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In-beam and decay spectroscopy of transfermium elements

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Abstract. Over the past few years a great deal of new spectroscopic data has been obtained for transfermium nuclei. Recoil separators, coupled with modern target position and focal-plane spectrometers, allow detailed studies of the structure and decay properties of transfermium nuclei to be peformed. In-beam studies using the recoil-gating and recoil-decay tagging techniques mainly provide information on yrast states, whilst complementary focal-plane decay studies give access to non-yrast and isomeric structures. In-beam studies of nuclei in this region have largely been performed at ANL and JYFL, and decay experiments at GSI, JYFL, GANIL and ANL. The present contribution is focussed on recent developments and experiments carried out by a number of collaborating institutes at JYFL.

PACS. 21.10.-k Properties of nuclei; nuclear energy levels – 23.20.-g Electromagnetic transitions – 29.30.-h Spectrometers and spectroscopic techniques

1 Introduction

The coupling of modern arrays of silicon and germanium detectors to recoil separators has in recent years allowed a wealth of new spectroscopic information to be obtained for heavy nuclei. With these devices, it is possible to perform in-beam studies at a production cross-section level much below 100 nb. Detailed focal-plane spectroscopy can still be carried out at a level at least one order of magnitude lower. Whilst the heaviest elements are still below the limits for extensive spectroscopy, nuclei in the transfermium region can be produced with cross-sections of up to around $2\,\mu$b through reactions of ^{48}Ca on various targets close to ^{208}Pb. The nuclei in this region are stabilized by shell effects, which create a barrier against spontaneous fission. The location of the next closed proton and neutron shells above ^{208}Pb has been a topic of theoretical work for several decades, and the predictions of various theories differ. Most calculations based on the macroscopic-microscopic method using Woods-Saxon or folded Yukawa potentials predict $Z = 114$ and $N = 184$ (see, *e.g.*, [1]). The situation with self-consistent mean-field models is not so clear, with different forces and approaches giving different predictions for the shell gaps. Most non-relativistic Hartree-Fock calculations predict $Z = 126$ and $N = 184$, whilst most relativistic mean-field calculations favour $Z = 120$ and $N = 172$. A detailed comparison of the predictions of the various forces and mean-field models can be found

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in ref. [2], and overviews of the progress in this area can be found in refs. [3,4,5] and references therein. Spectroscopic studies of nuclei in the transfermium region may help to shed light on this discussion in an indirect way. In the proton case, single-particle levels originating from the spherical $1h_{9/2}$, $1i_{13/2}$, $2f_{5/2}$ and $2f_{7/2}$ orbitals in the region of $Z = 120$ come down in energy with deformation and are close to the Fermi surface in the deformed nuclei close to ^{254}No. Of particular interest are the $2f_{5/2}$ and $2f_{7/2}$ spin-orbit partners, as the possible $Z = 114$ proton shell closure is related to the spin-orbit splitting of these states. The study of even-even nuclei in the region gives information concerning moments of inertia, and allows the extraction of the quadrupole deformation parameter, β_2. Studies of the odd-mass nuclei in the region may allow a determination of the ordering and separation of single-particle energy levels. If the data obtained in this region can be reproduced theoretically, constraints on the theory may lead to a consensus and more reliable predictions of the properties of superheavy nuclei.

2 Decay spectroscopy

The dominant decay mode for many of the nuclei in the region of ^{254}No is alpha decay. Alpha-decay spectroscopy at the focal plane of recoil separators is by no means a new technique, but advances in ion sources, target design and focal-plane detector technology mean that detailed spectroscopy can be performed on exotic nuclei within a realistic experiment time. The use of alpha-γ and alpha-electron coincidence techniques allows very clean spectra to be obtained, and transition multipolarities can be determined from internal conversion coefficients (provided the relevant detection efficiencies are known). Temporal correlations between different detector groups also allow the lifetimes of isomeric states and/or states populated by the alpha decay to be determined. Long chains of correlated alpha decays are often observed, thus the decay properties of several nuclei are obtained in a single measurement. Many experiments of this type have been carried out using the velocity filter SHIP at GSI, see ref. [6] for an overview. At JYFL, such studies are carried out using the RITU gas-filled recoil separator, which has a transmission efficiency on the order of 40% for the reactions described in this article [7]. A recent addition to the focal plane of RITU has been the GREAT spectrometer, designed by a large group of UK institutions and funded by the UK EPSRC [8]. A schematic of GREAT is shown in fig. 1.

