D. SPECTROSCOPY OF VERY HEAVY ELEMENTS

Progress in heavy nuclei continues, both through our program of decay studies of the very heaviest elements that can be produced in reactors, and by using fusion reactions. This forefront research in the very heaviest nuclei continues to be a domain where the ATLAS beams and the Fragment Mass Analyzer (FMA) can allow us to make major contributions.

d.1. Alpha Decay of ^{181}Pb (M. P. Carpenter, F. G. Kondev, R. V. F. Janssens, I. Ahmad, C. N. Davids, N. Hammond, T. L. Khoo, T. Lauritsen, C. J. Lister, G. Mukherjee, D. Seweryniak, S. Sinha, D. J. Jenkins,* P. Raddon,* R. Wadsworth,* S. F. Freeman,† S. M. Fischer,‡ G. Jones,§ A. J. Larabee,¶ and A. Liechty¶)

With the return of Gammasphere to ATLAS, our program continues to look at proton rich nuclei in the vicinity of the Z = 82 closed proton shell. One of recent measurements utilized the ^{90}Zr + ^{92}Mo reaction to produce ^{181}Tl and ^{181}Pb via the 1p and 1n channel, respectively. For this measurement, Gammasphere was coupled with the FMA to characterize both the ground and excited states in these two nuclei. At the focal plane of the FMA, the PGAC measured the mass, the DSSD detected the energies of both implants and α particles emitted from the decay of the implanted ions and associated daughter nuclides. In addition four Ge detectors surrounded the DSSD in order to measure γ rays in coincidence with detected particles.

^{181}Pb with N = 99 is the lightest odd-A Pb isotope identified thus far. In our measurement, we observe two α lines at 7010 and 7070 keV with nearly equal intensity. Both of these decays are correlated with the 6580-keV α decay of ^{177}Hg. Our observations are in contrast to a previous result which reported observing only one α line at 7065 keV.[1] In addition, the 7010-keV α line is in coincidence with a 77-keV γ ray. This γ ray was identified previously as resulting from the decay of a $9/2^-$ state to the $7/2^-$ ground state in ^{177}Hg.[2] Both α lines have the same half-life which is 39.6 ± 0.9 msec indicating that both associated with the decay from the same state in ^{181}Pb. While it is clear that the 7010-keV α feeds the 9/2- state in ^{177}Hg, an α-decay feeding directly the ground state in ^{177}Hg would have an energy of ~7088 keV. In addition, a 78-keV M1 transition is highly converted with a conversion coefficient of around four. Since the K threshold for Z = 80 is at 90 keV, the majority of the emitted electrons from the L-shell result in electron energies of ~60 keV which is the energy difference between the two observed α lines. Factoring all of this information together, it appears that the 7070-keV α results from the sum of the 7010-keV α and the electron emitted during the conversion process. In conclusion, we observe only one α decay coming from the ground state in ^{181}Pb and feeding the lowest $9/2^-$ state in ^{177}Hg. As a result, the ground state of ^{181}Pb must be $9/2^-$ as well. This is in contrast to the heavier odd-A Pb isotopes, where two α-decaying states were identified and associated with a high-spin ($13/2^+$) isomer state and a low-spin ($3/2^-$) ground state.

This change in the ground state results from the fact that the $p_{1/2}$, $p_{3/2}$, $f_{5/2}$ and $i_{13/2}$ orbitals should be emptied at N = 100. Below N = 100, one begins to empty either the $h_{9/2}$ or $f_{7/2}$ shell. Our measurements show that at N = 99, the $h_{9/2}$ orbital lies above the $f_{7/2}$ which was experimentally determined for the first time. This can be contrasted to ^{207}Pb where the ordering in energy is reversed. In addition, this result shows that the $7/2^-$ groundstates in ^{177}Hg[2] (N = 97) and ^{179}Hg[3] (N = 99) are built on weakly deformed prolate shapes as opposed to spherical states where the expected spin/parity would be $9/2^-$ as in ^{181}Pb.

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[1]K. S. Toth *et al.*, Phys. Rev. C **53**, 2513 (1996).

[2]A. Melerangi *et al.*, C **68**, 041301(R) (2003).

