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SPECTROSCOPY OF VERY HEAVY ELEMENTS*

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Recent results from spectroscopic studies of ^{254}No and ^{253}No, carried out at JYFL by using the JUROGAM-RITU-GREAT spectrometer system in in-beam and focal-plane tagging experiments, are presented and discussed.

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1. Introduction

Very heavy nuclei and heavy nuclei close to the proton-drip line can be produced via fusion-evaporation reactions with stable-ion beams and stable targets and can be identified by observing their characteristic particle-decay properties. These facts together with the short decay half-lives enable detailed off-beam and in-beam spectroscopic studies by employing tagging techniques. A major breakthrough was achieved when large Ge detector arrays were combined with the RITU gas-filled separator for Recoil-Decay-Tagging (RDT) experiments at JYFL. For the first time, it was shown that in-beam γ-ray spectroscopic studies of exotic α-decaying nuclei with production cross-sections down to ~ 20 nb are possible. The scientific results include first observations of excited states in around 50 isotopes with $Z = 52$–103.

Thanks to the nuclear shell effects, there are heavy nuclei with $Z > 100$ stable against fission. These shell effects are predicted to be large enough for creating an island of spherical super-heavy elements (SHE) around $Z = 114$–126, $N = 184$. Macroscopic–microscopic type calculations predict $Z = 114$, whilst HFB and RMF treatments tend to predict enhanced

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stability at $Z = 126$ and $Z = 120$, respectively [1]. Stringent tests for the various nuclear models used in these predictions would come from detailed spectroscopic studies of nuclei as close as possible to this region. The stability of known α-decaying trans-fermium nuclei around $Z = 102$ is supposed to originate from similar shell effects but in a deformed nucleus. Therefore, for testing nuclear models used to predict properties of SHE nuclei, it is important to test their performance in the trans-fermium region. Experimentally to be verified are the predicted deformation and moments of inertia as well as nucleon alignments.

Single-particle orbitals near the Fermi energy in deformed trans-fermium nuclei originate from single-particle orbitals near the Fermi energy of the expected spherical SHE nuclei. In order to determine the ordering and energies of the single-particle levels in the trans-fermium region more spectroscopic information is needed for odd-mass nuclei. The K isomers based on particle-hole excitations provide another approach for probing single-particle properties of trans-fermium nuclei. Such isomers have been found already in early alpha-decay experiments [2] and can further be studied in details by employing tagging methods.

The small production cross-sections make any kind of detailed spectroscopic studies of heavy elements extremely difficult. They are produced with available stable beams and targets in heavy-ion induced fusion-evaporation reactions. Due to fission, the production rates decrease rapidly with the proton number of the compound system, being down to 10 nb for example for the ^{40}Ar + ^{208}Pb reactions.

However, by using the doubly magic projectile ^{48}Ca and Pb, Bi or Hg targets, exceptionally high cross-sections of cold fusion evaporation reactions are obtained. Especially, the fusion of two doubly magic nuclei in the ^{208}Pb(^{48}Ca,$2n$)^{254}No reaction leads to an anomalously high production cross-section of around 2 μb providing a unique opportunity for probing single-particle and collective properties of near-yrast states in ^{254}No via focal-plane and in-beam experiments . In the similar ^{48}Ca induced reactions on the ^{204}Hg, ^{206}Pb, ^{207}Pb and ^{209}Bi targets, ^{250}Fm, ^{252}No, ^{253}No and ^{255}Lr are produced with cross-sections of 300–1000 nb. For the conventional in-beam spectroscopic measurements these yields are still far too low but are above the limit of sensitivity obtained in recent in-beam γ-ray experiments, where the RDT method has been employed. Moreover, a unique feature of the cold fusion-evaporation reactions leading to this heavy mass region is that basically only one reaction channel, in this case the $2n$ channel is open, which makes the channel selection easy compared to that in lighter nuclei.

