In-beam gamma-ray spectroscopy of very heavy elements

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Abstract

Data from in-beam gamma-ray spectroscopic experiments using recoil gating and recoil-decay-tagging (RDT) techniques carried out at the Jyväskylä Accelerator Laboratory (JYFL) for ^{254}No, ^{252}No, ^{250}Fm and ^{255}Lr are presented. The results and the future plans are discussed.

1 Introduction

Coulomb energy of the heavy nuclei with $Z > 100$ is so large that in the liquid drop picture these nuclei should be unstable against spontaneous fission. However, it has been shown theoretically that the nuclear shell correction energy is large enough for creating an island of spherical superheavy elements around $Z = 114$, $N = 184$. Moreover, the discoveries of alpha-decaying new elements up to $Z = 118$ reveal that this island is not separated from the continent of known nuclei by the see of fission as originally expected. The stability of these nuclei with $Z > 100$ is supposed to originate from the shell effects in a deformed nucleus. The most important component is the quadrupole deformation and a deformed shell gap appears at $N = 152$. It is important to verify the predicted deformations experimentally.

Properties of superheavy elements can be calculated using the Nilsson-Strutinsky shell-correction approach. The success of such approaches is closely related to the knowledge of the single-particle levels near the Fermi surface. Current theoretical models give different predictions of the proton and neutron magic numbers beyond $Z = 82$ and $N = 126$. Spectroscopic studies of the heaviest odd-mass nuclei are therefore of importance in order to determine the ordering and energies of the single-particle levels in this region.

Most of the scarce experimental information on the structure of heaviest nuclei has been obtained in alpha-decay studies [1, 2, 3]. Excited states up to $I^{\pi} = 8^{+}$ in ^{256}Fm have been seen in the beta-decay of the isomeric 8^{+} state of ^{256}Es [4]. Coulomb excitation has been used to populate excited states of ^{248}Cm up to a 5.1 MeV 30^{+} state [4].

In the present contribution, results from in-beam gamma-ray spectroscopic studies of heavy actinide nuclei, ^{254}No [5], ^{252}No [6] and ^{250}Fm produced in cold fusion-evaporation reactions have been presented. An important goal of these studies has been experimental establishment of deformation by determining level energies in the ground state bands. First attempts to study an odd-mass transfermium nucleus ^{255}Lr are also 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), ANL-Argonne (U.S.A.) and LMU University (Germany). Finally, future plans and developments going on are discussed.

2 Production cross-sections

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 about 2 μb providing a unique opportunity for an in-beam experiment on a transfermium nuclide. In the similar ^{48}Ca induced reactions on the ^{204}Hg, ^{206}Pb and ^{209}Bi targets, ^{250}Fm, ^{252}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 gamma-ray experiments, where the novel Recoil-Decay-Tagging (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.

3 RDT measurements at RITU

The gas-filled recoil separator RITU (Recoil Ion Transport Unit) has been designed to separate residues of fusion-evaporation reactions from beam particles and other reaction products, especially fission [7]. The position sensitivity of the focal plane Si detector of RITU enables the recoils to be correlated with their subsequent particle decay (so far α decay).

In the in-beam gamma-ray experiments at RITU the Jurosphere and SARI arrays have been used to detect prompt gamma-rays at the target area. The Jurosphere array consisted of 25 Compton-suppressed Ge- detectors (15 Eurogam Phase 1, 10 Nordball and/or TESSA detectors) and had a photo-peak efficiency of 1.5 - 1.7 % for 1.3 MeV gamma rays. The SARI array was a combination of four Ge- clover detectors, three of them segmented, placed in a close geometry. The photo-peak efficiency of the SARI array was 1.7 % when operated in add-back mode. The clover detectors didn't have any Compton suppression shields and therefore the resolving power in the observed spectra was not as good as for those obtained with the Jurosphere array.

