Spectroscopy of the heaviest elements

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Abstract. The addition of modern arrays of silicon and germanium detectors at the target and focal plane positions of recoil separators has led to a wealth of new spectroscopic data concerning the structure of heavy elements. A particular region of interest has been that of the deformed nuclei close to the \(N=152\) subshell gap. Both detailed decay and in-beam spectroscopic studies have provided complementary data on the location and ordering of single-particle states for proton number in the region of \(Z=100\) and neutron number \(N=152\). Instrumentation developments have allowed in-beam studies to be carried out at the unprecedented level of 20 nanobarns. The future prospects for such studies are also bright - new facilities employing high intensity stable beams are under construction and should yield lead to more significant results over the next decade. Additional long-term interest comes from the advent of next generation radioactive beam facilities which may allow limited studies in the heavy element region to be carried out.

1. Introduction
Experiments to study the structure of heavy and superheavy nuclei are at the extreme limit of current capabilities. Attempts to synthesise new superheavy elements generally only produce a handful of events and therefore cannot provide detailed spectroscopic data (see, for example, Refs. [1, 2]), but can provide valuable determinations of decay modes, half-lives and production cross sections. Such properties may be influenced by the shell corrections responsible for the stabilisation of these nuclei. In order to understand the structure and stability of the superheavy nuclei, it is of vital importance to gain information concerning the underlying single-particle spectrum. Such information may also help to solve the long-standing problem of the “Island of Stability”, where spherical superheavy nuclei should reside. The nuclei on this island should have proton and neutron number close to the next magic numbers beyond \(Z=82\) for protons and \(N=126\) for neutrons. It is well known that theoretical predictions of these magic numbers fail to reach consensus, giving values of \(Z=114, 120\) or 126 for protons and \(N=172\) or 184 for neutrons [3, 4, 5]. An impression of the experimental data available concerning the excited state structure of heavy nuclei can be gleaned from Figure 1, which shows the number of levels and bands known in a particular nucleus. The ground state spin assignment is also shown in a particular nucleus. The ground state spin assignment is also shown in the case of odd-mass nuclei. The figure is similar to that from Ref. [6], which provided a review of the experimental situation in 2008. It can be seen that less than ten odd-mass nuclei have a firm ground-state spin and parity assignment. There is also a clear concentration of knowledge close to the Cm, Bk and Cf isotopes which have half-lives long enough to allow production of a target. Such targets have been used in transfer reactions and in Coulomb excitation, yielding a considerable amount of spectroscopic information. Moving away from this region, the level
of knowledge drops rapidly, as it becomes necessary to rely on fusion-evaporation reactions to produce the nuclei of interest.

![Chart of the nuclides for elements from Cm to Db](chart.png)

**Figure 1.** Excerpt of the chart of the nuclides for elements from Cm to Db, reflecting the level of experimental knowledge.

It is this dearth of data which motivates the experimental campaigns to attempt studies of these nuclei in a number of laboratories around the world. Present centres for such studies are GSI, Dubna and JYFL in Europe, Berkeley and ANL in the U.S.A. and RIKEN and Tokai in Japan. Such studies also form a large part of the motivation for construction of new facilities and devices such as the S3 (Super Separator Spectrometer) to be served by the high intensity stable beams from the LINAG of SPIRAL2. In the following the experimental methods, recent highlights (with focus on in-beam studies) and future prospects for the spectroscopy of heavy nuclei are reported.

