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THE STRUCTURE OF HEAVY OCTUPOLE AND SUPERHEAVY QUADRUPOLE DEFORMED NUCLEI*

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We report here experimental attempts to determine the sign of the electric dipole moment (relative to the electric octupole moment) in the octupole deformed nucleus ^{226}Ra. Sensitivity to this quantity is observed in the measured yields of γ-ray transitions following very low energy Coulomb excitation. Recent progress is also reported in the development of new spectroscopic techniques that promise to elucidate the structure of deformed superheavy nuclei in the region of ^{254}No. The $4^+ \rightarrow 2^+$ transition in ^{254}No, as well as higher spin transitions, has been identified using recoil-tagged conversion electron spectroscopy.

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1. Introduction

From a historical perspective, the calculation of the electric dipole moment in pear-shaped nuclei has presented a challenge. The earliest calculations using the liquid-drop model predicted opposite signs for the electric dipole moment, defined with respect to the intrinsic nuclear frame [1,2]. There has been a long standing prediction [3,4] that the sign of the E1 moment changes for Ra isotopes as the mass is increased from 222 to 226. This arises from the shell correction to the bulk (droplet) contribution which becomes increasingly negative as N increases. The latter macroscopic-microscopic calculations successfully reproduce the near exact cancellation for the E1 moment which has been observed for ^{224}Ra [5]. The experimental challenge is to measure the sign of the electric dipole moment. While a measurement of this quantity in isolation is impossible, it is in principle possible to measure the sign of the E1 moment relative to the E3 moment for a mixed nuclear transition. While γ-ray decay properties depend very weakly on the E3 admixture and Coulomb excitation at close nuclear distances has little dependence on the E1 admixture, the latter can become sensitive to the relative amount of E1 and E3 for an optimal distance of closest approach. In the first part of this paper, we describe an experiment to measure the relative phase of the E1, E3 moments in which the sensitivity of low energy Coulomb excitation to this quantity was exploited.

The understanding of the structure of the heaviest, in particular SuperHeavy Elements (SHE), is essential for the development of mean field theories that are used to predict nuclear properties far from stability. Experimental insight into the structure of superheavy spherical nuclei can be obtained by direct measurement of the ground state properties of nuclei. Attempts to reach the spherical SHE have been made in recent years and candidates for alpha decay from several nuclei with $Z = 114$–118 have been reported [6,7]. Equally important information can come from the study of mid-shell deformed nuclei, since selected single particle orbitals that lie close to the spherical shell gap in SHE are close to the Fermi level in nuclei having large quadrupole deformation. Such information can come from alpha-decay studies or from in-beam spectroscopy. In the latter technique the prompt decay process is tagged by detection of the recoiling nucleus or by alpha decay from the recoil, using electromagnetic separators. In this manner, in-beam gamma-ray spectroscopy has enabled the rotational behaviour of the even–even nucleus ^{254}No to be studied up to spin $20\,\hbar$ [8,9]. In these experiments the reaction products, although populated with small cross sections ($\sigma < 3\mu$barn), have been separated from the dominant fission background.

In the second part of this paper we report here a new experimental method that promises greater flexibility than γ-ray spectroscopy in the study of heavy nuclei. Our technique allows the direct detection of internal conversion electrons emitted at the target and their tagging by recoil detection or Recoil Decay Tagging (RDT), using a broad-range, high efficiency electron spectrometer. The sensitivity of the technique is demonstrated here by applying it to the measurement of the rotational band in ^{254}No, in which conversion electrons corresponding to transitions from the $4^+ \to 2^+$ up to the $12^+ \to 10^+$ were observed in a relatively short running time. This technique has numerous applications in the study of heavy nuclei where internal conversion is a probable process, such as odd-mass nuclei whose decay sequence is dominated by low energy M1 transitions, superdeformed nuclei that decay by low energy E2 transitions, or spherical-deformed shape coexistent nuclei whose low lying states decay by E0 transitions to the ground state.

