increased. At this regime, the dissipated bias power remains a constant.

Based on a similar idea, we recently began experimenting with niobium air-bridges, coupled to a lithographic antenna sensitive to wavelengths in the far infrared to the millimeter wave range. The benefit of such structures is that the thermal isolation of the bolometer bridge is excellent due to the fact that superconducting films are very poor thermal conductors. Potentially, a great sensitivity can thus be achieved. We have fabricated and tested our first samples, and the agreement with the theoretical model assuming a normal state part in the middle of the bridge is very good. Preliminary noise measurements of the devices indicate a noise equivalent power of 6.5 $fW/Hz^{1/2}$, which is some two orders of magnitude improvement over the state of the art.

Efficient Electronic Cooling in Heavily Doped Silicon by Quasiparticle Tunneling

Success in development of low temperature micro-coolers based on NIS (normal metal – insulator – superconductor) junctions has stimulated intensive attempts to improve their performance. One unexplored approach is to use a heavily doped semiconductor instead of a normal metal in the cooler device. In this approach the superconductor can be brought into a metallurgical contact with the semiconductor. No additional insulating layer is required because the Schottky barrier in the semiconductor-superconductor (Sm-S) contact will form the tunnel barrier. The utilization of Schottky barriers is attractive because it essentially eliminates Ohmic leaks that can be a problem in thin large area tunneling barriers. From practical and technological points of view heavily doped silicon would be the best choice as the semiconductor. Especially, the use of silicon-on-insulator (SOI) substrates as a starting material would make the utilization of standard silicon micromachining techniques relatively easy in the fabrication of thermally isolated self-standing structures, which are required for lattice refrigeration.

S-Sm-S structure is very similar to the NIS structure and it may be used both for thermometry and for microcooler applications. The operation of cooler based on S-Sm-S structure is illustrated in Fig. 4. As in SINIS coolers, at low bias voltage ($V < \Delta/e$) the tunneling of electrons (with $E > E_F$) from n^{++}silicon into superconductor and the tunneling of quasiparticles (with $E < E_F$) from superconductor into n^{++}silicon results in cooling of the electron system in n^{++}silicon. The value of the electron–phonon coupling constant Σ in the cooled metal considerably affects the characteristics of the NIS cooler. The measured value of Σ in n^{++}silicon ($\Sigma \approx 1.0 \times 10^8$ W/K^5m^3, $N_e = 4.5*10^{19}$ cm^{-3}) is more than one order of magnitude lower than in copper and few times lower than in aluminum,

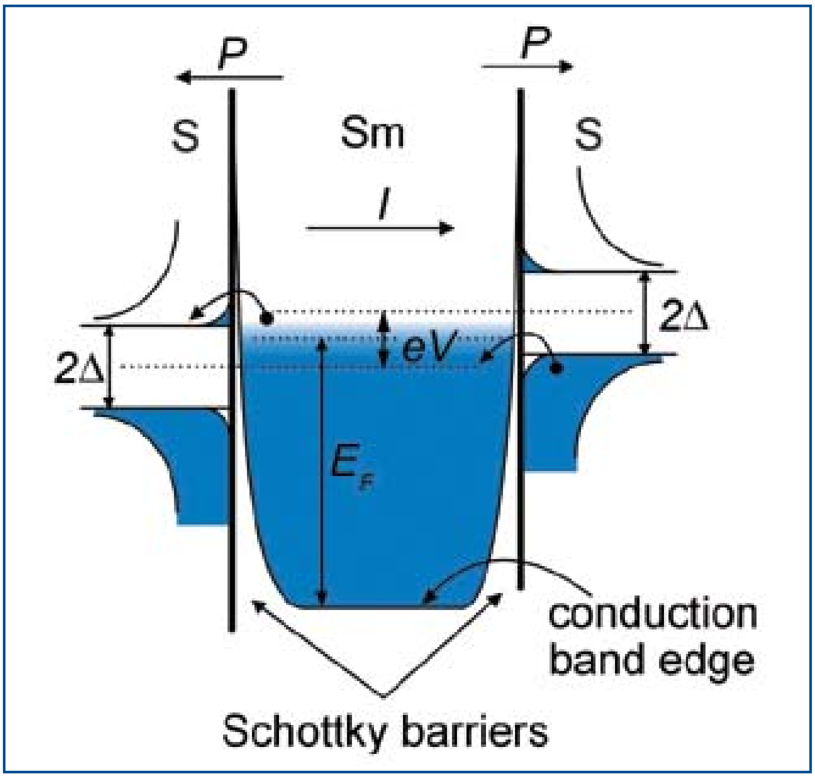


Fig. 4. Energy band diagram illustrating cooling in S-Sm-S structure. Heavily doped semiconductor (silicon) is attached between superconductors and Schottky barriers are formed at the contacts. S denotes superconductor and Sm semiconductor. 2Δ is the energy gap in the superconductor, E_F the Fermi energy of the semiconductor and *P* heat flow out of the semiconductor. *V* is the applied voltage and *I* is the resulting current.

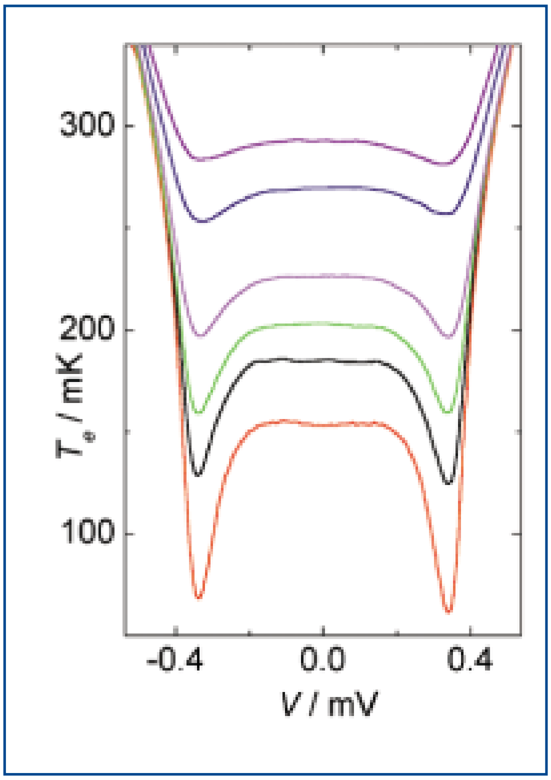
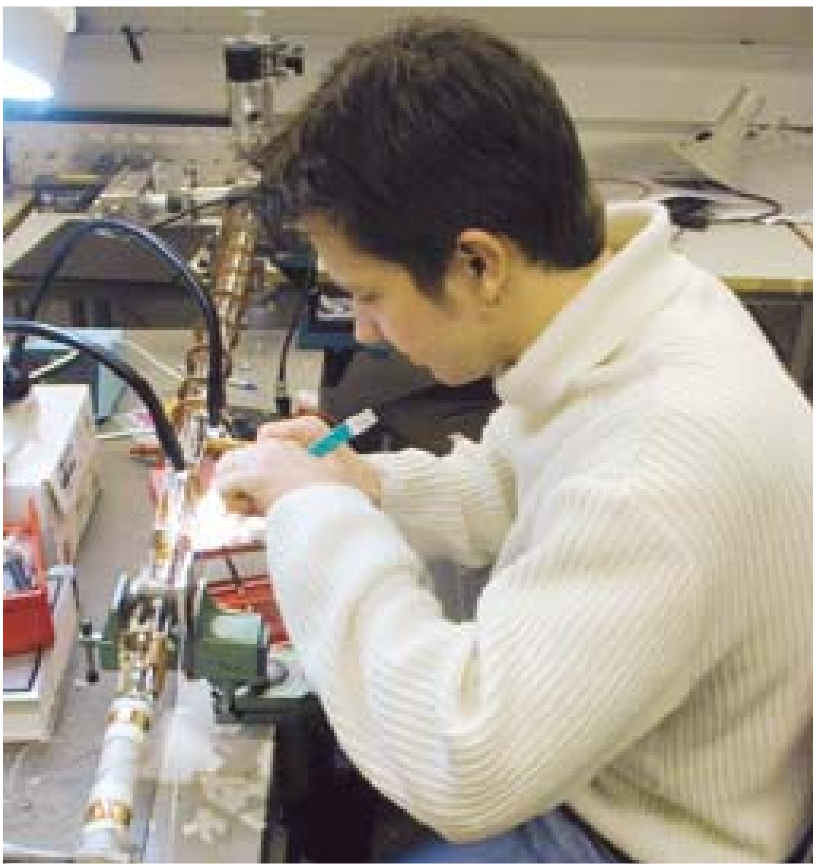


Fig. 5. The electron temperature in n^{++}SOI as a function of the voltage across the S-Sm-S cooler structure at different substrate temperatures T_0.



which allows significant cooling (or heating) of the electron system.

The electron temperature in n^{++}silicon as a function of the voltage across the S-Sm-S (Al - n^{++}Si - Al) structure for few substrate temperatures is presented in Fig. 5. The observed cooling effect is rather large: cooling of the electron system exceeds 60% at T_0=150 mK. The maximum cooling power of the device at T_0 = 150 mK is about 0.4 pW. Optimization of the contact resistance (using SOI film with higher carrier concentration) and further modification of the sample geometry for optimal cooling of the electron system should considerably improve the cooler performance.

Thermal effects in normal metal- insulator- superconductor (NIS) tunnel junctions

Research on the role of thermal fluctuations in small metallic islands has continued, and new low-noise, low-

Fig. 6. Low-noise dilution refrigerator (50 mK) wiring in progress.

temperature (50 mK) measurement set-up and cryostat has been developed. In conjunction with this research direction, we have investigated the applicability of SIN tunnel junctions for detection of intermediate frequency (up to 10 MHz) thermal signals. Surprisingly, we have discovered that at heating frequencies above approx. 10 kHz the SIN-thermometer changes its response in a drastic manner. Detailed study of this effect reveals that the quasiparticles on the superconducting side seem to be affected and pushed out of equilibrium quite easily. Several possibilities for controlling the quasiparticle distributions are being investigated.

Superconducting Quantum Bits

Among the many candidates for quantum bits, the solid state variety based on superconductivity continues to attract interest, because of the potentially very robust behaviour of devices at cryogenic temperatures. Both of the two main types, the charge qubit and the flux qubit, involve nanoscale junctions. They are characterised by both a charging energy and a Josephson energy, reflecting in a very direct way the particle and the wave aspect of the Cooper pairs in a superconductor. The work in the SQUBIT group has centered on the charge qubit type, where the number of Cooper pairs on a nanoscale island exhibit only a minor degree of quantum uncertainty.