### 2. Experimental methods

In general, the production and study of heavy and superheavy nuclei is carried out using fusion-evaporation reactions at recoil separator devices. Previously, most experiments would simply allow recoiling fusion-evaporation residues to be implanted into a silicon strip detector at the focal plane, and level assignments would mainly be based on α-decay properties alone. This approach suffers from the fact that in the case of odd-mass nuclei, the α decay is likely to populate an excited state through a favoured decay. The excited state will then usually decay to the ground state through electromagnetic transitions. In the absence of detectors sensitive to γ rays or internal conversion electrons, level assignments are difficult to make as the multipolarity of depopulating transitions cannot be determined. A related problem was referred to above, in that many nuclei in the region have poorly determined ground-state spins and parities. In the past decade or so, modern spectrometer systems have been developed for the focal planes of recoil separator devices. These spectrometer systems employ highly granular double-sided silicon detectors for implantation, a "tunnel" of silicon detectors at backward angles to detect radiation (α particles and electrons) escaping the implantation detector, and an array of germanium
detectors to detect $\gamma$ rays emitted in the decay process. Detailed descriptions of the GREAT spectrometer located at JYFL and the GABRIELA array in JINR Dubna can be found in Refs. [7] and [8], respectively. Spectrometers of this type give much fewer accidental correlations due to the high granularity of the implantation detectors, and enable internal conversion coefficients to be determined from electron and $\gamma$-ray intensity ratios. Whilst capable of providing much-needed data on low-lying single-particle structure and decay properties, focal plane experiments are in turn limited in that only states populated through decay are accessible. The favoured $\alpha$ decays which are most often observed mean that many states may be missed as they are not populated. Ideally the focal plane investigations should be complemented by in-beam spectroscopic studies which can reveal the properties of ground-state rotational bands and yrast level sequences. Experiments of this type are possible using the so-called Recoil-Decay Tagging (RDT) technique, first developed in the mid 1980’s but not widely exploited until the late 1990’s [9, 10, 11]. In this method, prompt $\gamma$ rays are detected in an array of germanium detectors surrounding the target at a recoil separator. The overwhelming majority of $\gamma$ rays detected come from fusion-fission reactions, the $\gamma$ rays of interest only representing a miniscule (1 in $10^8$) number of events. The interesting events can be selected by demanding a delayed coincidence with a fusion-evaporation residue detected at the focal plane of the recoil separator. In this manner essentially all $\gamma$ rays due to background processes are filtered from the data. This technique now allows experiments to be carried out at the level of tens of nanobarns (see below). In recent years the experimental program at the JAEA Tokai Tandem Accelerator has also provided excellent spectroscopic data using two methods, again one of which uses decay and one of which uses in-beam techniques. Detailed decay spectroscopy has been carried out using the He gas jet method, combined with $\alpha-\gamma$ coincidences. This approach is free from summing effects, which can cause problems in the experiments carried out with implanted activities (see e.g. Ref. [12]). The in-beam experiments have employed transfer reactions on neutron-rich targets to populate nuclei inaccessible through fusion-evaporation. The apparatus is comparatively simple, consisting of Si $\Delta E$-E telescopes and a small number of germanium detectors. Recent experiments have revealed the properties of rotational bands in $^{246}$Pu, $^{250}$Cm and an important state related to the $k_{17/2}$ spherical single-particle state in $^{240}$Cm [13, 14, 15].

3. Recent results

Since 1999, rotational bands have been established in the transfermium nuclei $^{246,248,250}$Fm, $^{251}$Md, $^{252,253,254}$No and $^{256}$Lr [16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 27]. These experiments (the majority of which have been carried out at JYFL in Finland) revealed, for example, differences in the alignment properties of the $N=150$ isotones when compared to the $N=152$ nuclei. The initial studies of $^{254}$No were at the cross section level of 3$\mu$b, using the $^{208}$Pb($^{48}$Ca,2n)$^{254}$No reaction. Most recently, the JUROGAMII array of germanium detectors coupled to RITU and GREAT has been used to study the the rotational structure of $^{246}$Fm through the $^{208}$Pb($^{40}$Ar,2n)$^{246}$Fm reaction. The JUROGAMII array is fully instrumented with digital electronics, and allows count rates of up to 30 kHz per germanium crystal to be used without significant deterioration of the spectrum quality. The cross section for the $^{208}$Pb($^{40}$Ar,2n)$^{246}$Fm reaction is of the order 11 nanobarns, and beam currents of 70 pnA were employed in order to produce sufficient nuclei (around 500) to delineate the rotational band [16]. Another technique which has been employed with great success in recent years was first suggested by Jones in 2002 [28]. It was suggested that when a heavy, deformed nucleus is implanted into a silicon strip detector at the focal plane of a separator in an isomeric state, the decay of the isomer is likely to proceed through a number of low-energy transitions to the ground state. As the proton number of the nuclei is large, the probability that the decay proceeds by internal conversion is high. A cascade of emitted conversion electrons results in a “calorimetric” sum energy signal, which gives an efficient tag for the isomeric decay using a conventional correlation analysis. The first case to
which the method was successfully applied was $^{254}$No in experiments at JYFL and ANL [29, 30]. Isomeric states in $^{254}$No (and $^{250}$Fm) were first observed in 1973 by Ghiors [31]. The recent experiments were the first to confirm the existence of these isomeric states, over thirty years later. The isomer in $^{254}$No was determined to have a spin and parity of $8^-$ with two-quasiproton configuration $\pi([514]7/2^- \otimes [624]9/2^+)$ [29, 30], decaying mainly via a 53 keV $E1$ transition to a $K^\pi = 3^+$ band. The configuration of the $K^\pi = 3^+$ band head was determined to be the two-quasiproton $\pi([521]1/2^- \otimes [514]7/2^-)$, involving the important $\pi[521]1/2^-$ state which comes down in energy with deformation and stems from the spherical $f_{5/2}$ state above the possible $Z=114$ shell gap. The method has also been applied to study the $K^\pi = 8^-$ states in the $N=150$ isotones $^{252}$No and $^{250}$Fm [32, 33, 19]. It has been shown that the $K^\pi = 8^-$ isomers have the two-quasineutron configuration $\nu([624]7/2^+ \otimes [734]9/2^-)$ and have a rather constant energy from $Z=94$ to $102$ [19, 33]. The fact that the isomers in the $N=150$ isotones are based on two-quasineutron configurations can be understood in terms of the Fermi level with respect to the $N=152$ subshell gap. In the $N=150$ isotones the Fermi level lies between the neutron $[624]7/2^+$ and $[734]9/2^-$ states which form the isomer. In the $N=152$ isotones the Fermi level moves into the $N=152$ gap and the isomeric neutron configurations are pushed up in energy [19]. Two new papers have recently been published reporting on possible four-quasiparticle isomeric states in $^{254}$No. The studies were carried out at GSI and Berkeley and obtained similar data, but present different interpretations of the decay scheme [34, 35]. 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. It remains an interesting challenge for future experiments to attempt to resolve this discrepancy.

