GAMMA AND ELECTRON SPECTROSCOPY OF THE HEAVIEST ELEMENTS*

P.T. Greenlees

Department of Physics, University of Jyväskylä
P.O. Box 35 (YFL), 40014, Finland

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The production and spectroscopic study of the heaviest elements has always been a central theme of nuclear physics. In recent years, a wealth of new data has been produced, both in terms of new elements (up to $Z = 118$) and in detailed spectroscopic studies of nuclei with masses above 240. Such studies provide data concerning nuclear parameters such as masses, decay modes, half-lives, moments of inertia and single-particle properties in systems with the highest possible number of protons. The main focus of current experiments is the search for the next closed proton- and neutron-shells beyond the doubly magic ^{208}Pb. This search can be made directly, by producing nuclei in the region of interest ($Z > 112$ and $N > 176$), or indirectly through the study of lighter deformed nuclei where the orbitals of interest at sphericity are active at the Fermi surface. In the latter case, the production cross-section is large enough to permit detailed in-beam and decay spectroscopic studies. These studies employ state-of-the art spectrometers such as the JUROGAM array of germanium detectors or the newly-commissioned SAGE combined conversion electron and gamma-ray spectrometer. Examples of recent highlights in studies of deformed heavy nuclei, along with the opportunities provided by current and future facilities to extend these studies are reviewed.

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1. Introduction

Over the past decade or so, great strides have been made in the study of the heaviest elements. Efforts to synthesise new elements have focused on using "hot-fusion" reactions with ^{48}Ca beams impinging on radioactive actinide targets, with great success. Synthesis of elements up to 118 have

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been claimed at Dubna, and in recent years experiments carried out at other laboratories have provided important confirmation of the decay chains in elements up to 114 (see, for example, Refs. [1, 2, 3, 4]). The most recent discovery in this series of measurements was the production of element 117 using an exotic berkelium target [5]. A plot of the upper part of the chart of the nuclides is shown in Fig. 1.

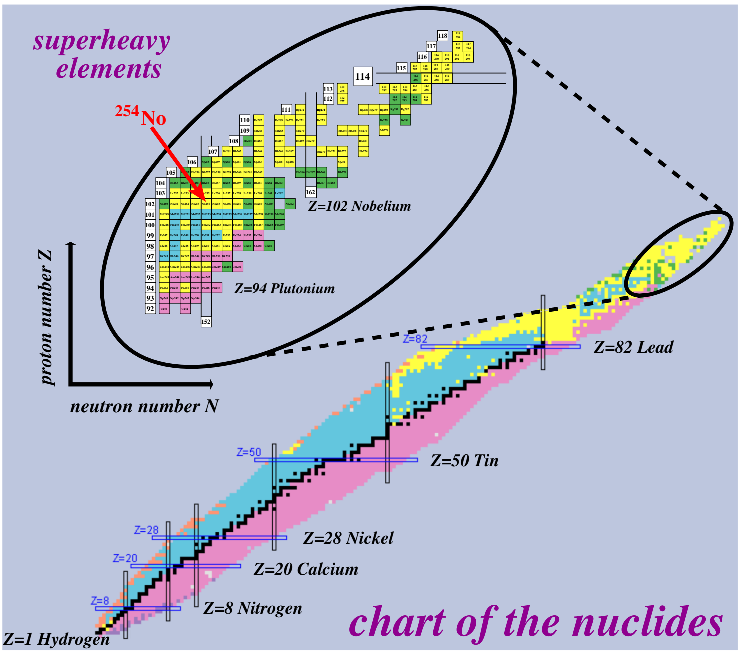

Fig. 1. Chart of the nuclides with excerpt showing current knowledge of the heaviest elements, including the recently discovered decay chains of element 117 [5].