In the present contribution, results from in-beam and focal-plane spectroscopic studies of ^{254}No are summarized. New results from in-beam studies of ^{253}No are presented and discussed. The experiments were carried out in the Accelerator Laboratory of the Department of Physics of the University of Jyväskylä (JYFL). The collaboration involved JYFL, University of Liverpool (UK), GSI (Germany), CEA-DAPNIA-Saclay (France), University of Helsinki (Finland), University of Köln (Germany), Argonne National Laboratory (USA) and Comenius University (Slovakia).

2. Instrumentation

The RITU separator at JYFL combined with the detector systems for prompt radiation at its target area and for delayed radiation at its focal plane, forms one of the most efficient facilities for spectroscopy of exotic heavy nuclei.

The gas-filled recoil separator RITU (Recoil Ion Transport Unit) was designed to separate residues of fusion-evaporation reactions from beam particles and from other reaction products, especially fission [3]. Recently a new focal plane spectrometer GREAT funded by the UK institutes has been constructed for RITU [4]. In the GREAT spectrometer the fusion evaporation residues and their particle decay are detected by a pair of double-sided silicon strip detectors (DSSSD). The strip pitch of the DSSSD's is 1 mm in both directions resulting in a total of 4800 pixels and enabling an identification of residues on the basis of their decay properties. Consequently, prompt γ-rays emitted by the fusion residues detected at the target area can be identified with high sensitivity (RDT technique). A transmission multi-wire proportional counter (MWPC) in front of the DSSSD's is used for further cleaning of the recoil and particle spectra of the DSSSD's. Behind the DSSSD's a planar double-sided germanium strip detector is used for detection of delayed γ-rays and X-rays from isomers and decay products. Higher-energy γ-rays are detected by large-volume segmented clover germanium clover detectors. The detection system is completed by a box of silicon PIN diode detectors surrounding the DSSSD's, which can be used to detect escaping alpha-particles or conversion electrons.

Since April 2003 the JUROGAM array has been used to detect prompt γ-rays at the target area. It consists of 43 Eurogam Phase-I type of Compton suppressed detectors and has a photo-peak efficiency of 4% for 1.3 MeV γ-rays.

The SACRED magnetic solenoid spectrometer was used to obtain in-beam electron spectra from heavy nuclei in RDT measurements at RITU [5]. In SACRED, conversion electrons emitted from the target into backward angles are guided by the solenoid field and distributed over a Si detector (diameter 2 cm), which is divided into 25 independent pixels enabling to detect electron–electron coincidences from cascades of highly converted transitions.

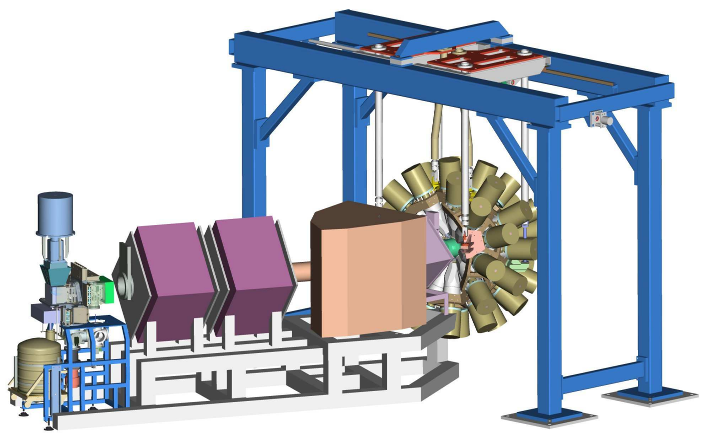

Fig. 1. The combination of the GREAT, RITU and JUROGAM devices employed in heavy element spectroscopy at JYFL. (Courtesy of D. Seddon, University of Liverpool.)

As a part of the GREAT project, a new type of data acquisition system, known as Total Data Read out (TDR) [6], has been developed. It operates without any hardware trigger, and is designed to minimize dead time in the acquisition process. All detector electronic channels run independently and are associated in software, the data words all being time-stamped from a global 100 MHz clock.

