

Identification of new transitions and mass assignments of levels in $^{143-153}\text{Pr}$

E. H. Wang,^{1,*} A. Lemasson,² J. H. Hamilton,¹ A. V. Ramayya,¹ J. K. Hwang,¹ J. M. Eldridge,^{1,†} A. Navin,² M. Rejmund,² S. Bhattacharyya,³ S. H. Liu,^{1,‡} N. T. Brewer,^{1,§} Y. X. Luo,¹ J. O. Rasmussen,⁴ H. L. Liu,⁵ H. Zhou,⁶ Y. X. Liu,⁷ H. J. Li,⁸ Y. Sun,⁹ F. R. Xu,⁶ S. J. Zhu,⁸ G. M. Ter-Akopian,¹⁰ Yu. Ts. Oganessian,¹⁰ M. Caamaño,¹¹ E. Clément,² O. Delaune,² F. Farget,² G. de France,² and B. Jacquot²

¹*Department of Physics and Astronomy, Vanderbilt University, Nashville, Tennessee 37235, USA*

²*GANIL, CEA/DSM-CNRS/IN2P3, Boulevard Henri Becquerel, BP 55027, F-14076 Caen Cedex 5, France*

³*Variable Energy Cyclotron Centre, 1/AF Bidhan Nagar, Kolkata 700064, India*

⁴*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

⁵*Department of Physics, Xi'an Jiaotong University, Xi'an 710049, People's Republic of China*

⁶*Department of Physics, Peking University, Beijing 100871, People's Republic of China*

⁷*Department of Physics, Huzhou University, Huzhou 313000, People's Republic of China*

⁸*Department of Physics, Tsinghua University, Beijing 100084, People's Republic of China*

⁹*Department of Physics, Shanghai Jiao Tong University, Shanghai 200240, China*

¹⁰*Joint Institute for Nuclear Research, RU-141980 Dubna, Russian Federation*

¹¹*USC, Universidad de Santiago de Compostela, E-15706 Santiago de Compostela, Spain*

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Background: The previously reported levels assigned to $^{151,152,153}\text{Pr}$ have recently been called into question regarding their mass assignment.

Purpose: We clarify the above questioned level assignments by measuring γ transitions tagged with A and Z in an in-beam experiment in addition to the measurements from ^{252}Cf spontaneous fission (SF) and establish new spectroscopic information from $N = 84$ to $N = 94$ in the Pr isotopic chain.

Methods: The isotopic chain $^{143-153}\text{Pr}$ has been studied from the spontaneous fission of ^{252}Cf by using Gammasphere and also from the measurement of the prompt γ rays in coincidence with isotopically identified fission fragments using VAMOS++ and EXOGAM at Grand Accélérateur National d'Ions Lourds (GANIL). The latter were produced using ^{238}U beams on a ^9Be target at energies around the Coulomb barrier. The γ - γ - γ - γ data from ^{252}Cf (SF) and those from the GANIL in-beam A - and Z -gated spectra were combined to unambiguously assign the various transitions and levels in $^{151,152,153}\text{Pr}$ and other isotopes.

Results: A band of 3 new transitions added to the known level in ^{145}Pr , 9 new transitions in two new bands in ^{147}Pr , 6 new transitions in a new level scheme for ^{148}Pr , two new bands with 17 new transitions in ^{149}Pr , and two new bands with 11 new transitions in ^{150}Pr were identified by using γ - γ - γ and γ - γ - γ - γ coincidences and A and Z -gated γ - γ spectra. The transitions and levels previously assigned to $^{151,153}\text{Pr}$ have been confirmed by the (A, Z) -gated spectra. Small changes have been made to their original level schemes. The transitions previously assigned to ^{152}Pr are now assigned to ^{151}Pr on the basis of the (A, Z) -gated spectra. Two new bands with 20 new transitions in ^{152}Pr and one new band with 7 new transitions in ^{153}Pr are identified from the γ - γ - γ - γ coincidence spectra and the (A, Z) -gated spectrum. In addition, new γ rays are also reported in $^{143-146}\text{Pr}$.

Conclusions: New levels of $^{145,147-153}\text{Pr}$ have been established, reliable mass assignments of the levels in $^{151,152,153}\text{Pr}$ have been given in the present work, and new transitions have been identified in $^{143-146}\text{Pr}$ showing the new avenues that are opened by combining the two experimental approaches.