The main goal of these production experiments is to locate the fabled "island of stability", a region of spherical nuclei centred at the next closed shells (magic numbers) for protons and neutrons. It is well known that current theories disagree on the location of the island, with models predicting $Z = 114$, 120 or 126 and either $N = 172$ or 184 (see, for example, Ref. [6]). Direct synthesis experiments can provide information concerning decay modes, decay energies, production cross-sections and so on. In order to truly understand the structure and stability of the heaviest elements, it is essential to also obtain more detailed spectroscopic data. Such data is, of course, difficult to obtain in experiments where only a few decay chains may be observed. An alternative approach which has gained momentum in recent years is to study lighter deformed nuclei, with proton number Z around 100 and neutron number N close to 152. This region is of interest in itself, with the occurrence of deformation and K-isomerism in systems with a large number of protons. Additional interest comes from the fact that orbitals active at the Fermi level in these deformed nuclei stem from orbitals which are relevant to the discussion of spherical shell gaps in much heavier nuclei. One of the most important orbitals is the proton $[521]1/2^-$, which stems from the $f_{5/2}$ orbital at sphericity. The separation of the $f_{5/2}$–$f_{7/2}$ spin-orbit partners plays a major role in determining the size of the shell gap at $Z = 114$. Nuclei in the region can be produced in greater numbers, allowing in-beam and decay spectroscopic studies. Studies of this type can yield information on moments of inertia and single-particle configurations which can be compared to theoretical predictions. Theoretical reproduction of data in this region would lead to improved confidence in the extrapolation of theory to predict the properties of the true superheavy elements.

2. Experimental approaches and overview

As mentioned above, in the past decade or so, great advances have been made in studies of nuclei in the vicinity of $Z = 100$ and $N = 152$ (see Ref. [7] for a review). These nuclei are generally produced through fusion-evaporation reactions with targets such as ^{206,208}Pb, ^{209}Bi or even ^{202,204}HgS, and beams of ^{48}Ca. Traditionally, studies were made at the focal plane of recoil separator devices whereby the nuclei of interest are implanted into a position-sensitive silicon detector and correlated decay chains are measured following the implantation event. Studies of this type were limited to observation of α decays and were susceptible to a loss of information, particularly in the case of odd-mass nuclei when excited states in the daughter nucleus may be populated. The development of true focal plane spectrometers capable of discriminating fusion products, α particles, conversion electrons and γ rays has led to a vast improvement in the quality of data available from such experiments. This has, in turn, led to a much more detailed understanding of the structure of these nuclei. The coupling of modern large arrays of germanium detectors to efficient recoil separators has also enabled a wealth of new spectroscopic information to be obtained. Since the pioneering study of ^{254}No carried out using GAMMASPHERE and the FMA, rotational bands have been observed in $^{246-250}$Fm, ^{251}Md, ^{252}No and ^{255}Lr [8,9,10,11,12,13,14]. These studies have been carried out with various arrays of germanium detectors coupled to the RITU gas-filled recoil separator. The most recent study of ^{246}Fm employed the JUROGAMII array, fully instrumented with digital electronics. The use of such electronics allowed beam intensities of up to 70 pnA to be used, unprecedented in in-beam studies. The production cross-section is only of the order of 10 nb, representing a new limit for studies in this region [9]. Another technique, now widely used, depends on the signals generated from the decay of a nucleus implanted into a silicon detector at the focal plane of a recoil separator. In high-Z nuclei, the probability that a low-energy transition decays by internal conversion rather than γ-ray emission is large. In some cases, the signal produced by the conversion electrons may be large enough to be detected above the electronic threshold. This is especially true if more than one electron is emitted, as the energies of the individual electrons will be "summed" due to the response of the electronics. This "calorimetric" method was first proposed by Jones, with an eye to studying K-isomerism [15]. Selected results obtained using this technique will be discussed in the following.

3. Decay and in-beam spectroscopy of ^{255}Lr

As mentioned in the introduction, the orbitals active at the Fermi level in deformed nuclei with $Z \simeq 100$ and $N \simeq 152$ are relevant to the discussion of the location of the next spherical shell gaps. Figure 2 shows the single-particle level structure expected in ^{250}Fm, calculated using a Woods–Saxon potential and "universal" parameters.