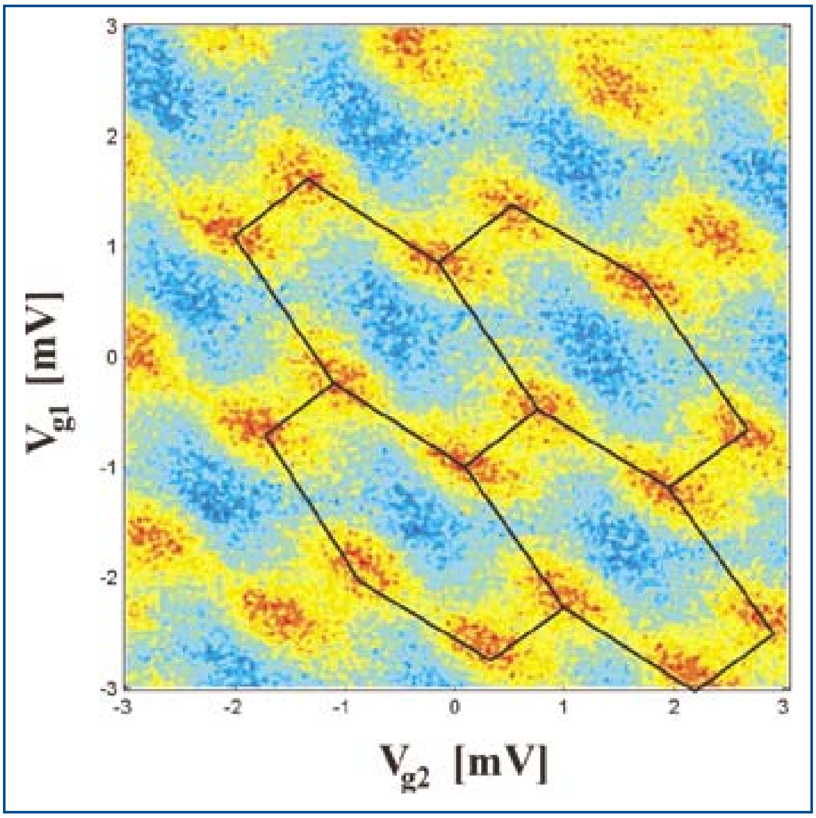


Fig. 7. The switching current in the three junction Cooper pair pump measured as a function of two gate voltages. The figure clearly shows the expected honeycomb structure of a charging energy.

One of the main problems which must be solved before any large scale computation can be performed is to reduce the decoherence time to a value where the theoretically well developed error correction codes can be applied. The theoretical squbit work in Jyväskylä has addressed this issue. A lower limit of the decoherence time has been found when the coupling to electromagnetic modes is considered, and specific predictions have been made concerning the magnitude of the dephasing rate for different types of realistic circuits as a function of both design parameters and temperature.

The decoherence time can be measured several ways. One way is to measure the charge, which is pumped around a closed, all-superconducting circuit containing three Josephson junctions and two islands, each coupled to a external gate voltage. When a periodic voltage is applied to the gates 90 degrees out of phase, a net current will be induced in the circuit. Due to quantum fluctuations in this pumped charge the pumping will not occur with probability one during one cycle if the pumping rate is higher than the decoherence time, whereas it will be one for smaller pumping frequencies. Frequencies are in the radio frequency regime, typically from MHz to GHz, the lower limit defined by the lowest measurable current. At the high frequency limit level crossing becomes an important limiting factor in the operation of a charge squbit. Numerical treatment of this problem suggests that the upper limit is of the order of GHz. Below this limit a measurement of the pumping efficiency vs. pumping frequency will therefore give a measure for the decoherence time.

With this purpose in mind samples of pump geometry have been produced and optimised with respect to the cross coupling between the gates, which is now reduced to about 15%. Also the reproducibility of the junction tunnel resistance is good, suggesting a high degree of symmetry in the individual junction resistances. The lines required for the RF signal have been installed in a rebuild cryostat, which has also been optimised for cooling. Presently the base temperature is about 70mK, which should be compared with the charging energy of about 1K and Josephson energies of a few hundred mK. A number of pump samples have been measured in order to map the charging energy vs. gate voltage with DC signals and showed the expected honeycomb structure. So far the periodicity has corresponded to single electron

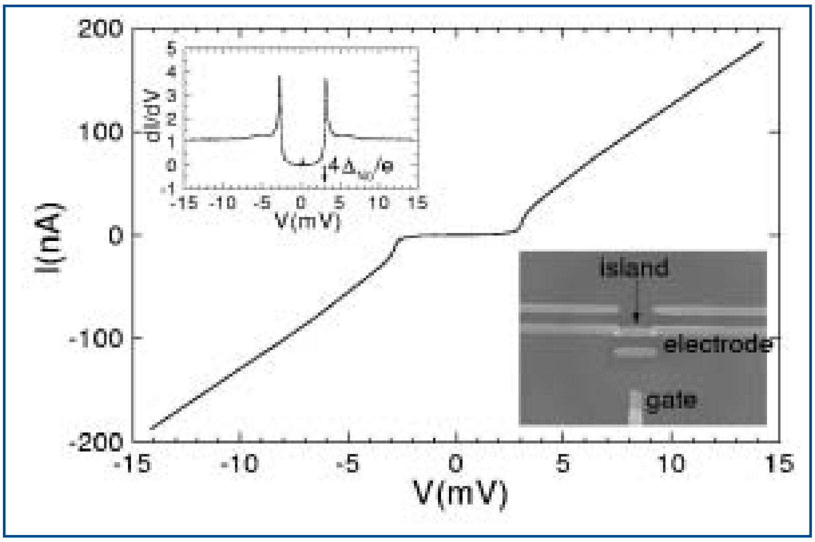


Fig. 8. *I-V* characteristics of the Nb/(Al-)AlO_x/Nb SET at a temperature below 200 mK. Inset (upper left): the dynamic conductance *dI/dV* vs voltages *V*. Δ_{Nb}=0.75 meV. Inset (lower right): scanning electron micrograph of the Nb/(Al-)AlO_x/Nb junctions fabricated by conventional two angle evaporation. The width of Nb wire (electrode) is about 0.24 mm.

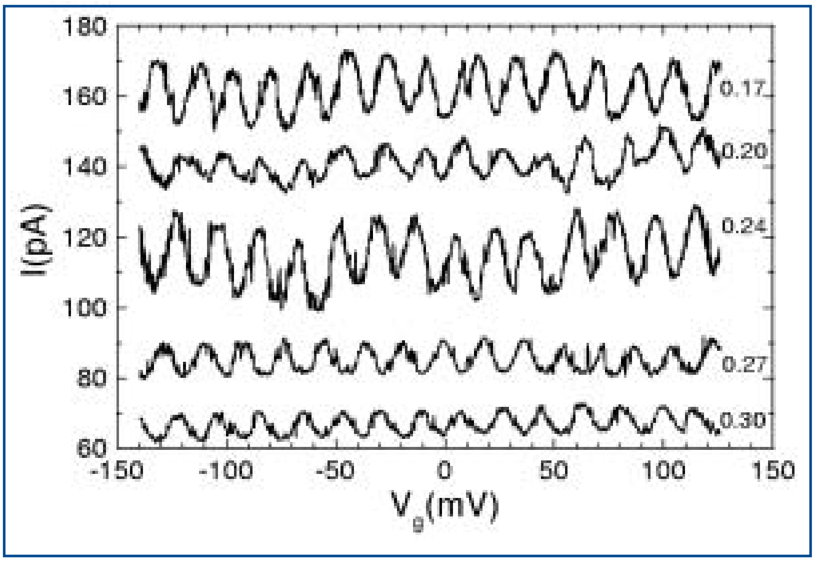


Fig. 9. The current *I* through the junctions vs. gate voltage V_g and as a function of bias voltage V_b at a temperature below 200 mK. V_b is displayed in unit of mV on the right hand side of each curve. Each curve is displaced in *y-axis* for clarity.

tunneling, also for measurements of the switching current and a number of filters in the cryostat lines has therefore been added or upgraded.

Niobium single electron transistors for quantum computing

To improve the operation of superconducting charge quantum bits, we have continued the development of Niobium-based technology. Using the conventional electron beam lithographic techniques, we have succeeded in fabricating Nb/(Al-)AlO_x/Nb superconducting single electron transistors (SET) whose transition temperature T_c = 4.6 K and junction size 100x100 nm^2 (inset of Fig. 1). The thicknesses of Nb and Al layers are 53 nm and 20 nm respectively. A clear superconducting gap of size 0.75 meV at temperatures lower than 200 mK is evident (Fig. 8), and gate-modulation of the current as a function of gate voltage V_g is also observed (Fig. 9). From the period of the gate modulation we estimate the gate capacitance to be 15 aF. The Josephson coupling energy E_J is about 32 meV, which is comparable to the charging energy E_c = 35 meV. It is important that the superconducting gap energy of Nb based SET is much higher than that of Al based SET, since the increased gap energy leads to a suppression of unwanted quasiparticle tunneling events, which is critical for proper operation of a superconducting quantum bit.

Thermometry using arrays of small tunnel junctions

Since almost ten years Coulomb blockade at small tunnel junctions has been known to provide primary thermometry. Today such Coulomb blockade sensors can be fabricated reliably by oxidizing an Al base electrode and covering the ≈1 nm thin oxide layer by another metal layer. However, for low temperature applications down to 10 mK, superconductivity of the Al electrode has to be suppressed. For this purpose we have investigated a couple of methods (in collaboration with Nanoway Oy):

a) Alloying the Al base electrode using a normal metal like Cu or Au. Although superconductivity is indeed suppressed, it turns out that those tunnel junctions with alloys are far less reliable and stable than those prepared with pure Al.

b) Installing a small (< 1 mm diameter) permanent magnet on the same Silicon chip near the tunnel junctions. The ≈1 Tesla magnetic dipole field is strong enough to suppress superconductivity of the Al electrode. It falls to the mT level already ≈5 mm away, so that other experiments are usually not affected by the stray field produced by such a temperature sensor.

An analysis of the statistics of about 100 samples prepared using method a), using the standard Simmons model, showed systematic dependencies of the properties of the tunnel junctions, especially preferred thickness values of the oxide layer, see figure 10. A thickness of about 0.9 nm is usually obtained after oxidizing a pure Al electrode. Thinner and thicker barriers result after depositing a second gold electrode on an oxidized Al electrode, and after oxidizing alloyed Al, respectively. The preferred thicknesses s_i (i = 0, 1, ...) appear separated by a constant difference, as if from i → i+1 the same type of atom layer is added. This could be expected for the growth of homogeneous oxide layers. Although it is a quite tempting interpretation, an alternative exists which we cannot test with our current equipment: The thickness dependence is not real but caused by impurities and defects in the oxide layer. These defects shorten the effective tunneling thickness of the oxide barrier. Simmons model then always yields a too large apparent thickness.

