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First evidence of excited states in the near-drip-line nucleus ^{126}Pr and signature inversion in $A\approx130$ nuclei

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γ-ray transitions have been identified for the first time in the near-drip-line nucleus ^{126}Pr, making it the lightest odd-odd praseodymium nucleus in which excited states have been reported. Evidence is presented for two rotational bands in ^{126}Pr, one strongly coupled and the other doubly decoupled. In addition, the preliminary reports of a band in ^{128}Pr are confirmed. The signature inversion phenomenon and trends in the energy staggering of the $\pi h_{11/2}\nu h_{11/2}$ bands are discussed for the Cs, La, and Pr nuclei.

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The mass 130 region represents an important laboratory to understand the role of different intruder and extruder orbitals on nuclear deformation. Mechanisms for the origin of enhanced deformation in this region are being investigated by searching for bands built on these orbitals in very neutron-deficient nuclei [1–3]. Significant advances have recently been made in the low-spin spectroscopy of the lightest nuclei in this region where the ground-state deformations are expected to increase as the neutron number decreases [2,4]. Ground-state deformations for nuclei near the proton drip line are suggested to be prolate with β_2 deformation values near 0.3 [4], which are nearly as large as some highly deformed bands observed in the heavier $A\approx130$ region (see Ref. [5], for example). Calculations by Vretenar *et al.* [6] place the proton drip line at ^{124}Pr for $Z=59$ nuclei, while current experimental information on neutron separation energies ends at ^{126}Pr [7]. Further progress towards the spectroscopy at and beyond the proton drip line in this mass region presents difficult challenges. In addition to requiring efficient and selective detection systems, these studies may well require the use of radioactive ion beams. However, we can try to approach these drip-line nuclei by using the most neutron-deficient stable beams and targets in conjunction with the most selective detection systems available today.

In the present work, we have extended the systematic study of the odd-odd praseodymium nuclei to the neutron-deficient ^{126}Pr and ^{128}Pr isotopes. Excited states have been observed for the first time in the near-drip-line nucleus ^{126}Pr and the yrast band in ^{128}Pr has been confirmed. We populated these nuclei in two separate experiments and identified them with a powerful combination of γ-ray spectrometers, light charged-particle arrays, and, in one experiment, a recoil mass spectrometer. The identification of $\pi h_{11/2}\nu h_{11/2}$ bands in ^{126,128}Pr allows for a systematic study of the signature inversion phenomenon [8] in Pr nuclei. Trends observed in the energy staggering are compared and contrasted with those seen in Cs ($Z=55$) and La ($Z=57$) nuclei.

Each experiment was performed using the ^{40}Ca+^{92}Mo reaction to populate the high-spin states of the ^{126,128}Pr nuclei in the αpn and $3pn$ channels, respectively. In one experiment, a thin (~450 μg/cm^2), self-supporting ^{92}Mo target was bombarded by a ^{40}Ca beam at 170 MeV, provided by the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory (ORNL). Excited states were studied using the Ge Clover detector array CLARION, the CsI portion of the charged particle detector array HyBall [9], and the Recoil Mass Spectrometer (RMS) [10]. CLARION consists of 11 clover Ge detectors and was complemented with ten smaller single-crystal HPGe detectors. Light charged particles (p and α) emitted by the deexciting compound nuclei were identified with 95 CsI scintillators coupled to photodiodes in a 4π configuration. The focal plane detector of the RMS was used in coincidence with the two arrays such that the mass, evaporated charged particles, and prompt γ rays of the recoils could be correlated on an event-by-event basis. Reference [11] illustrates the use of the RMS in this mass region with a preliminary subset of CLARION, where excited states in ^{125}Ce were identified. A charge-reset foil was placed ~10 cm behind the target in order to improve [12] the detection of recoils with highly-converted transitions near the ground state, possibly from short-lived ($\leqslant10$ ns) isomeric states. Observation of the ^{128}Pr recoils improved by a factor of 2–3 with the reset foil. γ rays associated with masses 126 and 128 were sorted into