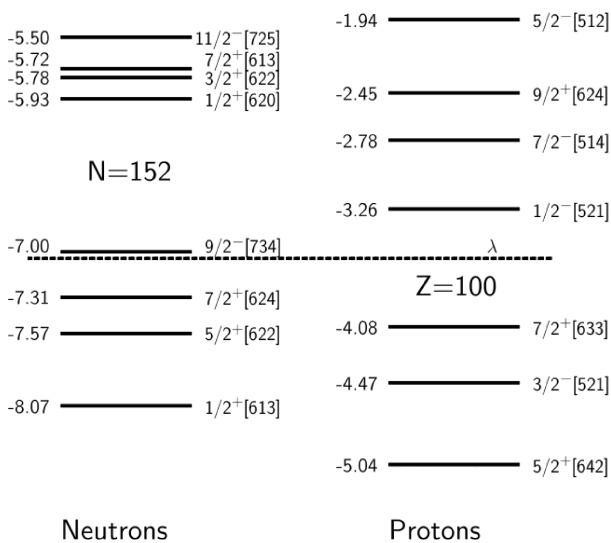

Fig. 2. Single-particle energies calculated using a Woods–Saxon potential with "universal" parameters and deformation parameters corresponding to those of ^{250}Fm.

It can be seen that for nuclei with $Z \simeq 100$ protons, the $[633]7/2^+$, $[521]1/2^-$, $[514]7/2^-$ and $[624]9/2^+$ states lie close to the Fermi surface. Similarly, for nuclei with around $N \simeq 152$ neutrons, one expects the $[622]5/2^+$, $[624]7/2^+$, $[734]9/2^-$ and $[620]1/2^+$ states to play an important role in the structure. Until around 2006, little was known of the structure of the

$Z = 103$, $N = 152$ nucleus ^{255}Lr. Decay experiments carried out using the LISE spectrometer in GANIL and the RITU gas-filled separator at JYFL allowed the α-decay scheme to be determined in more detail. It was determined that in addition to the ground-state α decay, there is an additional isomeric α-decaying state. Through α–γ coincidences and α-decay hindrance factors the ground state was assigned to be the [521]$1/2^-$ state, with the isomeric state being the [514]$7/2^-$ state at an excitation energy of only 37 keV (see Ref. [16] for details). A subsequent in-beam spectroscopic study using the JUROGAM array at RITU revealed rotational bands in ^{255}Lr, whose properties were consistent with the assignments given in the earlier work [14]. In addition to these studies, evidence for K-isomerism has also been found in experiments carried out at Dubna, GSI and Berkeley (see Refs. [17, 18, 19]). The data obtained in all three experiments were broadly consistent, with some variation due to the slightly different experimental arrangements and triggering methods. Another, high-lying isomeric state with a half-life of 1.4–1.8 ms was discovered, and assigned to be a three-quasiparticle configuration. The work of Jeppesen *et al.* provided a level scheme, suggesting the existence of two isomeric states. The first, with a spin and parity of $25/2^+$, was speculated to be a two-quasineutron configuration coupled to a single quasiproton with the possible structure $[\pi[624]9/2^+ \otimes \nu([725]11/2^- \otimes [624]7/2^+)]$. This $25/2^+$ state was then proposed to decay to a band structure above a $15/2^+$ three-quasiproton isomeric state, with possible configuration $\pi([514]1/2^- \otimes [514]7/2^- \otimes [624]9/2^+)$ (*i.e.* the three lowest one-quasiproton states). It was further suggested that the intermediate $15/2^+$ state decayed to a band based on the one quasiproton [624]$9/2^+$

