HIGH $\boldsymbol{K}$ BANDS IN MID-SUPERSHELL NUCLEI *

P.A. Butler[a], R.D. Humphreys[a], P.T. Greenlees[b]
R.-D. Herzberg[a], D.G. Jenkins[a], G.D. Jones[a], H. Kankaanpää[b]
H. Kettunen[b], P. Rahkila[b], C. Scholey[a,b], J. Uusitalo[b]
N. Amzal[a], C. Andreoiu[a], A. Andreyev[a], D. Appelbe[j]
J.E. Bastin[a], P.M.T. Brew[a], K. Eskola[c], S.J. Freeman[k], J. Gerl[d]
N.J. Hammond[a], K. Hauschild[e], K. Helariutta[d]
F.-P. Hessberger[d], A. Hürstel[e], P.J.C. Ikin[a], P.M. Jones[b]
D.T. Joss[j], R. Julin[b], S. Juutinen[b], A. Keenan[b], T.-L. Khoo[f]
W. Korten[e], P. Kuusiniemi[b], Y. Le Coz[e], M. Leino[b]
A.-P. Leppänen[b], M. Muikku[b], P. Nieminen[b], S.W. Ødegård[g]
R.D. Page[a], T. Page[a], J. Pakarinen[b], P. Reiter[h], J. Simpson[j]
G. Sletten[i], Ch. Theisen[e], B.J. Varley[k], and H.-J. Wollersheim[d]

[a]Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, U.K.
[b]Department of Physics, University of Jyväskylä, FIN-40014 Jyväskylä, Finland
[c]Dept. of Phys. Sci., University of Helsinki, FIN-00014 Helsinki, Finland
[d]GSI, D-64291 Darmstadt, Germany
[e]DAPNIA/SPhN CEA-Saclay, F-91191 Gif-sur-Yvette, France
[f]Argonne National Laboratory, Argonne, Illinois 60439, USA
[g]Department of Physics, University of Oslo, N-0316 Oslo, Norway
[h]Ludwig Maximilians Universität, D-85748 Garching, Germany
[i]Niels Bohr Institute, 2100 Copenhagen, Denmark
[j]CLRC Daresbury Laboratory, Warrington WA4 4AD, U.K.
[k]Schuster Laboratory, University of Manchester, Manchester M13 9PL

(Received November 12, 2002)

The spectrum of prompt conversion electrons emitted by excited ^{254}No nuclei has been measured, revealing discrete lines arising from transitions within the ground state band. A striking feature is a broad distribution that peaks near 100 keV and comprises high multiplicity electron cascades, probably originating from $M1$ transitions within rotational bands built on high K states. Evidence for the existence of isomeric states in ^{254}No is presented.

PACS numbers: 21.10.–k, 23.20.Lv, 23.20.Nx, 23.60.+e

* Presented at the XXXVII Zakopane School of Physics "Trends in Nuclear Physics", Zakopane, Poland, September 3–10, 2002.

1. Introduction

The understanding of the structure of the heaviest elements, in particular superheavy elements (SHE), is essential for the development of mean field theories that are used to predict nuclear properties far from stability (for reviews see [1, 2]). Experimental insight into the structure of superheavy nuclei can be obtained by direct measurement of the ground state properties of nuclei (for review, see [3]). Attempts to reach the spherical SHE have been reported recently in which the observation of α-decay from nuclei with $Z =$ 114, 116 and $N = 174$, 176 with lifetimes of the order of seconds has been claimed [4, 5]. 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 radioactive decay spectroscopy 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 (RDT), using electromagnetic separators. In this manner, in-beam γ-ray spectroscopy has enabled the rotational behavior of the even-even nuclei ^{252}No [6] and ^{254}No [7–9] to be studied up to spin 20 $\hbar$. In these experiments the reaction products, although populated with small cross sections ($\sigma \leq 3$ μbarn), have been separated from the dominant fission background. The measurements confirmed that nuclei having $Z \approx$ 100 and $N \approx 150$ have ground state deformation of $\beta \approx 0.3$. It is expected that these nuclei are the homologues of neutron rich Er-Hf in the lower oscillator shell where rotational bands built on high K states are observed. The quantification of the structure of these states will be important for fixing the parameters of models used to predict SHE properties.