3. Recent spectroscopic studies of ^{254}No

In our earlier experiments, the observation of discrete γ-ray lines from a rotational cascade of transitions up to $I = 20\,\hbar$ in ^{254}No [7], ^{252}No [8] and ^{250}Fm [9] reveals that these trans-fermium nuclei are indeed deformed and can in rotation compete against fission up to at least that spin. The kinematic moment of inertia values for these nuclei derived from the observed transition energies are approximately half of the rigid rotor value and are slightly increasing with spin (Fig. 2), obviously due to gradual alignment of quasi-particles. For ^{252}No the extracted values increase more rapidly at high spin indicating a more dramatic alignment of quasi-particles. The kinematic moment of inertia values for ^{250}Fm are almost identical to the ^{254}No ones at low spin but then follow the alignment pattern of ^{252}No at higher spin.

It is possible to extract the ground state deformation parameter β_2 from the extrapolated energy of the 2^+ state using global systematics [10,11]. The value we derived for ^{254}No is $\beta_2 = 0.27$, which is in good agreement with the values calculated using the macroscopic–microscopic method [12,13]. A β_2 value similar to that of ^{254}No is obtained for ^{250}Fm. The extracted value of $\beta_2 = 0.26$ for ^{252}No indicates that ^{252}No is slightly less deformed than ^{254}No and ^{250}Fm.

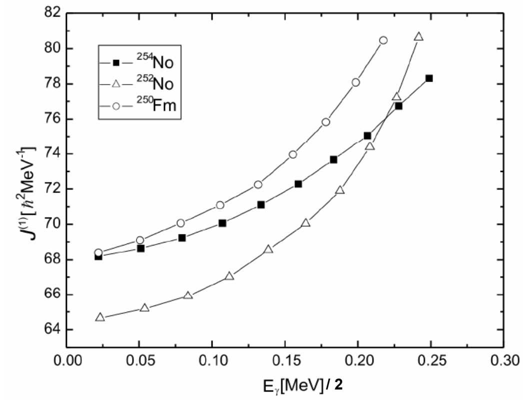

Fig. 2. Kinematic moments of inertia for ^{254}No, ^{252}No and ^{250}Fm extracted from the measured γ-ray energies.

The ^{254}No experiment was repeated by employing the JUROGAM array in connection with the upgraded RITU separator. A resulting recoil gated in-beam γ-ray spectrum is shown in Fig. 3. The yrast line is seen up to $I = 24\,\hbar$ and there are peaks in the spectrum representing linking transitions from sidebands in ^{254}No. The energy spacing between the marked 943 and 842 keV lines is equal to the energy spacing between the 2^+ and 4^+ states of the ground state band. Therefore, the corresponding transitions must de-excite a strongly fed non-yrast state of spin 3. Obviously feeding of such a state takes place via a fast highly converted M1 cascade not visible in the in-beam γ-ray spectrum.

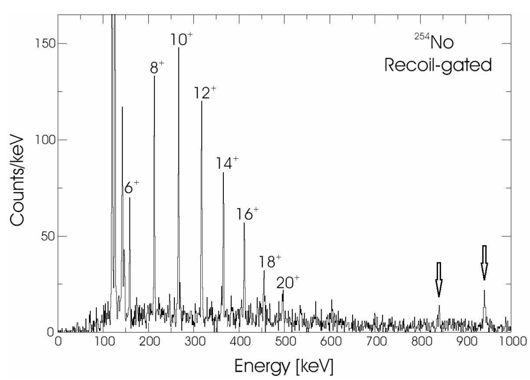

Fig. 3. Recoil gated singles γ-ray spectrum of ^{254}No detected by the JUROGAM array at RITU.

More support for this assumption was obtained in an in-beam experiment, where the SACRED spectrometer combined with RITU was used to measure prompt conversion electrons tagged with evaporation residues from the ^{208}Pb(^{48}Ca,2n)^{254}No reactions [14]. From the resulting electron spectra it was concluded that a significant part of de-excitations towards the ground state of ^{254}No proceeds via highly converted M1 cascades.