[3]F. G. Kondev *et al.*, Phys. Lett. **B528**, 221 (2002).

d.2. Octupole Correlations in Radium Nuclei (C. J. Lister, I. Ahmad, R. V. F. Janssens, M. P. Carpenter, S. M. Fischer, T. L. Khoo, F. G. Kondev, T. Lauritsen, E. F. Moore, D. Seweryniak, S. Zhu, N. J. Hammond,* G. D. Jones,* J. F. Smith,† and S. J. Freeman†)

Reflection asymmetric shapes in nuclei remain an interesting and fundamental feature of nuclear structure. In the entire chart of nuclides the light Ra-Th-U nuclei provide the best cases for study, with evidence for strong octupole correlations even at very low spin. The thorium nuclei were extensively investigated, but far less is known about the radium series. Our proposal to study the immediate neighbors of ^{226}Ra at ATLAS, through multinucleon transfer using a ^{207}Pb beam just above the Coulomb barrier, was accepted. Studying the gamma rays following multinucleon transfer using Gammasphere has become an established experimental technique, and ^{225,226}Ra should be especially well populated. Several neighbors that lie right at the center of the known octupole region should also be populated.

The key to the success of this study is the preparation of a suitable radioactive ^{226}Ra target. This target preparation, together with the availability of Gammasphere and the high-energy accelerated lead beams makes this study unique to Argonne. Because of the high specific activity, the target needed to be in the form of a small electroplated spot, less than 3 mm in diameter. Unfortunately, a great deal of difficulty was encountered with the production of this radium target. The material was ordered from Oak Ridge, but there were problems with the delivery schedule and the material needed further refining to remove contaminant radioisotopes that plated out more favorably and blocked the radium deposition. The final targets were too thin for practical use, so the beam time had to be reassigned. However, a new cycle of investigation started ‘‘offline” to procure and plate a new target during calendar year 2004 before the experiment is rescheduled for early calendar year 2005.

d.3. Energy Levels in ^{247}Cm Populated in the Alpha Decay of ^{251}Cf (I. Ahmad, R. R. Chasman, J. P. Greene, F. G. Kondev,* E. F. Moore, E. Browne,† C. E. Porter,‡ and L. K. Felker‡)

Alpha decay of ^{251}Cf was studied in order to determine the level structure of ^{247}Cm. Extremely pure sources of ^{251}Cf were obtained as the decay product of pure ^{255}Fm. Thin sources, for alpha spectrum, were obtained by collecting ^{251}Cf recoil atoms in the decay of ^{255}Fm. High-resolution alpha, electron, and gamma ray spectra were measured with passivated, implanted, planar silicon detectors, PIN diodes, and Ge spectrometers, respectively. In addition, level lifetimes were also measured by delayed-coincidence technique. The level scheme for ^{247}Cm deduced from the present work is displayed in Fig. I-27. The energies of single-particle states shown in this figure are fairly well reproduced by calculations using a Woods-Saxon potential. The detailed properties of ^{247}Cm levels measured in the present work are helpful in the interpretation of data on the isotone ^{253}No. The results of this study were published.[1]

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[1]Phys. Rev. C **68**, 044306 (2003).