2. Measurement of sign of electric dipole moment

Calculations using the (semi-classical) Coulomb excitation least-squares-search code GOSIA [10] suggest that, if the bombarding energy of a mass 40 projectile is about 1.5 MeV/A, the population of the 1^- state in ^{226}Ra is very sensitive to the assumed relative sign of the E1 and E3 matrix elements.

In an experiment carried out at the University of Jyväskylä a beam of 2 pnA ^{40}Ar irradiated a ^{226}Ra target of thickness $200\mu\text{g/cm}^2$. A parallel plate avalanche counter was employed to detect the backscattered ^{40}Ar ions over an angular range 115°–146° in the laboratory frame with precision of 2°. The γ-rays were detected using an array of 4 Compton suppressed TESSA detectors and 4 EUROGAM phase I detectors at 60° and 120° to the beam direction. The total peak efficiency of the array at 200 keV was about 1.5 %. The beam energy, produced using fourth harmonic acceleration in the JYFL $K = 130$ cyclotron, was 60 MeV. At this energy the yield of the 1^- state in ^{226}Ra changes by 30 % if the sign of the E1/E3 phase changes.

The yield of the 186 keV $1^- \to 2^+$ transition in ^{226}Ra (see figure 1) had a statistical uncertainty of 20 %. The largest contribution to the error came from the random background, which arises from the γ-ray radioactivity from ^{226}Ra (in particular the 186 keV transition in ^{222}Rn) and the elastic scattering rate. A full variational procedure was employed, in which the data were fitted, using GOSIA, by varying all E1, E2 and E3 matrix elements. In this case the data consisted of the measured yields and the previously measured matrix elements in ^{226}Ra [11]. In the fitting procedure it was assumed that the relative phase of the E1 moments to the E3 moments is given by the rotational model, and that the sign of (Q_1/Q_3) is either

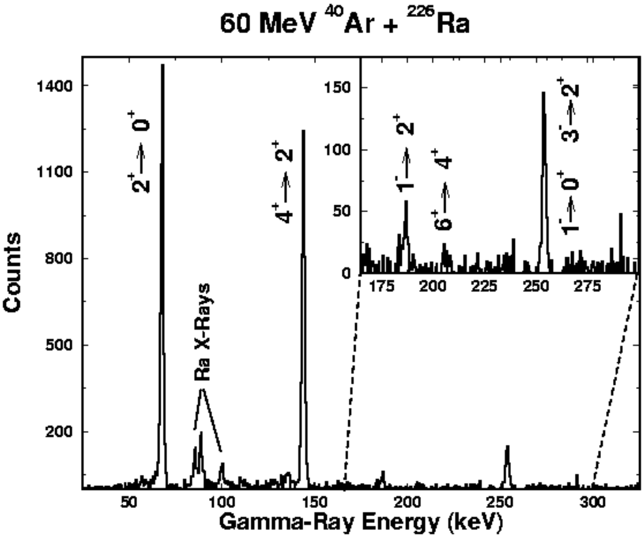

Fig. 1. Gamma-ray spectrum measured in coincidence with backscattered projectiles following the reaction 60 MeV ^{40}Ar + ^{226}Ra.

positive or negative. For the positive solution, the value of χ^2 per degree of freedom, with 2 degrees of freedom, was 4.6. For the negative solution it was 1.6. These values correspond to a probability level of 10 % and 45 %, respectively.

The data are not sufficiently accurate to establish which hypothesis for the relative phase is the correct one. Nevertheless, the experiment demonstrates that the measurements are indeed sensitive to this quantity. It will be necessary to reduce the experimental uncertainty on both the experimental yields and the matrix elements that can be measured independently without employing Coulomb excitation. This can be achieved in the first case by employing coincidence conversion electron techniques, and in the second case by making accurate measurements of the lifetimes of the 1^- and 3^- states. Such experiments designed to achieve these goals are being planned.