Since 1997, about 60 gamma-ray recoil-tagging or RDT experiments have been carried out at RITU. In most of those experiments structures of neutron deficient nuclei close to $Z = 82$ have been probed. Excited states were identified, for the first time, in more than 30 nuclides. In these experiments we have shown that the RDT method employed at RITU enables in-beam gamma-ray spectroscopy at the level of 100 nb production cross-section for heavy nuclei. As in a typical in-beam experiment a beam of about 10 pnA on a 0.5 mg/cm^2 target is used, the 100 nb cross-section represents a reaction rate of only about 40 per hour!

4 The ^{254}No experiment

The ^{48}Ca beam was delivered by the ECR ion source and the JYFL K=130 MeV cyclotron. The self-supporting stationary target was an enriched (99 %) ^{208}Pb metallic foil with a thickness of about 500 μg/cm^2. The RITU separator and the SARI clover-detector array were employed for collecting in-beam gamma-ray tagging data. The beam intensity limited by the clover-detector counting rates was about 10 pnA.

The maximum yield of ^{254}No alpha particles at the focal plane was observed at a bombarding energy of 216 MeV, as measured in the middle of the target. By using the value of 25 % for the RITU transmission this yield gives a cross-section of about 2 μb for the ^{208}Pb(^{48}Ca,2n)^{254}No reaction. The collected singles alpha-particle energy spectrum is dominated by three peaks from ^{254}No

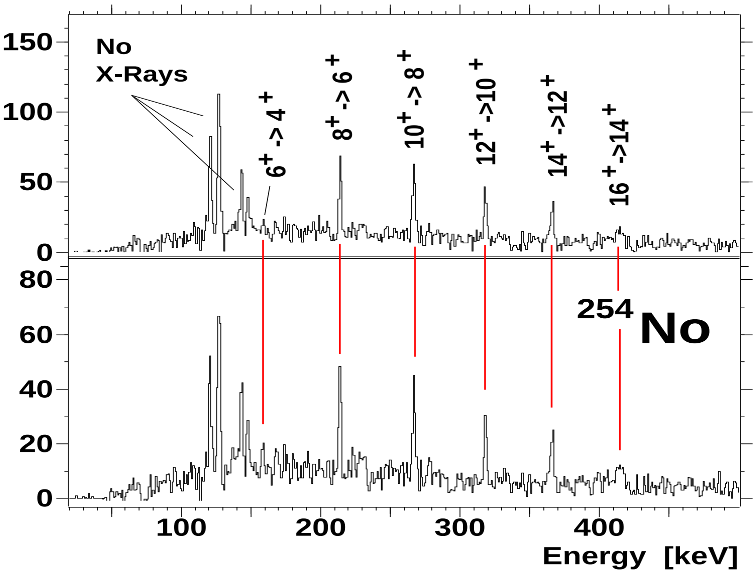

Figure 1: A singles gamma-ray spectrum from the ^{48}Ca + ^{208}Pb reactions gated with fusion-evaporation residues (upper). The same gamma-ray spectrum but in addition, tagged with the ^{254}No alpha decays (lower).

(8.09 MeV) and its decay products ^{250}Fm (7.43 MeV) and ^{246}Cf (6.75 MeV). A half-life of (48 ± 3) s was derived from the alpha-recoil time distribution for the ^{254}No alpha decay, which is slightly shorter than the previously published value of (55 ± 5) s [8].

Figure 1 (upper) shows a spectrum of gamma-rays observed in coincidence with recoil events falling within the selected energy window and a 100 ns wide time window in the gamma-recoil TAC spectrum. In Figure 1 (lower) the gamma-ray spectrum in coincidence with fusion products identified as ^{254}No nuclei on the basis of recoil-alpha correlations is shown. The maximum search time used was 200 s.

In addition to No X-rays transitions having energies of 158.9, 214.1, 267.2, 318.2, 266.5 and 414.0 keV were observed and assigned to originate from ^{254}No. The first five of these transitions were observed, for the first time, in a similar tagging experiment at ANL [9]. The pattern of the gamma-ray peaks in the spectra of Figure 1 reveals that the corresponding transitions form a cascade, obviously of E2 transitions in ^{254}No. In a later experiment at ANL, carried out with a bombarding energy of 219 MeV, two transitions of 456 keV and 498 keV following the same pattern were observed [10].