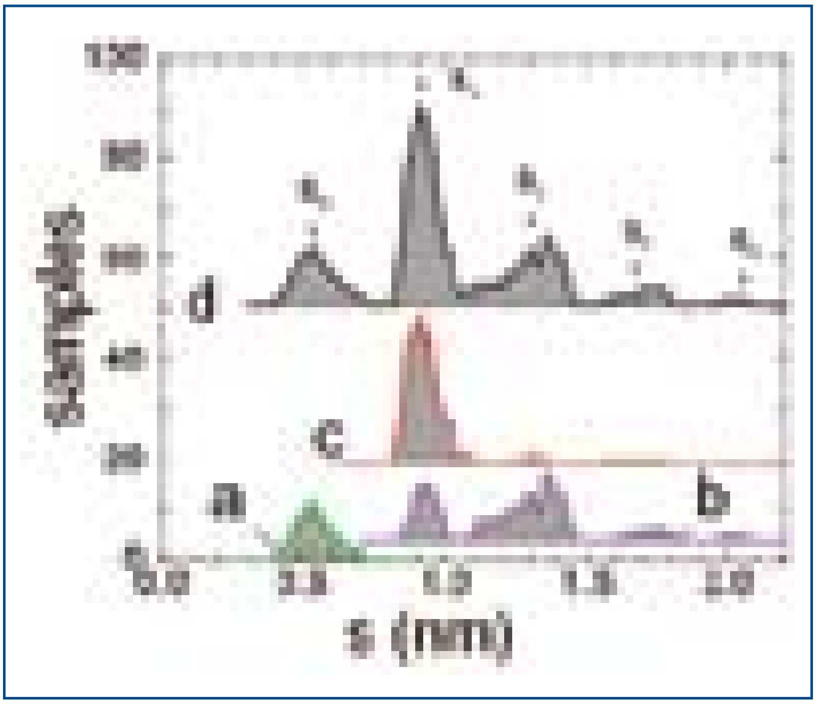


Fig. 10. Histogram of tunneling barrier thicknesses. A total of 99 samples have been measured. Trace a represents the Al-oxide-Au samples, trace b belongs to (M, Al)-oxide-M and (M, Al)-oxide-(Al, M) samples (M = Al, Cu, Au, or Nb), and trace c to the Al-oxide-M samples. Trace d is the sum of all samples. Traces b, c, and d are vertically displaced. The s_0, s_1, ... mark the preferred thicknesses.

Mesoscopic superconductivity

An interference of the "hot" quasiparticles in a superconductor was observed in two types of nanostructures. First type was an aluminum loop intercepted with a copper electrode through a tunnel barrier. Second type was an aluminum fork shorted with a copper bar through two parallel tunnel junctions. In both cases the tunnel current at a fixed bias voltage appeared to be a periodic function of an external magnetic field. Periodicity corresponds to one flux quantum enclosed by the interferometer area. Magnitude of the current oscillations depends on the bias voltage and close to the gap voltage reaches 30%.

It was also found that implantation of Er ions into an Al matrix reduces the superconducting critical temperature of this material. The effect might appear useful for fabrication of non-superconducting aluminum-based tunnel microstructures. The work was done in collaboration with the group of Prof. J. Räisänen.

Atomic clusters and quantum dots

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Electronic and ionic structure of small metal clusters. Density functional theory with ab initio pseudopotentials is used to study the electronic structure and stability of aluminium-lithium clusters. $AlLi_5$ has eight valence electrons and is a 'magic' cluster according to the jellium model. The possibility of making cluster based material based on these magic units was investigated by optimizing the geometry of superclusters consisting of up to 10 $AlLi_5$ units. However, the magic units loose their identity when bound together and the resulting cluster has a complicated structure where the Al atoms form eventually a chain-like configuration. The results show that Al atoms do not prefer to form a compact core surrounded by lithium.

We have also studied AlLi clusters with nearly similar numbers of Al and Li atoms in order to study the evolution of B2 and B32 phases of the alloy in bulk. Already with about 100 atoms in the cluster the electronic properties and the bulk modulus of the clusters starts to resemble those of the bulk phases.

Stacking faults in clusters. FCC and HCP are energetically as good structures for a hard sphere potential in bulk. In clusters the FCC structures are in generally favored due to the fact that the HCP structure can have the close-packed [111]-surface only in one direction. However, in some cluster sizes stacking faults appear in the ground states of clusters. We have optimized the close-packed cluster geometries using a fixed bond length. Stacking faults appear more frequently if the pairwise interaction is replaced with a nonlinear coordination dependent interaction derived from the tight binding model.

Clusters on surfaces. Alkali metal clusters on graphite surfaces are studied using Car-Parrinello technique. The surface is described with rigid or dynamic layers of graphite. Preliminary work studies how many graphite layers are needed to describe the dynamics of potassium diffusion paths on the surface. The aim is to study the effect of the surface on the geometry and electronic structure of two-dimensional clusters on graphite.

Cluster melting. Molecular dynamics is used to study melting of small sodium clusters and the effect of bulk and surface melting on the ionization potential. Initial results for icosahedral Na_{147} cluster indicate that the ionization potential decreases continuously with increasing temperature but with no marked change at the melting temperature. Ab initio molecular dynamics is used to study the dependence of the melting temperature on the cluster ground state geometry and electronic structure.

Double quantum dots. Density functional theory is used to study vertical double dots. In an electron-hole double dot one dot is filled with electrons and one with holes. In this case there is an attractive interaction between the particles in separate dots. The many-body correlation will lead to interesting transitions of the dot structure when the interdot separation is increased. At small distances the electron-hole attraction dominates and the particle density becomes deformed, the shapes being determined by the ultimate jellium model. At intermediate distances the particle density will become circular and at large distances when the confinement potential is weak the electrons and holes form bound states which will have a repulsive dipolar interaction between them. In the future we will also study electron-electron double dots. The interest there is especially the effect of the isospin: If the interdot distance becomes very small the effect of the other dot is to add one more decree of freedom to the electrons states.

Dot lattices. We have developed a band structure code to compute the electronic and magnetic structure of two-dimensional quantum dot lattices. In a single dot the magnetism is governed by the first Hund's rule. In a lattice of quantum dots the magnetic coupling is determined by the lattice structure, interdot distance and by the filling of the open shell in each single dot. Preliminary results show that in the case of a square lattice the coupling is antiferromagnetic if each dot has a half-full electron shell and ferromagnetic in other open shell cases. The result can be understood in the tight binding model using the Hubbard approximation. Figure 1 shows the complicated spin-density of the antiferromagnetic dot lattice with 9 electrons in each dot.

Quantum rings. Exact diagonalization techniques and simple model Hamiltonians are used to study the rotational spectra, persistent current, and thermodynamical properties of small quantum rings. The results show, for example, that the periodicity of the persistent current changes from ϕ_0 first to $\phi_0/2$ and eventually to ϕ_0/N when the ring gets narrower. The dependence of the total spin on the external magnetic field and on the flux through the ring show an intricate phase diagram shown in Figure 2.

Rotating Bose condensates. In a strong magnetic field the electronic structure of a quantum dot will be in a rotational state, which, in certain angular momentum values, can be described accurately with the Laughlin wave function of the fractional Hall effect. The laughlin state describes well the localization of electrons in a strong magnetic field. The exact results reveal the localization in the structure of the many-body spectrum. We have extended the Laughlin wave function with a trial wave function suggested by Papenbrock and Bertsch for rotating Bose condensates and shown that it describes well also rotating fermion systems. The comparison of bosonic and fermionic systems reveals that in a highly rotating states the correlations are dominated by localization of particiles, dictated by the Jastrow factor of the Laughlin state. Consequently, the excitation spectrum will be similar for both kind of particles and nearly independent of the interparticle interaction.

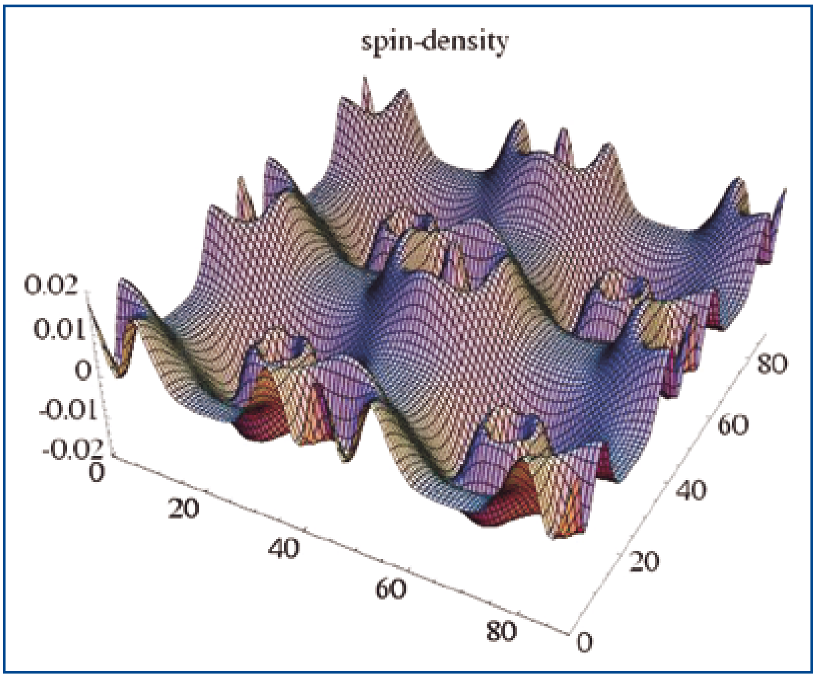

Fig. 1. Spin density of an antiferromagnetic square lattice of quantum dots with 9 electrons in each dot. Four unit cells are shown.