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I. INTRODUCTION

Studies of nuclear energy levels over long isotopic chains reveal structural changes as a function of N and provide an important test of nuclear models. Spontaneous fission (SF) has

provided a good approach to study nuclei over long isotopic chains [1]. In SF, the new transitions in a certain isotope are generally identified by gating on the known transitions in the particular isotope observed in β decay or by gating on known transitions in the complementary fission fragment, which are usually less neutron-rich and well studied in most of the cases. Usually, this procedure gives reliable identifications. However, in some cases, when the γ spectrum is complex, the overlapping of transition energies in different isotopes could lead to a wrong mass identification of the bands.

Recently prompt γ -ray spectroscopy of fully identified (A, Z) fission fragments produced in fusion-fission and transfer-fission reactions around the Coulomb barrier [2,3] have been reported where, owing to the advantage of

*enhong.wang@vanderbilt.edu

[†]Present address: Department of Physics, Union University, Jackson, TN 38305, USA.

[‡]Present address: West Physics Consulting, Atlanta, GA 30339, USA.

[§]Present address: Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA.

unambiguously identifying the fragments, the assignments of γ rays to a particular A and Z are directly obtained. The combination of the traditional high-fold γ -coincidence method [1] and this method [2,3] is expected to strengthen explorations and understanding of the evolution of nuclear structure as a function of both isospin and spin.

Historically, levels of several Pr isotopes have been identified from ^{252}Cf and ^{248}Cm SF [4–7]. Only $^{151,153}\text{Pr}$ were reported to have possible octupole correlations between parity-doublet bands [5]. As mentioned in Ref. [5], the octupole correlations in this region are associated with $\Delta N = 1$, $\Delta j = 3$, and $\Delta l = 3$ orbital pairs such as $\pi d_{5/2}-h_{11/2}$ near $Z = 56$ and $\nu f_{7/2}-i_{13/2}$ near $N = 88$. The mass assignments of the previously reported levels assigned to $^{151,152,153}\text{Pr}$ [5,7] have recently been called into question [8]. The γ -ray transitions and levels in $^{151,153}\text{Pr}$ reported in the previous work [5] were assigned to $^{152,154}\text{Pr}$ respectively in Ref. [8]. The two bands proposed to be in ^{152}Pr in Ref. [7] were assigned to $^{151,153}\text{Pr}$ separately [8]. The assignment of γ transitions to their corresponding nuclei is challenging owing to the closely spaced transitions and the complexity of the spectra. To have an unambiguous identification of the nuclei in the $A \sim 150$ mass region, two different techniques have been combined in the present work to investigate the high-spin states and the possible octupole correlations for neutron-rich Pr isotopes. In this paper, we provide new analysis of both ^{252}Cf SF and $^{238}\text{U} + ^9\text{Be}$ -induced fission data [2,3] with direct identification of fission fragment mass and Z to give reliable assignments of the levels and transitions in these Pr isotopes. New level schemes of $^{145,147-153}\text{Pr}$ and new transitions in $^{143-146}\text{Pr}$ are reported in the present work. The possibility of the occurrence of octupole correlations in the band structures of $^{149,151}\text{Pr}$ are indicated.

II. EXPERIMENTAL METHOD

Two complementary methods have been used to investigate the level structure of Pr isotopes, which include both the unambiguous identification of the mass (A) and the proton number (Z) of the emitting fission fragment using a large-acceptance spectrometer for in-beam measurements and the high-fold data from SF of a ^{252}Cf source. These complementary methods have allowed us to identify new transitions and extend the level schemes to higher spins. In the present work the new transitions identified using (A, Z) gated “singles” prompt γ -ray spectroscopy did not require knowledge of the spectroscopic information of the complementary fragment. This allowed the study of very neutron-rich nuclei, combining the unique in-beam identification with the high-fold γ - γ - γ coincidences from SF. In the following, double-gated coincidence spectra have a variable energy binning ranging from 0.7 keV/channel at 100 to 1 keV/channel at 1 MeV. The triple-gated coincidence spectra have a fixed binning of 1.3 keV/channel.