A very good fit to the kinematic moments of inertia derived from the observed transition energies of ^{254}No is obtained with Harris parameters of $J_0 = 68.2\ \hbar^2/\mathrm{MeV}$ and $J_1 = 162.4\ \hbar^4/\mathrm{MeV}^3$ when the observed lowest energy transition of 158.9 keV is assigned as the $6^+ \rightarrow 4^+$ transition. The extrapolated energies for the highly converted $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ transitions are (44.2 ± 0.4) keV and (102.0 ± 0.3) keV, respectively.

5 The ^{252}No experiment

Encouraged by the successful ^{254}No experiment, another similar tagging experiment was carried out to study excited states in ^{252}No. Now the ^{206}Pb(^{48}Ca,2n)^{252}No reaction at the beam energy of 215.5 MeV in the center of the 500 μg/cm^2 target was used. The SARI array was replaced by the Jurosphere array consisting of Compton suppressed Ge- detectors and consequently, much higher peak-to-total ratios were obtained than with the SARI array. The beam current was about 20 pnA and the total number of the detected ^{254}No alpha decays was 2800. Taking into account the 19 % fission- and 23 % β^+- decay branches of the ^{252}No ground state, this number converts to a cross-section of only about 300 nb for the ^{206}Pb(^{48}Ca,2n)^{252}No reaction. A half-life of (2.4 ± 0.3) s from the recoil-alpha time distribution was extracted for the ^{252}No ground state. This value is well in accordance with the ones from the earlier measurements.

Gamma-ray transitions of 167, 224, 278, 329, 376, 417, 453 and 484 keV in the ground state band of ^{252}No were assigned in an RDT analysis of the collected data. The resulting recoil gated and alpha tagged spectra of gamma-rays from ^{252}No are shown in Figure 2. The level scheme and spin assignments are based on a Harris fit and the comparison of the transition energies to those ones of ^{254}No. For the 2^+ state an energy of 46.4 ± 1.0 keV was extrapolated.

6 The ^{250}Fm experiment

The Jurosphere array was further employed in a tagging experiment to collect gamma-rays from the ^{204}Hg(^{48}Ca,2n)^{250}Fm reaction. A ^{48}Ca beam of 209 MeV in the center of a ^{204}HgS target was used. The target consisted of two foils each representing a 250 μm/cm^2 thickness of the ^{204}Hg isotope. The observed rate of 65 evaporation residues per hour at the focal plane of RITU with a beam current of 8 pnA represents a cross section of 1 μb for the production of ^{250}Fm.