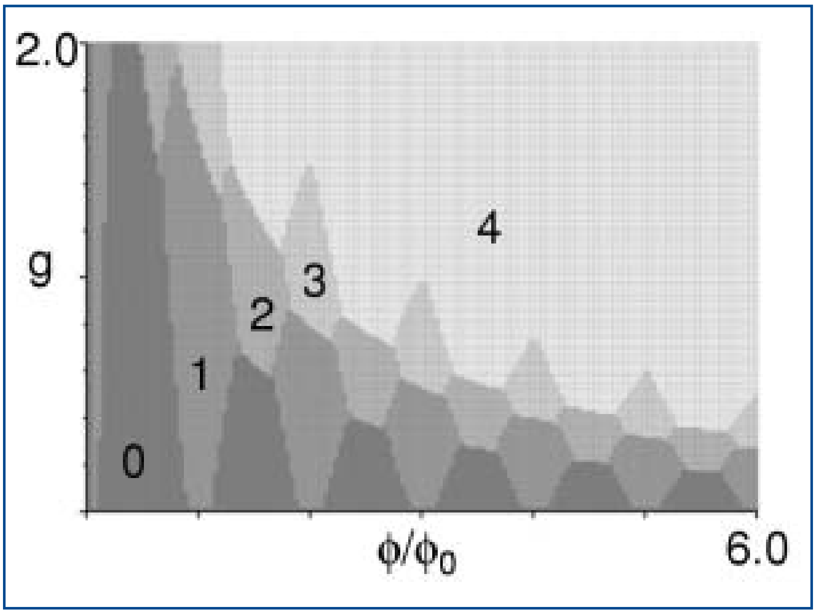

Fig. 2. Total spin of an eight electron ring as a function of the magnetic flux through the ring and the effective Lande factor. The latter describes the effective strength of the magnetic field at the ring.

Disordered materials and nonlinear physics

Jussi Timonen and Markku Kataja

http://www.phys.jyu.fi/research/dismat/

The main areas of research in this research group were elasticity and fracture of fibrous structures and random packings, dynamics of interfaces, properties of multiphase flows, and quantum dynamics of Bose-Einstein condensates. Applications were mostly in paper science and bone research.

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Markku Kataja, professor
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Elasticity and fracture of fibrous structures and random packings.

The rigidity transition in random networks of fibres was considered for stiff fibres whose crossing points were assumed fixed but without angular forces for mutual rotation. We found that the density of the network at which a percolating rigid cluster appears is somewhat higher than that for the connectivity percolation. Critical exponents related to the transition were determined quite accurately, and were found to be in the universality class of the central-force rigidity percolation. When one of the critical bonds of the rigid backbone was removed, the backbone broke into the same rigid bonds and rigid blobs independent of the critical bond. The numbers of rigid bonds and blobs were both found to diverge with system size, and the number of rigid blobs defined a new critical exponent.

A snow slab was modelled as an elastic brittle plate, attached by static friction to the underlying snow or ground. The important parameters are the grade of heterogeneity in the local slip thresholds, and the ratio of the average substrate slip to the average slab fracture threshold. For a strong pack of snow, a stable precursor of local slips appears when the frictional contacts are weakened (equivalent to rising temperature), which eventually trigger a catastrophic crack growth that suddenly releases the entire slab. In the opposite limit of very high slip thresholds, the slab simply melts when the temperature is increased. In the intermediate regime, the model displays features typical of real snow avalanches. It also suggests an explanation to why avalanches are impossible to forecast reliably based on precursor observations.

Previous work on modelling tectonic fault zones, allowing in particular braking of the blocks that form the gouge of the zone, was continued so that basically all phenomenological features of real faults could be shown to result from this model. The three main anomalies related to the conventional frictional slip models could thus be resolved: the very low effective friction, the absence of a measurable heat flux, and the principal stress direction at the fault. In addition, the characteristic size distribution of the quakes as well as the distribution of aftershocks (Omori's law) could be produced. This work included collaboration with the University of Stuttgart.

Dynamics of interfaces

We have previously shown that the roughening of slow combustion fronts propagating in paper asymptotically displays scaling exponents in agreement with the Kardar-Parisi-Zhang (KPZ) model with uncorrelated white noise, while the behaviour at short time and length scales is dominated by non-trivial effective noise. We extended our previous analyses to universal amplitude ratios and the universal coupling constant related to the strong coupling fixed point of the KPZ model. These are very sensitive tests of the scaling properties of the fronts, and were found to support the asymptotic KPZ behaviour. Also, the first-return distributions, both temporal and spatial, were determined for the fronts. These distributions revealed a similar crossover from short-scale to asymptotic KPZ behaviour. In addition to the steady-state persistence, results were obtained for the transient behaviour. These results comprise the so far most extensive experimental study of the scaling properties of interfaces, a problem for which new theoretical results continue to emerge. This work included collaboration with Helsinki University of Technology.

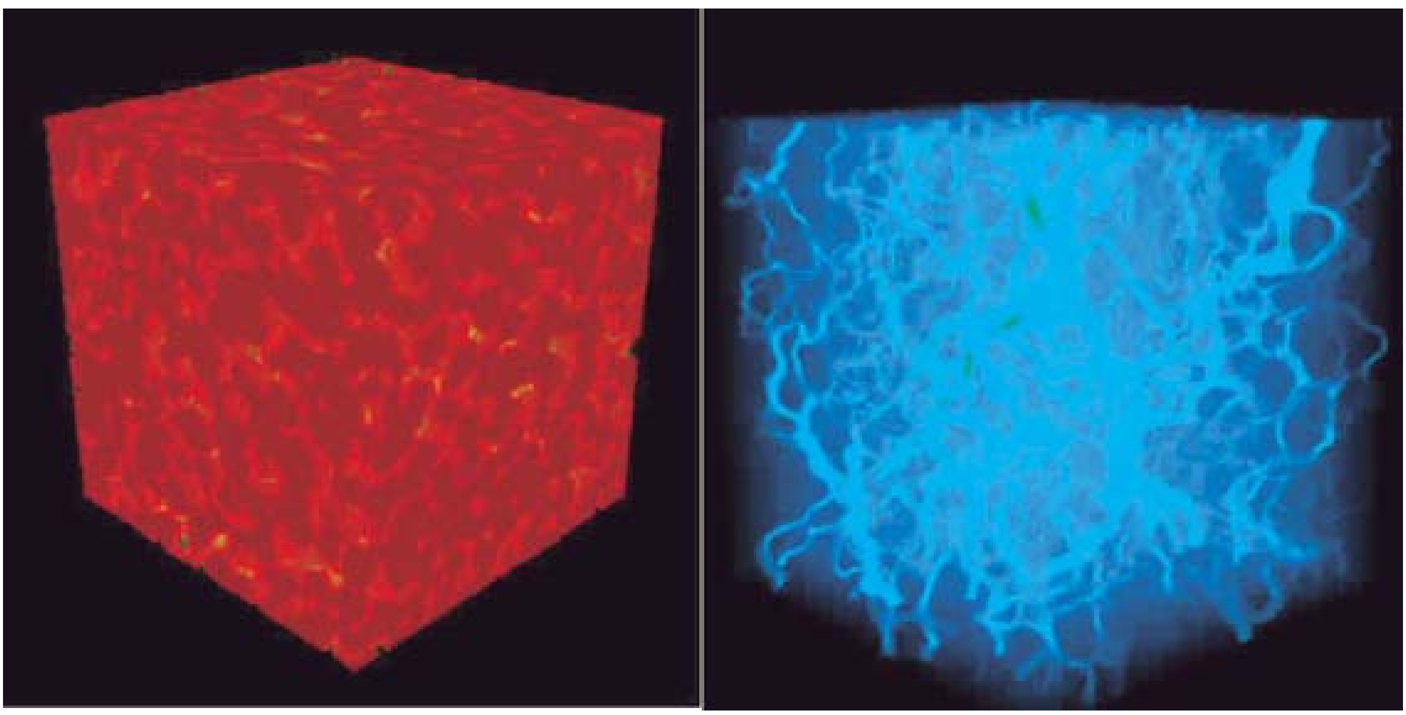
We also studied numerically and theoretically models of nonequilibrium interface propagation and related lattice models. First, slow combustion experiments were modelled by using the experimentally determined correlated noise as input in computer simulations. In these simulations noise can be manipulated in various ways to gain insight into the role of correlations in the observed dynamics. We also constructed simple effective models, which contain the relevant aspects of the underlying microscopy.

The second area of research was stochastic lattice models with asymmetric particle dynamics, some of which can also be mapped to models of kinetic roughening. Analytical results were obtained for cluster statistics and their extremal properties. Of particular interest was the size of the largest cluster as the system size increased. The maximum cluster size was shown to be divergent, and the behaviour was either logarithmic or a logarithm divided by a double logarithm depending on the choice of microscopic dynamics.

Flow in porous media

The previously partly reported work on the permeability of a tomographic reconstruction of a piece of Fontainebleau sandstone (see Fig. 1), and three of its theoretical constructions with the same porosity and specific surface area, was finalised. In this work a Lattice-Boltzmann method was also compared with a conventional finite-difference solver for Stokes flow. Both methods were found to mostly produce very similar results with fairly similar resource requirements. The features of the Lattice-Boltzmann method, which need special attention in this kind of problems, were also discussed in some detail. Permeability was found to be a very sensitive test of the quality of theoretical constructions so that the models that do not take the connectivity properties of the pore space into account, were found to have permeabilities an order of magnitude different from that of the tomographic reconstruction. This work included collaboration with the University of Stuttgart.

Fig. 1 a) Tomographic image of a Fontainebleau sandstone sample. b) Flow of fluid through the porespace of the sandstone structure as solved using the Lattice-Boltzmann method.



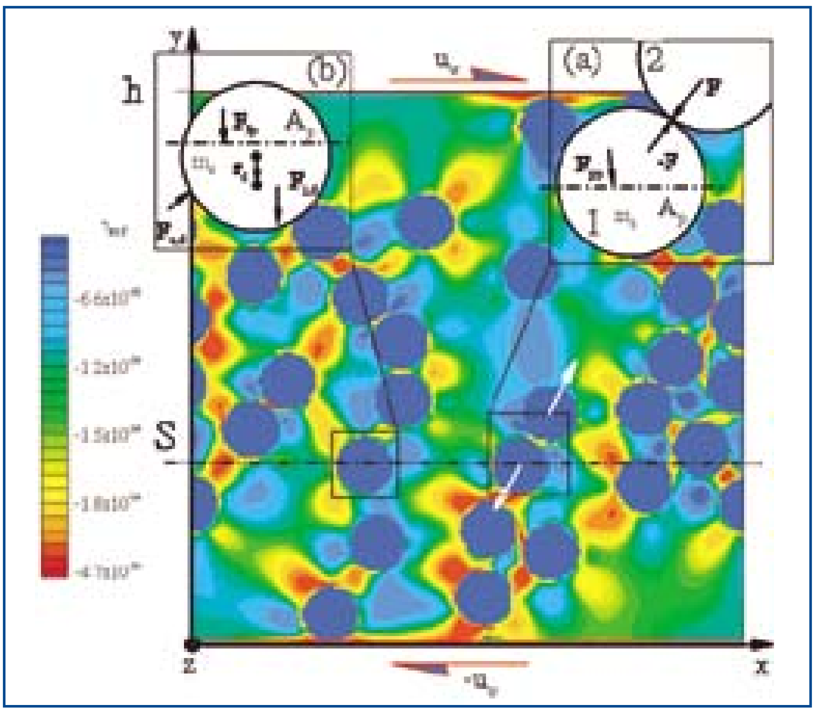
The same Lattice-Boltzmann method was applied to determine the permeability of two-dimensional porous screens, with a regular or random structure. We found that simple analytical expressions in terms of screen porosity very accurately described all simulation results, especially when the shape of the cross section of the fibres that make the screens was taken into account.