We report here a new experimental method that can reveal information on heavy nuclei additional to that obtained from gamma-ray spectroscopy. Our technique allows the direct detection of internal conversion electrons, emitted at the target, in a broad-range, high efficiency electron spectrometer. The electrons can be tagged by recoil detection or using RDT. The sensitivity of the technique is demonstrated here by applying it to the measurement of the low-lying transitions in the ground state band of ^{226}U, which are easily observed in a relatively short running time, and to a study of converted transitions in ^{254}No, for which the $4^+ \rightarrow 2^+$ up to the $10^+ \rightarrow 8^+$ transitions were observed. These studies reveal a striking difference in the background of unresolved transitions for the two reactions. We hypothesize that this arises from the expected presence of high-K multi-quasiparticle states near the Fermi surface in ^{254}No.

2. In-beam electron spectroscopy: SACRED

The electron spectrometer, SACRED [10], employs 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 annuli, divided into quadrants, 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 of maximum flux density 0.3 T generated by 4 separated, normal conducting coils. The target-detector distance is 540 mm. The beam axis is at an angle of 2.5° to the field axis, intersecting at the target position. This arrangement has the advantage of having an approximately collinear geometry, while ensuring that the beam is displaced by 25 mm from the field axis at the (upstream) detector position. The response of the detector to conversion electrons emitted in the decay of a ^{133}Ba source is shown in figure 1. The absolute efficiency is about 10% for energies < 350 keV. For in-beam measurements the delta electron background is reduced to an acceptable level by an electrostatic barrier placed between the target and the detector. Further details of the mechanical construction are given in Ref. [11].

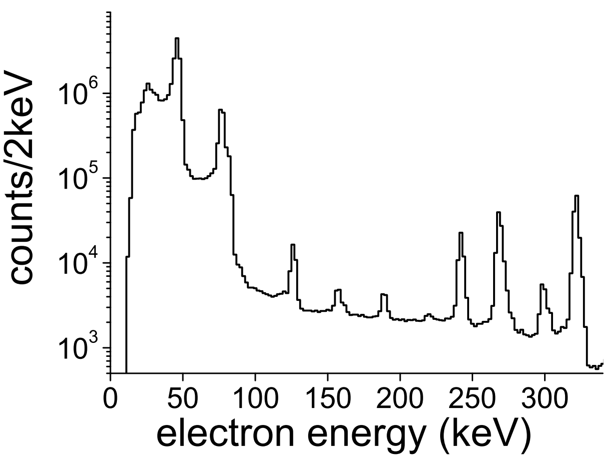

Fig. 1. Spectrum of ^{133}Ba source, showing the detector response on a logarithmic scale.

The collinear geometry, while offering the advantage of reducing both Doppler broadening of the electron lineshape and the delta electron flux in the backward direction, enabled the electron spectrometer to be coupled to the gas-filled recoil separator RITU [12]. The recoil products were transported in RITU to a 16-fold segmented and resistive silicon pad detector at its focal plane. This detector is divided into approximately 200 pixels.

The magnet volume of RITU and the section of SACRED containing the target are filled with 0.3 and 0.7 mbar helium gas for reactions induced by $A \approx 20$ and $A \approx 50$ projectiles respectively. This volume is separated from the remaining volume of SACRED by two 60 μg/cm^2 carbon foils of 15 mm radius and 170 mm separation with pumped intermediate volume. In this way the pressure of the region containing the barrier and the detector was maintained at about 10^{-6} torr, thus reducing the background from accelerated electrons produced following ionization of the residual gas molecules by the beam. The energy loss of 50–150 keV electrons in the target and foils is 1–1.5 keV.

3. Conversion electron measurements in ^{226}U

These experiments were carried out at the accelerator laboratory of the University of Jyväskylä. In the first experiment a 10 particle nA beam of 111 MeV ^{22}Ne (correcting for energy loss in the carbon foils) bombarded a ^{208}Pb target of thickness 200 μg/cm^2 for approximately 25 h. In this experiment the potential of the electrostatic barrier was -35 kV with respect to target and detector. The conversion electron spectrum of ^{226}U, produced in the $\sigma \approx 6$ μb $4n$ channel, is shown in figure 2(a).

