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Pushing the Limits: Nuclear Structure of Heavy Elements

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Abstract. Throughout the history of nuclear structure studies, searches for new phenomena have been carried out at the extremes. These extremes can be described in terms of nuclear excitation energy, spin, or in terms of proton or neutron number through the production of exotic nuclei far from stability. One extreme which has always been a centre for activity is that of mass and proton number - the desire to create new chemical elements and understand their nuclear structure. New elements up to proton number Z=118 have been created in the laboratory, but by nature these experiments cannot provide extensive information concerning nuclear structure. The extremely small production cross sections only allow a handful of atoms to be produced in a particular experiment. Over the past decade or so, experimental techniques have been developed which now allow detailed nuclear structure studies of nuclei with proton number Z of over 100. The current status of the field and some recent highlights from these studies are reviewed.

1. Introduction

The one hundred year history of studies of the atomic nucleus has been hallmarked by the execution of challenging experiments which have allowed the discovery of a myriad of phenomena. These phenomena range from exotic decay modes to highly extended nuclear shapes, and are often found by pushing the experimental limits to the extremes. A notable branch of experiments pushing to the extremes is that aimed at the synthesis of new chemical elements. By definition, these experiments aim to produce nuclei with an extreme proton number, and with the highest atomic masses that are known. To date, elements up to proton number Z=118 (ununoctium) have been produced in the laboratory, and elements up to proton number Z=112 have been studied sufficiently in a number of experiments to allow naming (copernicium). Recent experiments to confirm the decay properties of elements Z=114 and Z=116 should soon allow the naming process of these elements to begin [1]. The most recently produced element has Z=117 and was synthesised through bombardment of a ²⁴⁹Bk target with ⁴⁸Ca ions [2]. Recent reviews of the synthesis of superheavy elements can be found in Refs. [3, 4] and a diagram showing the current status of the upper extreme of the chart of the nuclides can be found in figure 1.

Experiments to synthesise superheavy elements can yield information concerning ground-state properties, but in order to access nuclear structure information as a function of excitation energy or spin, it is necessary to perform so-called in-beam experiments. Data from these experiments are essential to our understanding of the shell effects which are responsible for the stability of



Figure 1. Excerpt of the chart of the nuclides for elements from uranium to ununoctium. The last named element is copernicium, with proton number Z=112.

superheavy elements. Without these shell effects, superheavy nuclei would simply disintegrate due to the Coulomb repulsion between the large number of protons. Such in-beam studies require detection of prompt radiation, typically emitted within one nanosecond of production of the nucleus of interest. In order to detect the prompt radiation, detectors must be sited around the target position. The environment surrounding the target can be somewhat hostile - if high beam intensities are used, the counting rate in the detectors becomes very large and the quality of the spectroscopic data deteriorates. The counting rates must therefore be limited, which in turn limits the beam intensity which can be employed and the production cross section limit which can be reached. Typical synthesis experiments use beam intensities of around 1 particle μ A, with production cross sections of the order of picobarns. This should be contrasted with typical in-beam experiments, where beam intensities of the order of 10 particle nA are used. It is thus clear that the in-beam study of superheavy elements is precluded in a reasonable experiment time. In the following, methods to perform in-beam studies of heavy elements with proton number greater than 100 are presented, along with recent results from the field.

2. In-beam studies of heavy elements

2.1. Experimental techniques

As mentioned above, the study of excited states of heavy nuclei is hampered by rapidly decreasing production cross section as a function of increasing proton number. This rapid decrease in the *fusion-evaporation* cross section is accompanied with a relative increase in the *fusion-fission* cross section. That is, the huge majority of compound nuclei formed in the reaction simply decay immediately by fission rather than forming the nucleus of interest by evaporation of particles. This background of fission events makes in-beam studies still more difficult - fission creates a large number of γ rays which mask the γ rays of interest. In typical measurements,

the ratio of interesting to background γ rays can be of the order of 1 in 10⁹ and a powerful method to extract the interesting γ rays from the dominating background of fission is required. Such a method was developed in the mid-eighties at GSI in Germany and further used in the mid-nineties at Daresbury Laboratory in the U.K.. Known as the *Recoil-Decay Tagging* (RDT) technique, the method relies on the coupling of the detectors surrounding the target to a recoil separator in order to collect the fusion products of interest while effectively rejecting the fission products [5, 6, 7].