The lattice-Boltzmann method was also applied to capillary rise dynamics of liquids, which involved modelling the liquid-gas (surface tension) and liquid-solid (wettability) interfaces. The method was shown to describe the hydrodynamic behaviour inside the capillary tube provided that the ratio of tube diameter and and lattice spacing was large enough. The dependence of the dynamic contact angle on the capillary number was then analysed with and without gravity.

Properties of suspension flows

Flow of wood fibre suspensions was studied experimentally, in particular the drag reduction phenomenon due to formation of a lubrication layer of pure water at channel walls. We measured the thickness of this layer using a laser-optical device, and found that the layer is actually formed near the point of pressure loss saturation. The measured layer thickness was typically 10 to 50 mm for dense suspensions, and up to 500 mm for dilute suspensions below the sedimentation fibre consistency.

Fig. 2. A snapshot of a two-dimensional Couette flow (shear flow) of liquid-particle suspension solved by the lattice-Boltzmann method. The suspended particles are blue, and colour coding indicates viscous shear stress in the fluid phase. The two insets show the forces due to collisions **(a)** and hydrodynamic effects **(b)**.



We also studied optical tomography for measuring concentration profiles in liquid-particle suspensions. To this end we built a prototype laser tomographic device which can be used to infer the distribution of diffusion and absorption coefficients in a static two-dimensional set up. The design of the next-generation device for three-dimensional non-static set ups was started, and much of the work was focussed on improving the speed and signal-to-noise ratio of the data acquisition electronics.

The rheological properties and the underlying mechanisms of momentum transfer and shear stress of liquid-particle suspensions were studied using direct numerical simulations by lattice-Boltzmann techniques. The results obtained for Couette flow conditions (see Fig. 2) display complex flow phenomena that arise from the two-phase nature of the fluid, including a nonlinear velocity profile, layering and clustering of particles, and apparent slip near the walls. The general rheological behaviour of the suspension is dilatant. We found that the observed shear thickening is related to enhanced relative solid phase stress for increasing shear rates. The results obtained help understand the meaning of viscosity as measured by commonly used viscometers.

Finally, we also considered a particle suspension in channel flow, in which sedimentation of particles on the walls as well as hydrodynamic detachment of sedimented particles were both allowed. The relevant parameters of the problem are the solid volume fraction of the suspension and the detachment threshold, when the total number of particles is fixed and only small Reynolds number flows are considered. The phase space spanned by the two relevant parameters was investigated in detail (submitted to Nature so that no actual results can be given at this point).

Applications in paper science

Specific permeabilities of newsprint and fine paper pulps we determined, and a power-law form was introduced for the effective porosity under compression of the related paper samples. An extensive set of measurements was made on samples made of three different pulps with varying degree of beating or ratio of mechanical and chemical pulp. Simulations with the lattice-Boltzmann method of flow through three-dimensional networks of fibres, with and without added small particles that describe the “fines” content of pulps, were also made to better interpret the measured results. The contributions of porosity and specific surface to the permeability of paper were thus determined, and channeling effects were discussed. This work included collaboration with the KCL and Metso Paper.

A novel method for measuring the formation of fibre networks during filtration of liquid-fibre suspensions was introduced. The device consists of a mold equipped with a pulsed ultrasound-Doppler anemometer for measuring the local time-dependent velocity field of the fibre phase during filtration. Simultaneously, the pressure drop across the filtrated layer and the total flux of the suspension is measured. We can resolve the full space-time evolution of velocity, volume fraction and pressure (stress) separately for the fibre phase and for the fluid phase. We thus find e.g. the stress-strain history of a given fibre layer and the evolution of the local flow resistance of the fibre network during the process. This method allows us to study in detail the filtration prosess and the material properties of the consolidating fibre network, which has not been possible before. This work involved collaboration with VTT Energy.

Applications in bone research

We constructed an ultrasound device that was used to measure the signal velocity in plastic phantoms as well as in tibia of volunteer individuals. By detecting the intensity of the signal as a function of time and distance, we could determine two different wave modes. The fast mode was the normal longitudinal sound, which in tibia propagates in the cortical surface layer. This cortical layer is fairly insensitive even to such pathological changes in bone as osteoporosis. All existing devices for measuring ultrasound speed in bone use this mode of propagation, and we could show that they are therefore incapable of truly assessing the bone condition. The second slow mode we could identify as an asymmetric Lamb wave, one of the so called guided modes that probe the bone structure much deeper than the cortical surface layer. The velocity of this mode was shown to strongly correlate with changes in the trabecular part of the tibia caused by osteoporosis (being also sensitive to the thickness of the bone). It is evident that the speed of this mode can be used to assess the condition of bone (two patent applications pending). This work included collaboration with the Department of Health Science at the University of Jyväskylä.

Bose-Einstein condensates

We first considered a Boson Hamiltonian that describes coupling of two identical condensate fields, and included also higher order n-body interactions between the Bosons. A similar Hamiltonian could as well be used to describe beam splitters of coherent atomic beams. We showed that the typical Rabi oscillations in the occupation probabilities of the condensates, with eventual collapses and revivals, are exactly produced in the limit of very strong coupling. Solution of the problem involved its mapping into a lattice particle problem in two dimensions, in terms of which the basic features of quantum dynamics find an easy interpretation. At the same time we constructed a new exactly solvable lattice problem.

The method was then generalized into the case with an energy offset between the condensates (or trapped sets of ultracold atoms), and the delta-function interactions between the trapped atoms were also taken into account. The strong (Josephson type) coupling limit was again considered in detail. The dynamics of non-eigenstate initial states of the system were shown to exhibit a transition from dispersive dynamics to coherent localized oscillations (in the Fock space). This transition is controlled by the coupling strength and the energy offset between the traps. The dynamics were also shown to be exactly those of a Heisenberg chain in a linear magnetic field. As all logical operations of quantum computing can be realized for Heisenberg chains, it is evident that quantum state engineering or quantum computing can at least in principle be realized in coupled-trap systems of ultracold atoms with the two mentioned parameters. With the present experimental techniques these two parameters should be fairly easily controllable. This work involved collaboration with the Steklov Mathematical Institute in St. Petersburg.

Finally, we also considered the instability leading to collapse of attractive condensates. This problem was solved by first transforming the relevant Gross-Pitaevskii system into Newton´s equations of motion for particles with a constraint. The quantum pressure arising from the kinetic energy of the condensate particles was shown to change sign during the process of collapse, so that a potential barrier was formed which blocked a fraction of particles from taking part in the actual collapse. For realistic initial conditions, the fraction of collapsing particles turned out to be about 0.7 of the total number of particles. This can be used to estimate the fraction of the condensate that is evaporated in the explosion that is an inevitable outcome of collapse. This work involved collaboration with the University of St. Petersburg.

High energy physics

Ultrarelativistic heavy ion collisions

Vesa Ruuskanen and Kari J. Eskola

http://www.phys.jyu.fi/research/urhic/

The interplay between the experimental and theoretical research is quite intense in the field of ultrarelativistic heavy ion collisions (URHIC). The successful start of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven in summer 2000 and the anticipation of the ALICE experiment at the CERN Large Hadron Collider (LHC) in 2006 has inspired and strengthened also the theoretical work on URHIC. Our goal in the theoretical and phenomenological studies of nuclear collisions at the RHIC and LHC energies has been (1) to predict the primary production using next-to-leading order perturbative QCD (pQCD) and the conjecture of gluon saturation, (2) to describe the evolution of produced matter from the calculated initial state to final free hadrons by applying hydrodynamics, (3) to obtain hadron spectra, as well as the integrated observables from the hydrodynamic calculation, (4) to study hard processes in hadronic and nuclear collisions by applying pQCD, and (5) at the CERN Super Proton Synchrotron (SPS) energy, to apply the hydrodynamical model in the calculation of thermal photon emission in lead—lead collisions.

This research is financially supported by the Academy of Finland. URHIC (theory) has been approved to start as a new project in the Theory program of the Helsinki Institute of Physics in 2002. We have been in collaboration with researhers in the Physics Department of the University of Helsinki, CERN (Geneve) and Nordita (Copenhagen) in Europe, and in Lawrence Berkeley National Laboratory, University of Arizona, Ohio State University and University of Minnesota in the USA. We have also actively participated in the work of the international Hard Probe collaboration, currently having a series of workshops at the Theory Division of CERN.

Vesa Ruuskanen, professor
Kari J. Eskola, academy researcher
Kimmo Tuominen, scientist -31.8.
Heli Honkanen, graduate student
Vesa Kolhinen, graduate student (diss. 5.10.)
Sami Räsänen, graduate student
Harri Niemi, MSc student

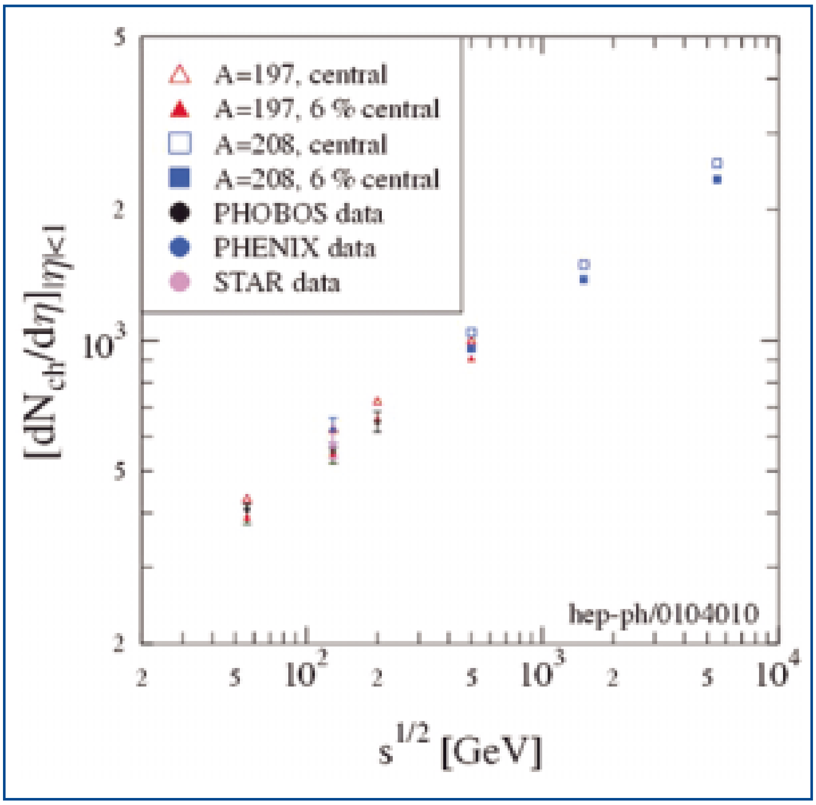
The experimental effort on URHIC is expanding considerably. Our group is now coordinating the final planning and implementation of T0 detector for ALICE. The work to develope the software for the Inner Tracking System and in-beam tests continues. Our group will be heavily involved with the bonding of silicon detectors. The detector development will also be connected to the NA60 experiment at SPS.