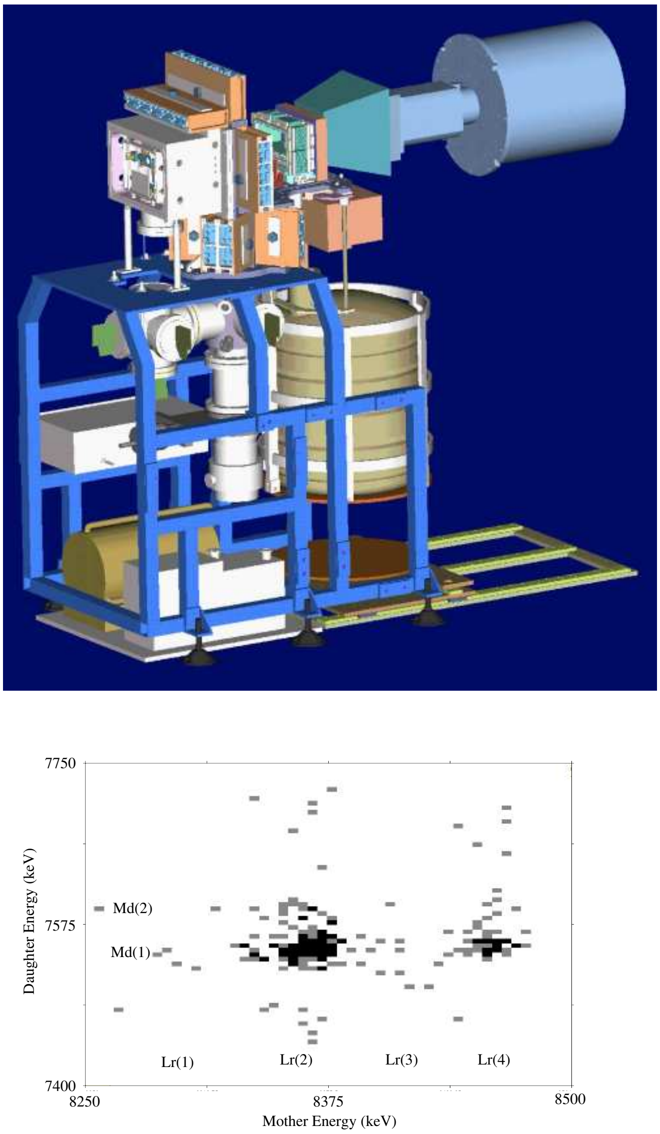

Fig. 1. Upper part: a schematic of the UK Universities GREAT spectrometer, currently installed at the focal plane of the RITU gas-filled recoil separator. Lower part: an alpha-alpha correlation plot obtained using an early implementation of GREAT, see text for details.