A. $^{238}\text{U} + ^9\text{Be}$ -induced fission

The measurements of transfer and fusion-induced fission were performed at Grand Accélérateur National d'Ions Lourds (GANIL) using a ^{238}U beam at 6.2 MeV/u, with a typical

intensity of 0.2 pA, impinging on a 10- μm -thick ^9Be target. The advantage of the inverse kinematics used in this work is that fission fragments are forward focused and have a large velocity, resulting in both an efficient detection and isotopic identification in the spectrometer. A single magnetic field setting of the large-acceptance spectrometer VAMOS++ [9], possessing a momentum acceptance of around $\pm 20\%$, placed at 20° with respect to the beam axis, was used to identify uniquely the fission fragments. The detection system ($1 \times 0.15 \text{ m}^2$) at the focal plane of the spectrometer was composed of (i) a multiwire parallel plate avalanche counter (MWPPAC), (ii) two drift chambers (x, y), (iii) a segmented ionization chamber (ΔE), and (iv) 40 silicon detectors arranged in a wall structure (E_r). The time of flight (TOF) was obtained using the signals from the two MWPPACs, one located after the target and the other at the focal plane (flight path $\sim 7.5 \text{ m}$). The parameters measured at the focal plane [(x, y) , ΔE , E_r , TOF], along with the known magnetic field were used to determine, on an event-by-event basis, the mass number (A), charge state (q), atomic number (Z), and velocity vector after the reaction for the detected fragment. Isotopic identifications of elements were made up to $Z = 63$ with a mass resolution of $\Delta A/A \sim 0.4\%$ [10]. The prompt γ rays were measured in coincidence with the isotopically identified fragments, using the EXOGAM array [11] consisting of 11 Compton-suppressed segmented clover HpGe detectors (15 cm from the target). The velocity of the fragment along with the angle of the segment of the relevant clover detector were used to obtain the γ -ray energy in the rest frame of the emitting fragment. Error on the γ -ray energies of the strong transitions is 0.5 keV, while for the weak transitions it could be as much as 1 keV. As compared to the results presented in Ref. [10] for the Zr isotopes, the present work is the result of further improvements in the analysis, especially improving the Z identification, and also involves a larger data set. Figure 1 shows a two-dimensional spectra of A vs “singles” E_γ for the Pr isotopes using such a data set which also allows one to view directly the evolution of the various transitions as a function of mass number.

B. ^{252}Cf spontaneous fission

The experiment with ^{252}Cf was carried out at the Lawrence Berkeley National Laboratory (LBNL). A 62- μCi ^{252}Cf source was sandwiched between two Fe foils of thickness 10 mg/cm². By using 101 Ge detectors of Gammasphere, the data were sorted into 5.7×10^{11} γ - γ - γ and higher fold γ events (3D cube) and 1.9×10^{11} γ - γ - γ and higher fold γ coincident events (4D cube). These γ coincident data were analyzed by the RADWARE software package [12]. γ -ray energies of the strong transitions have errors of 0.1 keV, while the errors on the weak transitions could be as much as 0.5 keV.

Another similar experiment was performed earlier at LBNL by using 72 Ge detectors of Gammasphere with a 28- μCi ^{252}Cf source. Less γ - γ - γ and higher-fold coincidence events were collected in this experiment, but the data were built according to several discrete coincidence time windows ranging from 4 to 500 ns of the γ rays [13,14].

To independently confirm the mass assignments obtained above (Fig. 1), the relative yield curves of the yttrium partner

