High-spin level scheme and decay of the 67-μs isomer in ^{142}Pm

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An in-beam γ-ray spectroscopy experiment for ^{142}Pm has been performed via the ^{128}Te(^{19}F,5n) reaction at beam energies of 75 MeV through 95 MeV. Excitation functions and γ-γ coincidences have been measured. Detailed analysis of γ-γ coincidence relationships leads to a revised high-spin level scheme for ^{142}Pm. The $\pi h_{11/2}\otimes\nu h_{11/2}^{-1}$ multiplet in this nucleus has been identified and the discussion is based on a systematic of corresponding states in neighboring odd-odd nuclei. The previously known 67-μs isomer and associated decay γ rays have been placed into the new level scheme. This long-lived isomer is proposed to be a four-hole state with predominantly the $(\pi g_{7/2}^{-1}d_{5/2}^{-2}\otimes\nu h_{11/2}^{-1})_{13^-}$ configuration.

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I. INTRODUCTION

The high-spin level structures of spherical odd-odd nuclei below the $Z=64,N=82$ are among the most complex encountered experimentally because of the existence of a large number of low-lying two quasiparticle (2-qp) multiplets. The high-spin members of such 2-qp states are often isomeric, leading to difficulties in building high-spin level schemes via a standard in-beam γ-ray spectroscopy experiment. The low-lying levels observed up to the 8^- isomer in ^{142}Pm have been interpreted as due to 2-qp excitations [1]. Given the doubly closed-shell nature of ^{146}Gd [2], the 8^- isomer has been interpreted to be a fully aligned member of the $\pi d_{5/2}^{-1}\otimes\nu h_{11/2}^{-1}$ multiplet [3]. It is then natural to expect that the high-spin members of the $\pi g_{7/2}^{-1}\otimes\nu h_{11/2}^{-1}$ and $\pi h_{11/2}\otimes\nu h_{11/2}^{-1}$ multiplets should exist at low excitation. Indeed, such 2-qp states have been identified in the neighboring odd-odd ^{140}Pm [3], ^{142,144}Eu [4], and ^{144,146}Tb [5,6] nuclei. Athough, no such candidates seem to exist in the recently reported level scheme of Ref. [7], however, Kenefick and co-workers reported [8] the observations of a $T_{1/2}=67$ μs isomer and decay γ rays of 43, 381, 428, 456, 639, 883, and 1020 keV. The authors assigned this isomer to ^{142}Pm based on the K x-γ coincidences and comparison of relative yields of the 2.0-ms and 67-μs isomers produced in the cross-checked reactions [9]. Consequently, the $T_{1/2}=67$ μs isomer has been assumed to be 10^+ feeding directly to the 8^- level via a 43-keV transition [10], with the other γ rays unassigned. It is surprising that the newly established level scheme [7] was proposed to be built on the 8^- state instead of the 10^+ state. The authors of Ref. [7] claimed that the observed 43-381-639-882 keV cascade could be assigned to ^{141}Pm. In view of this, we carried out a conventional in-beam γ-spectroscopy experiment to re-investigate the high-spin level structure of ^{142}Pm. In this paper, we report a new high-spin level scheme of ^{142}Pm established using the ^{128}Te(^{19}F,5n) ^{142}Pm reaction. The previously known 67-μs isomer and associated γ rays [8,9] have been placed into the level scheme of ^{142}Pm on the basis of γ-γ coincidence relationships. The high-spin members of the $\pi g_{7/2}^{-1}\otimes\nu h_{11/2}^{-1}$ and $\pi h_{11/2}\otimes\nu h_{11/2}^{-1}$ multiplets in ^{142}Pm have been suggested and the discussion is based on the systematic trends in nuclei with such multiplets. The configuration of the 67-μs isomer is also proposed and discussed.

The low-lying level structure of ^{142}Pm has been initially investigated by Funke *et al.* [1]. A level scheme including the long-lived ($T_{1/2}=2.0$ ms) β^+ decaying isomer has been established. It was not until recently that the high-spin level scheme of ^{142}Pm had been reported using the ^{133}Cs(^{13}C,4n)^{142}Pm reaction [7]. We have also noticed that the strong coincidence cascade 381-639-882 keV was observed earlier by Piiparinen *et al.* in the ^{141}Pr+^{3}He reaction [11], but this cascade was proposed to be from an unknown isomer in ^{140}Pm. Aryaeinejad *et al.* [12] placed all the γ rays reported in Ref. [8] except for the 43-keV transition into the level scheme of ^{141}Pm from their (α,4$n\gamma$) work. However, this assignment could not be confirmed in a later experiment using the ^{126}Te(^{19}F,4n)^{141}Pm reaction [13]. During the course of this investigation, a revised level scheme of ^{141}Pm has been reported [14] in which the 43-381-639 keV cascade was assigned to ^{141}Pm feeding the $15/2^-$ level. To the extent of our knowledge, the assignment of the 381-, 428-, 456-, 639-, 883-, and 1020-keV lines to ^{141}Pm has not been carefully studied through measurements of γ-ray excitation functions.

II. EXPERIMENTAL DETAILS AND RESULTS

The excited states in ^{142}Pm were populated via the ^{128}Te (^{19}F,5n)^{142}Pm reaction. The ^{19}F beam was provided by the tandem accelerator at the China Institute of Atomic Energy (CIAE). The target consisted of an isotopically enriched ^{128}Te metallic foil of 2.2 mg/cm^2 thickness with a 2.3 mg/cm^2 Au backing. The γ rays were detected by ten BGO(AC)HPGe's (high purity germanium detectors with bismuth germanate anti-Compton suppressors), with energy resolutions of 2.0–2.5 keV at 1.33 MeV. The detectors were calibrated using standard ^{152}Eu and ^{133}Ba sources. Excitation

TABLE I. γ-ray energy E_γ, relative intensity I_γ (normalized to the 380.8-keV line), angular distribution ratio $R_{AD}(\gamma)$, excitaion energy E_i, and proposed initial I_i^π and final I_f^π spin-and-parity. The information on states below the 2-ms isomer is not listed in the table.