It was obtained by requiring that the detection of any electron at the target using SACRED be accompanied by the detection of recoils in the focal plane detector of RITU within a time window of ± 50 ns of their arrival at the focal plane. The recoils are identified by requiring that there is an alpha decay of energy range 7.49–7.63 MeV within 800 ms in the same pixel of the implantation detector. There were 1280 tagged recoils detected in this experiment. Figure 2(b) shows a simulated spectrum obtained using the Monte Carlo program described in Ref. [10], corresponding to the same number of recoils as observed experimentally. The simulation assumes that the observed conversion electrons only arise from transitions previously observed in an array of γ-ray spectrometers and identified using the RDT technique [13]. More details of the conversion electron experiment and its results, in particular the first firm assignment of the energy of the 2-0 transition, are given in Ref. [14]. It is evident from comparison of the experimental and simulated spectrum that the excess background observed over that accounted for by the simulation is quite small. The simulation takes into account the transport of the electrons in the magnetic and electric fields, scattering in or from the detector, energy sharing at the pixel boundaries, and threshold effects.

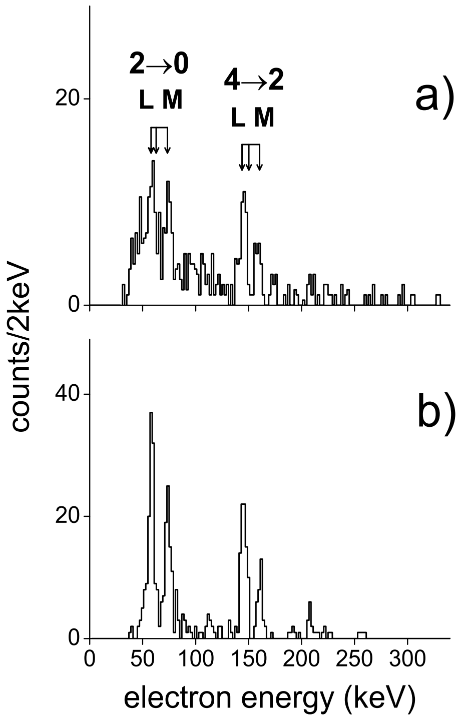

Fig. 2. (a): Experimental conversion electron spectrum (corrected for the contribution from random coincidences) tagged by the characteristic α-decay of ^{226}U. In this spectrum the energies are not corrected for Doppler shift. Transitions in the ground state band are identified. (b): Simulated spectrum for ^{226}U as described in the text.

4. Measurement of high multiplicity continuum in ^{254}No

In a second experiment a beam of 219 MeV ^{48}Ca was employed. In this case the average beam energy in the center of the ^{208}Pb target (216 MeV) corresponds to the maximum of the yield of the reaction ^{208}Pb(^{48}Ca, $2n$)^{254}No. Targets of thicknesses 250 μg/cm^2 and 400 μg/cm^2 of enrichment 98% ^{208}Pb were each bombarded by a beam of 1.5–3 particle nA for approximately 110 h each. The potential of the electrostatic barrier was -40 kV. Figure 3(a) shows the total electron spectrum tagged by the detection of fusion products.

In this case it is not necessary to verify that the recoils are ^{254}No by measuring their alpha decay as there are no other competing compound nucleus channels: the combined population of ^{253,255}No is $\approx$ 1% of that of ^{254}No [15, 16]. The electron spectrum which is tagged by the subsequent decay of