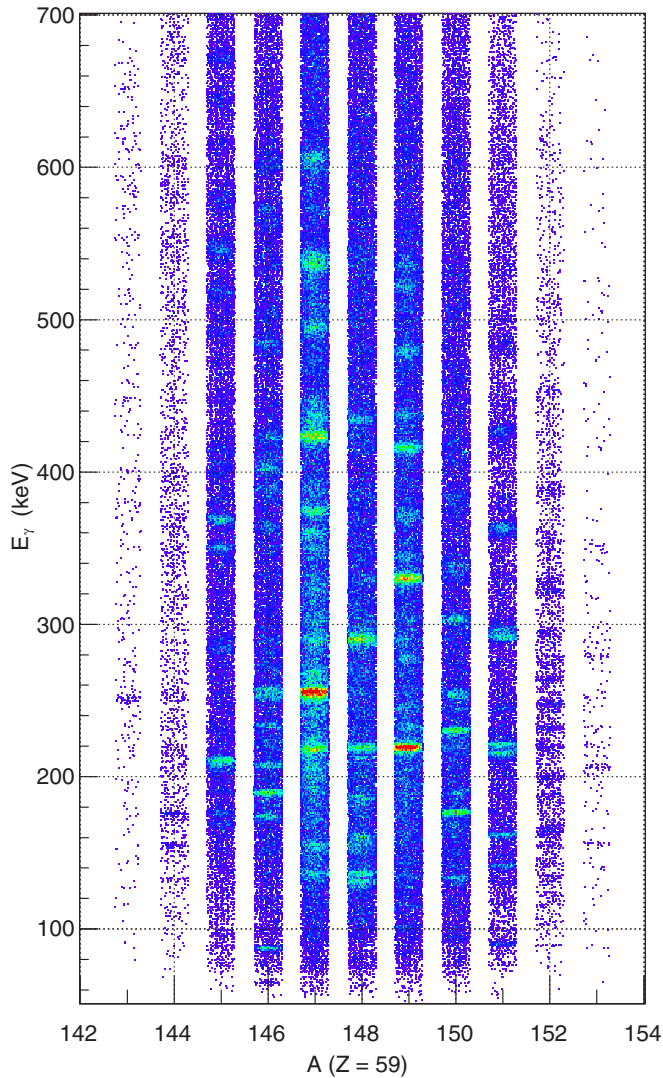


FIG. 1. (Color online) Doppler-corrected γ -ray energy as a function of the mass number (A) of the Pr ($Z = 59$) fragment identified in VAMOS++.

isotopes coincident with $^{151,152,153}\text{Pr}$ were measured. Figure 2 is a set of Y yield curves measured by double or triple gating on transitions in $^{151-153}\text{Pr}$. The intensity summations of all the observable transitions which directly feed the ground state were used as a representative of the respective Y yields. The ^{97}Y isotope has an isomeric state at a level energy of 667.5 keV (1.17 s). Therefore, the intensity summation of two transitions (668.6 and 989.9 keV), which feed the 667.5-keV state, was used instead. In the ^{252}Cf binary SF, a pair of correlated partners is produced and followed by neutron emission after fission. The yield is generally maximized at the $3n$ or $4n$ channel [15]. In Fig. 2, the highest yields were populated at around $^{98,97,96}\text{Y}$ for $^{151,152,153}\text{Pr}$ respectively, which are all $3n$ reaction channels for these Pr isotopes. Further Gaussian fitting analysis for the curves indicates that the fitting peaks for $^{151,152,153}\text{Pr}$ are located at the respective $3.4n$, $3.3n$, and $2.8n$ channels. These yield distribution curves of the Y partner isotopes are consistent with the mass assignments of levels in $^{151,152,153}\text{Pr}$.

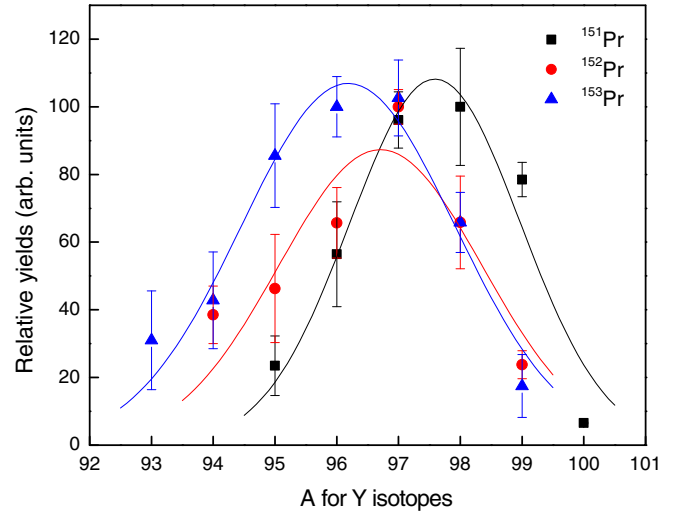


FIG. 2. (Color online) Relative yield curves of yttrium by gating on transitions in ^{151}Pr (black square symbols), ^{152}Pr (red circular symbols), and ^{153}Pr (blue triangular symbols) from ^{252}Cf SF data. Each Pr gate yield set is normalized to the highest Y yield for comparison. Fission partners of $3n$ channels for ^{151}Pr , ^{152}Pr , and ^{153}Pr are ^{98}Y , ^{97}Y , and ^{96}Y , respectively. The gaussian fittings for Pr gate yields are also shown as lines in the same colors.

III. EXPERIMENTAL RESULTS

In this section new transitions for $^{143-147}\text{Pr}$ are reported using in-beam fission, whereas the new level schemes of $^{145,147-153}\text{Pr}$ were obtained by combining both the data sets.

A. ^{143}Pr

The A- and Z-gated γ -ray spectrum on ^{143}Pr is shown in Fig. 3. Three new transitions—251(1), 445(1), and 554(1) keV—were identified. Other transitions are not labeled.