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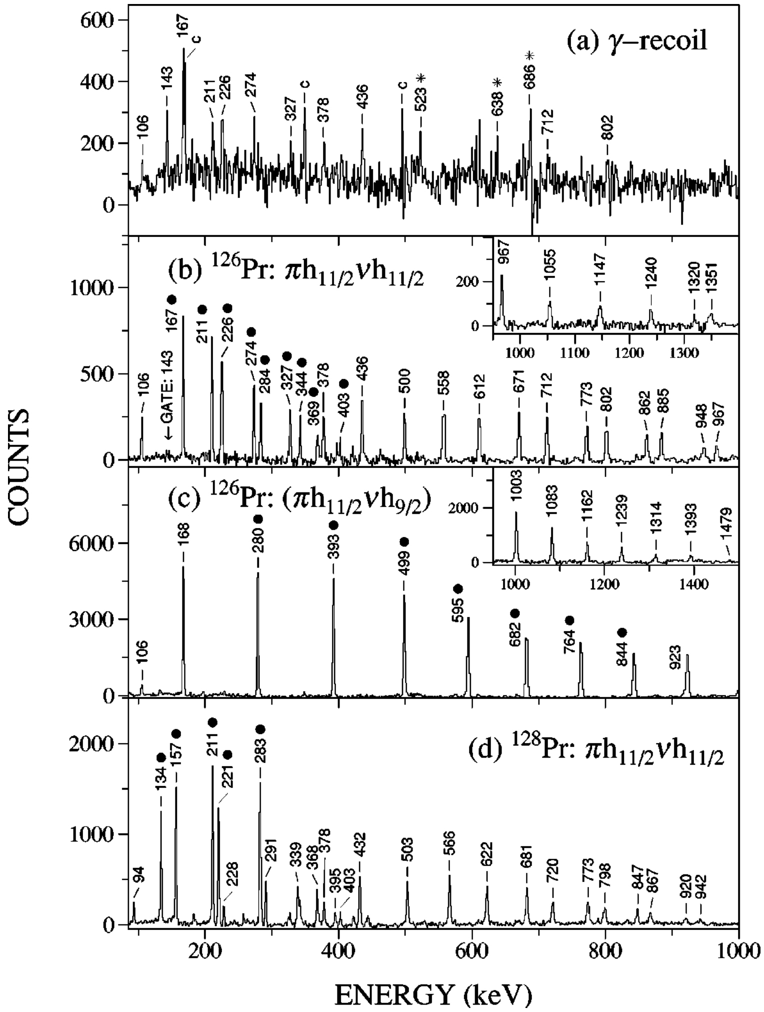

FIG. 1. (a) Spectrum of transitions in coincidence with $A=126$ recoils after a fraction of the γ rays coincident with the $\alpha 2p$ channel (^{126}Ce) were subtracted. The three strongest transitions in ^{126}Ce are observed in the spectrum and are labeled with a ''c.'' Peaks marked with an asterisk could not be identified with a band structure. (b) Spectrum of the strongly-coupled band in ^{126}Pr from the GAMMASPHERE experiment produced by summing over all the double-gated coincidence spectra between the 143-keV transition and the γ rays denoted with a filled circle. The inset is the high-energy portion of the $\alpha=1$ signature of band 2. (c) Spectrum of the doubly-decoupled band in ^{126}Pr from the GAMMASPHERE experiment. A sum over all the possible double gates of the transitions marked with a filled circle was used to produce the spectrum. The high-energy inset is a result of summing the spectra from many double gates on higher lying transitions in the band. (d) Spectrum of the yrast band of ^{128}Pr as observed in the mass 128 gated matrix from the ORNL experiment. The spectrum is the sum of coincidence spectra gated on the transitions denoted with a filled circle.

separate $E_\gamma \times E_\gamma$ coincidence matrices and were subsequently analyzed with the RADWARE software package [13]. A total of ~0.9 and 4.5 million γ-γ events were observed in the 126 and 128 mass-gated matrices, respectively. Matrices of E_γ vs p and α multiplicities, with the same mass-gated conditions, were also sorted such that γ-charged particle coincidence relationships could be investigated.

In a second experiment, emphasizing the population of the highest spin states possible, the ^{40}Ca beam was accelerated to an energy of 184 MeV by the ATLAS facility at Argonne National Laboratory (ANL). The GAMMASPHERE spectrometer [14], with 99 suppressed Ge detectors, was operated in conjunction with the MICROBALL CsI array [15] for γ-ray and charged-particle detection, respectively. The transitions found to be in coincidence with $\alpha p X n$ and $3pXn$ exit channels were sorted into separate $E_\gamma \times E_\gamma \times E_\gamma$ cubes and were also analyzed with the RADWARE package. Over 580 million γ^5 or higher fold events were recorded in the experiment with ~7.5% and 13% of the data associated with the αp and $3p$ gating requirements, respectively.