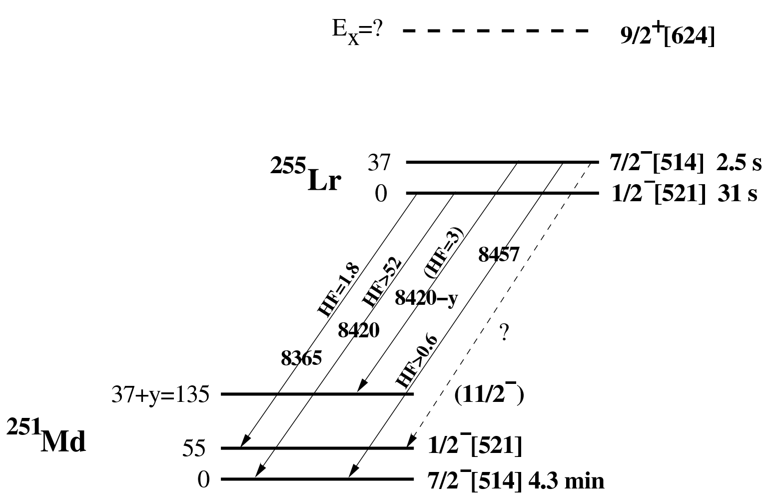

Fig. 3. Partial decay scheme of ^{255}Lr.

state. Importantly, it was concluded that the $[624]9/2^+$ state must lie within 30 keV of the known $[514]7/2^-$ state, as no strong $E1$ γ-ray transition connecting the two states was observed. On the basis of this and the earlier α-decay work, it is expected that the $[521]1/2^-$, $[514]7/2^-$ and $[624]9/2^+$ states all lie within an energy range of below 100 keV. This is of importance for the following discussion of isomeric states in ^{254}No. The suggested low-lying structure of ^{255}Lr is shown in Fig. 3.

4. *K*-isomerism in ^{250}Fm and ^{254}No

K-isomerism in ^{250}Fm and ^{254}No was first observed in 1973 by Ghiorso *et al.*, though in this original work it was not possible to delineate the level scheme or to make an assignment of the configurations from the data [20]. It took over thirty years to confirm the existence of these isomeric states, in experiments at RITU and the FMA using the calorimetric method suggested by Jones. The results were published simultaneously and were consistent, determining the isomer in ^{254}No to have a spin and parity of 8^- with two-quasiproton configuration $\pi([514]7/2^- \otimes [624]9/2^+)$ [21, 22]. The $K^\pi = 8^-$ isomer decays mainly via a 53 keV $E1$ transition to a $K^\pi = 3^+$ band and subsequently to the ground-state band via several high-energy γ-ray transitions. The configuration of the $K^\pi = 3^+$ band head was determined to be the two-quasiproton $\pi([521]1/2^- \otimes [514]7/2^-)$.

It has also been possible to determine the configuration of the isomeric state in ^{250}Fm originally discovered by Ghiorso. In this case, it was possible to observe $M1$ and $E2$ transitions in a strongly-coupled band built above the isomeric state. The $M1/E2$ intensity ratios show that the $K^\pi = 8^-$ isomer has the two-quasineutron configuration $\nu([624]7/2^+ \otimes [734]9/2^-)$ — the two states shown on either side of the Fermi surface in Fig. 2 [11]. The systematic behaviour of $K^\pi = 8^-$ states in the $N = 150$ isotones was presented in the work of Robinson *et al.* [23]. It was shown that the excitation energy of the $K^\pi = 8^-$ states was rather constant over a wide range of proton number (within 75 keV from $Z = 94$–102), lending support to the two-quasineutron assignment. Added to the fact that the assignment in ^{248}Cf is supported by transfer reaction data, some confidence in the data and configurations established in the $N = 150$ isotones is reasonable.