Initial state of the QGP from pQCD and saturation: Gluon and quark minijets with transverse momenta in the range $p_T \sim 1...2$ GeV »Λ_{QCD}, are expected to dominate the formation of the QGP in URHIC at collider energies. Production of such semihard quanta can be computed in perturbative QCD (pQCD). A major uncertainty, however, has traditionally been the unknown contribution of the next-to-leading order (NLO) terms, $\sim\alpha_s^3$, of the partonic cross sections. For the transverse energy (E_T) production from the minijets into a rapidity acceptance window, we have been able to formulate and answer the NLO problem exactly. Supercomputing, needed for performing the 7-dimensional Monte Carlo integrations with complicated kinematical cuts, has been provided by the Center for Scientific Computing (SCS, Finland). The main results are the exact magnitude of the NLO contributions, the fact that pQCD is indeed applicable at the few-GeV scales, and a clear reduction in the degree of uncertainty as compared with the lowest-order calculation. Currently, we are extending the NLO formulation to other infra-red safe minijet quantities. For URHIC, in particular, the NLO contributions directly affect the determination of the initial densities and the formation times of the QGP.

As non-Abelian fields, gluons are self-interacting. When sufficiently many gluons are produced into a phase-space volume element, non-linearities become important and instead of multiplicating the gluons fuse, and the growth of the number of gluons becomes inhibited. Using this conjecture for minijet gluons produced in *AA* collisions, we have shown that a saturation of gluon production takes place at transverse momenta $p_{sat} \sim 1$ GeV at RHIC and ~ 2 GeV at the LHC for $A \sim 200$. The saturation scale thus is a dynamical scale which depends on $\sqrt{s}$, *A* and on the centrality the collision. It also determines the formation time of the initial QGP system. The computed number and energy densities of the produced gluons at saturation indicate that a rapid thermalization is possible. Based on the saturated minijet initial conditions and on a formulation of the subsequent evolution of the QGP as a boost-invariant isentropic hydrodynamic evolution, we have correctly predicted the measured charged particle multiplicities $dN_{ch}/d\eta$ for Au+Au collisions at $\sqrt{s}$=56, 130 and 200 *A*GeV at RHIC. Predictions for the LHC/ALICE have also been made, see fig. 1. In addition, we have analytically shown how the measured multiplicities probe the gluon densities at saturation. For particle spectra and E_T distributions, a more detailed, transversally expanding hydrodynamical system has been studied (cf. next section). Currently, we are working on the rapidity dependence of the initial conditions of the QGP.

Hydrodynamical evolution of nuclear collisions: Abundant collisions taking place in the dense parton matter predicted from pQCD and gluon saturation, will change the momentum distributions and lead to collective flow of final particles. Hydrodynamics provides a framework to study this evolution. Even though the hydrodynamic results on a system of nuclear size cannot be pushed too far, a strong feature in its favour is that conservation laws are automatically implemented. The main features of hadron spectra can be expected to be well described. Also it can provide a reasonably sound framework to study phenomena, like electromagnetic emission or flavour evolution during the expansion stage.

Combining the pQCD and hydrodynamic calculations we have predicted for central collisions the final, observable

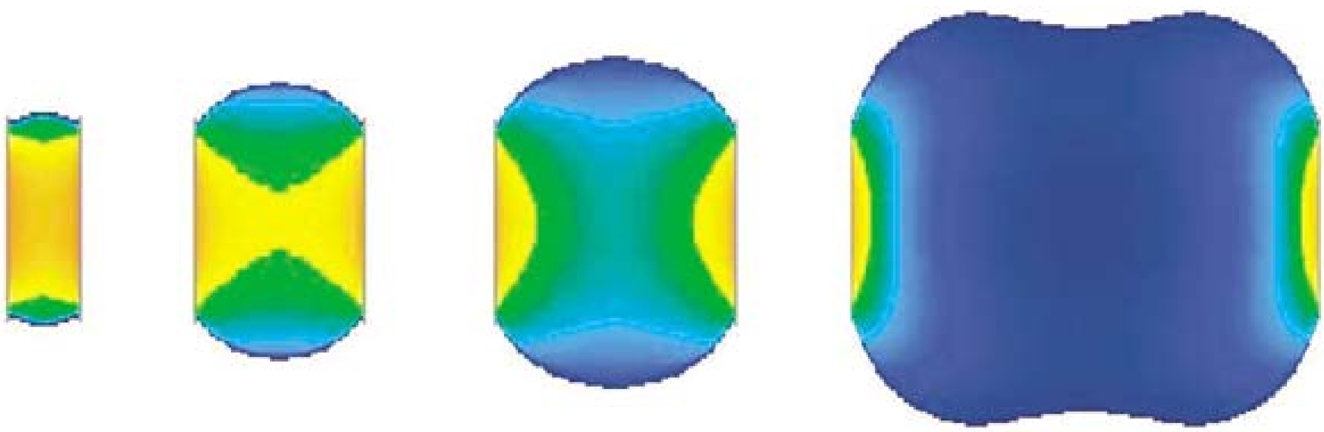


transverse momentum spectra of different hadrons. Integrating and summing the transverse momentum spectra gives the observable multiplicity (fig. 1) and transverse energy. The key effect of expansion is the reduction of transverse energy by a factor of order 3. This is a consequence of the assumed thermalization and the asymmetry of the flow which initially is weak in the transverse direction and strong (scaling flow) in the longitudinal direction. Direct experimental verification of the pQCD prediction of the initial minijet state with large transverse energy scale combined with the measurement of much smaller final scale would provide a very strong case for the (partial) thermalization of final state particles. In the future work the possibility to observe any thermal signals, the signals from secondary collisions, must be carefully restudied. Also we are performing a detailed comparison between the transverse momentum spectra computed from hydrodynamics on one hand and from pQCD parton production and fragmentation on the other. As a separate work the latter calculations are systematically compared to experimental results from $\bar{p}p$ and pp collisions.

Evidence of the formation of collective flow has been obtained from studies of azimuthal asymmetry of momentum distributions, which is most readily interpreted as a formation of elliptic flow. Comparison with experimental data shows that the dependence on centrality of the ellipticity v_2 of the flow is well descibed by the hydrodynamical model. Similarly as a function of transverse momenta the calculated values compare well with the RHIC measurements up to transverse momenta close to 2 GeV. At larger values of p_T and for more peripheral collisions hydrodynamics predicts too large ellipticity for the flow. It is obvious that hydrodynamics with the assumption of full thermalization will fail for peripheral collisions with small initial particle density. Detailed experimental data on elliptic flow, like the dependence on particle species, will soon be available. This provides tools for closer inspection of the space-time evolution of the collision and, promisingly, calculations show sensitivity on model details, like equation of state and freeze-out conditions.

At SPS energy, we have calculated the spectrum of thermal photons using initial conditions constrained from the hadron spectra and the very latest emission rates. The results show that the experimentally observed excess of photons over the known sources can be understood as photons emitted from the secondary collisions during the expansion of final state matter.

Nuclear parton distributions: Inclusive cross sections of hard processes in high energy nuclear collisions are used as a reference in the search of the signals of the QGP. These processes, such as production of large-mass dileptons and direct photons, are computable in a factorized form if the momentum scales involved are large enough and if the number densities of different parton flavours in the colliding nuclei, the nuclear parton distributions (nPDF), $f_{i/A}(x,Q^2)$, are known. Also in the pQCD computation of the QGP initial state the nPDF are an essential ingredient. We have determined the nPDF in a pQCD (DGLAP) analysis applying constraints from the measured structure functions F_2^A in deeply inelastic lepton-nucleus scatterings, the Drell-Yan cross sections in p*A*, and conservation of baryon number and momentum. A parametrization, EKS98, of the nuclear effects in the parton distributions, has been released for public use and implemented in the CERN routine library PDFLIB. To reduce the remaining uncertainties in the sea-quark distributions at large momentum fractions (x 0.3), we have studied the possibility to make use of the Drell-Yan dilepton data in p*A* and Pb+Pb collisions at the SPS. To constrain the nuclear gluon distributions further, we have studied lepton pair production from heavy meson decays in p*A* collisions, which will be measured by the experiments at the SPS (NA60), RHIC (PHENIX, STAR) and LHC (ALICE, CMS). Currently, we are studying the effects of adding non-linearities in the DGLAP evolution equations.



Theoretical particle physics and cosmology

Jukka Maalampi

Neutrino physics is one of the most vital research areas in particle physics today. This is mainly due to the recent experimental verification of neutrino oscillations and neutrino masses. Plenty of new experiments are in operation or under planning and much theoretical work going on aiming to clarify and solve the fundamental questions associated with neutrinos and their interactions.

Our research has focused ultimately on the question of the origin of neutrino masses and mixings. The mass generation mechanism of neutrinos is still unknown, but the smallness of neutrino masses seem to indicate the existence of a new, so far unexplored mass scale in particle physics. Neutrinos can provide us with valuable information about this scale and the new pysics related to it. In a scheme we have studied new interactions at some high energy scale generate small lepton number violating masses to neutrinos making the original Dirac neutrino to split into two Majorana neutrinos with a small mass difference. We have also studied the effects of the possible extra spatial dimensions on neutrino masses and mixings. Viability of these models was investigated by confronting them with the oscillation and other neutrino data.