4. Future prospects with stable beams
At present, there are a number of developments under way which aim to exploit intense stable beams to produce heavy and superheavy nuclei. In Europe, the most notable of these is the planned Super Separator Spectrometer S3, which will be constructed at SPIRAL2 in GANIL. A schematic of S3 is shown in Figure 2. S3 will be served by the intense stable beams from the LINAG of SPIRAL2, where the intensities are expected to reach the level of 10 particle $\mu$A for heavy ions such as $^{48}$Ca. In order to suppress the unreacted beam, the first stage of the separator consists of a momentum achromat, which will transport the fusion products to an intermediate image point. It is also envisaged that arrays of germanium detectors could be installed at this point to perform experiments with secondary reactions. The second part of S3 consists of a mass spectrometer, with an expected mass resolving power of the order of 300. Simulations suggest that for the $^{48}$Ca + $^{248}$Cm reaction to produce element 116 the transmission of the device is of the order of 60%, with the resolving power quoted above. If realised, may allow the mass and therefore the evaporation channel of the superheavy elements to be determined for the first time. Other developments of note are the dedicated facility at RIKEN, which will use beams from the RILAC and house the new GARISII gas-filled recoil separator. It is expected that it
may be possible to produce up to three atoms per day of element 114 at the facility. In GSI, it is also hoped that an intensity upgrade of the UNILAC will allow still more intense beams to be produced. The relatively new TOSCA gas-filled separator has already yielded interesting results and has a complementary spectroscopy program alongside the chemistry and synthesis program for which it was constructed [36]. In the near future, an attempt will be made to observe X-rays in coincidence with α decays from element 115. Such a measurement would allow an unambiguous assignment of the proton number of the daughter nucleus and confirm that the observed decay chains originate from purely neutron evaporation channels. Also at GSI, there are plans to construct a new separator known as IRIS, with the aim of separating products from deep-inelastic (DI) transfer reactions using very heavy beam and target combinations. The cross sections to produce neutron-rich isotopes in the Fm region are much greater than those with fusion-evaporation reactions, and the DI reactions also have the potential to populate nuclei inaccessible by other means.

In terms of in-beam spectroscopy, a recent development is the construction of the SAGE combined conversion-electron and γ-ray spectrometer in JYFL. The spectrometer was designed and constructed by a collaboration of the University of Liverpool, STFC Daresbury Laboratory and JYFL. The spectrometer is located at the target position of RITU and is intended for use in RDT measurements of heavy nuclei, where internal conversion forms a significant part of the decay intensity. The device consists of a magnetic solenoid to transport conversion electrons from the target to a 90-element pixelated silicon detector located upstream of the target. The geometry is close to collinear to minimise the effects of Doppler broadening, and a high-voltage barrier is employed to suppress the enormous flux of delta electrons produced by the beam in the target. Gamma rays are detected using 34 of the 39 germanium detectors of the JUROGAMII array. Further details of the construction can be found in Ref. [37].

The γ-ray spectroscopy communities are also eagerly awaiting the advent of the next generation arrays of germanium detectors AGATA and GRETA. In particular, the hosting of the GRETINA array at the Berkeley Gas-Filled Separator offers a potentially outstanding device for in-beam studies of heavy elements.
5. Possibilities with radioactive beams

It is often assumed that the low intensities expected at the radioactive beam facilities currently under construction preclude studies of heavy elements. Indeed, one may have to wait for facilities such as EURISOL to obtain the highest intensities that current technology will allow. However, it is expected that intensities at facilities such as SPIRAL2 may reach $10^{10}$ pps for the most intense beams. Figure 4 shows a plot of the required beam time in hours to produce 10 full energy $\alpha$ decays at the focal plane of a recoil separator. This number of events is typical, for example, in production of a new isotope. It can be seen that with a beam intensity of $10^{10}$ pps around one week of beam time would be required to reach a cross section limit of the order of 60 nb, indicating that some elementary production experiments may be feasible.
Figure 4. Plot showing the required beam time to produce ten full energy α decays as a function of cross section for a radioactive beam intensity of $10^{10}$ pps.

6. Summary
Over the past decade or so, a great deal of spectroscopic information has been collected which has revealed details of the collective and single-particle structure of heavy nuclei, particularly in the region close to $^{254}$No. Other exciting developments such as the direct mass measurements at SHIPTRAP (not discussed here) and the possibility of performing laser spectroscopic studies at the focal plane of S$^9$ bring renewed interest in the region [38]. New devices and facilities under construction will ensure that this trend will continue for some time to come.

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