A focal plane experiment at RITU was performed for the investigation of delayed radiation from possible K-isomers in ^{254}No by employing the same reaction and the GREAT spectrometer [15]. Two isomeric states were identified, one of them associated with the $T_{1/2} = 280$ ms isomer found 33 years ago [2]. To obtain detailed spectroscopic information a calorimetric method [16] was used: The recoil-gated energy signal representing the energy sum of cascade conversion electrons and Auger electrons absorbed in the same pixel of the GREAT-DSSSD detector was used to gate γ-rays detected by the segmented Planar Ge detector and the large Clover Ge detector of GREAT. The resulting spectra for the decay of the long-living isomer in Fig. 4 demonstrate the power of the GREAT spectrometer. The strong L X-ray peaks reveal that most of the low-energy peaks marked in the spectrum of the planar Ge detector are due to M1 transitions, obviously originating from a rotational band fed in the decay of the isomer. The isomeric state is assumed to be de-excited by the 53 keV E1 transition appearing as a strong γ-ray line in the spectrum. The 841 and 943 keV lines seen in the in-beam spectrum also appear in the spectrum of the Clover detector and have an M1 character. Consequently, the isomer feeding the M1 band presumably has $I^\pi = 8^-$ and the band head is a 3^+ state, which is de-excited by the 841 and 943 keV transitions to the yrast states. A more detailed

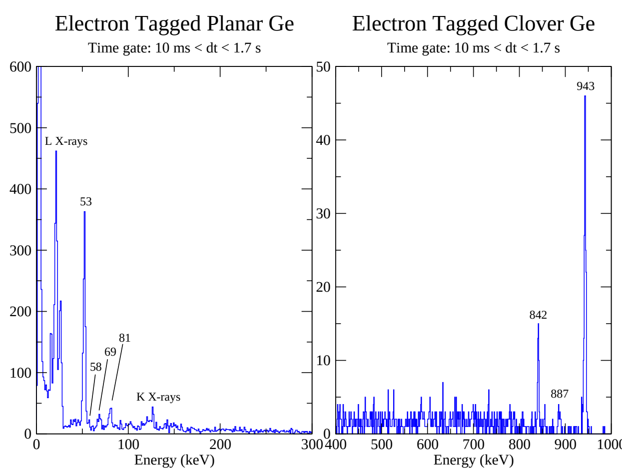

Fig. 4. Gamma-ray spectra following the de-excitation of the $T_{1/2} = 280$ ms isomer in ^{254}No. The spectra are gated with a sum signal of conversion electrons and collected by the Planar and the Clover Ge detectors of the GREAT spectrometer at the focal plane of RITU.

study of the transition energies and M1/E2 ratios of the band render it possible to associate the 3^+ state with a proton two-quasi-particle configuration and to locate the 8^- isomer at 1293 keV in excitation energy (Fig. 5). In earlier microscopic–macroscopic calculations both neutron- and proton two-quasi-particle 8^- state have been calculated at around this excitation energy, whilst the more recent mean field calculations cannot reproduce such a low-lying state [17]. The summed electron energies and γ-rays emitted in the decay of the other isomer with $T_{1/2} = 184\mu$s indicate that it lies at around 2.5 MeV and could be the 16^+ state representing the product of two-proton and two-neutron choices for the 8^- isomer.