Neutrinos play an important role in astrophysics and cosmology. Very high-energy neutrinos are created in active galactic nuclei (AGN), which can tell us about the

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processes taking place in the center of galaxies and can also be used to probe the basic properties of neutrino interactions. We have investigated the possibility of testing this way the existence of the so-called triplet Higgs bosons, which according to some models may play an important role in the creation of neutrino masses.

The synthesis of light elements in the early universe depends sensitively on neutrino interactions and the number of light neutrino species. Mixings between active and sterile neutrinos are of crucial importance in this respect, since they may induce oscillations that bring sterile neutrinos into thermal equilibrium thereby increasing the effective number of light neutrino species. Our group has studied the dynamics of active-sterile neutrino oscillations in the early universe using full momentum-dependent quantum-kinetic equations. The results confirm the existence of a “chaotic region” of mixing parameters, for which the final sign of the asymmetry, and hence the prediction of the primordial helium abundance cannot be accurately determined.

http://www.phys.jyu.fi/research/neutrino/index.html

Quantum gravity

Markku Lehto

http://www.phys.jyu.fi/research/gr/

The current interest of the General Relativity Group involves quantum gravity, especially those aspects related to discrete spacetime models. Our viewpoint is that at the fundamental level Nature should be described by a theory based on discrete structures rather than on continuous manifolds as is the case in prevailing theories. This approach raises deep questions about the structure of such a theory. For example: does 'discrete' necessarily imply the existence of a fundamental length scale, and is the exact Lorentz invariance completely lost in a discrete framework? The answer to both of these questions turns out to be negative, and this has to be taken into account when constructing a discrete model. On the other hand, we argue that any sensible physical theory should be based upon a certain set of physical principles rather than on clever mathematics alone. The search for such principles in the case of quantum gravity is extremely hard, but certainly some principles should exist, since we are dealing with a physical theory, after all.

Many familiar issues of spacetime, such as dimension, topology and metric, change drastically in the context of quantum gravity, as opposed to their meaning in general relativity and standard quantum mechanics. They become dynamical variables, and it is not clear whether we should even speak of topology and metric on the Planck scale; it may as well turn out that such large-scale familiarities are consequences of some entirely different entities functioning on the fundamental level. So, we are led to abandon most of the essential concepts in general relativity. In addition to the above-mentioned, these include the concept of a spacetime point and continuous manifolds, the most essential parts of the formulation of general relativity.

Quantum mechanics presents also deep and significant problems concerning the successful marriage of these two theories, and the reason for these problems is simple: quantum theory relies completely on Newton's view of space and time. The challenge, then, is to devise a quantum theory in which space and time emerge from the relationships among objects, as is the case in general relativity. One possible approach towards this goal would be to reduce quantum mechanics essentially to information theory. If this turns out to be possible, it would give strong motivation to attempt to tie all conceptual and formal aspects of the theory to information-theoretic framework. Information theory might also be the most physical framework, since all of physics is based on interactions, which are nothing but exchange of information between systems.

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Markus Luomajoki, graduate student
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ALICE experiment at CERN

Vesa Ruuskanen and Wladyslaw Trzaska

Vesa Ruuskanen, professor (JYFL/HIP)
Wladyslaw Trzaska, senior scientist
Nikolai Ameline, scientist 1.9.-
Maxim Komogorov, scientist (HIP/JYFL)
Wladimir Lyapin, scientist (HIP/JYFL)
Mariana Bondila, graduate student

Since 1998 the HIP-JYFL team is part of the international collaboration constructing ALICE experiment at CERN. The experiment is scheduled to start operation in 2005 and will use the new LHC collider that is currently under construction near Geneva, Switzerland.

During 2001 an important decision was made to shift a significant part of bonding of Silicon Strip Detector (SSD) modules into the new Detector Laboratory located in Kumpula Campus of Helsinki University. SDD modules cover the two outermost layers of the Inner Tracker System (ITS) of the ALICE detector. The total area of the two SDD layers is nearly 6 m^2. The module assembly chain consists of several phases from which the most critical ones require unique single-point tape-automated bonding (TAB) technique. Use of this technique allows for efficient reduction of the mass of the detector modules. Readout chips operating the detector modules will be bonded to 12 µm thick Kapton microcables where 14 µm thick Al leads connect the chips to detectors and hybrids. All the bonding phases use the single-point TAB technique. The unique design of the microcables was possible using space technology developed in Ukrain. The most valuable feature of the design is 5-fold reduction in thickness (thus in the radiation length as well) as compared to the current industrial standards.

The second major contribution of the HIP-JYFL team is the T0 detector for ALICE. It will provide pre-trigger timing, a high quality start signal, and rough but rapid determination of the longitudinal vertex position. It will also work as the backup for the main multiplicity detector. Till 2001 several design options for T0 were being developed in parallel. Our HIP-JYFL group made significant contribution to the most challenging version. It was based on microchannel plates (MCP). Finally, the more conservative (and less expensive) solution was chosen. It will use Cherenkov radiators coupled to photo-multiplier tubes (PMT). Nevertheless, our previous R&D work was not in vain. All the fast electronics developed by us for MCP will work with PMT pulses as well. Further, thanks to our MCP know-how and benefiting from our close collaboration with the Applied Physics group at JYFL, we have made a major breakthrough in the way the energy loss of charged ions in thin absorbers is measured. In recognition of our experience in fast timing and trusting our experimental home base at JYFL, the HIP-JYFL team was given the role of the Project Leader for the T0 detector. This work is carried out in close collaboration with Russia and with the representatives of all the other forward detectors and with the TOF detector. Lately, also the team from Houston (USA) has expressed their interest to join our work on T0.

Parallel to hardware development we are involved in ALICE software. Our main interests were in the data analysis of ITS test experiments and in the creation of sound architecture for ITS software. In 2001 our representative (Mariana Bondila) was a member of ALICE Software Board.

http://www.phys.jyu.fi/research/hendes/alice/ALICE.html

Industrial collaboratorion

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

Industrial contacts related to *accelerator physics*: European Space Agency, ESA/ESTEC, together with HIREX Engineering Ltd. from France performed three SEE tests in RADEF and, at the same time, evaluated the station. In addition, RADEF was chosen to one of the most promising projects in the international evaluation of Tekes' Space 2000 Technology Programme. Therefore, ESA's Industrial Policy Committee took note of JYFL as a candidate for one of the European radiation test laboratories, specialized to deliver high energy/penetration Heavy Ion Beams. Also, Royal Institute of Technology from Stockholm and Swedish Space Corporation Ltd. performed two SEE and RadHard tests in RADEF-station during the first quarter of the year. The aim was to test memory electronics belonging to the European SMART-1 spacecraft.

A new radiotherapy technology project was commenced in March with a funding from Tekes, Jyväskylä Science Park Ltd. (JSP) and Acatec Ltd.. In the project a new method of measuring gamma radiation field was developed in co-operation with Tampere University Hospital (Department of Oncology) and Central Finland Health Care District (Radiotherapy Hospital). The hospitals provided therapy accelerators and the real test environment for the project's use. According to the plan, the method will be included into the radiotherapy verification system owned by JSP. Radef Research Ltd., a spin-off of JYFL, will act as an R&D-partner in the new project aimed to start during the spring 2002.

The co-operation with Radiation and Nuclear Safety Authority, STUK, and the close relations to JSP and the local funding agencies made it possible, that a new spin-off company Doseco Oy, split from STUK, choose Jyväskylä for its business branch. The company already now employs two persons graduated from JYFL and, because of its business line with dosemeter services and related area, offers excellent possibilities for further co-operation. Several common projects are in progress and will be realized after the company moves its office to Jyväskylä in May 2002. Also, the co-operation with MAP Medical Technologies Ltd. continued. MAP finalized its gas target installation by the end of the year. The commercial iodine-123 production is under way.

The group on *accelerator based materials physics* is developing a resistive charge division based position sensitive detector for electrons. This work is carried out in collaboration with SiTek Electro Optics, Partille, Sweden.

The *nanotechnology group* has well established 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 Metorex International company from Espoo. At the first stage the work has been motivated by the need of on-chip integrable ultrasensitive sensors in space research. During the past year close collaboration with Vaisala Oy was initiated to develop methods and sensors of weather conditions based on micro- and nanotechnology. This research is timely because of the foreseeable advantages due to very low power consumption, high reproducibility in production and low manufacturing costs of such sensors as compared to those of conventional bulk technology. The Nanoway company, a spin-off from the university's nanotechnology group is producing and marketing the nanothermometer invented and initially developed in our physics department. There is well defined niche market for this product and especially along with the discovery of how to extend the operation from cryogenic temperatures up to room temperature, it may well be attractive to even a wider range of customers. Nanoway also provides micro- and nanotechnical services to interested companies and institutes.

The disordered materials group has continued its long standing collaboration with companies dealing with paper machine technology and paper making. On the doctoral thesis level several projects were carried out during 2001. Two projects involved collaboration with Metso Paper, focussing on modelling various paper-making processes. Numerical simulation tools for a realistic microscopic description of spreading of a droplet in a porous substrate were also developed in relation to the new electronic printing techniques programme funded by TEKES. Similar simulation tools were developed for the rheological properties of pigment suspensions as part of another TEKES programme. In both these projects several industrial partners were involved. The research group was also involved with coordination of a large consortium on industrial multiphase flow processes, in which the role of the group was mainly to develop new measuring techniques for fibre suspensions. This project was also funded by TEKES and by the industry. In this respect the results achieved in developing optical tomographic techniques is described above in the section of disordered materials and nonlinear physics. Industrial involvement in this project included Metso Paper, Foster Wheeler and Fortum. A related project together with Fortum, focussing on polymer suspension, was also initiated. A large scale simulation software was constructed for Tamfelt for design and permeability simulations of new paper machine fabrics. This project was very challenging in the sense that it involved modelling of realistic woven structures as well as microscopic simulations of flow through these structures. In addition to these postgraduate level projects, several Master's thesis projects were carried out on various aspects of the paper making processes. A related effort was an EU/Esprit project coordinated by Daimler-Chrysler, in which tools were developed for interactive three-dimensional visualisation, based on virtual reality techniques, of simulations of fluid flows related to product development. Several European companies took part in this Visit Project. Work on diffusion and permeabilty of rock samples was continued in collaboration with Posiva in Finland and SKB in Sweden. Recently a completely new device was constructed for measuring the bulk volume of samples of any shape, based on applying the principle of acoustic Helmholtz resonance. Finally, a spin-off company of the Physics, Health Sciences and Mathematical Information Technology Departments of the University, BonAlyse Oy, has rather successfully commercialised the software for analysing tomographic images of bone, developed previously in collaboration with researchers from these departments. A new development in this area of application is the development of a novel method and a related device to use guided ultrasonic waves in assessing bone quality. Preliminary results, from scientific as well as from commercial point of view, look very promising, and two new patent applications have already been made.