E_γ(keV)[a]	I_γ[b]	$R_{AD}(\gamma)$	E_i	I_i^π	I_f^π
44.0	21.8		1809.1	(10^+)	(9^+)
52.0	5.1		3872.1	(15)	(14)
61.8			5031.3		(16)
88.4			3886.5	(14^-)	(13^+)
142.9	25.6[c]	0.89(6)	4015.0	(16)	(15)
148.7	3.2	0.80(13)	3886.5	(14^-)	(13^+)
175.4	8.2	0.74(9)	4061.6	(15)	(14^-)
192.3	10.1	0.82(7)	5810.1	(20)	(19)
195.1	5.3	0.83(10)	5810.1	(20)	(19)
205.8	2.6		4391.5		
214.8	2.1	0.76(15)	7030.0	(22)	(21)
221.3	19.7[c]	0.83(6)	4236.3	(17)	(16)
221.4	<1		5008.2	(18)	
241.2	2.3		4061.6	(15)	(14)
248.8	2.5		4640.3		
251.9	1.2		4324.9		
277.9	5.6	0.80(10)	4339.6	(16)	(15)
315.1	24.4[c]	1.04(7)	3143.6	(14^-)	(13^-)
315.6	4.0		5672.0		
324.7	1.8		4339.6	(16)	(16)
325.2	6.6		5356.4		
329.8	4.1	0.95(11)	4391.5		
380.8	100.0[c]	0.86(8)	2189.9	(11^+)	(10^+)
426.8	10.8	0.84(10)	1309.8	(9^-)	(8^+)
437.6	3.1	0.81(14)	3737.9	(13^+)	(12^+)
447.3	<1		4786.9		(16)
449.2	1.9		4774.1		
455.2	10[c]	1.27(10)	1765.1	(9^+)	(9^-)
498.0	1.9	0.87(15)	3798.1	(13^+)	(12^+)
519.3	7.0	1.11(8)	4391.5		(15)
526.8	1.1		4324.9		(13^+)
554.7	4.3	0.86(11)	7030.0	(22)	(21)
565.7	<1		4072.9		
609.6	4.5	0.85(11)	5617.8	(19)	(18)
638.6	89.7[c]		2828.5	(13^-)	(11^+)
665.3	9.0	0.65(8)	6475.4	(21)	(20)
691.6	4.0		5031.3		(16)
728.5	10.1	0.79(8)	3872.1	(15)	(14^-)
742.8	5.6	1.23(12)	3886.5	(14^-)	(14^-)
771.7	4.2	0.70(12)	5008.2	(18)	(17)
772.9	<1		4072.9		
882.2	144.9[c]	0.77(8)	1765.1	(9^+)	(8^-)
991.6	68[c]	0.82(5)	3820.1	(14)	(13^-)
1005.0	6.8	0.76(9)	6815.0	(21)	(20)
1019.4	22.5		2828.5	(13^-)	(10^+)
1042.1	7.7[c]		4185.7		(14^-)
1057.9	5.8[c]	0.95(12)	3886.5	(14^-)	(13^-)
1097.7	6.9	0.93(9)	4969.8	(16)	(15)
1110.4	4.4	0.45(11)	3300.0	(12^+)	(11^+)
1317.2	<1		3507.1		(11^+)
1378.6	11.2	1.31(7)	5614.8	(19)	(17)
1381.4	12.4	1.32(8)	5617.8	(19)	(17)
1490.6	<1		3300.0	(12^+)	(10^+)
1548.0	2	1.13(16)	3737.9	(13^+)	(11^+)
1608.2	1.1	1.23(18)	3798.1	(13^+)	(11^+)

[a]Uncertainties between 0.3 and 0.9 keV.
[b]Uncertainties are within 15% depending on their intensities.
[c]Obtained from the singles spectrum.

functions were measured in 5 MeV increments at the energy range of 75–95 MeV and the largest yield of ^{142}Pm was found at 90 MeV. Then, γ-γ coincidence measurements were performed at this beam energy with a coincidence window of 400 ns. A total of 75×10^6 γ-γ coincidence events were accumulated and sorted into a symmetric matrix for off-line analysis. To determine the multipolarity of emitted γ rays, the detectors were divided into 2 groups positioned at ±40° (or ±140°) and ±90° with respect to the beam direction. Two asymmetric matrices were constructed from the coincidence data [4,15]: one matrix with detectors at $\theta_1 = \pm 40°$ (or ±140°) and another with $\theta_2 = \pm 90°$ against those at all angles. From these two matrices, the angular distribution asymmetry ratios defined as $R_{AD}(\gamma)=I_\gamma(\theta_1)/I_\gamma(\theta_2)$ were extracted from the γ-ray intensities $I_\gamma(\theta_1)$ and $I_\gamma(\theta_2)$ in the coincidence spectra gated by γ transitions of any multipolarities. Usually a single gate was used for strong peaks. For some weak transitions, the sum-gated spectra were used to increase statistics. Stretched quadrupole transitions were adopted if $R_{AD}(\gamma)$ values were larger than unity, and dipole transitions were assumed if $R_{AD}(\gamma)$'s were significantly less than 1.0. It should be noted that the extracted $R_{AD}(\gamma)$ values are assumed to be insensitive to angular distribution effects of gating γ transitions. However, this is not exactly true because the limited angular coverage of the experimental set-up does not wash out angular distribution effects completely. We have checked the $R_{AD}(\gamma)$ values for the γ transitions of known multipolarities using either $E2$ or $M1$ transitions as gates. The average values of $R_{AD}(\gamma)=1.24$ and 0.75 were obtained for the known $E2$ and $M1$ transitions in ^{143}Pm [16].

The relative intensities for some strong lines were extracted from a singles spectrum in the detector placed near the 55°. For most of the weak or contaminated γ rays, the relative intensities were obtained from the coincidence spectra. The γ-ray energies, spin and parity assignments, relative γ-ray intensities, and the $R_{AD}(\gamma)$ ratios are presented in Table I.

