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TOWARDS THE STRUCTURE OF THE HEAVIEST NUCLEI*

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Recent progress in the development of new spectroscopic techniques promises to elucidate the structure of deformed superheavy nuclei in the region of ^{254}No. In-beam γ-ray spectroscopy has revealed the yrast structure of ^{252,254}No and conversion electron studies have been made of ^{253,254}No. Knowledge of the collective and single particle structure of nuclei in this mid-shell region provides important data to mean field models that are used to predict the properties of superheavy spherical nuclei.

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1. Introduction

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, with firm evidence for $Z = 112$ [1] and candidates for alpha decay from several nuclei with $Z = 114$–116 have been reported [2]. 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

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the rotational behaviour of the even–even nuclei ^{252,254}No to be studied up to spin $20\hbar$. In these experiments the reaction products, although populated with small cross sections ($\sigma < 3\mu$barn), have been separated from the dominant fission background.

A new experimental method that promises greater flexibility than γ-ray spectroscopy in the study of heavy nuclei has been recently developed. 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 technique has been applied to the measurement of the rotational band in ^{254}No, in which conversion electrons corresponding to transitions from the ground state band 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.

2. In-beam gamma-ray spectroscopy of even–even nobelium isotopes

A very important development in the gamma-ray spectroscopy of heavy nuclei has been the coupling of germanium detector arrays at the target to recoil separators capable of "tagging", or identifying prompt gamma-ray emission by direct measurement of the mass of the recoiling nucleus or by measurement of radioactive decay. In the case of decay tagging (RDT), it is necessary to make both time and position measurements at the focal plane in order to correlate the decay process with the events measured at the target [3]. The technique is currently capable of identifying prompt gamma-rays from nuclei populated with cross-sections of a few hundred nanobarns. The realisation that the cross-section using the reaction ^{208}Pb(^{48}Ca,2n)^{254}No ($\approx 3\mu$b), employing doubly-closed shell projectile and target, is sufficient for RDT measurements led to the observation of the ground state rotational band in the $Z = 102$, $N = 152$ nucleus up to spin $20\hbar$ [4, 5] This measurement is significant because it confirms that ^{254}No is well deformed, with a value for $\beta = 0.32 \pm 0.02$ [6]. The quadrupole deformation is deduced from the extrapolated $2^+ \rightarrow 0^+$ transition energy and the systematic dependence of the lifetime of the 2_1^+ state on its energy [6]. This observation is consistent with expectations of several classes of mean field theories, *e.g.* [7], which all predict that the stability against fission of this mid-shell nucleus arises from shell corrections enhanced because of quadrupole deformation.

Recently, measurements have been carried out [6] following the reaction ^{206}Pb(^{48}Ca,2n)^{252}No, which has a cross section of about 300 nbarns. This experiment was carried out at Jyväskylä using the JUROSPHERE γ-ray detector array [3] in conjunction with the gas-filled separator RITU [8]. The ground state rotational band was observed up to spin $20\hbar$ and shows an upbend (see figure 1) at a frequency $\hbar\omega = 200$ keV which is absent from ^{254}No. The deduced quadrupole deformation in this case is 0.31 ± 0.02 [6].

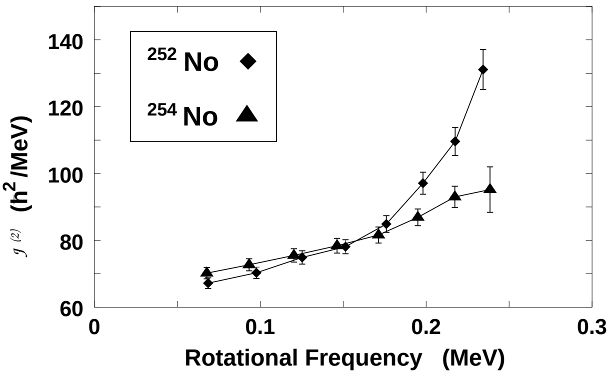

Fig. 1. Dynamical moment of inertia as a function of rotational frequency for ^{252,254}No. Taken from Ref. [6].

3. Electron conversion measurements in ^{254}No

In these experiments the SACRED [9] electron spectrometer was employed, configured in a new geometry in which the electron trajectories are nearly parallel to the beam direction [10]. 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 RITU. 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.