The spectrometer consists of a pair of double-sided silicon strip detectors (DSSSDs) placed side-by-side, each with 60×40 strips of pitch 1 mm, which act as implantation detectors. Thus, the RITU focal-plane distribution is effectively covered with a detector of 120×40 strips in the x- and y-directions, respectively. The DSSSDs measure the energies of implanted ions and their subsequent decays. Immediately behind the DSSSDs is a segmented planar germanium detector (24×12 strips of width 5 mm, 15 mm thickness) which is used to detect low-energy gamma- and X-rays. Surrounding the DSSSDs on the upstream side is an array of 28 silicon PIN diode detectors in a "box" which can be used to detect escaping alpha particles and conversion electrons. Each PIN diode has dimensions 28 mm × 28 mm and a thickness of 500 μm. A large-volume 16-fold segmented clover germanium detector is mounted above the DSSSDs to detect higher-energy gamma rays. The detector arrangement is completed by a multiwire proportional counter (MWPC) upstream of the DSSSDs. The MWPC is position sensitive, and also measures the energy loss of the recoiling ions. The MWPC can be used in conjunction with the DSSSDs to distinguish recoiling ions and their decay products. A further, major part of the GREAT project was the development of a new triggerless Total Data Readout (TDR) data acquisition system [9]. The idea behind the system is to reduce to a minimal level the acquisition dead time. As the name suggests, the data from all detector channels are read out and time-stamped with a 100 MHz clock (10 ns resolution). The data are then collated and merged into a time-ordered stream. Correlations between the various detector groups can then be performed in software and filtering can be performed to reduce the total amount of data prior to storage. An early implementation of GREAT was used in an experiment to study the alpha decay of ^{255}Lr, produced using the ^{209}Bi(^{48}Ca, 2n)^{255}Lr reaction at a bombarding energy of 221 MeV. Theoretical predictions for ^{255}Lr suggest that the ground state has a spin and parity $I^{\pi} = 7/2^{-}$. The ordering and excitation energies of the low-lying states below 1 MeV differ depending on the model used (see refs. [10,11]), but single-particle states with spins and parities of $I^{\pi} = 1/2^{-}, 9/2^{+}, 7/2^{+}$ and $5/2^{-}$ are expected. Thus, it is reasonable to assume that the presence of isomeric states is likely. Shown in the lower part of fig. 1 is an alpha-alpha correlation plot produced from the data obtained in the experiment using RITU and GREAT. To create the plot a search is made for correlated chains of the form recoil-mother alpha-daughter alpha in the same pixel of the DSSSDs. An additional constraint is that the mother alpha must be detected within 3 minutes of the recoil implant, and that the daughter alpha must be detected within 15 minutes of the recoil implant. Several clusters of events can be seen in the figure, which are assigned to be correlations of the alpha decay of ^{255}Lr and its alpha decay daughter ^{251}Md. Analysis of the decay lifetimes suggests that there are at least two alpha-decaying states in ^{255}Lr. Two alpha decay lines are also assigned to the decay of ^{251}Md and analysis suggests that these lines originate from the same state. Alpha-gamma coincidence data support this interpretation. A similar experiment was carried out by the collaboration using the LISE spectrometer at GANIL. A consistent data set was obtained, with improved alpha-gamma and alpha-electron coincidence data. Analysis of the data from both these experiments is ongoing and will be published in due course [12,13]. Since these early measurements with GREAT, experiments have also been carried out to study the decay of ^{253,255}No and also to confirm the presence of an isomeric state in ^{254}No for which evidence was found both in JYFL and at ANL [14,15]. The isomeric state in ^{254}No was originally observed by Ghiorso *et al.* over thirty years ago [16].

3 In-beam spectroscopy

Over the past few years a number of in-beam experiments have been dedicated to investigation of transfermium nuclei. These experiments began with the observation of the ground-state rotational band in ^{254}No using GAMMASPHERE and the FMA at Argonne National Laboratory. The results obtained showed that ^{254}No is deformed, with an estimated quadrupole deformation parameter $\beta_2 = 0.27$, and that the fission barrier persists up to a spin of at least $14\hbar$ [17]. A later experiment carried out at JYFL using the SARI germanium array and RITU confirmed and extended the ground-state band up to a spin of $16\hbar$ [18]. These (and all subsequent experiments) employed the recoil-gating and recoil-decay tagging (RDT) techniques. As mentioned in sect. 1, the use of such techniques allows the study of nuclei produced with cross-sections much below 100 nb. The following sections describe some of the recent highlights from in-beam conversion-electron and gamma-ray spectroscopic studies.