Transitions found in coincidence with $A=126$ recoils from the ORNL experiment were predominately identified with ^{126}Ce [16,17] from the $\alpha 2p$ channel. However, by subtracting the $\alpha 2p$ γ rays from the $A=126$ projection, several transitions for ^{126}Pr emerge as shown in Fig. 1(a). Setting coincidence gates on many of these candidates in the cube coincident with an α particle and a proton from the GAMMASPHERE data revealed the strongly-coupled sequence displayed in Fig. 1(b). Cubes coincident with $2p$, $3p$, $4p$, $\alpha 2p$, $2\alpha p$, and 2α were also investigated, but this band was not present. Thus, the band appearing in the αp data is not due to the missing or misidentification of charged particles by the MICROBALL, but instead the result of it occurring with the emission of an α and a p leading to praseodymium nuclei. Combining the facts that this structure is (i) correlated with mass 126 from the ORNL experiment and (ii) is associated with the emission of an α particle and a proton from the ANL experiment, one can conclude the sequence must be identified with ^{126}Pr. This is the first conclusive evidence of any transitions in this proton-rich nucleus, which becomes the lightest odd-odd Pr nucleus in which excited states have been observed. Tentative spin assignments for this band were based on energy level systematics as described by Liu *et al.* [18]. The first $h_{11/2}$ proton and $h_{11/2}$ neutron alignments, which are found in the neighboring nuclei ^{125}Ce [11] and ^{127}Pr [1], respectively, are not observed in this band. Therefore, the blocking of these crossings strongly suggests a configuration of $\pi h_{11/2} \nu h_{11/2}$ for the strongly-coupled band in ^{126}Pr, as labeled in the level scheme of Fig. 2.

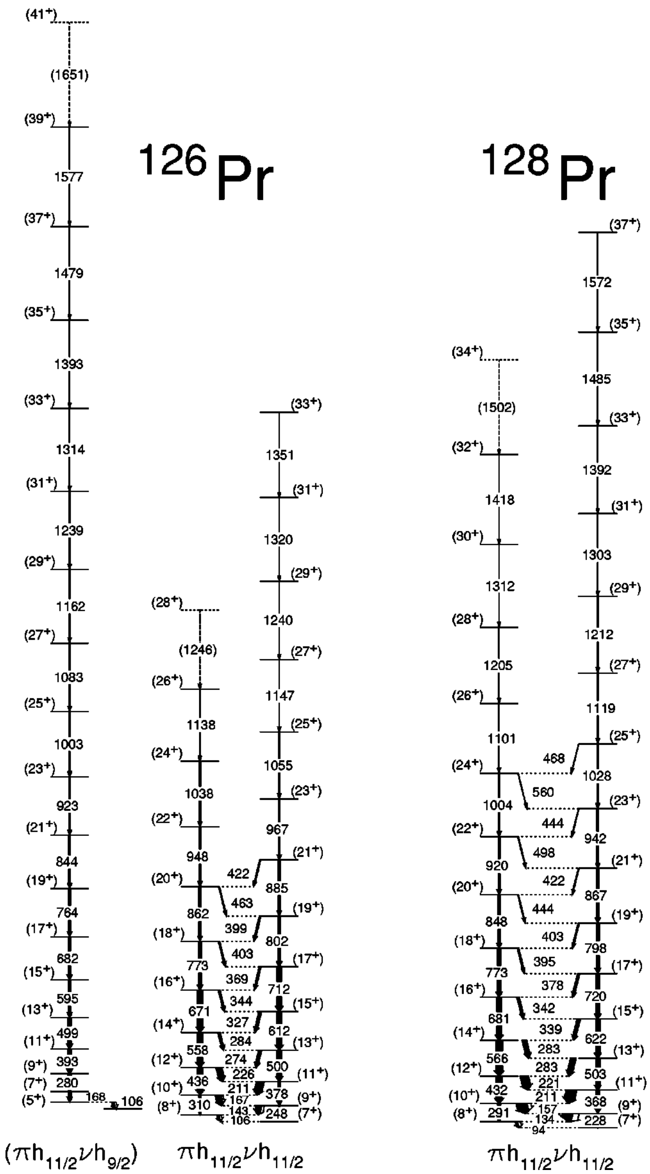

FIG. 2. Level scheme for ^{126}Pr and a partial level scheme for ^{128}Pr. The width of the arrows is proportional to the transition's relative intensity. Configuration assignments for the bands are given. Tentative transitions are denoted with dashed lines.