Figure 1(a) presents the excitation functions for some intense γ rays observed in this experiment. The figure shows

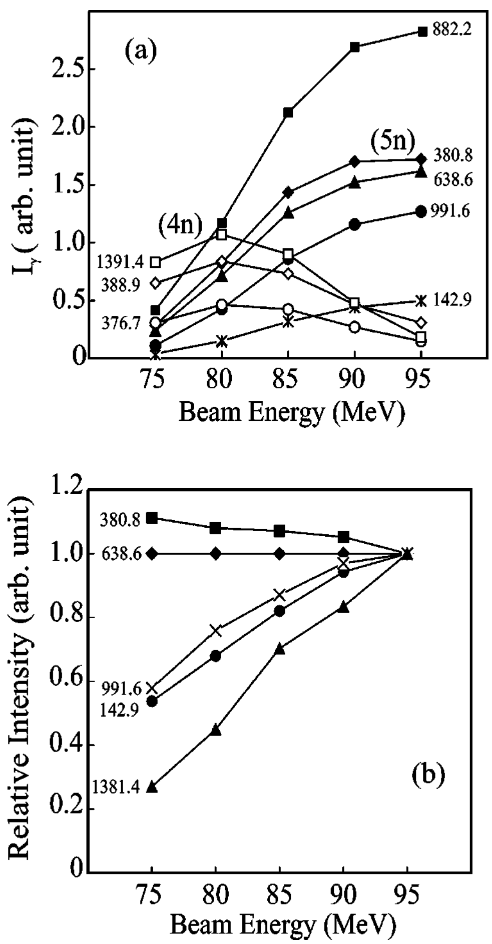

FIG. 1. (a) Excitation functions for the γ rays observed in the $^{19}F+^{128}Te$ reaction and (b) relative excitation functions for the γ rays assigned to ^{142}Pm. The intensities are normalized to the 638.6 keV transition at each beam energy.

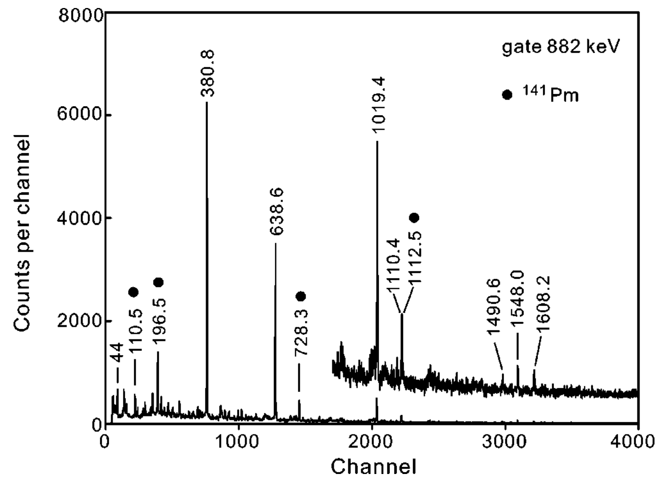

FIG. 2. Coincidence spectrum gated on the 882-keV line showing the relative intensities of γ rays from ^{142}Pm (381- and 639-keV lines) and from ^{141}Pm (111-, 197-, and 728-keV lines) [14].

that the excitation functions for the 142.9-, 380.8-, 638.6-, 882.2-, and 991.6-keV transitions are well separated from those of ^{143}Pm (e.g., 377-, 389-, and 1391-keV transitions), and they have a similar trend as a function of beam energy. The 142.9- and 991.6-keV transitions have been assigned to ^{142}Pm [7]. It is thus reasonable to assign the 380.8-, 638.6-, and 882.2-keV γ rays to ^{142}Pm as well. This assignment is in agreement with Ref. [9] but not with Refs. [11,12,14]. To get information on the relative ordering for the intense γ rays in ^{142}Pm, the relative excitation functions are plotted in Fig. 1(b). It is clear that the 991.6-, 142.9- and 1381.4-keV γ rays correspond to the de-excitation of higher-lying levels while the 380.8- and 638.6-keV lines correspond to the γ rays of lower-lying levels. It is worth noting that the 882-keV line has been found to be the strongest $15/2^- \rightarrow 11/2^-$ yrast transition in ^{141}Pm [14]. In the current experiment, this nucleus was produced by the 6n evaporation reaction but with lower cross section because the beam energy was below the peak of the excitation function. This has been demonstrated in the 882-keV gated spectrum shown in Fig. 2, where the 380.8- and 638.6-keV transitions are much stronger than the 728- and 196.5-keV lines (the next strongest yrast transitions in ^{141}Pm [14]). This is quite different from the results reported in Ref. [14] using the $^{133}Cs(^{12}C,4n)^{141}Pm$ reaction. The lower relative intensities of the 728- and 196.5-keV transitions with respect to the 380.8- and 638.6-keV lines indicate that the 882-keV transition is a double line from both ^{141}Pm and ^{142}Pm.

The γ-γ coincidence relationships reported in Ref. [7] for ^{142}Pm have been confirmed in this work. In addition, the 175.4-keV γ ray, previously placed in the level scheme of ^{142}Pm, is found to be in coincidence with the 380.8- and 882.2-keV and some new γ rays. Detailed analyses on the γ-γ coincidence relationships have been made, leading to a revised level scheme shown in Fig. 3. Several representative coincidence spectra are presented in Fig. 4 in which some important crossover transitions (or cascades) can be clearly identified. The observed crossover transitions (e.g., the 1019.4-keV line and 148.7–1548.0-keV cascade) fix the ordering of 638.6- and 380.8-keV transitions. We assign the strongest 882.2-keV γ ray to feed directly to the 8^- (2 ms) isomer. A low-energy 44-keV γ ray was found in coincidence with each of the transitions in the strongest 638.6-380.8-882.8 keV cascade, and it is thus placed in the present level scheme of Fig. 3. On referring to the experimental results of Kenefick and co-workers [8,9], we proposed that the 2828.5-keV level should be the long-lived isomer with $T_{1/2}=67$ μs reported in Refs. [8,9]. Our data set showed that the 991.6-keV transition had very weak coincidence (with the 400 ns window) with γ rays below the 2828.5-keV level. Thus the previously known 991.6-keV γ ray is expected to feed directly to this isomer rather than to the 8^- state [7].

The multipolarity of the emitted γ rays has been obtained from the measured $R_{AD}(\gamma)$ ratios using the appropriate γ rays as gates. For example, $R_{AD}(\gamma)$'s were extracted to be $\sim$0.80 for the 380.8-, 426.8-, and 882.2-keV transitions and $R_{AD}(\gamma)$ $\sim$1.27 for the 455.2-keV line when the sum gates of 148.7-, 175.4-, 1548.0-, and 1110.4-keV γ rays were used. We therefore propose I=9,9,10,11 for the levels at 1309.8, 1765.1, 1809.1, and 2189.9 keV, respectively, assuming that the