B. ^{144}Pr

The A- and Z-gated γ -ray spectrum on ^{144}Pr is shown in Fig. 4. The 133(1)-keV peak could be the 133.5-keV transition identified in ^{144}Ce β decay [16]. It should be pointed

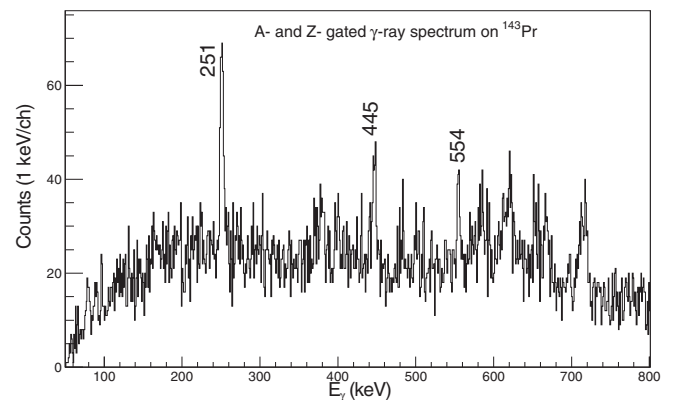


FIG. 3. Partial ^{143}Pr A- and Z-gated γ -ray spectrum obtained from $^{238}\text{U} + ^9\text{Be}$ -induced fission data.

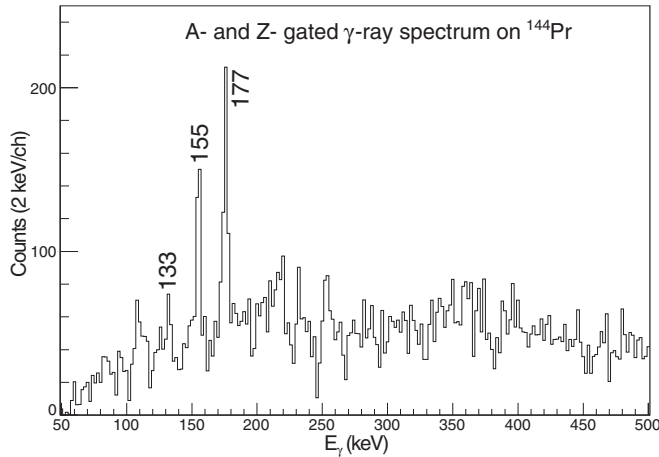


FIG. 4. Partial ^{144}Pr mass- and Z-gated γ -ray spectrum obtained from $^{238}\text{U} + ^9\text{Be}$ -induced fission data.

out that the unbiased singles nature of the data allows the identification of low-multiplicity transitions seen in β decay. In addition, two new transitions—155(1) and 177(1) keV—were also identified. Owing to the complexity of the spectrum and lack of γ - γ coincidences in this odd-odd nucleus, other transitions above 200 keV are not labeled and no level scheme is presented.

C. ^{145}Pr

The A- and Z-gated γ -ray spectrum on ^{145}Pr is shown in Fig. 5(a). The 207.6-, 211.6-, 284.5-, and 492.2-keV peaks were previously identified in ^{145}Ce β decay [17]. The 350.9-keV peak could be an overlap of a 350.9-keV transition (decay from 350.9-keV level to the ground state seen in β decay) and another 350.9-keV transition (decay from 540.1-keV level to a 188.8-keV level in β decay) identified in β decay [17]. Figures 5(b) and 5(c) show γ -ray spectra gated on the 211.6- and 546-keV transitions, respectively. In these spectra, the coincident 204.0-, 207.6-, 368.8-, 492.2-, 546.3-, and 672.3-keV transitions can be seen. From the energy spacing of the 211.6-, 368.8-, 546.3-, and 672.3-keV transitions and the intensities shown in Fig. 5(a), these γ rays are possibly $E2$ transitions in a rotational band. Thus, spins and parities of levels in this band are tentatively assigned. The level scheme for ^{145}Pr is shown in Fig. 6. It should be pointed out that in the β -decay measurements the 211.6 keV is weak, whereas in the present work it is very intense, showing the complementarity of the in-beam and decay work. There is coincidence evidence in the (A,Z)-gated data for a 350-415-keV cascade feeding a 168-keV transition. It is not definitive that this cascade feeds into the 207-212 cascades, so it is not placed in the level scheme. The (A,Z)-gated γ coincidence data (Fig. 5) indicate the 176.7-keV transition is in coincidence with the 207-212-284-368-546-keV cascade, but it is not clear where to place it. The observed 190.0-, 230.1-, 518.0-, 579.8-, and 616.7-keV transitions are also new but we have no coincidence data to place them.