3. Electron conversion measurements in ^{254}No

In these experiments we employed the SACRED [12] electron spectrometer configured in a new geometry in which the electron trajectories are nearly parallel to the beam direction [13]. SACRED consists of a single Si PIN wafer, 500 microns thick, segmented into 25 pixels connected to individual amplification and timing channels. The geometry is circular, with 6 quadranted annuli surrounding the central element. The outer diameter of the detector is 28 mm. Electrons are transported from the target to the detector using a solenoidal magnetic field generated by four separated, normal conducting coils. The target-detector distance is 550 mm. The beam axis is at an angle of 2.5 deg to the field axis, intersecting at the target position. This arrangement has the advantage of an approximately collinear geometry, while ensuring that the beam is displaced by 25 mm from the field axis at the detector position. Focusing of the beam through the aperture at this position reduces the background from electrons produced near the detector. It also results in a large beam size at the target that distributes the electrons produced at the target, dominated by low energy delta electrons, more evenly over the detector. The delta electron background is reduced to an acceptable level by an electrostatic barrier placed between the target and the detector.

The collinear geometry, while offering the advantage of reducing Doppler broadening of the electron lineshape and a reduction in delta electron yield in the backward direction, enabled the electron spectrometer to be coupled to the gas-filled recoil separator RITU [14]. In this case the recoil products were transported in RITU to a parallel plate proportional counter and segmented silicon pad detector at its focal plane. The magnet volume of RITU and the section of SACRED containing the target that is connected to RITU were filled with 0.7 mbar helium gas. This volume is separated from the remaining volume of SACRED by two foils of 50 μg/cm^2 carbon with pumped intermediate volume. In this way the pressure of the region between the barrier and detector was maintained at 10^{-6} torr or better, thus reducing the background from accelerated electrons produced following ionisation of the residual gas molecules by the beam.

The beam of 219 MeV ^{48}Ca was provided by the ECR source and $K = 130$ cyclotron of the accelerator laboratory of the University of Jyväskylä. The beam energy was selected so that the average beam energy in the centre of the target (216 MeV) corresponds to the maximum of the yield of the reaction ^{208}Pb(^{48}Ca, $2n$)^{254}No. The target, whose thickness was variously 400 μg/cm^2 and 250 μg/cm^2, was bombarded by a beam of 1.5 pnA for approximately 4 days. The potential of the electrostatic barrier (with respect to target and detector) was -40 kV when the thicker target was used and -45 kV in the case of the thinner target.

Figure 2 shows an electron spectrum tagged by the detection of ^{254}No recoils. Even though the data analysis performed to produce this spectrum is preliminary, the sequence of discrete conversion-electron lines corresponding to the $4^+ \to 2^+$ up to the $12^+ \to 10^+$ transitions in ^{254}No is clearly visible. The average energy resolution arises mostly from the 4 keV intrinsic resolution of the individual detector channels. In the previous experiments where γ-rays were detected in ^{254}No [8,9] the $4^+ \to 2^+$ transition was not observed because of internal conversion.