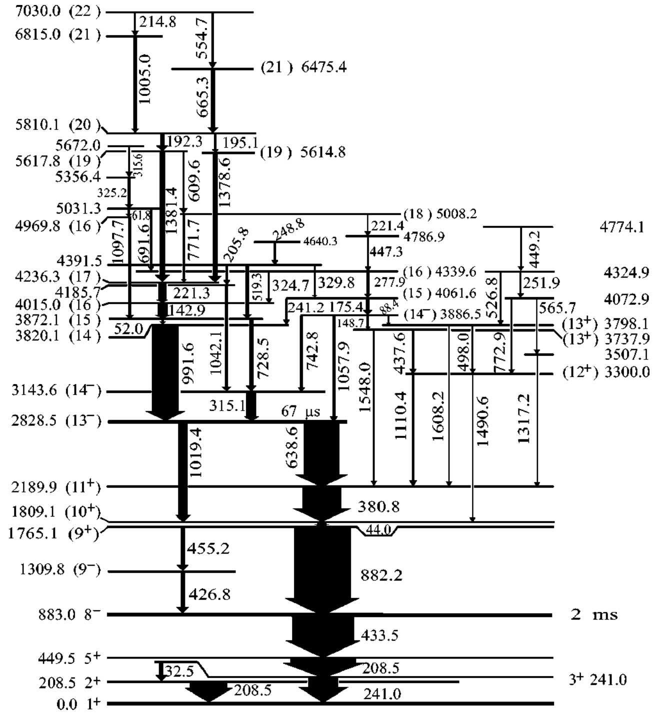

FIG. 3. Level scheme of ^{142}Pm deduced from the present work. The widths of the arrows are approximately equal to the relative intensities of the observed γ rays.

44-keV line corresponds to a $\Delta I = 1$ transition. Positive parity is proposed for the last three of these levels on the basis of level structure systematics and theoretical considerations (which will be discussed in Sec. III). $R_{AD}(E_\gamma = 1110.4\text{-keV})$ was determined to be 0.45(11), indicating that the 1110.4-keV γ ray corresponds to a mixed $M1/E2$ transition with a negative mixing ratio. This leads a spin and parity assignment to $I^\pi = 12^+$ for the 3300.0-keV level. This assignment is further supported by the observation of a 1490.6 -keV crossover transition. The dipole character of the 437.6-, and 148.7-keV lines ($R_{AD} \sim 0.81$, and 0.80, respectively) and the observation of a 1548-keV quadrupole crossover transition suggest $I^\pi = 13^+$ and $14^\pm$ for the levels at 3737.9 and 3886.5 keV, respectively. The $14^\pm$ state de-excites to lower-lying levels via several parallel transitions which can be clearly seen in Fig. 4(a). $R_{AD}(\gamma)$'s were extracted to be 1.23(12) and 0.95(12) for the 742.8- and 1057.9-keV lines. The former is most likely a $\Delta I = 0$ or 2 transition, and the latter a $\Delta I = 1, M1/E2$ mixed transition with a positive mixing ratio. Therefore we suggest $I^\pi = 13^\pm$ for the 2828.5-keV level and $I^\pi = (12, 14)^\pm$ for the 3143.6-keV excited state, respectively. Negative parity is preferred because of the branching ratios of the 638.6- and 1019.4-keV decay γ rays. In fact, if the 10^+ and 11^+ are adopted for the 1809.1- and 2189.9-keV levels, the $I^\pi = 13^-$ assignment for the isomer gives an $M2 + E3$ mixed transition for the 638.6-keV line and a pure $E3$ character for the 1019.4-keV decay. These two transitions with proposed multipolarities are able to compete, leading to the comparable intensities observed. The $\Delta I = 1$, dipole or mixed character for the 991.6-, 52.0-, 315.1-, and 728.5-keV transitions [see the $R_{AD}(\gamma)$ ratios in Table I] ex-

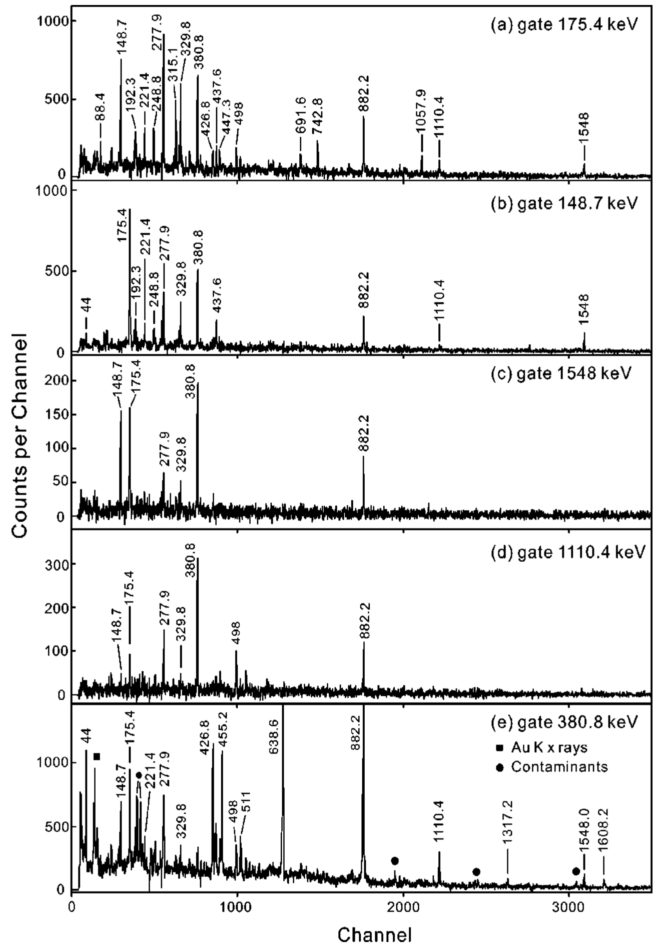

FIG. 4. Selected coincidence spectra emphasizing the transitions bypassing the 67-μs isomer.

cludes the 12^- assignment for the 3143.6-keV level. Accepting the $I^\pi = 13^-$ assignment for the 2828.5-keV level, we have suggested the spin and parity for the levels above the 13^- isomer on the basis of measured $R_{AD}(\gamma)$ ratios (see Table I) and crossover transitions. Finally, from the intensity balance at 1809.1- and 1765.1-keV levels, the experimental conversion coefficient was deduced $\alpha_T(44\text{ keV}) \sim 6.0$ favoring an $M1 + E2$ mixed transition for the 44-keV line. Applying this argument to the 52-keV transition, we conclude that the 52-keV gamma ray most likely results from a $\Delta I = 1$ dipole transition. This is consistent with the assignment in Ref. [7].