A doubly-decoupled sequence, shown in Fig. 1(c), could also be associated with the αp condition from the GAMMASPHERE data in a similar manner as that described above. It was found to be more strongly populated in the ANL experiment than either of the yrast bands from ^{125}Pr [19] ($\alpha p2n$ channel) and ^{127}Pr [1] (αp channel). Thus, it is likely a result of the αpn exit channel leading to ^{126}Pr, although, an irrefutable assignment cannot be made without mass identification. This decay sequence could not be established in the ORNL experiment, as shown in Fig. 1(a). The population intensity was likely below the experimental sensitivity level as this band was observed to be less intense in the GAMMASPHERE experiment than the strongly-coupled band (note that the relative intensities of the transitions are depicted by the arrow widths in Fig. 2). Energy level systematics have led to tentative spin assignments and a tentative configuration assignment of $\pi h_{11/2}\nu h_{9/2}$, although the $\pi h_{11/2}\nu(d_{3/2}/s_{1/2})$ configuration cannot be ruled out since both would likely form a doubly-decoupled sequence. Further discussion of this band will be presented in a forthcoming publication [20].

The identification of structures in ^{128}Pr was established from the γ-γ-recoil data measured in the ORNL experiment. Figure 1(d) shows a summed coincidence spectrum of a band from the mass 128 gated γ-γ matrix. By examining the γ-charged particle matrix, we were also able to determine that the strongest and cleanest transitions in this band were associated with a $3p$ evaporation. This additional information allows for the structure to be unequivocally associated with ^{128}Pr as it is the only $A=128$ nucleus which is in coincidence with the emission of three protons from this reaction. These observations confirm preliminary results reported by Watson *et al.* [21] and Galindo-Uribarri *et al.* [22], where this same band was observed up to a spin of $(19)\hbar$. In Ref. [21] mass-gating techniques similar to those described above were used, but without a charged-particle detector, and in Ref. [22] a charged-particle detector was employed, but without mass gating. Once again, the first $h_{11/2}$ proton and neutron alignments are blocked in this band, which leads to a configuration assignment of $\pi h_{11/2}\nu h_{11/2}$. The band was extended to high spins using the GAMMASPHERE data as shown in the partial level scheme of Fig. 2. Six additional bands were identified in ^{128}Pr and will be discussed in detail in a future publication [20].

Strongly-coupled bands are composed of two $\Delta I=2$ sequences which have different signatures[1] ($\alpha=0$ or 1 for odd-odd systems). One signature is often energetically favored over the other due to the decoupling parameter and the favored signature can normally be predicted by the j of the orbitals involved [23]. However, there are configurations (normally involving intruder orbitals) where the expected favored signature lies higher in energy than the unfavored signature. This is known as signature inversion [8] and it has been reported in odd-odd nuclei of the mass 80 [24], 130 [18], and 160 [25] regions at lower spins. In the mass 130 region, the inversion phenomenon is found in the $\pi h_{11/2}\nu h_{11/2}$ bands where the expected favored signature is $\alpha=1$. Figure 3 displays the energy staggering, defined as $\Delta E=[E(I)-E(I-1)]-[E(I+1)-E(I)+E(I-1)-E(I-2)]/2$, of the $\pi h_{11/2}\nu h_{11/2}$ structures in several Cs, La, and Pr isotopes. The signature inversion can be observed at lower spins where the $\alpha=0$ signature (filled squares) lies lower in energy, but at higher spins the Coriolis force restores ''normal'' ordering of the sequences.

An adequate explanation for inversion has been elusive, although several attempts have been made suggesting triaxiality [8], a pn interaction [26], triaxiality with a pn interaction [35], and QQ pairing [36] as possible reasons for this behavior. The validity of the theories is often tested by how

[1]Signature is the quantum number associated with the rotation of a deformed nucleus around a principal axis by 180°.