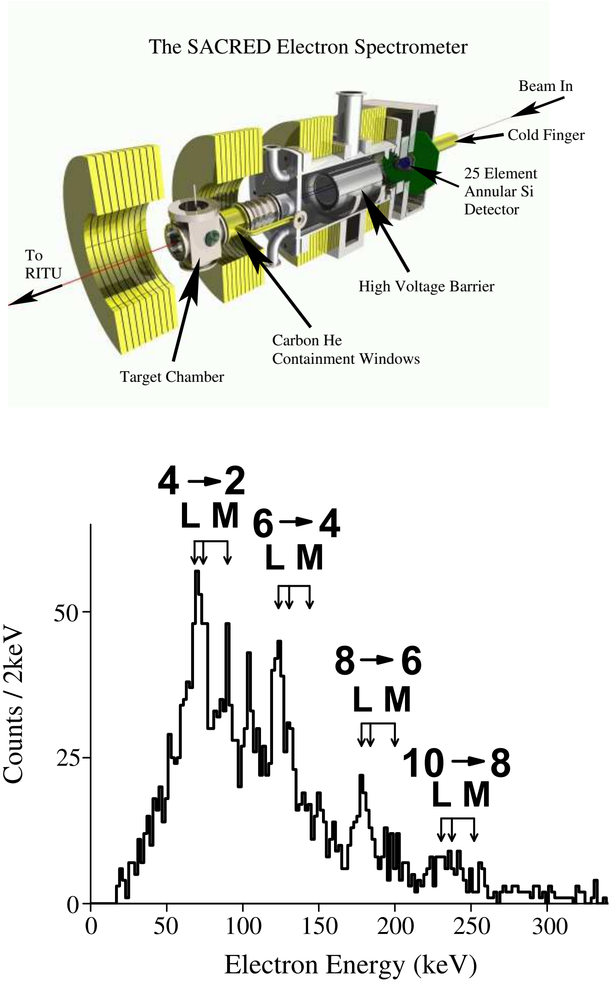

Fig. 2. Upper panel: a schematic of the SACRED conversion-electron spectrometer. Lower panel: recoil-gated singles conversion-electron spectrum from ^{254}No, see text for details.

3.1 Conversion-electron spectroscopy

The SACRED electron spectrometer is a unique device for the study of conversion electrons emitted in the decay of heavy nuclei. Operated at JYFL in collaboration with the University of Liverpool, the spectrometer was originally used "stand-alone" in a transverse geometry for electron-electron coincidence measurements. The spectrometer employed a superconducting solenoid magnet, and generally used light ion reactions. A detailed description of SACRED in this mode can be found in ref. [19]. In order to use SACRED in recoil-gating and RDT studies, the spectrometer was recently redesigned to operate in a geometry close to collinear with the beam axis. A schematic of SACRED is shown in the upper part of fig. 2.

The solenoidal magnetic field ($\simeq 0.3\,\mathrm{T}$) is generated by four copper coils, through which a current of 560 A is passed. Electrons produced at the target are transported to a 25 element annular Si detector, allowing electron-electron coincidences to be measured. The intense background of delta electrons is suppressed with the aid of a high voltage barrier, which is normally operated at a voltage of -30 to $-45\,\mathrm{kV}$. The He filling of RITU is separated from the high voltage region by a system of carbon foils. Further details and example spectra can be found in ref. [20]. In conjunction with RITU, SACRED has so far been used in experiments to study ^{250}Fm, ^{251}Md and ^{253,254}No [21,22,23]. One of the highlights from this series of experiments was the observation of evidence for the existence of high-K bands in ^{254}No (see ref. [23]), in an experiment led by the group from the University of Liverpool. The recoil-gated total singles electron spectrum from the measurement is shown in the lower part of fig. 2. Peaks corresponding to transitions in the ground-state rotational band can clearly be observed, including the 4^+ to 2^+ transition which had not previously been observed. Also to be noted is the broad distribution of events below the peaks, which is more intense than that normally observed in such measurements. These events have a higher multiplicity than the ground-state band transitions, and are not in prompt coincidence with the ground-state band, indicating that they feed isomeric states. Evidence for such isomeric states has already been observed in focal-plane experiments, as mentioned in sect. 2. The conclusion reached is that these events are due to high-K bands in ^{254}No which decay mainly via highly converted transitions, giving rise to the broad distribution of events seen in fig. 2. A more detailed discussion of the analysis and interpretation can be found in ref. [23].