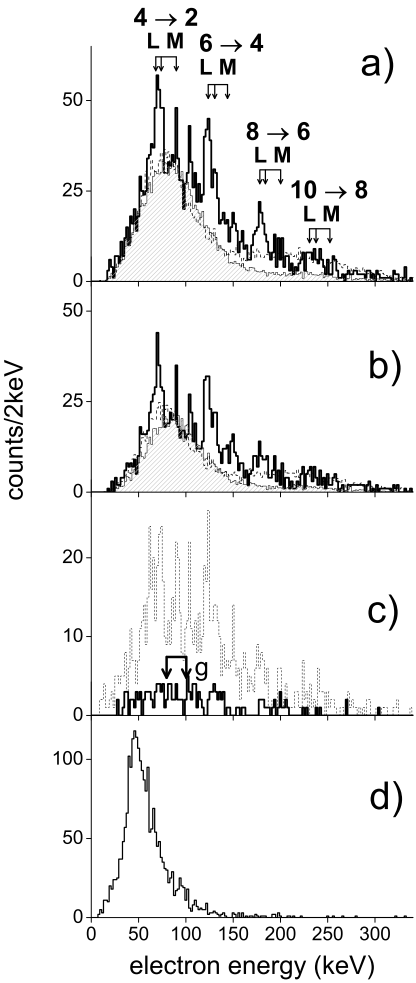

Fig. 3. (a): The experimental conversion electron spectrum tagged by ^{254}No recoils, corresponding to any number of electrons detected in SACRED (solid bold line). In this spectrum the energies are not corrected for Doppler shift. The lowest transitions in the ground state band are identified. Also shown are the simulated spectra as described in the text for $g_K = 0$ (hashed area with solid line border) and for $g_K - g_R = 0$ (dashed line). (b): as (a) except that experiment and simulation correspond to the detection of a single electron. (c): Spectrum of second electron in coincidence with a selected region (labelled 'g') of energy for the first electron, tagged by recoils (solid bold line). Also shown is the experimental spectrum tagged by α-decay for any number of electrons detected (dashed line). (d): electron spectrum taken in random coincidence.

alpha particles in the energy range 8.04 to 8.15 MeV, with a search time of 600 s (see dashed line in figure 3(c)), has approximately half the total counts, as expected. We were able to distinguish evaporation residues, target-like recoils, scattered beam and radioactive decay products by employing a parallel plate proportional counter in front of the silicon implantation detector.

Two features are apparent from figure 3(a). First, the conversion electrons corresponding to transitions in the ground state rotational band up to spin 10 in ^{254}No are identifiable (the structure observed at $\approx$ 65 and 105 keV arises from hitherto unidentified transitions in ^{254}No). The details of these measurements, in particular the first direct measurement of the energy of the 4–2 transition, are given in Ref. [14]. The second noticeable feature is the pronounced background, centered at around 100 keV. The intensity of this background is much larger than the background observed in the spectrum corresponding to ^{226}U transitions (figure 2(a)). The most interesting property of the background is that it has a much higher electron multiplicity than that of the discrete transitions. This is demonstrated by demanding that the spectrum is only incremented if no other electrons are detected in any of the SACRED pixels within 100 ns of the detection of the first electron. The resulting spectrum is shown in figure 3(b) in which the peak to background is significantly improved. The simulation code can be used to roughly estimate the mean electron multiplicity, as it provides an accurate model of the response of the SACRED spectrometer. It remains to model the mechanism by which the entry states in ^{254}No depopulate and emit conversion electrons. The simplest model is to assume that only the ground state band is populated, so that there is no other source of conversion electrons. In this case the relative intensities of the transitions feeding the 4^+ state are taken from the gamma-ray measurements [8, 9]. The present measurements indicate that the intensity of the 6–4 and the 4–2 transitions are the same [14], and these are assumed to be the same as that of the 2–0 transition. The measured yield of the 6–4 L transition in the ground state band is 126 ± 18 for a single electron detected, 160 ± 30 for any number of electrons detected (ratio $\mathcal{R}_{(6-4)} = 0.78 \pm 0.16$), for a total of 7150 recoils. In the simulation, carried out for four times the number of recoils to that recorded in the measurement, the values for the yield of the 6–4 transition are respectively 1280 and 1530 ($\mathcal{R}_{(6-4)} = 0.84$). The measurements are consistent with the simulation if about 40% of the population of ^{254}No passes through the lowest transitions. On average 3.7 electrons are emitted simultaneously in this decay path, including the undetected 2–0 transition.

In order to model the background, we assumed that this arises from decays within a single rotational band built on a $K = 8$ isomeric bandhead and populated with the same entry spin distribution as that measured for all states by Reiter *et al.* [9]. The value of g_K is taken to be 0, with $g_R = 0.3$.