Figure 2. Schematic drawing of the JUROGAM array coupled to the RITU gas-filled recoil separator and the GREAT focal plane spectrometer. The apparatus has been used with tremendous success to exploit the recoil-decay tagging technique and reveal the structure of transfermium nuclei.

The RDT method is outlined in figure 2, which schematically shows the JUROGAM array of germanium detectors coupled to the RITU gas-filled recoil separator [8] and the GREAT focal plane spectrometer [9]. Prompt γ rays are detected in the array of germanium detectors surrounding the target, and fusion products are separated from fission products and primary beam by the dipole magnet of the separator according to their magnetic rigidity. The fusion products of interest are then implanted into position-sensitive silicon detectors at the focal plane of the separator. The time of implantation, energy, and position in the detector are recorded. The prompt γ -ray energies and times are also recorded in such a way that those γ rays emitted by a particular implanted nucleus can be extracted (on the basis of a fixed time-of-flight for the recoil). As the recoiling nuclei are implanted in the silicon detector, any subsequent decay from the ground or isomeric states can also be recorded. The focal plane detection system is capable of measuring charged particles, γ rays and internal conversion electrons. As the position in the silicon detector is again recorded for any subsequent decays, *correlations* can be made between the decay event and recoil implant, and hence the γ rays of interest. This is the procedure known as recoil-decay tagging. The first study of a transfermium nucleus to be carried out in this manner was that of 254 No, in an experiment carried out at Argonne National Laboratory (ANL) using the Fragment Mass Analyser (FMA) and the GAMMASPHERE array of germanium detectors [10]. The reaction employed was a beam of ⁴⁸Ca impinging on a ²⁰⁸Pb target, producing ²⁵⁴No through the two-neutron evaporation channel with a cross section of approximately 3 μ b. Since this first study, a large number of experiments have been carried out both at ANL and mainly at the Accelerator Laboratory of the University of Jyväskylä, Finland (JYFL). In these studies, rotational bands have been observed in ^{246–250}Fm, ²⁵¹Md, ^{252,253}No and ²⁵⁵Lr, yielding information concerning the deformation, moments of inertia, alignment properties and single-particle structure of these nuclei. Details of the experiments and results can be found in Refs. [11, 12, 13, 14, 15, 16, 17, 18, 19]. Much of this work is also reviewed in Ref. [20].

2.2. Recent advances

As mentioned above, a limiting factor in experiments to study transfermium nuclei in-beam is the counting rate of events in the germanium detectors surrounding the target. With traditional analogue electronics, the counting rates are typically limited to 10 kHz per detector. In the past few years, it has become possible to digitise the preamplifier signals directly in flash ADCs with typical sampling rates of 100 MHz and 14-bit resolution. Trapezoidal shaping is then performed by an algorithm in the ADC card, with the end result being the capability to operate the germanium detectors at much higher counting rates without loss in resolution and a relatively lower level of pile-up events. The use of digital electronics rendered possible an experiment to measure ²⁴⁶Fm, produced with a cross section of only 11 nb. In this experiment, the JUROGAMII array of germanium detectors was instrumented with TNT2D electronics cards, allowing count rates of up to 40 kHz and beam intensities of up to 71 pnA to be employed [11]. Gamma-ray spectroscopy of high-Z elements is also hindered by the competing process of internal conversion, which dominates in the decay of low-energy transitions common in these well-deformed nuclei. For example, a 150 keV transition with pure E2 multipolarity in a nucleus with Z=100 has a total internal conversion coefficient of 4.3, meaning that it is 81% converted. It is thus clear that simultaneous measurement of γ rays and internal conversion electrons is desirable in these studies. In early 2010, a device designed to perform such studies was commissioned at JYFL, known as SAGE. The SAGE spectrometer consists of a solenoid magnet to transport electrons from the target to a pixellated silicon detector with 90 elements. The system therefore allows electron-electron, electron- γ and γ - γ coincidence events to be collected. All silicon and germanium detectors in the device are again instrumented with digital electronics to allow higher counting rates. A detailed description of SAGE can be found in Ref. [21] and in the contribution of Papadakis elsewhere in these Proceedings.