The γ-γ coincidence relationships for levels above the 13^- isomer reported in Ref. [7] have been confirmed in this work, leading to the similar level scheme as in Ref. [7]. The main difference, however, is the multipolarity assignments for the corresponding γ radiations compared to the previous work. Of most importance, the $E2$ multipolarity adopted for the 991.6-keV line [7] cannot be confirmed in this work since $R_{AD}(E_\gamma = 991.6\text{ keV}) = 0.82(5)$ suggests strongly that the 991.6-keV transition is a $\Delta I = 1$ dipole or mixed one. The $R_{AD}(\gamma)$ ratios have been checked carefully for the 67-μs isomer and no angular distribution effects [i.e. $R_{AD}(\gamma) \sim 1.0$] have been found for the 638.6-, 380.8-, and 882.2-keV lines if any of these strong lines is used as a gate.

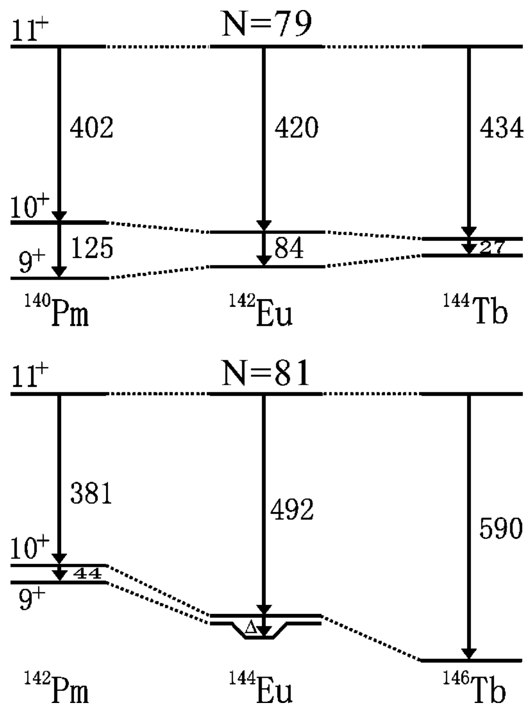

FIG. 5. Members of the $\pi h_{11/2}\nu h_{11/2}^{-1}$ multiplet in ^{140}Pm [3], ^{142}Eu [4], ^{144}Tb [5], ^{142}Pm, ^{144}Eu [4], and ^{146}Tb [6].

III. DISCUSSIONS

It has been shown [1] that the low-lying excited states in odd-odd nucleus ^{142}Pm could be interpreted as 2-qp excitations. The low-lying high-spin isomers with $I^{\pi}=8^-$ have been observed systematically in ^{140}Pm [3], ^{142}Pm [1], and ^{142,144}Eu [4], corresponding to the $\pi d_{5/2}^{-1}\otimes\nu h_{11/2}^{-1}$ configuration. Thus it is expected that the next high-spin 2-qp states should be associated with the $\pi g_{7/2}^{-1}\otimes\nu h_{11/2}^{-1}$ and $\pi h_{11/2}\otimes\nu h_{11/2}^{-1}$ configurations. Such 2-qp multiplets should be yrast and easy to observe using (HI,xn) reactions. Indeed, the first 9^- state was identified in ^{144}Eu at 1338-keV excitation and was assigned to be the $\pi g_{7/2}^{-1}\otimes\nu h_{11/2}^{-1}$ two-hole state [4]. In view of this and the similar excitation energy of the 1309.8-keV level in ^{142}Pm, we propose the same negative parity configuration for this level. This spin-and-parity assignment is consistent with the extracted $R_{AD}(\gamma)$ ratios for the 426.8-keV and 455.2-keV transitions [see $R_{AD}(\gamma)$ ratios in Table I]. Given the similar low-lying level structures in the $N=81$ isotones ^{144}Eu and ^{142}Pm, the next three levels at 1765.1, 1809.1, and 2189.9 keV could be assigned as 9^+, 10^+, and 11^+ of the $\pi h_{11/2}\otimes\nu h_{11/2}^{-1}$ multiplet. For a systematic comparison, we present, in Fig. 5, the level spacing of the $\pi h_{11/2}\otimes\nu h_{11/2}^{-1}$ multiplets in the $N=79$ and 81 isotones: ^{140}Pm [3], ^{142}Eu [4], ^{144}Tb [5], ^{142}Pm (this work), ^{144}Eu [4], and ^{146}Tb [6]. The systematic trends in the energy splitting between the 11^+ and 10^+ levels and the degeneracy of the 10^+ and 9^+ states strongly suggest that the observed three levels in ^{142}Pm originate from the $\pi h_{11/2}\otimes\nu h_{11/2}^{-1}$ configuration. The energy splitting between the 11^+ and 10^+ levels is the largest for the Tb isotopes in each of the isotones and for ^{146}Tb this energy splitting may be related to the pure proton-particle and neutron-hole interactions. The energy splitting decreases gradually with decreasing proton number for the $N=79$ isotones, while this decrease becomes more significant for the $N=81$ isotones. On the other hand, the 9^+ and 10^+ states are close-lying, and this degeneracy becomes weaker when the respective core moves away from the $Z=64$ closed shell.

The maximum angular momentum formed in a 2-qp configuration is 11^+ in the odd-odd ^{142}Pm, and therefore the higher-spin states above 11^+ should be associated with the coupling of 2-qp multiplets to the core excitations. Multiquasiparticle excitations, such as the coupling of the quasiproton in the $g_{7/2}$, $d_{5/2}$, or $h_{11/2}$ orbit to a $h_{11/2}$ neutron hole, play an important role in building the high-spin states in ^{142}Pm. Given ^{146}Gd ($Z=64$) as a doubly-closed nucleus, we believe the most likely configuration for the 2828.5-keV level is $(\pi g_{7/2}^{-1}d_{5/2}^{-2}\otimes\nu h_{11/2}^{-1})_{13^-}$ based on the following considerations. First, the yrast $(\pi g_{7/2}^{-1}d_{5/2}^{-1})_{6^+}$ state in neighboring ^{144}Sm has been found to be a $T_{1/2}=880$ ns isomer [17]. Coupling a $h_{11/2}$ neutron hole to the 6^+ state leads to a long-lived isomer in ^{143}Sm with $I^{\pi}=23/2^-$ [18]. Removing a $d_{5/2}$ proton from ^{143}Sm leads to a structure of $(\pi g_{7/2}^{-1}d_{5/2}^{-2}\otimes\nu h_{11/2}^{-1})_{13^-}$ in ^{142}Pm. The excitation energy of this state is very close to that of the $23/2^-$ isomer in ^{143}Sm, supporting the configuration assignment for the 13^- isomer in ^{142}Pm. Second, the excitation energy of the $(\pi g_{7/2}^{-1}d_{5/2}^{-2}\otimes\nu h_{11/2}^{-1})_{13^-}$ fully aligned state in ^{142}Pm can be estimated using an empirical shell model (see Ref. [19] and references therein). This theoretical approach has been successfully applied to the neighboring nuclei [4,19–23]. Decomposing the $(\pi g_{7/2}^{-1}d_{5/2}^{-2}\otimes\nu h_{11/2}^{-1})_{13^-}$ structure into $[(\pi g_{7/2}^{-1}d_{5/2}^{-2})_{15/2^+}\otimes\nu h_{11/2}^{-1}]_{13^-}$, the excitation energy can be calculated using the expression:

$$\begin{aligned} E^{^{142}\mathrm{Pm}}_{[(\pi g_{7/2}^{-1}d_{5/2}^{-2})_{15/2^+}\otimes\,\nu h_{11/2}^{-1}]_{13^-}} &= E^{^{143}\mathrm{Pm}}_{(\pi g_{7/2}^{-1}d_{5/2}^{-2})_{15/2^+}} + E^{^{145}\mathrm{Gd}}_{\nu h_{11/2}^{-1}} + S + \Delta^{^{144}\mathrm{Eu}}_{(\pi g_{7/2}^{-1}\otimes\,\nu h_{11/2}^{-1})_{9^-}} \\ &\quad + 2\sum_{I=7,8}\left[\sqrt{9(2I+1)}W\left(\frac{5}{2}\frac{5}{2}\frac{19}{2}\frac{11}{2};4I\right)\right]^2 \\ &\quad \times\Delta^{^{144}\mathrm{Eu}}_{(\pi d_{5/2}^{-1}\otimes\,\nu h_{11/2}^{-1})_I} = 2723\ \mathrm{keV}, \end{aligned} \tag{1}$$

$$\begin{aligned} \Delta^{^{144}\mathrm{Eu}}_{(\pi g_{7/2}^{-1}\otimes\,\nu h_{11/2}^{-1})_{9^-}} &= E^{^{144}\mathrm{Eu}}_{(\pi g_{7/2}^{-1}\otimes\,\nu h_{11/2}^{-1})_{9^-}} - E^{^{145}\mathrm{Gd}}_{\nu h_{11/2}^{-1}} - E^{^{145}\mathrm{Eu}}_{\pi g_{7/2}^{-1}} + B_{^{145}\mathrm{Gd}} \\ &\quad + B_{^{145}\mathrm{Eu}} - B_{^{144}\mathrm{Eu}} - B_{^{146}\mathrm{Gd}} = -550.1\ \mathrm{keV}, \end{aligned} \tag{2}$$

$$\begin{aligned} \Delta^{^{144}\mathrm{Eu}}_{(\pi d_{5/2}^{-1}\otimes\,\nu h_{11/2}^{-1})_{8^-}} &= E^{^{144}\mathrm{Eu}}_{(\pi d_{5/2}^{-1}\otimes\,\nu h_{11/2}^{-1})_{8^-}} - E^{^{145}\mathrm{Gd}}_{\nu h_{11/2}^{-1}} - E^{^{145}\mathrm{Eu}}_{\pi d_{5/2}^{-1}} + B_{^{145}\mathrm{Gd}} \\ &\quad + B_{^{145}\mathrm{Eu}} - B_{^{144}\mathrm{Eu}} - B_{^{146}\mathrm{Gd}} = -430.6\ \mathrm{keV}, \end{aligned} \tag{3}$$

where E represents excitation energy of the corresponding nucleus [4,16,18,24], and W the Racah coefficient [25]. The binding energy term is $S=B_{^{142}\mathrm{Pm}}+B_{^{146}\mathrm{Gd}}-B_{^{143}\mathrm{Pm}}-B_{^{145}\mathrm{Gd}}=1265.9$ keV [26]. Δ is the proton-neutron residual interaction. In Ref. [4] the 7^- state in ^{144}Eu was calculated to lie at $\sim$1450 keV which could be used to estimate the interaction

$$\Delta^{^{144}\mathrm{Eu}}_{(\pi d_{5/2}^{-1}\otimes\nu h_{11/2}^{-1})_{7^-}} = E^{^{144}\mathrm{Eu}}_{(\pi d_{5/2}^{-1}\otimes\nu h_{11/2}^{-1})_{7^-}} - E^{^{145}\mathrm{Gd}}_{\nu h_{11/2}^{-1}} - E^{^{145}\mathrm{Eu}}_{\pi d_{5/2}^{-1}} + B_{^{145}\mathrm{Gd}} + B_{^{145}\mathrm{Eu}} - B_{^{144}\mathrm{Eu}} - B_{^{146}\mathrm{Gd}} \simeq 1450 - E^{^{145}\mathrm{Gd}}_{\nu h_{11/2}^{-1}} - E^{^{145}\mathrm{Eu}}_{\pi d_{5/2}^{-1}} + B_{^{145}\mathrm{Gd}} + B_{^{145}\mathrm{Eu}} - B_{^{144}\mathrm{Eu}} - B_{^{146}\mathrm{Gd}} = -108.6\ \mathrm{keV}. \quad (4)$$

For the hole-hole case one expects the residual interaction energy to be negative. If the largest value of zero is assumed for the $\Delta^{^{144}\mathrm{Eu}}_{(\pi d_{5/2}^{-1}\otimes\nu h_{11/2}^{-1})_{7^-}}$, the maximum excitation energy could be estimated to be 2797 keV for the $(\pi g_{7/2}^{-1}d_{5/2}^{-2}\otimes\nu h_{11/2}^{-1})_{13^-}$ state in ^{142}Pm. The calculated excitation energy of $\approx$2750 keV is in good agreement with the experimental observation of $E_x(13^-)=2828.5$ keV. Third, nonobservation of such an yrast 13^- level in the $N=81$ isotone ^{144}Eu provides a complementary argument for the configuration assignment for the 13^- isomer in ^{142}Pm. This is easy to understand concerning the four-hole nature for the 13^- level in ^{142}Pm since such a four-hole state cannot be formed in ^{144}Eu with $Z=63$. Indeed, it has been shown that the yrast states above the 11^+ level in ^{144}Eu correspond to the $\pi g_{7/2}^{-1}\nu h_{11/2}^{-1}\otimes 3^-$ coupling and the $h_{11/2}$ proton excitations [4]. Finally, the isomerism of the 13^- level in ^{142}Pm may be understood, at least qualitatively, considering the configuration change for the de-excitation of the 13^- state. The de-excitation of this 13^- isomer corresponds to a configuration change of $(\pi g_{7/2}^7\pi d_{5/2}^4\otimes\nu h_{11/2}^{-1})_{13^-}\rightarrow(\pi g_{7/2}^8 d_{5/2}^2 h_{11/2}\otimes\nu h_{11/2}^{-1})_{11^+,10^+}$. If the paired particles and the neutron are merely spectators, then this transition could be simplified as a hindered two-particle transition of $\pi(d_{5/2}^2)\rightarrow\pi(g_{7/2}h_{11/2})$ where one of the unpaired $d_{5/2}$ protons is excited to the $g_{7/2}$ orbit forming a closed subshell and the other to the $h_{11/2}$ orbit.