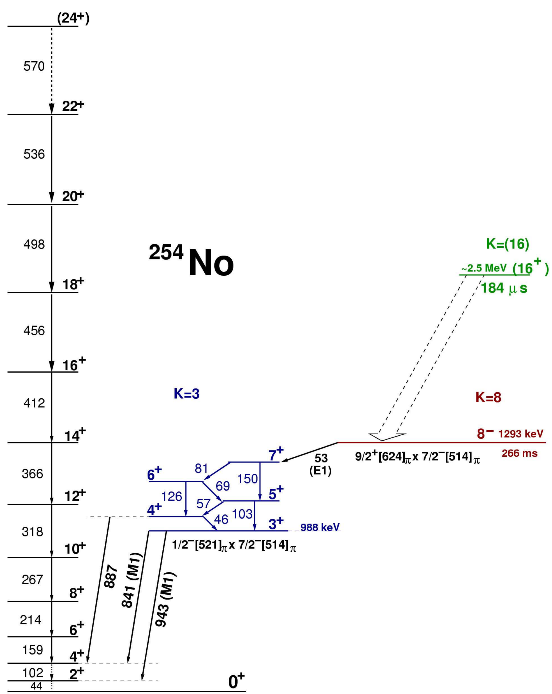

Fig. 5. Level scheme of ^{254}No deduced in experiments carried out at JYFL [15].

4. In-beam spectroscopy of ^{253}No

The first in-beam study of the odd-neutron nucleus ^{253}No was carried out at Argonne National Laboratory [18], by employing the GAMMASPHERE array at FMA. In a careful study of γ-ray coincidence spectra a strongly-coupled rotational band was constructed. The observed structure was assigned the $7/2^+[624]$ configuration, the band-head being placed at an excitation energy of 355 keV above the $9/2^-[734]$ ground state. A complementary tagging measurement of prompt conversion electrons from the ^{207}Pb(^{48}Ca,$2n$)^{253}No reactions was carried out using the SACRED electron spectrometer at JYFL. The spectra seemed to show that the electrons observed were more likely to come from a strongly-coupled rotational structure based upon the $9/2^-[734]$ state. A further in-beam γ-ray spectroscopic measurement was carried out at JYFL using JUROGAM at RITU. The total recoil-gated γ-ray singles spectrum obtained is shown in Fig. 6 [19]. The level of statistics obtained is greater than that of the previous study, and at low energy a number of small peaks are visible which clearly originate from the previously unobserved inter-band M1 transitions between the two signatures of the strongly coupled band. The level scheme of the previous study [18] is confirmed but the preliminary results from the coincidence and M1/E2 γ-ray branching ratio analysis favor the $9/2^-[734]$ assignment for the band.

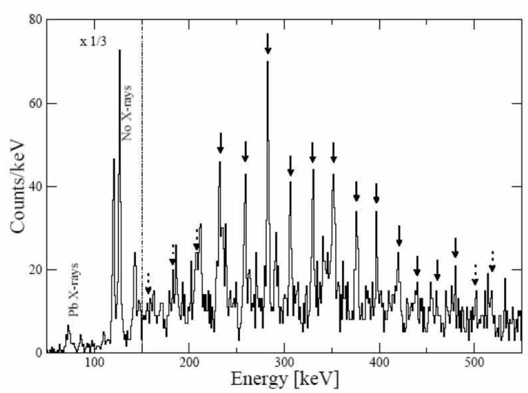

Fig. 6. Recoil gated singles γ-ray spectrum of ^{253}No detected by the JUROGAM array at RITU.

5. Perspectives

For more detailed spectroscopic studies of very heavy nuclei further developments of instrumentation are in progress. Clearly a spectrometer capable to obtain in-beam γ-ray conversion electron coincidence information is called for. A project, called SAGE, for the design and construction of such a spectrometer for tagging measurements has been funded by the EPSRC of the UK.

In general, it is important to combine information extracted both from in-beam and decay studies. The beam intensity in in-beam studies is limited by the counting rates of the detectors at the target area. In case of γ-ray detection this limit is typically 10 000 counts per second per germanium detector. Today several projects are going on for developments of digital front-end electronics for such detectors. It is expected that in this way the detector rate limits can be increased up to 100 000 counts per second. In terms of beam intensity this increase represents a step from approximately 10 to 100 pnA on a 1 mg/cm^2 target. Such an increase will push the limit of in-beam spectroscopy down to a level of few nanobarn in the production cross-section. In the off-beam focal plane studies of heavy nuclei the maximum beam intensity (up to several $p\mu$A) is typically set by the durability of the target.

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