The newly initiated *electronics research* in the department is establishing contacts with industry. The professorship in electronics is sponsored by local municipalities and industry, and an agreement about research and teaching collaboration was signed between Enermet company and University of Jyväskylä in 2000. This includes, among other things a three year appointment of a senior assistant to promote research and teaching in areas interesting to both parties.

Education

http://www.phys.jyu.fi/teaching/

Physics is taught in the University of Jyväskylä at all academic levels. The degrees granted are Bachelor of Science (BSc), Master of Science (MSc), Licentiate of Philosophy (PhLic) and Doctor of Philosophy (PhD). For the MSc, the specific major within the discipline of physics can be chosen as physics, theoretical physics, applied physics, electronics or physics teaching. Students may freely choose their specialisation during their studies, with the exception of the master's programme in paper science and technology within the specific major of applied physics and the teacher education, where the student quotas are restricted. The total number of annual lecture courses is around 55.

The main areas of advanced and graduate studies are:

- Experimental nuclear and accelerator-based physics
- Theoretical nuclear and particle physics and quantum gravity
- Theoretical and experimental condensed matter physics
- Applied physics (nanoscience, nanotechnology, disordered and porous materials, paper science and technology, electronics, and fluid mechanics)
- Teacher education.

Basic studies. In the summer 2001 the number of applicants for physics studies was 531, with 296 indicating physics as their first choice. In the autumn of 2001 the Physics Department enrolled 92 new students, and the total number of undergraduate students was 515, 24% of them women. Most of the new students were admitted on the basis of their high school record and national maturity test, the rest via an entrance examination. In 2001 the number of MSc degrees awarded in physics was 42, a new record in the history of the Department. The total number of credit points earned by the students was 5544, equivalent to 11088 ECTS credits. The median age for completing an MSc was 28.6 years. Employment opportunities for newly graduated MSc holders are very good.

Teacher training in physics has been under revision since the late 1980's in response to the increasing shortage of qualified teachers in schools. Good results have been obtained: the Department has been in the recent years the dominant unit in physics teacher's education in Finland. In 2001 there were 17 graduates in teacher's education line. A new professor was nominated in 2001 to take care and further develop the physics teacher's education in the Department.

Graduate education. The number of graduate students in 2001 was 55. Eleven (10 men, 1 woman) PhD degrees were completed. The median age of a new PhD was 30 years. The Department participates in four national graduate schools: condensed matter physics (6 students), particle and nuclear physics (6 students), pulp and paper science and technology (one student), and teacher education (one student in part). In addition, its research groups have supported graduate students from their grants, and the university has actively promoted graduate education with local funds.

Develoment of teaching. The Department organized in the beginning of the autumn semester "a flying start" to its new students. The purpose of this intensive two weeks' program, organized now for the first time, was to familiarize students from the beginning of their studies with the research and other activities, as well as the personnel, of the Department.

The evaluation of regular lecture courses and student laboratories has formed since 1996 an essential part of the development of teaching. The evaluation is carried out through student questionnaires. The questionnaires are analysed and results discussed with the students, and they are posted on the Web. The students of the Department chose Markku Lehto as the best teacher.

Adult education and Open University. Adult education in the University of Jyväskylä offers an opportunity to study physics in the Open University with free admission. This programme consists mainly of basic physics courses, and it is offered also to those university students who study physics as a minor. This teaching is monitored by the Department of Physics.

The Department of Physics has actively supported the national development effort *Finnish Mathematical and Natural Science Awareness 2002* whose goal is to raise the level of mathematical and scientific knowledge in Finland. About 30 secondary and primary school teachers and engineers have started in 2001, and another 20 will start in 2002, supplementary-education programs, organized by the Department together with the Open University, to become qualified physics teachers.

Courses for Secondary School Students. Many student groups from the schools of Central Finland visited the Department during the year, and our teachers and researchers visited schools to tell about the education and research activities of the Department. The Department organized two courses ("Laboratory Course for High School Students" and "Physics and Mathematics of Phenomena") for talented upper secondary school students. About 70 students participated in these courses during the year 2001.

International Summer School. The International Summer School of the University of Jyväskylä has been in session every August since 1991. Its aim is to offer advanced courses on various topics in mathematics and science. All instruction is in English. Annually 250-350 students from some 25 countries have attended the School. The programme of the summer school consisted of a large selection of courses in physics, biology, chemistry, mathematics, computer science and information systems, and statistics. The physics courses make up a part of the curricula of the national graduate programs.

	1996	1997	1998	1999	2000	2001
MSc degrees	39	36	41	37	36	42
PhD degrees	4	4	9	5	9	11

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Note: ä=a, ö=o, å=a

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Pasi Jalkanen, Kanavoitumisen mallintaminen Si0,75Ge0,25-yhtenäiskiteessä Flux7.7 tietokonesimulaatio-ohjelmalla

Lasse Miettinen, SACRED-elektronispektrometri in-beam -mittauksissa

Esko Hintikka, Matkapuhelinjärjestelmään liittyvät säteilyilmiöt

Esa Rehn, Kuitususpensiovirtauksen seinämäkerroksen mittaaminen

Riitta Peräinen, Hestenesin voimakäsitetesti mekaniikan oppimisen mittarina

Jani Maaranen, Kiinteän aineen efektiivisen diffuusiokertoimen ja permeabiliteetin määrittäminen heliumkaasumittalaitteistolla

Kyösti Silvasti, Auringon säteilyenergian tutkimisen hyödyntäminen koulussa

Kimmo Kärkkäinen, Kaksoiskvanttipisteet

Jari Hyväluoma, Radioaktiivisten merkkiaineiden käyttö Si0,20Ge0,80:in itsediffuusiomittauksissa

Lasse Ikäläinen, Yläasteen oppilaiden käsityksiä lämpöopin ilmiöistä

Petri Nokisalmi, Sädehoidon fotonikenttien monitorointi PSAC-monilankailmaisimella

Petri Niemi, Kontaktipintamittalaitteen antaman informasation yhteys SC-paperin rakenteeseen ja syväpainettavuuteen

Marko Ruottinen, Sellun kimmokertoimen parantaminen - vaikutus taivekartongin taivutusjäykkyyteen

PhLic theses

Vesa Kyllönen, Diffuusio yhdistepuolijohteissa
JYFL Laboratory Report 2/2001

Mika Laajalahti, Through-diffusion and permeability measurements of rock and havar samples using Helium gas method
JYFL Laboratory Report 3/2001

PhD theses

Kimmo Tuominen, Perturbative QCD and production of high density matter in ultrarelativistic nuclear collisions
JYFL Research Report 1/2001

Jukka Mäkinen, The mechanical and geometrical properties of fibrous structures
JYFL Research Report 2/2001

Kari Peräjärvi, Studies of ion transport in gases; applications in nuclear physics
JYFL Research Report 3/2001

Matias Aunola, Analysis of the tunnelling-charging Hamiltonian of a Cooper pair pump
JYFL Research Report 4/2001

Janne Poranen, Experimental techniques for studying NIP dynamics in metered size press coating
JYFL Research Report 5/2001

Saara Nummela, Studies of neutron-rich nuclei close to magicity
JYFL Research Report 6/2001

Harri Kankaanpää, In-beam spectroscopy of very heavy elements
JYFL Research Report 8/2001

Vesa Kolhinen, Nuclear parton distributions: A perturbative QCD analysis
JYFL Research Report 9/2001

Zoran Radivojevic, Production and spectroscopy of very neutron-rich nuclei
JYFL Research Report 10/2001

Pasi Kuusiniemi, Studies of 225,226U alpha decay chains using a gas-filled recoil separator
JYFL Research Report 11/2001

Pasi Repo, Quantum mechanical models of black holes
JYFL Research Report 12/2001

Degrees
(alphabetical order)

BSc degrees
(main subject)

Pasi Hiltula (appl. physics)
Jaakko Joutsi (physics)
Petri Nokisalmi (appl. physics)
Reijo Pokela (appl. physics)
Sani Selin (appl. phys.)
Tero Somppi (appl. phys.)

MSc degrees
(main subject)
* = MSc includes teachers' pedagogical studies

Antti Eskelinen (physics) *
Olli Harju (physics) *
Jukka Henttinen (appl. physics) *
Harri Holopainen (physics) *
Pekka Huhtala (physics) *
Jari Hyväluoma (physics)
Jussi Hämäläinen (physics)
Jari Ikonen (electronics)
Lasse Ikäläinen (physics) *
Pasi Jalkanen (physics)
Veikko Koittola (appl. physics)
Tero Kokkonen (physics) *
Markus Kortelainen (theor. physics)
Pekka Koskinen (physics)
Jarmo Kouko (appl. physics)
Jani Kumpulainen (electronics)
Marjo Kupila (physics) *
Mirtta Kurki (physics) *
Sami Kähkönen (appl. physics)
Kimmo Kärkkäinen (theor. physics)
Olli Laamanen (physics)
Vesa Lahtinen (physics) *
Olli-Matti Leistola (physics) *
Ville Leskinen (appl. physics)
Markus Lindstedt (physics) *
Seismo Malm (physics)
Jari Nissinen (physics) *
Petri Nokisalmi (appl. physics)
Antti Nuottajärvi (appl. physics)
Ville Nyrhinen (electronics)*
Tero Pelkonen (physics) *
Riitta-Liisa Peräinen (physics) *
Esa Rehn (appl. physics)
Sami Rinta-Antila (physics)
Sami Räsänen (theor. physics)
Juha Saatsi (theor. physics)
Jari Salmela (electronics)
Sani Selin (appl physics)
Kyösti Silvasti (physics) *
Mika Tammenoja (appl. physics)
Jussi Vainikainen (theor. physics)
Jussi Ylinen (physics) *

PhLic degrees

Kyllönen, Vesa (physics)
Laajalahti, Mika (appl. physics)

PhD degrees

Matias Aunola (theor. physics)
Harri Kankaanpää (physics)
Vesa Kolhinen (theor. physics)
Pasi Kuusiniemi (physics)
Jukka Mäkinen (appl. physics)
Saara Nummela (physics)
Kari Peräjärvi (physics)
Janne Poranen (appl. physics)
Zoran Radivojevic (physics)
Pasi Repo (theor. physics)
Kimmo Tuominen (theor. physics)