3.2 Gamma-ray spectroscopy

As mentioned in the introduction to this section, impetus for in-beam studies of transfermium nuclei was gained with the observation of the ground-state band in ^{254}No at ANL. At ANL, these studies continued with experiments to measure the entry distribution and formation mechanism of ^{254}No, and a measurement of ^{253}No [24,25] in which evidence for two strongly coupled rotational bands was observed. At JYFL, the JUROSPHERE germanium detector array was employed in studies of ^{250}Fm, ^{252}No and ^{255}Lr. A review of the results obtained can be found in ref. [26]. The most recent germanium array to be built at JYFL is JUROGAM, which consists of 43 Compton-suppressed EUROGAM Phase-I type detectors, with a total photopeak efficiency of approximately 4.2% at 1.3 MeV. After the EUROBALL array was dismantled, the EUROBALL owners committee granted the use of thirty Phase-I type detectors for an extended period, with the remainder coming from the UK-France loan pool. A photograph of JUROGAM installed at the target position of RITU is shown in fig. 3. The GREAT project TDR data acquisition system is also used for all in-beam experiments at JYFL, and in the case of JUROGAM the Compton suppression is also performed in software. A new target chamber was recently installed by the IReS Strasbourg group, which allows the use of a rotating target wheel for experiments which require high beam intensities. JUROGAM has been used extensively for studies of neutron-deficient and heavy nuclei, and in the transfermium region experiments for ^{250}Fm, ^{251}Md and ^{254}No have been performed [27,28,29]. In the ^{254}No experiment, evidence was found for transitions from non-yrast states for the first time. The results of that measurement are presented in the contribution of Eeckhaudt *et al.*, in these proceedings [29]. A highlight of the JUROGAM experiments has been the study of ^{251}Md led by the CEA-Saclay group [28].

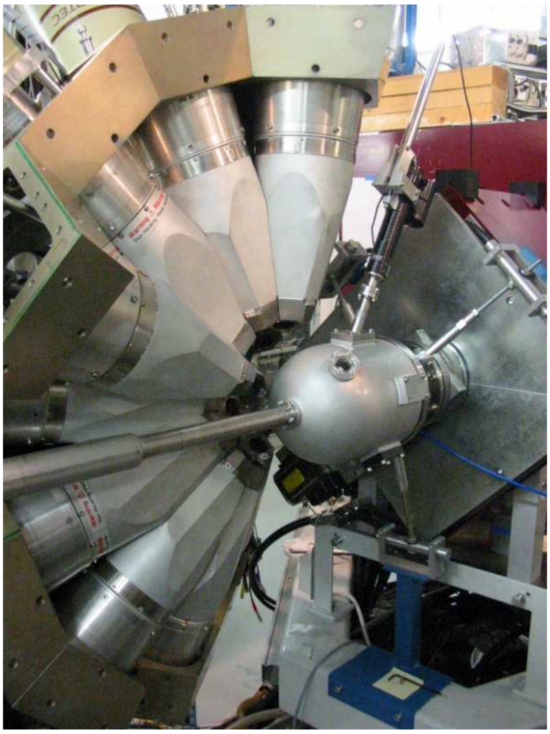

Fig. 3. The JUROGAM array of 43 Compton-suppressed Ge detectors installed at the target position of the RITU gas-filled recoil separator.

Gamma-ray spectroscopic studies of high-Z odd-mass nuclei can be strongly affected by the configuration of the odd particle. It can be expected that the decay intensity is strongly fragmented in many rotational bands. In well-deformed nuclei, the signature partners of strongly coupled bands will be linked by low-energy $M1$ transitions. The degree to which these interband $M1$ transitions compete with the intraband $E2$ transitions is governed by the magnitude of the $g_K - g_R$ term, and in the case of

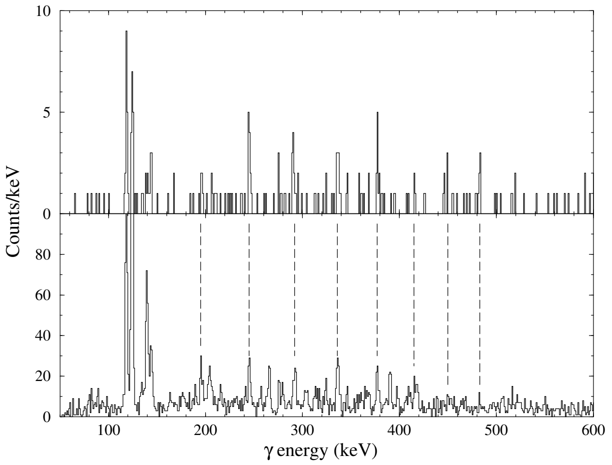

Fig. 4. Recoil-gated gamma-ray spectra of ^{251}Md obtained using the JUROGAM Ge array. Upper panel: sum of gamma-gamma coincidence spectra gated with the marked transitions. Lower panel: total gamma-ray singles spectrum.