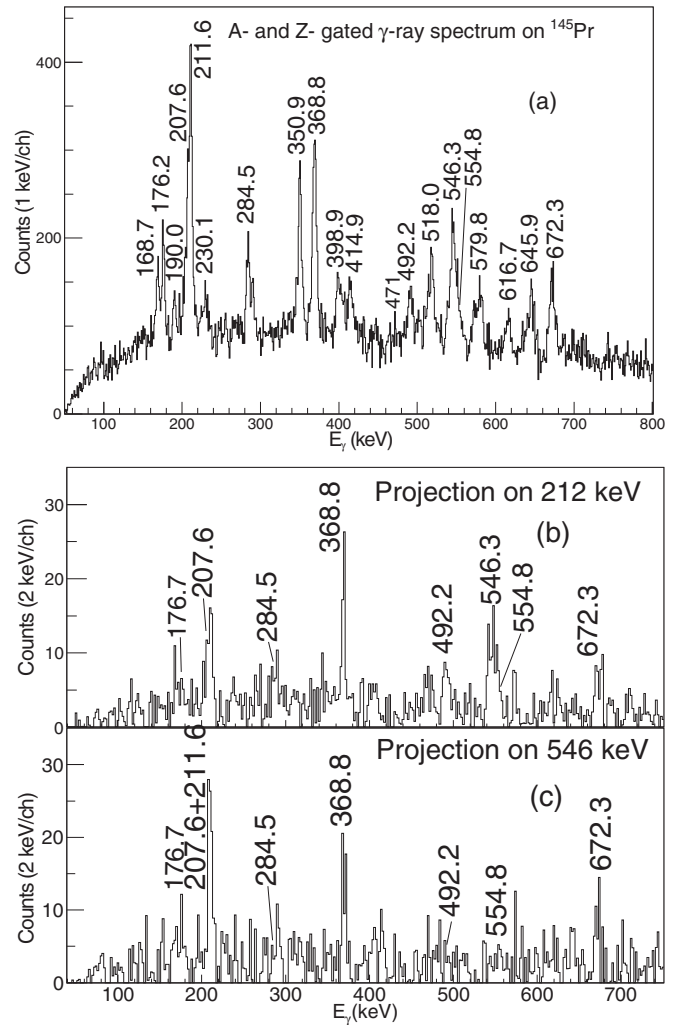


FIG. 5. Partial ^{145}Pr mass- and Z-gated γ -ray spectra obtained from $^{238}\text{U} + ^9\text{Be}$ -induced fission data. Panel (a) is single γ -ray spectrum. Panel (b) is a gated spectrum on the 211.6-keV transition and part (c) gated on the 546-keV transition, respectively.

D. ^{146}Pr

The A- and Z-gated γ -ray spectrum on ^{146}Pr is shown in Fig. 7(a). The 87.2-keV transition can be identified with that previously known in ^{146}Ce β decay [18]. Figure 7(b) is a spectrum gated on the 188.9-keV transition. In this spectrum, the coincident 87.2-, 173.9-, and 484.6-keV transitions can be seen. With only these data it was not possible to build a level scheme.

E. ^{147}Pr

The new level scheme for ^{147}Pr is shown in Fig. 8. In this case, the known transitions were previously observed in the β decay of ^{147}Ce [19,20]. The ground-state, 2.7-, 27.9-, 93.2-, and 246.4-keV levels were tentatively proposed to have positive parity [19]. The 363.3-keV level was proposed to have a negative parity [19]. The (A,Z)-gated γ spectrum is shown in Fig. 9, where evidence for a high-spin band is seen. A new band is assigned to ^{147}Pr by observing the γ rays in coincidence with the 138.7-, 218.5-, and 243.7-keV transitions. A partial