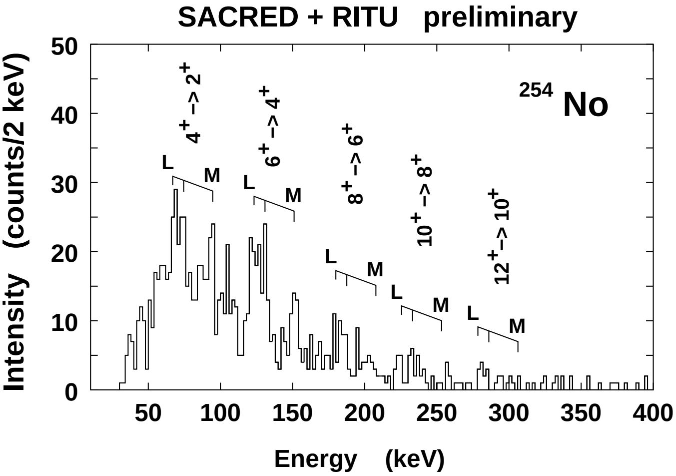

Fig. 2. Electron spectrum at the target position obtained by recoil tagging following the reaction ^{208}Pb(^{48}Ca, $2n$)^{254}No. A barrier voltage of -40 kV was employed for most of the experiment. The beam current was 1.5 pnA, with total irradiation time of about 4 days. The peaks are labeled according to the decay scheme of Ref. [9]; the dispersion is 2 keV/channel. The data analysis used to create this spectrum is at a preliminary stage.

The most interesting feature of figure 2 is the continuous background beneath the discrete line structure, which peaks at around 75 keV. This does not arise from scattering of electrons from the detector (in the SACRED geometry the electrons have almost normal incidence on the detector and the probability of backscattering is less than 20%). Figure 3 demonstrates that the electron multiplicity of the background is significantly higher than that of the discrete line structure. In this figure (which represents a subset of the total data) events are selected according to two criteria: (1) if a hit is recorded in only one of the 25 detector pixels; or (2) if one or more hits are recorded in the detector. As expected, the intensity of the ground state rotational band shows no difference: the estimated electron multiplicity for transitions above the 40 kV barrier is 2 and the hit probability ($= \langle m\varepsilon_{\mathrm{e}}\rangle$) is 0.15. In contrast, the background is reduced by a factor of 2 by demanding a single hit, suggesting that it has an electron multiplicity of around 5–10.

There are at least two possible sources for this background. One possibility is that it is largely atomic in origin, arising from the collisions of the recoiling nobelium atoms with the lead atoms in the target. It cannot arise from Ca + Pb collisions: the normal (singles) “delta” background peaks at the barrier voltage whereas the spectral shape in coincidence with recoils is very different. Another possibility is that the background has a nuclear origin, such as from a quasi-continuum of M1 transitions. There are several