$K = 1/2$ by the decoupling parameter, a, and the related magnetic decoupling factor, b. In ^{251}Md, theoretical calculations predict a $[521]\frac{1}{2}^-$ ground state, with $[633]\frac{7}{2}^+$ and $[514]\frac{7}{2}^-$ states at low excitation energies (see, *e.g.*, refs. [10,11]). The $K = 1/2$ configuration is calculated to have a decoupling parameter of around 0.9, which leads to the expectation that the decay sequence should be dominated by a single band of $E2$ transitions. The $[633]\frac{7}{2}^+$ configuration has a calculated g_K value of 1.3, resulting in a pair of strongly coupled bands and a decay sequence dominated by $M1$ transitions. The $[514]\frac{7}{2}^-$ configuration has a calculated g_K value of 0.7, again resulting in strongly coupled bands, but with the decay dominated by $E2$ transitions. The experiment employed the ^{205}Tl(^{48}Ca, 2n)^{251}Md reaction at a bombarding energy of 218 MeV. Gamma-ray spectra from the measurement are shown in fig. 4. The lower panel shows the total recoil-gated singles gamma-ray spectrum which was collected with an irradiation time of close to two weeks. The spectrum is dominated by Md X-rays (indicating strong internal conversion) and is somewhat complex. One clear rotational band can however be seen in the spectrum. The assignment of this sequence of peaks into a band is supported by the spectrum shown in the upper panel, which is a sum of gated gamma-gamma coincidence spectra. The gating transitions are marked. In the two spectra, there is no clear indication of a signature partner band, which leads to the tentative conclusion that the band is associated with the $K = 1/2$ configuration. Further analysis of this data is in progress and will be published in due course [28].

From the data obtained in the various experiments carried out at JYFL and ANL it has been possible to extract the dynamical moment of inertia, $\mathcal{J}^{(2)}$. Figure 5 shows the dynamical moment of inertia for the $N = 150$ isotones ^{250}Fm, ^{251}Md and ^{252}No along with ^{248}Fm (one point) and ^{254}No. The differing behaviour of ^{252}No and ^{254}No has been known for some time, and is well reproduced theoretically [11,30]. For the first time it has been possible to obtain systematic data for the nuclei in this region, and it is of interest to note the similarity in behaviour of the moment of inertia at higher spins in the $N = 150$ isotones. Obtaining systematic data on the $N = 152$ isotones may be an even greater experimental challenge, as the production cross-section for ^{256}Rf is approximately 15 nb, and that for ^{255}Lr around 300 nb.

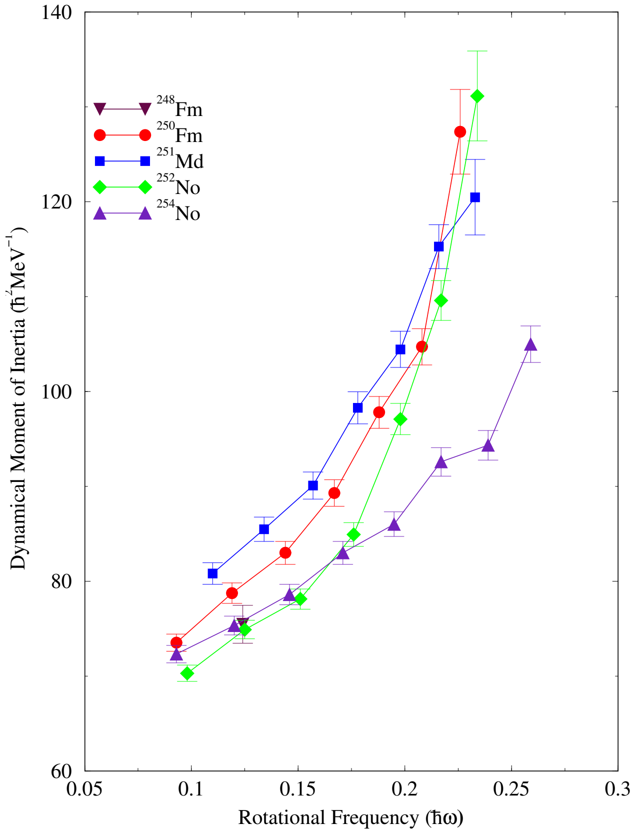

Fig. 5. Experimental dynamical moments of inertia for several transfermium nuclei.