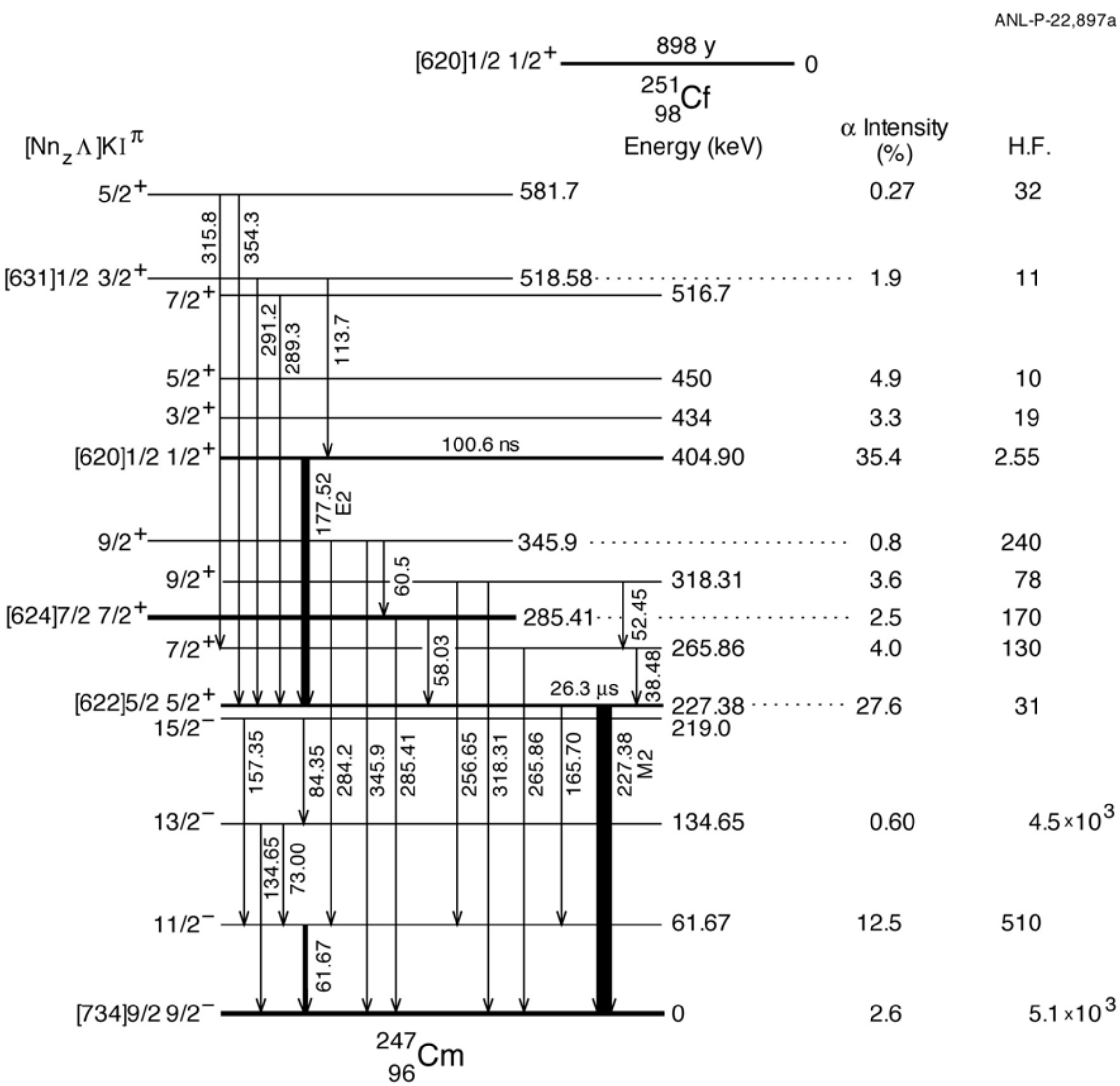

Fig. I-27. Level scheme of ^{247}Cm deduced from the study of ^{251}Cf alpha decay.

d.4. Proton Single-Particle States in ^{249}Bk (I. Ahmad, E. F. Moore, R. R. Chasman, J. P. Greene, M. P. Carpenter, C. J. Lister, R. V. F. Janssens, T. Lauritsen, D. Seweryniak, F. G. Kondev,* R. W. Hoff,† J. E. Evans,† R. W. Lougheed,† C. E. Porter,‡ and L. K. Felker‡)