The fact that the isomer in ^{254}No has a two-quasiproton structure, rather than a two-quasineutron structure, can be understood with reference to the deformed shell gaps at $Z = 100$ and $N = 152$. In going from ^{250}Fm to ^{254}No (adding two protons and two neutrons), the Fermi surface for neutrons moves into the $N = 152$ deformed shell gap, and above the $[624]7/2^+$ and $[734]9/2^-$ states responsible for the high-K state. In addition, the proton Fermi surface moves above the $Z = 100$ shell gap and closer to the $[514]7/2^-$ and $[624]9/2^+$ states. It should be expected then, that the two-quasineutron configuration is pushed higher in energy in ^{254}No, whilst the energy of the two-quasiproton configuration is lowered [11]. This interpretation is also consistent with the expectation from the studies of ^{255}Lr that the [521]$1/2^-$, [514]$7/2^-$ and [624]$9/2^+$ states all lie within a small energy range.

Recently, two new papers have been published reporting on possible four-quasiparticle isomeric states in ^{254}No. The studies, carried out at GSI and Berkeley, present somewhat inconsistent interpretations of rather similar γ-ray decay data [24, 25]. In the GSI work, a single strongly-coupled rotational band built on the $K^\pi = 8^-$ isomeric state was established up to a spin of 15^-. The 15^- state was fed by a 606 keV transition from an intermediate state, which in turn was fed from the (second) isomeric state. It was not possible to observe the transition from the isomer to the intermediate state. No firm assignment was made for the configuration of the high-lying isomer, but it was claimed that the data support the original assignments for the $K^\pi = 3^+$ and $K^\pi = 8^-$ states. In contrast, the level scheme presented by the Berkeley group suggests that the isomeric state is a four-quasiparticle $K^\pi = 16^+$ state which decays via an intermediate $K^\pi = 10^+$ two-quasineutron band to the $K^\pi = 8^-$ band and finally to the $K^\pi = 3^+$ band. The $K^\pi = 10^+$ band is suggested to be due to the unfavoured coupling of the neutron [734]$9/2^-$ and high-lying [725]$11/2^-$ states. Based on the fact that the two-quasineutron $K^\pi = 10^+$ state decays to the $K^\pi = 8^-$ band, it is concluded that the $K^\pi = 8^-$ state must also have a two-quasineutron structure. The assignment of two-quasiproton structure to the $K^\pi = 3^+$ band is also supported by the Berkeley data.

The Berkeley interpretation therefore seems to be in conflict with the rather consistent picture set out above. In order to have a low-lying two-quasineutron $K^\pi = 8^-$ state at $N = 152$, the size of the experimentally well-established $N = 152$ shell gap must be reduced. The interpretation also seems at odds with the finding in ^{255}Lr that all three low-lying states are within 100 keV, which implies that the two quasiproton $K^\pi = 3^+$ and $K^\pi = 8^-$ states must also be close in excitation energy. However, it must be said that a number of calculations exist which predict the two-quasineutron configurations below the two-quasiproton configurations (see Ref. [25] and references therein). Further investigation of the predicted single-particle levels and cross-checking with the known experimental single-particle states is necessary to determine the reliability of these calculations. Here, the acid test is correct prediction of the well-established two-quasiproton $K^\pi = 3^+$ state, the assignment of which was confirmed in all experiments.

5. New developments and future

Worldwide, a large number of developments are currently underway or planned which will no doubt further studies of heavy and superheavy elements. Of note are the dedicated facilities based around the new GARIS II separator at RIKEN, the S^3 separator-spectrometer for use with the intense stable ion beams from the LINAG of SPIRAL2 and the possible intensity upgrade at GSI to feed the SHIP and TASCA separators. These developments are certain to yield improved data on the decay properties of the heaviest nuclei and enable the search for yet more new elements. In-beam spectroscopic studies will be enhanced by the novel SAGE spectrometer, recently commissioned at JYFL and developed by a collaboration of the University of Liverpool, Daresbury Laboratory and JYFL. The spectrometer is designed to simultaneously detect both γ rays and internal conversion electrons, vitally important in the study of heavy nuclei. A photograph of SAGE installed at the target position of RITU is shown in Fig. 4, see Ref. [26] for further details. In order to go below the current spectroscopic limit of around 10 nb,