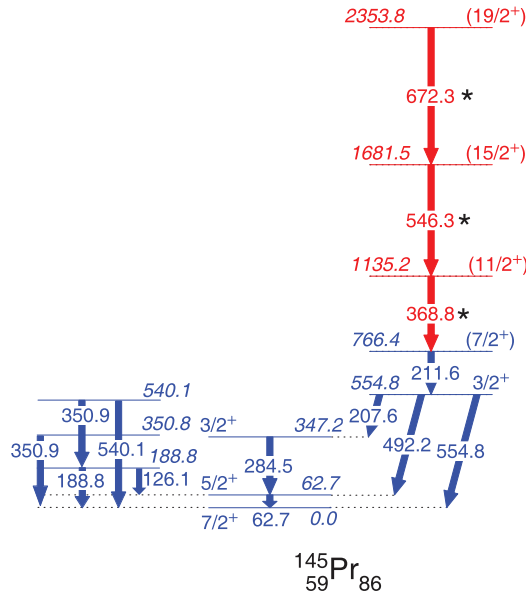


FIG. 6. (Color online) The new level scheme of ^{145}Pr in the present work. Transitions and levels previously reported in β -decay work are labeled in blue. New ones in the current work are labeled in red and with an asterisk. The width of the transitions in the level scheme in the current work does not indicate the relative intensity.

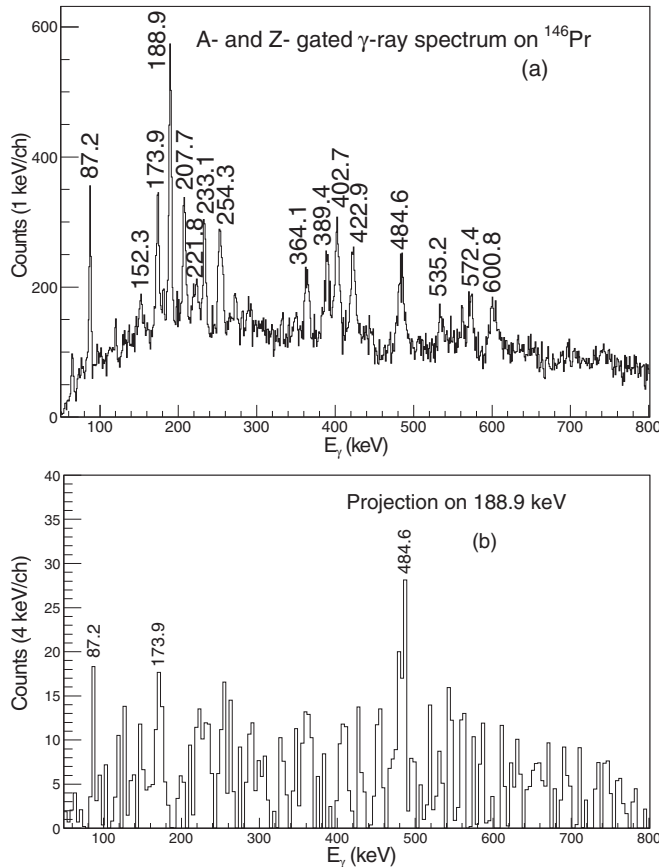


FIG. 7. Partial ^{146}Pr A- and Z-gated γ -ray spectra obtained from $^{238}\text{U} + ^9\text{Be}$ -induced fission data. Panel (a) is single γ -ray spectrum. Panel (b) is a spectrum gated on 188.9-keV transition.

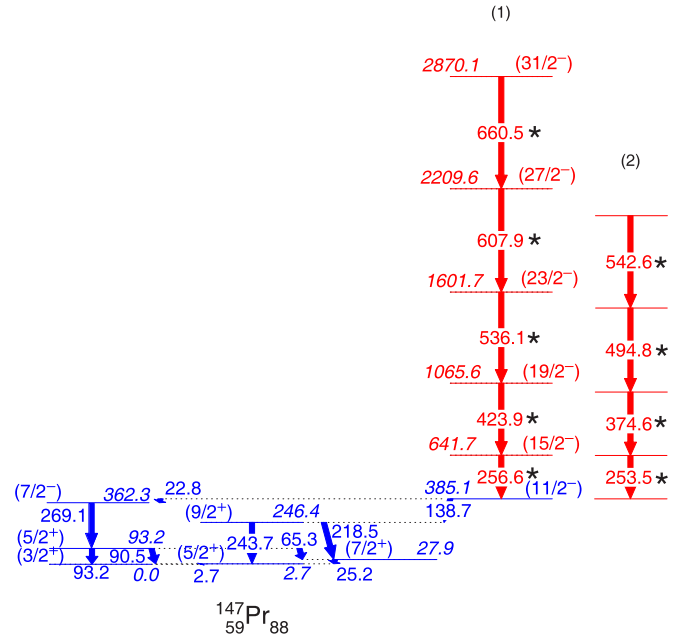


FIG. 8. (Color online) The new level scheme of ^{147}Pr in the present work. Transitions and levels previously reported in β -decay work are labeled in blue. New ones in the current work are labeled in red and with an asterisk. It is possible that there is a low-energy transition between the 256.6- and 138.7-keV transitions, as discussed in the text.