2.3. Rotational and high-K structure of transfermium nuclei

Over the past decade, a large number of experiments have been performed to study nuclei in the region of ²⁵⁴No, making a detailed discussion of all the results obtained beyond the scope of this short review. In early experiments, it was possible to delineate the ground-state (yrast) rotational bands and as experimental improvements led to a higher level of sensitivity, attention moved to the study of so-called high-K structures. In the deformed nuclei with $Z \simeq 100$ and $N \simeq 152$, there are a number of high-omega orbitals near the Fermi surface ([633]7/2⁺, [514]7/2⁻ and $[624]9/2^+$ for protons and $[622]5/2^+$, $[624]7/2^+$ and $[734]9/2^-$ for neutrons). It is thus reasonable to expect that the occurrence of high-K isomers will be prevalent in these nuclei. It is possible to form both two quasi-proton and two quasi-neutron $K^{\pi}=8^{-}$ states by coupling the $[514]7/2^{-}$ and $[624]9/2^{+}$ states for protons and the $[624]7/2^{+}$ and $[734]9/2^{-}$ states for neutrons. Long-lived isomeric states were discovered in the 1970s in both ²⁵⁴No and ²⁵⁰Fm [22], but only recently has it become possible to determine the configuration of these states. When the nuclei are implanted in the silicon detector at the focal plane of the separator, it is possible that they are still in the excited, isomeric state. When the isomer decays, a number of internal conversion electrons may be emitted which give an observable signal in the electronics system. This signal provides a clean trigger marking the decay of the isomer. This trigger can then be used to preferentially select only those γ rays which are associated with the isomeric state (see figure 2). This method was first proposed by Jones in 2002 [23], and has since resulted in K-isomers being studied in ^{248,250}Fm, ^{252,253,254}No, ²⁵⁵Lr and ²⁵⁶Rf [12, 14, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34]. The quality of data which can be obtained is shown in figure 3, which displays spectra of prompt singles γ rays in ²⁵⁰Fm. The upper panel shows recoil-gated γ -ray singles, which are obtained by demanding the detection of a fusion-evaporation product at the focal plane. The data were taken using the RITU and JUROGAM set-up described above. In many cases, it is only necessary to require the delayed coincidence with a fusion evaporation product, as the channel of interest dominates the total fusion-evaporation cross section. The yrast rotational band can be observed up to a spin of $22\hbar$, and evidence is seen for decays from non-yrast states (e.g. the transition at 834 keV). It should also be noted that no candidates for the 4⁺ to 2⁺ or 2⁺ to 0⁺ transitions are seen due to the competition from internal conversion discussed above.



Figure 3. a) Recoil-gated and b) isomer-tagged γ -ray singles spectra from ²⁵⁰Fm. The experiment was carried out using the RITU gas-filled recoil separator and the JUROGAM array of germanium detectors. See ref. [14] for details.

The lower panel shows prompt γ rays detected when it is demanded that an isomeric transition