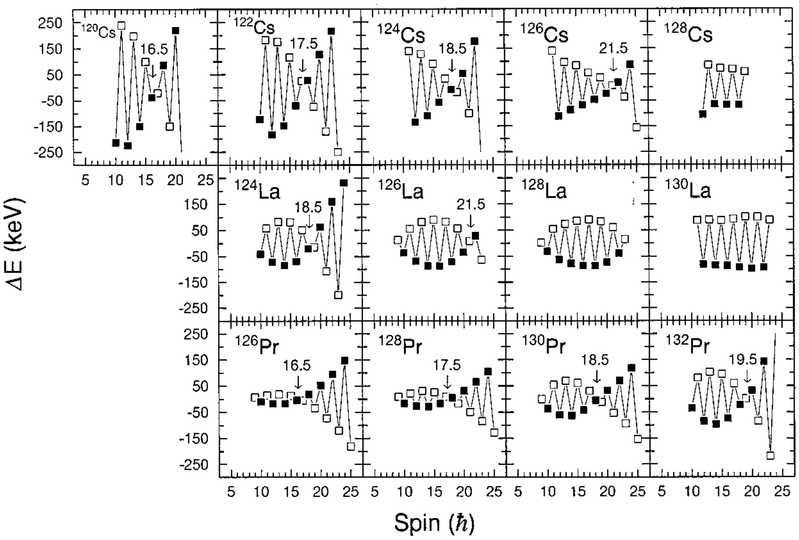

FIG. 3. Energy staggering, defined in the text, as a function of spin for the $\pi h_{11/2}\nu h_{11/2}$ bands in odd-odd Cs $(Z=55)$, La $(Z=57)$, and Pr $(Z=59)$ nuclei. The $\alpha=0$ $(\alpha=1)$ signature is denoted by filled (open) squares. Arrows depict the spin at which the signature inversion ends. Spin assignments for all nuclei shown were adopted from Liu *et al.* [18]. Data from nuclei not described in the present work were taken from ^{120}Cs [26], ^{122}Cs [27], ^{124,126}Cs [28], ^{128}Cs [29], ^{124}La [28], ^{126}La [30], ^{128,130}La [31], ^{130}Pr [32], ^{132}Pr [33,34].

well the model reproduces systematic trends; therefore, establishing these experimental trends is crucial for understanding the mechanism(s) behind signature inversion. With the observance of the $\pi h_{11/2}\nu h_{11/2}$ bands in ^{126,128}Pr, it is now possible to examine the systematics in the praseodymium nuclei. The spin at which the inversion ends (marked by arrows in Fig. 3) increases with neutron number N for all three isotopic chains (see Fig. 3). For an isotonic chain, the amount of initial staggering reduces as Z is increased, which may be a result of increasing deformation with Z. A trend observed by Smith *et al.* [37] is that the amount of initial staggering decreases with increasing N for the Cs nuclei. Recently, Xu *et al.* [36] suggested that QQ pairing causes the inversion and that the force decreases as N is increased from 65 to 71; therefore, they were able to reproduce this latter trend. However, an *opposite* result is found for the Pr nuclei in Fig. 3 as the initial staggering increases with N. This indicates that the force(s) responsible for the inversion in the Pr nuclei increases as the neutron Fermi surface increases and/or as the quadrupole deformation decreases. A remarkably consistent amount of initial staggering is observed in the La chain, with perhaps a small increase in staggering with N. The opposing systematics of the Cs and Pr nuclei are rather surprising as consistent trends in the amount of staggering with N are observed in the mass 160 [25] region. A substantial challenge is therefore posed for the model in Ref. [36], or any model, to account for the differing trends in this mass region.

In summary, progress towards discrete γ-ray spectroscopy near the proton drip line has been made in odd-odd praseodymium nuclei as excited states in ^{126}Pr were observed for the first time. The selectivity of the RMS and the charged-particle array HyBall in combination with the CLARION Ge array at ORNL, as well as the power of GAMMASPHERE in conjunction with the MICROBALL, was used to positively identify the structures. Signature inversion is observed in the $\pi h_{11/2}\nu h_{11/2}$ bands and contrasting trends in the amount of energy staggering as a function of neutron number exist between the Cs and Pr nuclei. Further theoretical analysis is required in order to understand this unusual phenomenon.