Although many superheavy elements were discovered recently, there is still controversy regarding the location of the proton shell in this mass region. It is therefore important to experimentally determine the energies of single-particle levels in the heaviest available nuclei. The heaviest odd-proton nuclide available in the largest quantity is the alpha decaying ^{253}Es ($T_{1/2}$ = 20.47 d) isotope. We studied the level structure of its daughter ^{249}Bk by measuring the gamma-ray spectra of a highly enriched ^{253}Es sample. This Es sample was obtained by milking the daughter ^{253}Es which grew in a ^{253}Cf source material produced in the High Flux Isotope Reactor (HFIR) at the Oak Ridge National Laboratory. This source was chemically pure and was ^{254}Es free. We did not observe any contaminant gamma ray in this sample. Using gamma singles spectra, measured with high-resolution Ge detectors, we were able to identify many weakly populated states that decay by γ rays withintensities as low as 1.0×10^{-6}% per ^{253}Es alpha decay. A gamma-gamma coincidence experiment was performed with the Gammasphere spectrometer at Argonne in order to determine the decay pattern of high-lying states. The high efficiency and resolving power of Gammasphere allowed us to identify many weak gamma rays that were not observed in the singles spectrum. An example of gamma ray spectrum gated by 762-keV photopeak is displayed in Fig. I-28. Information on low spin states of ^{249}Bk was also obtained from gamma-ray spectroscopic study following β^- decay of ^{249}Cm at Livermore. The ^{249}Cm sample was produced by neutron irradiation of ^{248}Cm. Using the results of the present study and the data available from the previous ^{248}Cm(α,t) investigation, a number of single-particle states were identified in ^{249}Bk, including: $7/2^+$[633], 0.0 keV; $3/2^-$[521], 8.78 keV; $1/2^+$[400], 377.55 keV; $5/2^+$[642], 389.17 keV; $1/2^-$[530], 569.19 keV; $1/2^-$[521], 642.95 keV; $9/2^+$[624], 1040.2 keV; and $7/2^+[633] \times 0^+$, 1223.0 keV. An article is being prepared for publication.

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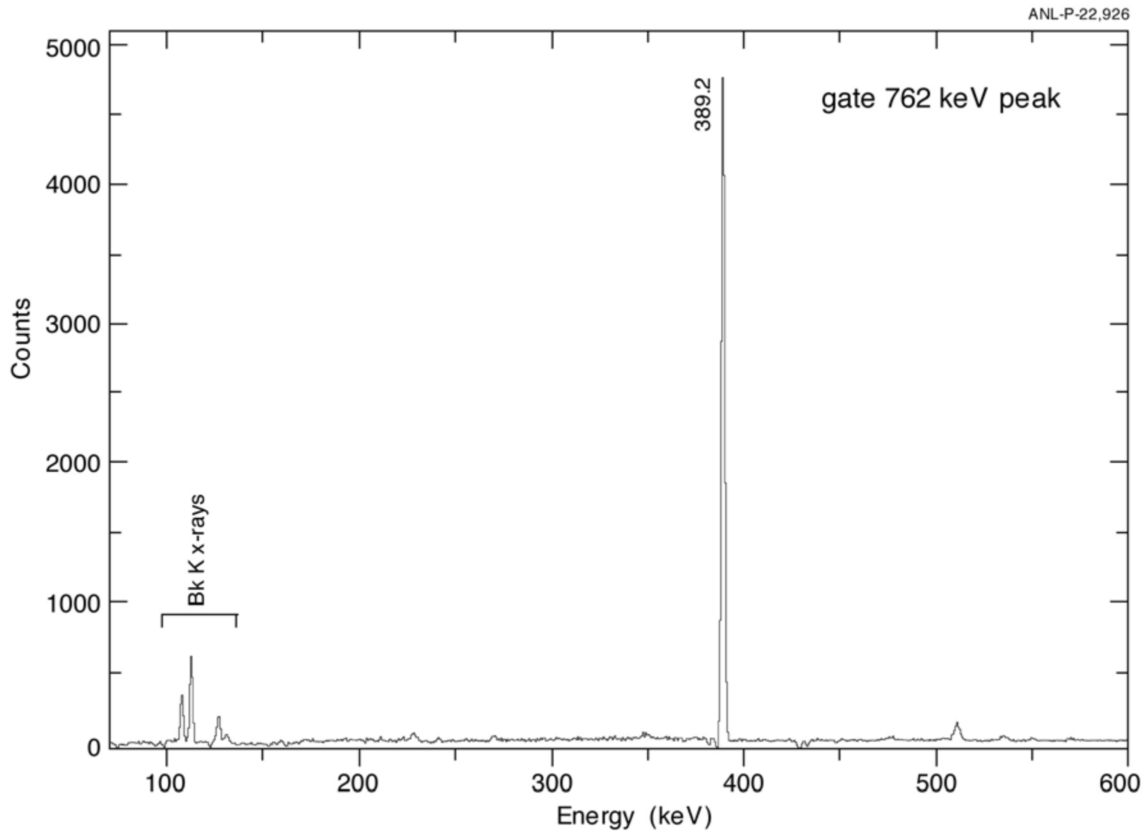