A recoil-gated gamma-ray spectrum shown in the upper part of Figure 3,

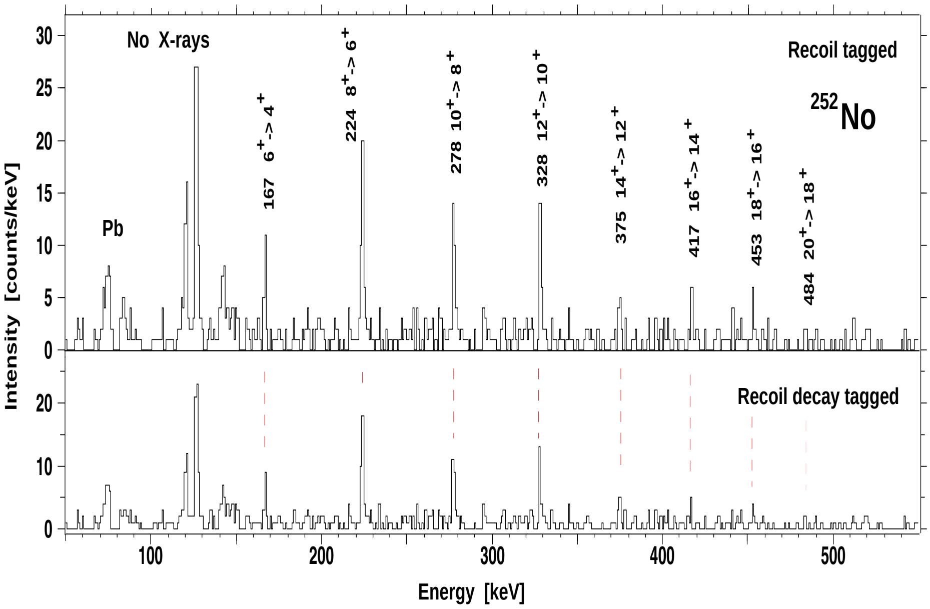

Figure 2: A recoil gated singles gamma-ray spectrum (upper) from the ^{48}Ca + ^{206}Pb reactions. The same spectrum but in addition tagged with the ^{254}No alpha decays (lower).

reveals Fm X-rays and a regularly spaced peaks obviously representing the yrast gamma rays from ^{250}Fm. This is confirmed in the lower part of Figure 3, which shows the corresponding alpha-tagged RDT spectrum. By using a Harris fit similar to ^{254}No and ^{252}No, the spin assignments shown in Figure 3 can be made. The exrapolated energy for the 2^+ state of ^{250}Fm is 44.0 ± 1.0 keV.

7 Discussion on the results for ^{254}No, ^{252}No and ^{250}Fm

The observation of discrete gamma-ray lines of transitions from levels with $I = 16 - 20$ reveals that these transfermium nuclei can compete against fission up to at least that spin.

The moment of inertia values for ^{254}No, ^{252}No and ^{250}Fm derived from the observed transition energies are about half of the rigid rotor value and are slightly increasing with spin (Figure 4), obviously due to gradual alignment of quasiparticles. For ^{252}No the measured values increase more rapidly at high spin indicating a more dramatic alignment of quasiparticles. Cranked Shell

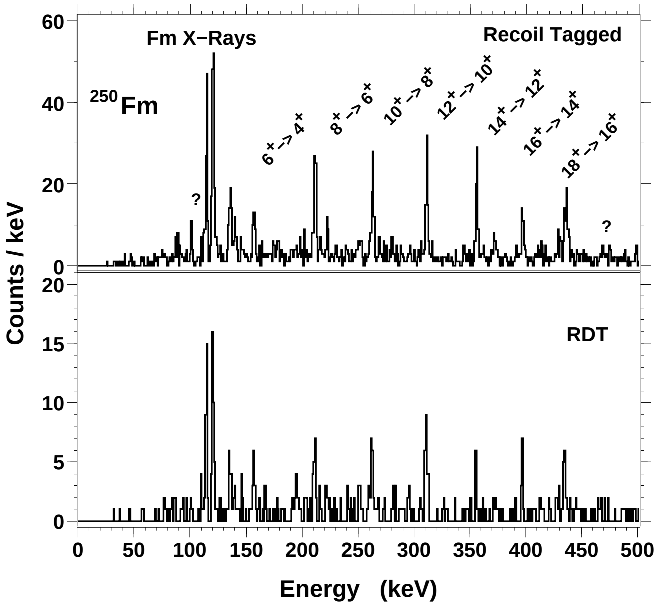

Figure 3: A recoil gated singles gamma-ray spectrum (upper) from the ^{48}Ca + ^{204}Hg reactions. The same spectrum but in addition tagged with the ^{250}Fm alpha decays (lower).

Model calculations were performed for ^{252}No and ^{254}No by using the deformed Woods-Saxon potential with "universal" parametrization [11] and deformation parameters from ref. [12]. These calculations show that in ^{254}No an alignment of two $h_{11/2}$ neutrons should take place at a transition energy of about 500 keV while in ^{252}No it should happen already at 440 keV. Therefore the observed upbend in ^{252}No can be associated with this alignment. The 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_1^+ state using global systematics [13, 14]. The value we derived for ^{254}No is $\beta_2 \approx 0.27$, which is in good agreement with the values calculated using the macroscopic-microscopic method [15, 16]. A β_2 value similar to ^{254}No is obtained for ^{250}Fm. The extracted value of $\beta_2 = 0.26$ for ^{252}No indicated that ^{252}No is less deformed than ^{254}No and ^{250}Fm.