The positive parity levels 12^+,13^+ at 3300.0 and 3737.9 keV may correspond to the core excitations of 2^+ coupling to $(\pi h_{11/2}\otimes\nu h_{11/2}^{-1})_{11^+}$ with probable admixture of $(\pi g_{7/2}^{-1}\otimes\nu h_{11/2}^{-1}\otimes 3^-)_{12^+}$ for 12^+. The fully aligned state $(\pi g_{7/2}^{-1}\otimes\nu h_{11/2}^{-1}\otimes 3^-)_{12^+}$ has been observed and suggested in ^{144}Eu at similar excitation energies [4]. The first excited 2^+ state in ^{142}Nd is at 1.575 MeV [27], which is very close to the energy difference between the 13^+ and 11^+ levels, supporting our configuration assignments. We have also calculated the excitation energies for both $(\pi g_{7/2}^{-1}\otimes\nu h_{11/2}^{-1}\otimes 3^-)_{12^+}$ and $(\pi h_{11/2}\otimes\nu h_{11/2}^{-1}\otimes 2^+)_{13^+}$ fully aligned states using the empirical shell model approaches [4]; it gives

$$E^{^{142}\mathrm{Pm}}_{(\pi g_{7/2}^{-1}\nu h_{11/2}^{-1}\otimes 3^-)_{12^+}} = E^{^{142}\mathrm{Pm}}_{(\pi g_{7/2}^{-1}\nu h_{11/2}^{-1})_{9^-}} + E^{^{144}\mathrm{Sm}}_{3^-} + \Delta^{^{143}\mathrm{Sm}}_{(\nu h_{11/2}^{-1}\otimes 3^-)_{17/2^+}} + \Delta^{^{143}\mathrm{Pm}}_{(\pi g_{7/2}^{-1}\otimes 3^-)_{13/2^-}} + S = 1309.8 + 1810.1 + \left(E^{^{143}\mathrm{Sm}}_{(\nu h_{11/2}^{-1}\otimes 3^-)_{17/2^+}} - E^{^{143}\mathrm{Sm}}_{\nu h_{11/2}^{-1}} - E^{^{144}\mathrm{Sm}}_{3^-}\right) + \left(E^{^{145}\mathrm{Eu}}_{(\pi g_{7/2}^{-1}\otimes 3^-)_{13/2^-}} - E^{^{145}\mathrm{Eu}}_{\pi g_{7/2}^{-1}} - E^{^{146}\mathrm{Gd}}_{3^-}\right) = 3077.9\ \mathrm{keV}, \quad (5)$$

and

$$E^{^{142}\mathrm{Pm}}_{(\pi h_{11/2}\nu h_{11/2}^{-1}\otimes 2^+)_{13^+}} = E^{^{142}\mathrm{Pm}}_{(\pi h_{11/2}\nu h_{11/2}^{-1})_{11^+}} + E^{^{142}\mathrm{Nd}}_{2^+} + \left(E^{^{141}\mathrm{Nd}}_{(\nu h_{11/2}^{-1}\otimes 2^+)_{15/2^-}} - E^{^{141}\mathrm{Nd}}_{\nu h_{11/2}^{-1}} - E^{^{142}\mathrm{Nd}}_{2^+}\right) + \left(E^{^{143}\mathrm{Pm}}_{(\pi h_{11/2}\otimes 2^+)_{15/2^-}} - E^{^{143}\mathrm{Pm}}_{\pi h_{11/2}} - E^{^{142}\mathrm{Nd}}_{2^+}\right) = 3873.8\ \mathrm{keV}. \quad (6)$$

where the binding energy term S vanishes in this special case [16–18,27–29]. We take the interaction $\Delta_{(\pi g_{7/2}^{-1}\otimes 3^-)_{13/2^-}}=-69$ keV from ^{145}Eu [28] instead of $\Delta^{^{143}\mathrm{Pm}}_{(\pi g_{7/2}^{-1}\otimes 3^-)_{13/2^-}}$ because of the lack of the $(\pi g_{7/2}^{-1}\otimes 3^-)_{13/2^-}$ state in ^{143}Pm [16].

To understand the high-spin structures above the 3820.1-keV level, multiquasiparticle excitations involving one or two protons to the $h_{11/2}$ orbit must be considered. Such multiquasiparticle states have been observed and calculated to be at 4.5–5.5 MeV excitations in ^{144}Eu. Since the spin and parity assignments are tentative for the higher-lying levels, and the spectroscopic information obtained from this experiment is quite limited, further experimental investigations of properties such as internal conversion, polarization, g-factor, and half-life measurements are needed. This is, however, beyond the scope of this work.

IV. CONCLUSIONS

The high-spin level structure of ^{142}Pm has been reinvestigated via a conventional in-beam γ-spectroscopy experiment using the $^{128}\mathrm{Te}(^{19}\mathrm{F},5n)^{142}\mathrm{Pm}$ reaction. The previously known 67-μs isomer has been assigned to ^{142}Pm rather than to ^{141}Pm through the γ-ray excitation function measurements. A much revised high-spin level scheme of ^{142}Pm has been established on the basis of γ-γ coincidence relationships and energy sums. The 67-μs isomer and corresponding decay γ rays have been placed into the level scheme due to observations of several crossover cascade transitions. We have assigned the 9^+, 10^+, and 11^+ levels as the members of the $\pi h_{11/2}\otimes\nu h_{11/2}^{-1}$ multiplet which fit well into systematics. The fully-aligned 9^- state of the $\pi g_{7/2}^{-1}\otimes\nu h_{11/2}^{-1}$ configuration has also been observed and suggested. The 67-μs isomer is most likely a fully-aligned four-hole state with the $(\pi g_{7/2}^{-1}d_{5/2}^{-2}\otimes\nu h_{11/2}^{-1})_{13^-}$ configuration. Its excitation energy can be well reproduced using the empirical shell-model approaches. The high-spin 2-qp states coupling to the 2^+ and 3^- core excitation are also proposed. The observation of these levels seem to be consistent with systematic expectations.