Fig. I-28. ^{253}Es γ ray spectrum measured with the Gammasphere, in coincidence with 762-keV peak. Only one γ ray is observed in coincidence. The intensity of the 762 keV γ ray is 3.0×10^{-6}% per ^{253}Es α decay.

d.5. Electrons from A 0.3s Isomer In ^{254}No* (T. L. Khoo, R. Blinstrup, D. Seweryniak, I. Ahmad, M. P. Carpenter, C. N. Davids, S. Freeman, J. Greene, N. Hammond, R. V. F. Janssens, F. G. Kondev, T. Lauritsen, C. J. Lister, G. Mukherjee,* P. A. Butler,† P. Chowdhury,* J. A. Cizewski,‡ R. Gramer,* R. D. Herzberg,† A. Heinz,§ P. Ikin,† M. Johnson,‡ G. D. Jones,† E. Ngijoi-Yogo,* and P. Reiter¶)

Data on pairing and single-particle energies are essential for reliable predictions of the stability of the superheavy elements. The single-particle energies constitute the basis of the shell-correction energy, which provides the essential binding energy, and pairing further lowers the ground-state energy. The energies and configurations of 2-quasiparticle high-K isomers in heavy shell-stabilized nuclei provide information on both single-particle energies and the pair gap.

High-K isomers are expected in shell-stabilized nuclei around ^{254}No because there are many high-Ω single-particle orbitals near the Fermi level. An isomer was identified[1] in ^{254}No ($T_{1/2}$ = 0.28 s), but no information on its decays exists. We observed the electrons accompanying the decay of this isomer in an experiment where nobelium nuclides are produced with the ^{208}Pb(^{48}Ca,2*n*) reaction at ATLAS. The evaporation residues were transported and identified with the Fragment Mass Analyzer (FMA) and implanted in 1 × 1-mm^2 pixels of a Si double-sided strip detector. In the *same pixel* where a residue was implanted, electrons from the decay of an isomer were observed in a 1.4-s time interval, followed by α decays from the ground state of ^{254}No within a 120-s interval. (Similar results were obtained[2] at Jyväskylä.) The source of the electrons was unambiguously characterized by: (i) identification of ^{254}No; (ii) time and spatial correlations of residue, electron and α; and (iii) the electron and α decay half-lives. Figure I-29(a) shows the experimental electron spectrum, which represents the sum energy from transitions in the ground band following the isomer decay. Figures I-29(b,c) show the calculated spectra expected from isomers with either K = 7$^-$ or 8$^-$, respectively, which decay to either the 6$^+$/8$^+$ or 8$^+$ members of the ground band. The calculated spectra are attenuated at low sum-energy with an approximate efficiency curve to reflect the effect of electronic thresholds. Above 305 keV, which has a contribution from only the $8^+ \rightarrow 6^+$ transition, Fig. I-29(b) better resembles the measured spectrum. Specifically, the ratio of counts above 350 keV to the total counts are 0.12, 0.14 and 0.32 for panels (a, b and c). Thus a K = 7$^-$ assignment is favored, with a probable configuration $\pi\{7/2^-[514],\ 7/2^+[633]\}$. A search for the γ rays directly depopulating the isomer is planned.

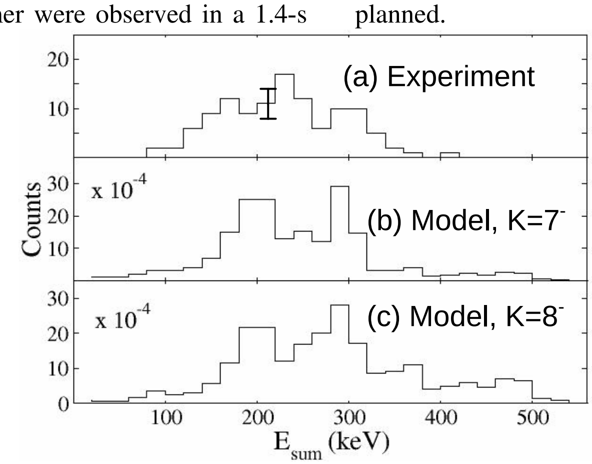

Fig. I-29. The measured electron sum-energy spectrum is shown in panel (a). The calculated spectra with assumptions of K^π = 7$^-$ and 8$^-$ for the isomer are shown in panels (b and c); the low-energy yield has been attenuated by using an estimated efficiency curve below 170 keV. The simulated spectra were multiplied by 10^{-4}, to give approximately the same total counts as the experimental spectrum.