For this band we assumed a constant moment of inertia of 100 $\hbar^2$ MeV^{-1}, slightly larger than that of the highest transitions in the ground state band (this allows a better fit to the low energy part of the spectrum). The electron energies are then randomized by applying a gaussian distribution of $\sigma = 10$ keV, to account for the presence of many such bands having differing moments of inertia. The calculated spectrum, also carried out for 28,600 recoils as for the previous simulation and then renormalised by a factor of 0.10, is shown also in figure 3(a). The measured intensity of the background matches the calculated intensity, implying that approximately 40% of all detected recoils proceed through these paths. The expected values of g_K for the lowest 2 quasi-particle $K^\pi = 8^-$ bands in ^{254}No are ≈ -0.3 ($\frac{9}{2}^-[734]_\nu$ $\frac{7}{2}^+[613]_\nu$, Ref. [17]), 0 ($\frac{9}{2}^-[734]_\nu$ $\frac{7}{2}^+[624]_\nu$, Ref. [18]) and 1 ($\frac{9}{2}^+[624]_\pi$ $\frac{7}{2}^-[514]_\pi$, Refs. [17,18]). For this range of values of g_K the calculated ratio of integrated counts for single and any electron detected ($\mathcal{R}_{\rm bkg}$) is 0.57–0.59, similar to the measured value of 0.58 ± 0.03. The corresponding value of the mean electron multiplicity for these paths is in the range 7–8. In the extreme case when $(g_K - g_R) = 0$ (purely electric transitions) the calculated value of $\mathcal{R}_{\rm bkg}$ is 0.64, corresponding to an electron multiplicity of 4 distributed evenly between $I \to I-1$ and $I \to I-2$ transitions. In this case the calculated spectrum overestimates the high energy part of the spectrum (see dashed line in figure 3(a),(b)). If it is assumed that the bandhead is not isomeric, so that the $K = 8$ state decays immediately to the 8^+ member of the ground state band, then the value of $\mathcal{R}_{\rm bkg}$ for $g_K = 0$ is 0.47 (multiplicity 10). This feeding pattern cannot be significant, as demonstrated in figure 3(c) which shows the spectrum of electrons in coincidence with a selected region of the background.

Finally, we have to consider the possibility that the background is largely atomic in origin and that it arises from the atomic collisions of the recoiling nobelium atoms with the Pb atoms in the target. We believe that this possibility is unlikely as the background has a very different shape to that arising from the delta background produced by collisions of beam particles with the target. Figure 3(d) shows the electron spectrum taken in random coincidence, which is identical in spectral shape to the singles spectrum. It peaks in intensity at an energy that is close to the barrier voltage. In addition, we compared the integral background yield per nobelium recoil detected for when the target thickness was 250 μg/cm^2 (4710 recoils) and when the target thickness was 400 μg/cm^2 (2440 recoils). The measured values were very similar, 0.177 ± 0.008 and 0.170 ± 0.010, respectively. If the background arose from No+Pb atomic collisions it might be expected that the yield would scale with the target thickness.

5. Isomers in ^{254}No measured in focal plane of RITU

In order to directly observe isomeric states in ^{254}No we employed part of the GREAT spectrometer [19] positioned at the focal plane of RITU. In this experiment GREAT consisted of a double sided strip silicon detector (DSSD) with 60 vertical strips and 40 horizontal strips of 1 mm pitch, surrounded by 28 28×28 mm^2 PIN detectors. The heavy recoils from the 219 MeV ^{48}Ca + ^{208}Pb reaction were implanted into the DSSD which was cooled to $\approx -20^\circ$ C. Following the experiment about 700 position correlated recoil — α events were found in a search time of 200 s, that correspond to the decay of ^{254}No. For these events we searched for low energy (less than 1 MeV) signals which occurred at the same X–Y position but within 10 s of the recoil implantation. The time spectrum of such events (with respect to the recoil) is shown in figure 4. About 70 such events were observed, some of which had a distribution in time corresponding to a half-life of about 1/3 s. We tentatively interpret these events as arising from the internal conversion of transitions within the ground state rotational band in ^{254}No that are populated by the decay of a high K isomeric state; this triple correlation technique has been described by Jones [20]. If this interpretation is correct, then the fraction of all nobelium recoils that arrive in the focal plane in an isomeric state can be determined if the efficiency for the detection of the conversion electrons is known; our crude estimate is that this fraction is similar to the value deduced from the in-beam measurements described above. The lifetime of the isomeric state is consistent with that measured by Ghiorso *et al.* [21].