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[1] S.M. Mullins *et al.*, Phys. Rev. C **58**, R2626 (1998).
[2] B.H. Smith *et al.*, Phys. Lett. B **443**, 89 (1998).
[3] A. Galindo-Uribarri, Rev. Mex. Fis. **45 S2**, 55 (1999).
[4] P. Möller, J.R. Nix, W.D. Myers, and W.J. Swiatecki, At. Data Nucl. Data Tables **59**, 185 (1995).
[5] F.G. Kondev *et al.*, Phys. Rev. C **60**, 011303(R) (1999).
[6] D. Vretenar, G.A. Lalazissis, and P. Ring, Phys. Rev. Lett. **82**, 4595 (1999).
[7] G. Audi and A.H. Wapstra, Nucl. Phys. **A565**, 66 (1993).
[8] R. Bengtsson, H. Frisk, F.R. May, and J.A. Pinston, Nucl. Phys. **A415**, 189 (1984).
[9] A. Galindo-Uribarri, HyBall Charged-Particle Detector System, URL <http://www.phy.ornl.gov/hribf/research/equipment/hyball>
[10] C.J. Gross *et al.*, Nucl. Instrum. Methods Phys. Res. A **450**, 12 (2000).
[11] E.S. Paul *et al.*, Phys. Rev. C **58**, 801 (1998).
[12] T.M. Cormier, P.M. Stwertka, H. Herman, and N.G. Nicolis, Phys. Rev. C **30**, 1953 (1984).
[13] D.C. Radford, Nucl. Instrum. Methods Phys. Res. A **361**, 297 (1995).
[14] R.V.F. Janssens and F. Stephens, Nucl. Phys. News **6**, 9

(1996).

[15] D.G. Sarantites, P.-F. Hua, M. Devlin, L.G. Sobotka, J. Elson, J.T. Hood, D.R. LaFosse, J.E. Sarantites, and M.R. Maier, Nucl. Instrum. Methods Phys. Res. A **381**, 418 (1996).

[16] T. Morek *et al.*, Eur. Phys. J. A **3**, 99 (1998).

[17] E. Padilla *et al.* (unpublished).

[18] Y. Liu, J. Lu, Y. Ma, S. Zhou, and H. Zheng, Phys. Rev. C **54**, 719 (1996).

[19] D.R. LaFosse (private communication).

[20] D.J. Hartley *et al.* (unpublished).

[21] D.C.B. Watson *et al.*, Daresbury Laboratory, Annual Report, 1986–1987, Appendix, 1987, p. 31.

[22] A. Galindo-Uribarri, V.P. Janzen, and D. Ward, Atomic Energy of Canada Ltd., AECL-11534 PR-TASCC-11, 3.1.8, 1996.

[23] A. Bohr and B.R. Mottelson, *Nuclear Structure*, Vol. 2 (Benjamin, New York, 1975).

[24] S.L. Tabor, Heavy Ion Phys. **2**, 239 (1995).

[25] C.-H. Yu *et al.*, in *Proceedings of the Workshop on Gammasphere Physics*, edited by M.A. Deleplanque, I.Y. Lee, and A.O. Macchiavelli (World Scientific, Singapore, 1996), p. 254.

[26] B. Cederwall *et al.*, Nucl. Phys. **A542**, 454 (1992).

[27] J.F. Smith, C.J. Chiara, D.B. Fossan, G.J. Lane, J.F. Lewicki, J.M. Sears, and P. Vaska, Phys. Rev. C **58**, 3237 (1998).

[28] T. Komatsubara *et al.*, Nucl. Phys. **A557**, 419c (1993).

[29] E.S. Paul, D.B. Fossan, Y. Liang, R. Ma, and N. Xu, Phys. Rev. C **40**, 619 (1989).

[30] B.M. Nyakó, J. Gizon, D. Barnéoud, A. Gizon, M. Józsa, W. Klamra, F.A. Beck, and J.C. Merdinger, Z. Phys. A **332**, 235 (1989).

[31] M.J. Godfrey, Y. He, I. Jenkins, A. Kirwan, P.J. Nolan, D.J. Thornley, S.M. Mullins, and R. Wadsworth, J. Phys. G **15**, 487 (1989).

[32] C.M. Petrache *et al.*, Nucl. Phys. **A635**, 361 (1998).

[33] K. Hauschild *et al.*, Phys. Rev. C **50**, 707 (1994).

[34] C.M. Petrache *et al.*, Nucl. Phys. **A603**, 50 (1996).

[35] N. Tajima, Nucl. Phys. **A572**, 365 (1994).

[36] F.R. Xu, W. Satula, and R. Wyss, Nucl. Phys. **A669**, 119 (2000).

[37] J.F. Smith *et al.*, Phys. Lett. B **406**, 7 (1997).