is recorded in the focal plane. It should be noted that these data are a subset of those shown in the spectrum in the upper panel. The isomer-tagging technique clearly allows this more weakly populated structure to be extracted from a complicated spectrum. Data such as these are very important in determining the configuration of the isomeric state. Sensitivity to the configuration comes from the fact that the B(M1) to B(E2) ratio is proportional to $(g_K - g_R / Q_0)$, and that the effective g_K value depends on the single-particle structure. A measurement of the ratio of M1to E2 intensities in a high-K rotational band can then help determine the configuration. In the N=150 isotones (²⁵⁰Fm, ²⁵²No, etc) there is clear evidence that the observed $K^{\pi}=8^{-}$ isomeric states have two quasi-neutron configurations. Detailed discussion of these assignments can be found in Refs. [14, 25]. The picture in the N=152 isotones ²⁵⁴No and ²⁵⁶Rf is unfortunately not so clear. The most studied isotope is ²⁵⁴No, with recent experiments at GSI and Berkeley obtaining excellent data sets with high statistics. However, the interpretations of the two groups are somewhat different, leading to different conclusions regarding the structure of the isomeric states. The experimental data can be found in Refs. [29, 30] and a summary of the differences in the level schemes can be found in Ref. [35]. A similar situation exists with the challenging case of ²⁵⁶Rf, which can be produced with a cross section of only around 17 nb. Again, two experiments (carried out at Berkeley and ANL) obtain different results and therefore have a different interpretation of the data. At Berkeley, evidence was found for as many as three isomeric states, with half-lives of the order of 20 microseconds. A γ -ray transition with an energy of 900 keV was also deduced to form part of the decay scheme. The Berkeley group suggested that the isomeric states were two quasi-particle in nature [33]. At ANL, evidence was found for only one isomeric state and no evidence for a coincident γ ray could be found. The ANL team also suggested that the observed isomer must have a four quasi-particle configuration [34]. Experiments at the nanobarn cross section level are rather challenging, and an increase in statistics is certainly required to draw definite conclusions in this case.

It has already been noted that the lowest spin states are not observed in these studies due to internal conversion. However, the excitation energies of the lowest states can be deduced rather reliably by fitting the moment of inertia of the rotational band according to the prescription of Harris [36]. The kinematic and dynamic moments of inertia can be expressed as:

$$\mathcal{J}^{(1)} = \mathcal{J}_0 + \mathcal{J}_1 \omega^2, \tag{1}$$

$$\mathcal{J}^{(2)} = \mathcal{J}_0 + 3\mathcal{J}_1\omega^2,\tag{2}$$

respectively. The expression

$$I = \mathcal{J}_0 \omega + \mathcal{J}_1 \omega^3 + 1/2, \tag{3}$$

can then be used to determine the excitation energy of the unobserved 2^+ and 4^+ states. The behaviour of the excitation energy of the 2^+ state as a function of proton or neutron number can reveal information concerning the shell structure of these heavy nuclei. As pointed out in Ref. [37], the moment of inertia (and hence 2^+ energy) is sensitive to the strength of the pairing correlations. At a shell gap, the pairing correlations are reduced and the moment of inertia increases, giving a lower 2^+ energy. The experimental and theoretical 2^+ energies are compared for isotopes and isotones in figures 4 and 5. The theoretical values are taken from Ref. [37] and are calculated using the macroscopic-microscopic approach and the cranking approximation. The model yields deformed shell gaps at Z=100 and N=152, and indeed for the isotopes of fermium and nobelium there are clear minima at N=152 in the 2^+ energies. For the N=150isotones, there is also a minimum at Z=100 in the theoretical prediction of figure 5.

Experimentally, it is not yet clear where the minima are for the fermium and nobelium isotopes. Measurements of excited states in 252 Fm and 256 No would be extremely desirable in order to complete the picture. For the isotones, a complete picture only exists for the case of N=150. It is interesting to note that a clear minimum exists at Z=98, rather than Z=100



Figure 4. Systematic behaviour of the excitation energies of the lowest 2^+ states in even-even nuclei in the region of 254 No. (a) Isotopes as a function of neutron number. (b) Isotones as a function of proton number.



Figure 5. Predicted theoretical behaviour of the excitation energies of the lowest 2^+ states in even-even nuclei in the region of 254 No, extracted from Ref. [37]. (a) Isotopes as a function of neutron number. (b) Isotones as a function of proton number.

where it is expected that the deformed shell gap resides. Again, measurement of 252 Fm and 256 Rf would enable the picture to be completed for the N=152 isotones.

3. Summary

Over the past decade or so, a great number of experiments have been carried out to study the excited state structure of heavy nuclei. Experimental advances now mean that it is possible to obtain data at the level of 10 nanobarns, with beam intensities of several tens of particle nA. In future, the next generation of γ -ray tracking arrays such as AGATA and GRETINA will allow this level to be decreased further, pushing the limits of proton number and mass for which nuclear structure data can be obtained.

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