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[1]A. Ghiorso *et al*., Phys. Rev. C **7**, 2032 (1973).
[2]R. Herzberg *et al*., private communication.

d.6. Limiting Angular Momentum in ^{254}No (T. L. Khoo, D. Seweryniak, I. Ahmad, M. P. Carpenter, C. N. Davids, S. Freeman, J. Greene, N. Hammond, R. V. F. Janssens, F. G. Kondev, T. Lauritsen, C. J. Lister, P. A. Butler,‡ P. Chowdhury,† J. A. Cizewski,§ R. Gramer,† R. D. Herzberg,‡ A. Heinz,¶ P. Ikin,‡ M. Johnson,§ G. D. Jones,‡ G. Mukherjee,* E. Ngijoi-Yogo,† and P. Reiter||)

Our investigations of the shell-stabilized nobelium nuclei show that they, perhaps surprisingly, survive up to high angular momentum and that the fission barrier is >5 MeV for spins larger than 10 $\hbar$. In other words, shell-stabilized nuclei are quite robust at high spin. Stimulated by these experiments, several self-consistent mean-field theory calculations found that the fission barrier that the barrier remains sizeable at high spin. The HFB predictions of Egido and Robledo[1] suggest that ^{254}No should survive up to spin 30 - 40 $\hbar$. Self-consistent mean-field theories, with interactions determined from properties of lighter nuclei, provide a promising method for predicting the properties of superheavy nuclei, particularly since they do not employ parameters tailored to different mass regions. However, the reliability of these predictions needs to be tested by comparison to data of shell-stabilized nuclei and also by expanding the small database for this comparison.

To determine how much angular momentum a ^{254}No nucleus can sustain before it is torn apart by fission, we conducted an experiment with Gammasphere operated in coincidence with the FMA. This combination provides a capability, which is unique in the world for reactions with sub-μb cross sections, namely the ability to detect γ rays with both high resolution and with 4-π calorimetric capability. We attempted to measure the two-dimensional entry distribution, i.e. the initial spin-energy distribution of the nucleus. However, a technical problem with Gammasphere precluded measurements of the BGO energy and, hence, of the sum energy in the reaction. The multiplicity information remained intact. The maximum input angular momentum was increased from ~20 to ~33 $\hbar$ by using a higher beam energy than in our previous experiment[2] -- from 219 to 223 MeV. (The temptation to use an even higher energy was tempered by the decreasing cross section.) The results show a hit distribution that demonstrates a distinct increase in the average angular momentum of ^{254}No. At this stage of the analysis, however, we cannot claim an equally unambiguous increase in the maximum spin.

Another aim of the experiment was to test mean-field theory, which predicts a backbend[3] in the moment of inertia plot around spin 30 in ^{254}No, due to the diving of the $9/2^-$[734] *j15/2* neutron and $7/2^+$[633] *i13/2* proton quasiparticle levels into the vacuum. In contrast, HFB calculations[1] with the Gogny force suggest a backbend at much higher spin (45). Hence, a backbend can provide a sensitive test of the predicted energies of these high-*j* orbital energies. The ground band of ^{254}No was definitely observed up to spin 22, with monotonically increasing transition energies. Above that, the very sparse coincidence data suggest a backbend. However, one cannot be so confident about this observation since one no longer benefits from the smooth extension of the moment of the inertia. Analysis of the data continues.

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[1] L. Egido and L. Robledo, Phys Rev. Lett. **85**, 1198 (2000).
[2] P. Reiter *et al*., Phys Rev. Lett. **84**, 3542 (2000).
[3] A. Afanasjev *et al*., Phys. Rev. C **67**, 024309 (2003).