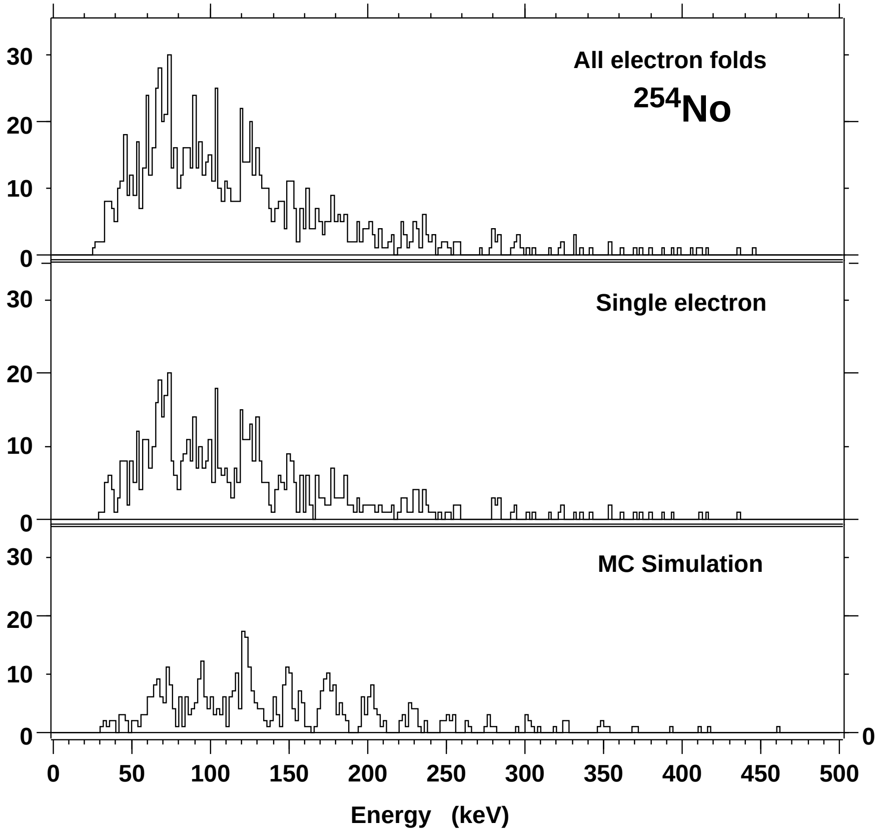

Fig. 3. Electron spectra (number of counts in the vertical axis) for the same reaction as described in figure 2. Upper figure: events are selected if a hit is recorded in any of the 25 detector pixels of SACRED. Middle figure: events are selected if a hit is recorded in only one of the detector pixels. Lower figure: simulated spectrum, assuming that only the ground state rotational band contributes to the spectrum. Only the first half of the experimental data, during which the electrostatic barrier was 40 kV, has been sorted to produce these spectra.

high Ω orbitals near the Fermi surface of ^{254}No (*e.g.* [514]7/2$^-$, [624]9/2$^+$ protons, [624]7/2$^+$, [734]9/2$^-$ neutrons) that can give rise to low lying 2 quasi-particle high K rotational bands whose $\Delta I = 1$ in-band transitions would mostly decay by internal conversion.

4. Summary

We have demonstrated that at very low bombarding energies the Coulomb excitation yield of low lying negative parity states in octupole deformed nuclei is sensitive to the relative phase of the electric dipole and octupole matrix elements. This will allow us to obtain information about the shape of the electric charge distribution in pear-shaped nuclei, and enable the sign of the electric dipole moment be inferred directly from experimental measurements.

We have also shown that the detection of internal conversion electrons emitted at the target, when tagged by recoil detection, is now offering comparable sensitivity to γ-ray spectrometry. The SACRED electron spectrometer, used in conjunction with the gas-filled spectrometer RITU, has been used to measure the ground state rotational band in the deformed superheavy nucleus ^{254}No. In addition to clearly observing transitions depopulation states from the 4^+ to the 12^+, the experiment revealed the presence of a background that may originate from the in-band decay of low-lying two quasiparticle high K bands.

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REFERENCES

[1] A. Bohr, B.R. Mottelson, *Nucl. Phys.* **4**, 529 (1957); *Nucl. Phys.* **9**, 687 (1958).
[2] V.M. Strutinsky, *At. Energ.* **4**, 150 (1956).
[3] G.A. Leander *et al.*, *Nucl. Phys.* **A453**, 58(1986).
[4] P.A. Butler, W. Nazarewicz, *Nucl. Phys.* **A533**, 249 (1991).
[5] R.J. Poynter *et al.*, *Phys. Lett.* **B232**, 447 (1989).
[6] Yu.Ts. Oganessian *et al.*, *Nature* **400**, 242 (1999); *Phys. Rev.* **C62**, 041604(R) (2000); *Phys. Rev.* **C63**, 011301(R) (2001).
[7] V. Ninov *et al.*, *Phys. Rev. Lett.* **83**, 1104 (1999).
[8] P. Reiter *et al.*, *Phys. Rev Lett.* **82**, 509 (1999); *Phys. Rev. Lett.* **84**, 3542 (2000).
[9] M. Leino *et al.*, *Eur. Phys. J.* **A6**, 63 (1999).
[10] T. Czosnyka *et al.*, *Bull. Amer. Phys. Soc.* **28**, 775 (1983).
[11] H. Wollersheim *et al.*, *Nucl. Phys.* **A556**, 261 (1993).
[12] P.A. Butler *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A381**, 433 (1996).
[13] H. Kankaanpää *et al.*, to be published.
[14] M. Leino *et al.*, *Nucl. Instrum. Methods Phys. Res.* **B99**, 653 (1995).