4 Future prospects

The power of the recoil-gating and RDT techniques in both electron- and gamma-ray spectroscopic studies of very heavy nuclei has been clearly demonstrated. In the near future, the groups from the University of Liverpool, Daresbury Laboratory and JYFL will collaborate to develop a device to simultaneously measure gamma rays and conversion electrons. Based on the JUROGAM and SACRED spectrometers, the device will be known as SAGE. Such a system will allow the measurement of electron-gamma coincidences and will be a powerful tool for the investigation of heavy nuclei. Also under development is a system of digital electronics, which will allow higher detector counting rates to be used. This effectively means that higher beam intensities can be employed, giving greater statistics in a given irradiation time and lowering the spectroscopic limits still further. Even with the current combination of JUROGAM and RITU and conventional electronics, it may be possible to attempt the study of ^{256}Rf. Challenging studies of the odd-mass nuclei ^{253}No and ^{255}Lr are also planned for the near future.

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References

1. S. Ćwiok *et al.*, Nucl. Phys. A **611**, 211 (1996).
2. M. Bender *et al.*, Phys. Rev. C **60**, 034304 (1999).
3. M. Bender, P.-H. Heenen, P.-G. Reinhard, Rev. Mod. Phys. **75**, 121 (2003).
4. A.V. Afanasjev *et al.*, Phys. Rev. C **67**, 24309 (2003).
5. S. Hofmann, G. Münzenberg, Rev. Mod. Phys. **72**, 733 (2000).
6. M. Leino, F.P. Heßberger, Annu. Rev. Nucl. Part. Sci. **54**, 175 (2004).
7. M. Leino *et al.*, Nucl. Instrum. Methods B **99**, 653 (1995).
8. R.D. Page *et al.*, Nucl. Instrum. Methods B **204**, 634 (2003).
9. I.H. Lazarus *et al.*, IEEE Trans. Nucl. Sci. **48**, 567 (2001).
10. S. Cwiok, S. Hofmann, W. Nazarewicz, Nucl. Phys. A **573**, 356 (1994).
11. M. Bender, P. Bonche, T. Duguet, P.-H. Heenen, Nucl. Phys. A **723**, 354 (2003).
12. P.T. Greenlees *et al.*, to be published.
13. Ch. Theisen *et al.*, to be published.
14. P.A. Butler *et al.*, Acta. Phys. Pol. B **34**, 2107 (2003).
15. G. Mukherjee *et al.*, to be published in AIP Conf. Proc.
16. A. Ghiorso *et al.*, Phys. Rev. C **7**, 2032 (1973).
17. P. Reiter *et al.*, Phys. Rev. Lett. **82**, 509 (1999).
18. M. Leino *et al.*, Eur. Phys. J. A **6**, 63 (1999).
19. P.A. Butler *et al.*, Nucl. Instrum. Methods A **381**, 433 (1996).
20. H. Kankaanpää *et al.*, Nucl. Instrum. Methods A **534**, 503 (2004).
21. J.E. Bastin *et al.*, to be published in Phys. Rev. C.
22. R.D. Humphreys *et al.*, Phys. Rev. C **69**, 064324 (2004).
23. P.A. Butler *et al.*, Phys. Rev. Lett. **89**, 202501 (2002).
24. P. Reiter *et al.*, Phys. Rev. Lett. **84**, 3542 (2000).
25. T.L. Khoo *et al.*, submitted to Phys. Rev. Lett.
26. R.-D. Herzberg, J. Phys. G **30**, R123 (2004).
27. A. Pritchard *et al.*, to be published.
28. A. Chatillon *et al.*, to be published.
29. S. Eeckhaudt *et al.*, these proceedings.
30. T. Duguet, P. Bonche, P.-H. Heenen, Nucl. Phys. A **679**, 427 (2001).