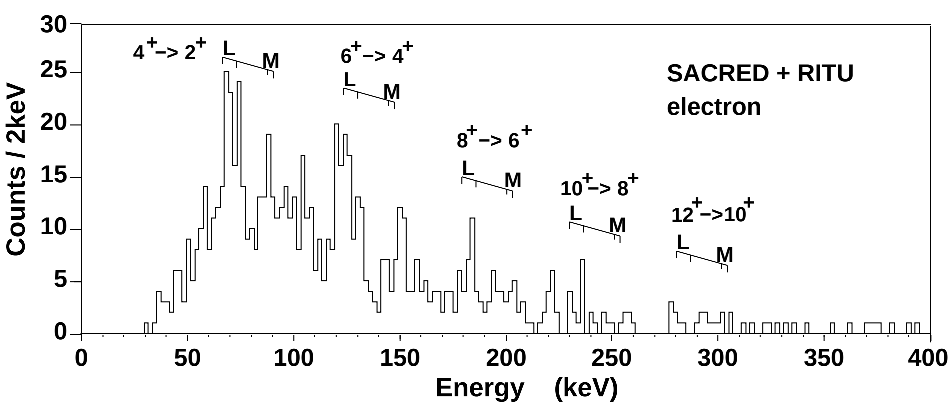

Fig. 2. Electron spectrum at the target position obtained by recoil tagging following the reaction ^{208}Pb(^{48}Ca, $2n$)^{254}No. A barrier voltage of -40 kV was employed for most of the experiment. The beam current was 1.5 pnA, with total irradiation time of about 4 days. The peaks are labeled according to the decay scheme of Ref. [5]; the dispersion is 2 keV / channel. The data analysis used to create this spectrum is at a preliminary stage.

Figure 2 shows an electron spectrum tagged by the detection of ^{254}No recoils [11]. Even though the data analysis performed to produce this spectrum is preliminary, the sequence of discrete conversion-electron lines corresponding to the $4^+ \rightarrow 2^+$ up to the $12^+ \rightarrow 10^+$ 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 [4, 5] the $4^+ \rightarrow 2^+$ transition was not observed because of internal conversion.

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

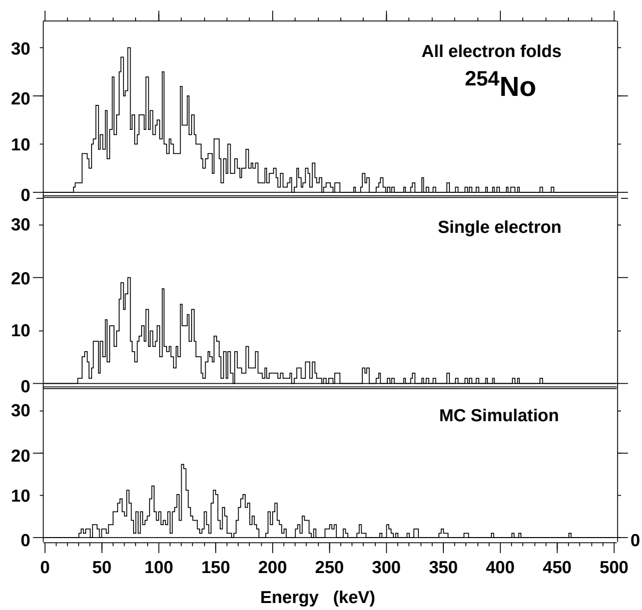

Fig. 3. Electron spectra (number of counts in the vertical axis) for the same reaction as described in figure 2. Upper figure: events are selected if a hit is recorded in any of the 25 detector pixels of SACRED. Middle figure: events are selected if a hit is recorded in only one of the detector pixels. 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.

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 ($= \langle m\varepsilon_e \rangle$) 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 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. Location of next spherical shell gaps

It is remarkable that the different mean field approaches give different predictions for the location of the next spherical magic numbers beyond ^{208}Pb. Systematic studies [12, 13] of three types of mean field, Strutinsky, Skyrme-Hartree-Fock (SHF), and Relativistic Mean-Field (RMF), give respectively (114,184], (124–126,184) and (120,172) for the next spherical shell closures (Z, N). The weakness of the macroscopic-microscopic approach appears to be its lack of self-consistent treatment of surface properties such as proton diffuseness [12]. The difference between the SHF and RMF approaches seems to lie in the treatment of the spin-orbit force [13]. These differences are magnified for heavy systems in which the single-particle spectrum becomes compressed, the spin-orbit splitting is attenuated, and Coulomb effects are enhanced [12].