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[1] L. Funke, W. D. Fromm, H. J. Keller, R. Arlt, and P. M. Gopytsch, Nucl. Phys. **A274**, 61 (1976).
[2] P. Kleinheinz, S. Lunardi, M. Ogawa, and M. R. Maier, Z. Phys. A **284**, 351 (1978).
[3] G. de Angelis, S. Lunardi, D. Bazzacco, J. Rico, F. Terrasi, M. Piiparinen, A. Atac, and J. Nyberg, Z. Phys. A **374**, 93 (1993).
[4] M. Piiparinen, A. Atac, J. Blomqvist, G. B. Hagemann, B. Herskid, R. Julin, S. Juutinen, A. Lampinen, J. Nyberg, G. Sletten, P. Tikkanen, S. Törmänen, A. Virtanen, and R. Wyss, Nucl. Phys. **A605**, 191 (1996).
[5] M. Sferrazza, M. A. Cardona, D. Bazzacco, S. Lunardi, E. Maglione, and G. de Angelis, Z. Phys. A **354**, 157 (1996).
[6] R. Collatz, N. Amzal, Z. Meliani, C. Schück, Ch. Vieu, J. S. Dionisio, P. Kleinheinz, and J. Blomqvist, Z. Phys. A **359**, 113 (1997).
[7] Sarmishtha Bhattacharya, Somen Chanda, Dipa Bandyopadhyay, Swapan Kumar Basu, G. Mukherjee, S. Muralithar, R. P. Singh, and R. K. Bhowmik, Phys. Rev. C **58**, 2998 (1998).
[8] R. A. Kenefick, D. R. Zolnowski, R. L. Spross, G. Glass, J. C. Hill, and W. W. Bowman, in *Proceedings of the International Conference on Nuclear Physics*, edited by J. de Boer and H. J. Mang (North-Holland/Elsevier, Amsterdam, 1973), p. 233.
[9] R. A. Kenefick and D. R. Zolnowski, Texas A&M University, Cyclotron Institute, Annual Report, 1975, p. 24.
[10] J. K. Tuli, Nucl. Data Sheets **89**, 641 (2000).
[11] M. Piiparinen, M. Kortelahti, A. Pakkanen, T. Komppa, and R. Komu, Nucl. Phys. **A342**, 57 (1980).
[12] R. Aryaeinejad, P. M. Walker, R. B. Firestone, and Wm. C. McHarris, Phys. Rev. C **32**, 1855 (1985).
[13] E. Gulmez, M. W. Drigert, and J. A. Cizewski, Phys. Rev. C **39**, 1809 (1989).
[14] Sarmishtha Bhattacharyya, Somen Chanda, Tumpa Bhattacharjee, Swapan Kumar Basu, R. K. Bhowmik, S. Muralithar, R. P. Singh, and S. S. Ghugre, Nucl. Phys. **A730**, 23 (2004).
[15] Y. H. Zhang, M. Oshima, Y. Toh, X. H. Zhou, M. Koizumi, A. Osa, A. Kimura, Y. Hatsukawa, T. Morikawa, M. Nakamura, M. Sugawara, H. Kusakari, T. Komatsubara, K. Furuno, H. L. Wang, P. Luo, C. S. Wu, and F. R. Xu, Phys. Rev. C **68**, 054313 (2003).
[16] H. Prade, L. Käubler, U. Hagemann, H. U. Jäger, M. Kirchbach, L. Schneider, F. Stary, Z. Roller, and V. Paar, Nucl. Phys. **A333**, 33 (1980).
[17] J. Kownack, H. Ryde, V. O. Sergejew, and Z. Sujkowski, Nucl. Phys. **A196**, 498 (1972).
[18] J. Kownacki, J. Ludziejewski, Z. Sujkowski, H. Arnold, and H. Ryde, Nucl. Phys. **A236**, 125 (1974).
[19] J. R. Jongman, J. C. S. Bacelar, A. Baanda, R. F. Noorman, Th. Steenbergen, W. Urban, M. J. A. de Voigt, J. Nyberg, G. Sletten, J. Dionisio, Ch. Vieu, J. M. Lagrange, and M. Pautrat, Nucl. Phys. **A581**, 165 (1995).
[20] T. Glasmacher, D. D. Caussyn, P. D. Cottle, J. W. Holcomb, T. D. Johnson, K. W. Kemper, M. A. Kennedy, and P. C. Womble, Phys. Rev. C **47**, 2586 (1993).
[21] T. Rzaca-Urban, W. Urban, J. L. Durell, W. R. Phillips, B. J. Varley, Ch. P. Hess, C. J. Pearson, W. J. Vermeer, Ch. Vieu, J. S. Dionisio, M. Pautrat, and J. C. Bacelar, Nucl. Phys. **A588**, 767 (1995).
[22] A. Ercan, R. Broda, P. Kleinheinz, M. Piiparinen, R. Julin, and J. Blomqvist, Z. Phys. A **329**, 63 (1988).
[23] A. Kuhnert, D. Alber, H. Grawe, H. Kluge, K. H. Maier, W. Reviol, X. Sun, E. M. Beck, A. P. Byrne, H. Hübel, J. C. Bacelar, M. A. Deleplanque, R. M. Diamond, and F. S. Stephens, Phys. Rev. C **46**, 484 (1992).
[24] A. Pakkanen, J. Muhonen, M. Piiparinen, and J. Blomqvist, Nucl. Phys. **A373**, 237 (1982).
[25] R. D. Lawson, *Theory of the Nuclear Shell Model* (Oxford University Press, Oxford, 1980).
[26] G. Audi and A. H. Wapstra, Nucl. Phys. **A595**, 409 (1995).
[27] H. Prade, J. Doring, W. Enghardt, L. Funke, and L. Kaubler, Z. Phys. A **328**, 501 (1987).
[28] D. Bazzacco, A. M. Haque, K. O. Zell, P. von Brentano, and C. Protop, Phys. Rev. C **21**, 222 (1980).
[29] Jerzy Ludziejewski and Hans Arnold, Z. Phys. A **281**, 287 (1977).