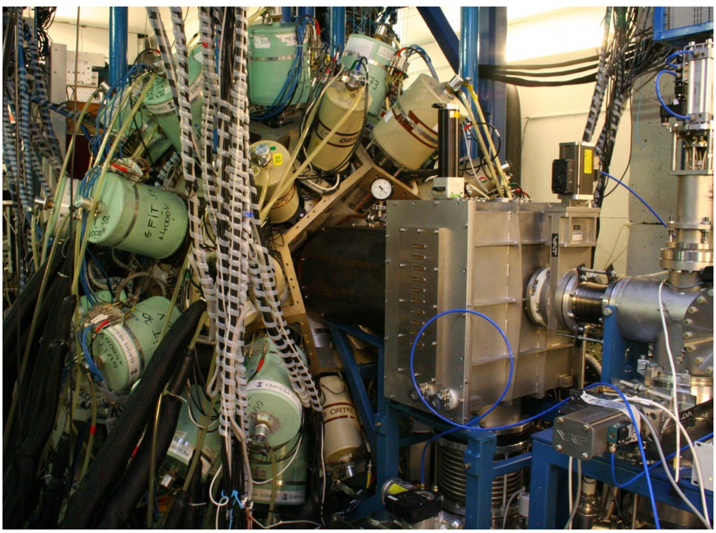

Fig. 4. Photograph of the SAGE combined electron-γ spectrometer installed at the target position of RITU.

the next generation of arrays of germanium detectors using γ-ray tracking will be required. The final realisation of the full AGATA and GRETA arrays is therefore eagerly awaited. The Nuclear Physics community is also eagerly awaiting the advent of the next generation of Radioactive Beam Facilities, such as SPIRAL2 and HIE-ISOLDE. It is interesting to consider the potential of such facilities to contribute to the study of heavy nuclei. Whilst the expected intensities are lower than those at current stable beam facilities, there is some room for optimism. Figure 5 shows a plot of beam intensity *versus* cross-section required to accumulate 300 full-energy α decays in a one week irradiation time. This is the minimum level of statistics required for an in-beam study or a more detailed decay study. One can see that for intensities of around 10^{10} pps (which may be expected for the most intense SPIRAL2 beams), a cross-section limit of around 100 nb is reached.

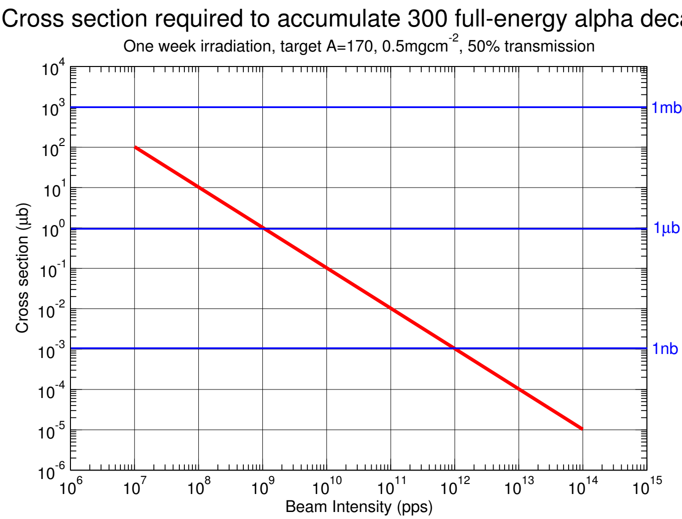

Fig. 5. Beam intensity *versus* cross-section required to accumulate 300 full-energy α decays in a one week irradiation.

In summary, the study of heavy nuclei remains an active and interesting field. Current and future developments will ensure that research in this region of the nuclear chart will continue to provide new data allowing nuclear models to be tested at the upper extreme of nuclear existence.

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