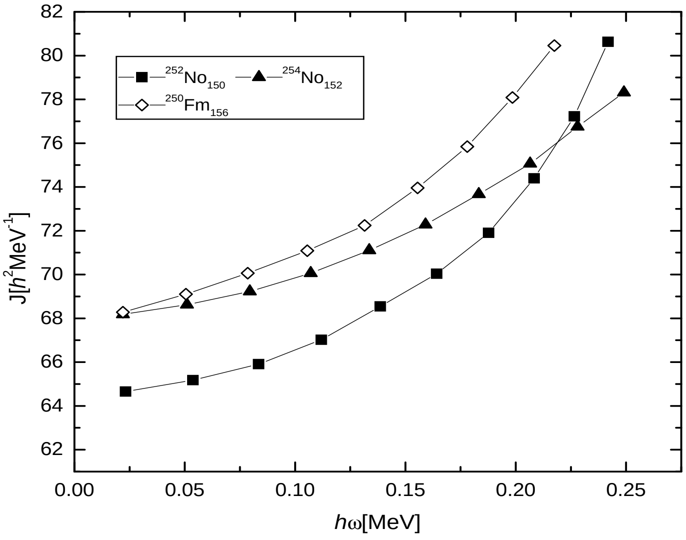

Figure 4: The kinematic moments of inertia for ^{250}Fm (diamonds), ^{252}No (squares) and ^{254}No (triangles).

8 The ^{255}Lr experiment

An RDT experiment similar to that for the even-mass No nuclei was carried out to study excited states in ^{255}Lr. The ^{209}Bi(^{48}Ca,2n)^{255}Lr reaction at a bombarding energy of 221 MeV was used. About 2200 correlated recoil-alpha pairs were observed corresponding to a reaction cross-section of about 300 nb. In the prompt recoil-gated and recoil-gated and alpha-tagged gamma-ray spectra, no clear candidates for gamma-ray transitions in ^{255}Lr was observed. However, the observation of strong Lr X-ray peaks in these spectra implies that the yrast transitions in ^{255}Lr are strongly converted. Consequently, when comparing the ^{255}Lr spectra with the ^{252,254}No spectra, it is obvious that the decay along the yrast line of ^{255}Lr does not proceed via a cascade of E2 transitions but rather via a cascade of M1 transitions. This decay might well be more complicated depending on the coupling of the odd proton i.e. on the orbital the odd proton occupies and the related g-factor.

9 Future plans

In the in-beam experiments discussed above the maximum current of the ^{48}Ca beam on the target was limited by the counting rate of the Ge detectors. A large contribution of this rate was due to scattering of the beam in the He gas and the gas window situated upstream of the target. For suppressing this background a differential pumping system near the target is now available for the future experiments.

Many unidentified weak gamma-ray lines are seen in the singles spectra of Figures 1, 2 and 3. It is obvious that coincidence information is needed to find the origin of those lines. For this reason, in the 2003 in-beam gamma-ray campaign at the RITU separator at JYFL, the 1.7 % Jurosphere array will be replaced by a 4 % JuroGam array of 45 Eurogam Phase 1 detectors.

As in an alpha decay excited states of the final nuclei are also fed and as there are long-living isomeric states expected in heavy nuclei, a sophisticated focal plane spectrometer is needed at RITU. For these purposes a novel GREAT spectrometer system has been designed by the UK physicists and is now available for the 2003 campaign.

For E2 transitions below 230 keV and M1 transitions below 440 keV, internal electron conversion dominates over the gamma-ray emission in nuclei with $Z \approx 102$. Therefore, especially in the study of odd-mass heavy nuclei methods of in-beam conversion-electron spectroscopy are called for. For these purposes an electron spectrometer, SACRED, has been constructed [17]. Recent results from SACRED experiments at RITU are discussed in the contribution of R.-D. Herzberg.

Acknowledgements

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