Further information about the location of the next spherical shell gaps can be extracted from the systematic behaviour of the $B(E2 : 2^+ \rightarrow 0^+)$ of nuclei lying in the shell above ^{208}Pb. According to the $N_p N_n$ systematics of reference [14], the value of the $B(E2)$ for nuclei with $Z > 100$ should be very different for the different assumptions for the proton and neutron number at the next spherical closed shell. Figure 4 shows the values of $B(E2)$ obtained from lifetime *versus* excitation energy systematics [6] for

^{252,254}No for the three scenarios $Z = 114$, $N = 184$; $Z = 120$, $N = 172$; and $Z = 126$, $N = 184$. Unfortunately the experimental uncertainty does not distinguish between these possibilities. Precise measurements of the energy of the 2_1^+ state in ^{256}Rf, either by in-beam measurements using the $\sigma \approx 5$ nb cross section ^{208}Pb(^{50}Ti,$2n$)^{256}Rf [15] or by the 10 % α branch following the $\sigma \approx 300$ pb reaction ^{208}Pb(^{54}Cr,$2n$)^{260}Sg [16] should, however, be able to make the distinction.

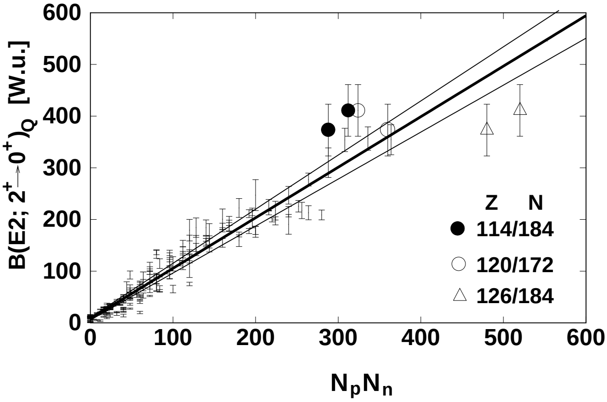

Fig. 4. Experimental $B(E2 : 2^+ \rightarrow 0^+)$ values *versus* the product $N_p N_n$. The values obtained for ^{252,254}No are indicated assuming that the next spherical gap is at $Z = 114$, $N = 184$ (closed circles), $Z = 120$, $N = 172$ (open circles) and $Z = 126$, $N = 184$ (open triangles), respectively. The straight line is the expected trend taken from Ref. [14].

5. Study of odd-mass nuclei

Definitive experimental information on the positions of the next closed shells can only come from direct measurements of superheavy spherical nuclei whose Z, N values lie close to the magic numbers. However, the various mean field parameterisations can be tested by examining the single particle properties of mid-shell deformed nuclei. For example, the $Z = 114$ shell gap is replaced by a gap at $Z = 126$ if the $p_{\frac{1}{2}}$, $p_{\frac{3}{2}}$ and $f_{\frac{5}{2}}$ single particle levels are lowered with respect to the $i_{\frac{11}{2}}$ level. In this case the position of the [521]1/2 deformed proton level, close to the Fermi level for $Z = 102$, is critical. Similarly, the neutron shell gap is also sensitive to the exact position of the single particle levels. For example, there are two sets of parameters commonly used in the Nilsson model that have been extracted from fitting experimentally measured single particle levels, with relatively little input from nuclei heavier than ^{208}Pb. For the mass 250 region, the values of μ and κ are very different for the two sets [17]. One set of parameters predicts that the yrast sequence of ^{253}No is a strongly coupled band; the other set predicts that a gamma-ray sequence should be clearly observable [18]. An attempt has been made at Argonne National Laboratory [19] to study the odd mass nucleus ^{253}No by observing the recoil-tagged gamma-ray emission at the target. In this case strong internal conversion and fractionation of intensity hindered identification of gamma-ray sequences, inferring that the yrast sequence contains strongly coupled signature partner bands with rather large values of $g_K - g_R$. This already provides some information about the structure of the levels near the Fermi surface. Recently, an experiment was carried out using SACRED in conjunction with RITU [22, 23] in which prompt electrons from ^{253}No were identified. The observed spectrum shape is consistent with the yrast band consisting of a strongly coupled rotational band in which the intensity is carried by dominant $M1$ transitions. This would be expected if the ground state band has the expected [734]9/2 configuration predicted by both Hartree Fock [20, 21] and Woods Saxon [21] calculations.

6. Summary

New developments in nuclear spectroscopy are taking place, which will allow measurements of the structure of deformed superheavy systems. In-beam γ-ray measurements of even-even nuclei in the rotational superheavy region, ^{252,254}No, have been carried out, revealing the properties of the ground state rotational bands up to spin $20\hbar$. Measurement of prompt conversion electrons emitted from even-even and odd mass nuclei populated at sub-microbarn cross-sections is also now possible.The SACRED electron spectrometer, used in conjunction with the gas-filled spectrometer RITU, has been used to measure the ground state rotational structure of ^{253,254}No. The data have been used to test mean field theories that are extrapolated from medium-mass nuclear systems to the superheavy region.

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