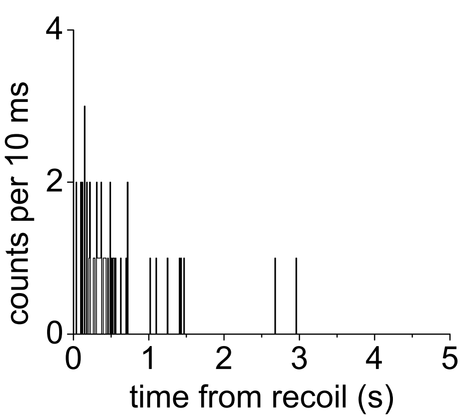

Fig. 4. Distribution in time of low energy events that occur at the same position in X and Y as the recoil implantation and the α-decay of ^{254}No, measured in the GREAT spectrometer.

6. Summary

We can conclude from our experimental observations that a large fraction of the entry states in ^{254}No, populated in this reaction, decay via M1 cascades that will not be detected in γ-ray arrays, and measurements of entry distributions should be modified to take this into account. The M1 cascades will naturally arise from the population of two-, four- and many-quasiparticle excitations that will often have bandheads with high K-values. The lowest $K^{\pi} = 8^{-}$ bands are expected to lie at an excitation energy of around 1–1.5 MeV [17, 21]. Such bandheads are expected to be isomeric with lifetimes, based on systematics [22], of greater than 1 ms. From focal plane spectroscopy we have independent evidence for the existence of such isomeric states in ^{254}No that are populated with a large isomeric ratio.

We thank R. Bengtsson, W. Nazarewicz, P. Stevenson and P. Walker for useful discussions. We are also grateful to Patrick Coleman-Smith, Peter Cooke, John Cresswell, Khalid Fayz, Ian Lazarus, Simon Letts, Vic Pucknell, Paddy Regan, Janet Sampson, Dave Seddon, Andy Smith, Jim Thornhill, Bob Wadsworth and Dave Wells, for their contributions to the construction of GREAT. This work was supported by the EU 5th framework programme 'Improving Human Potential — Access to Research Infrastructure' (HPRI-CT-1999-00044), The Academy of Finland under the Finnish Centre of Excellence Programme 2000-2005, the U.K. Engineering and Physical Sciences Research Council, and the U.S. Department of Energy.

REFERENCES

[1] S. Ćwiok *et al.*, *Nucl. Phys.* **A611**, 211 (1996).

[2] A.T. Kruppa *et al.*, *Phys. Rev.* **C61**, 034313 (2000).

[3] S. Hofmann, G. Münzenberg, *Rev. Mod. Phys.* **72**, 733 (2000).

[4] Yu. Ts. Oganessian *et al.*, *Phys. Rev.* **C62**, 041604(R) (2001).

[5] Yu. Ts. Oganessian *et al.*, *Phys. Rev.* **C63**, 011301(R) (2001).

[6] R.D. Herzberg *et al.*, *Phys. Rev.* **C65**, 014303 (2002).

[7] P Reiter *et al.*, *Phys. Rev. Lett.* **82**, 509 (1999).

[8] M. Leino *et al.*, *Eur. Phys. J* **A6**, 63 (1999).

[9] P. Reiter *et al.*, *Phys. Rev. Lett.* **84**, 3542 (2000).

[10] P.A. Butler *et al.*, *Nucl. Instr. Meth.* **A381**, 433 (1996).

[11] H. Kankaanpää, PhD thesis, University of Jyväskylä (2001).

[12] M. Leino *et al.*, *Nucl. Instr. Meth.* **B99**, 653 (1995).

[13] P.T. Greenlees *et al.*, *J. Phys. G: Nucl. Part. Phys.* **24**, L63 (1998).

[14] R.D. Humphreys *et al.*, to be published.

[15] M. Itkis *et al.*, *Nuov. Cim.* **111A**, 783 (1998).

[16] V.J. Zagrebaev *et al.*, *Phys. Rev.* **C65**, 014607 (2001).

[17] V.G. Soloviev *et al.*, *Sov. J. Nucl. Phys.* **54**, 748 (1991).

[18] S. Ćwiok, W. Nazarewicz, priv. comm.

[19] P.A. Butler *et al.*, *Acta Phys. Pol. B* **32**, 619 (2001).

[20] G.D Jones, *Nucl. Instr. Meth.* **A488**, 471 (2002).

[21] A. Ghiorso *et al.*, *Phys. Rev.* **C7**, 2032 (1973).

[22] P. Walker, G. Dracoulis, *Hyper. Int.* **135**, 83 (2001).