coincident γ -ray spectrum obtained with ^{252}Cf SF data is shown in Fig. 10. In this spectrum with gate on a previously known transition and the strongest transition in Fig. 9, one can clearly see the known 218.5- and 243.7-keV transitions, new 423.9-, 536.1-, 607.9-, and 660.5-keV transitions, and the Y partner transitions. Note that the 179.2-keV transition labeled in the spectrum is a new transition in ^{100}Y . The work including the new level scheme of ^{100}Y will be published later. These new transitions in ^{147}Pr are confirmed in the (A,Z)-gated spectrum on ^{147}Pr (Fig. 9). The 2.7- and 25.2-keV transitions are not observed in the current work because the 3D and 4D cube data cut off the energy from 33.3 keV. The 66- and 72-keV transitions in this double gate come from the coincidence of the 138-keV transition in ^{107}Tc . The 103-keV transition in this gate in Fig. 10 is caused by the 138- and 255-keV transitions in ^{103}Mo . These three contamination transitions are not seen in the 256.6–423.9-keV gated spectrum, so are not in ^{147}Pr . The time gated data from ^{252}Cf SF indicate a short lifetime (<20 ns) of the 385.7-keV level. However, because no lifetime of this level was reported by Mantica *et al.* in β -decay work [19], there might be a very low-energy transition between the 138.7- and 256.6-keV transitions. This possible short lifetime would also explain the rather low intensity of the 138.7-keV transition in the prompt (A,Z)-gated spectrum. Such a loss of intensity has already been found in the case of the neutron-rich Zr isotopes [10]. The gated spectrum on the 374-keV transition of (A,Z)-gated data shows evidence for a 253–374–495–542 cascade, as seen in Fig. 9(c). This cascade is also confirmed by the ^{252}Cf SF data, but not in coincidence with any other transitions reported in ^{147}Ce β decay in

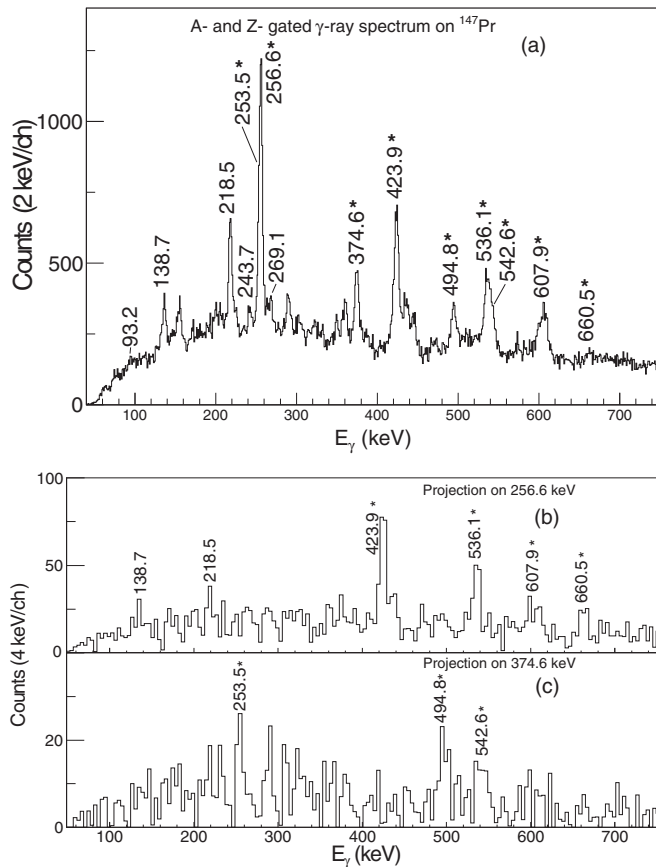


FIG. 9. (a) Partial ^{147}Pr A- and Z-gated γ -ray spectrum obtained from $^{238}\text{U} + ^9\text{Be}$ -induced fission data. Panel (b) is a spectrum gated on the 256.6-keV transition and panel (c) is a spectrum gated on the 374.6-keV transition. The * indicates new transitions.

Ref. [19,20]. Thus, level energy of this cascade is not placed in the level scheme. Other unlabeled transitions identified in

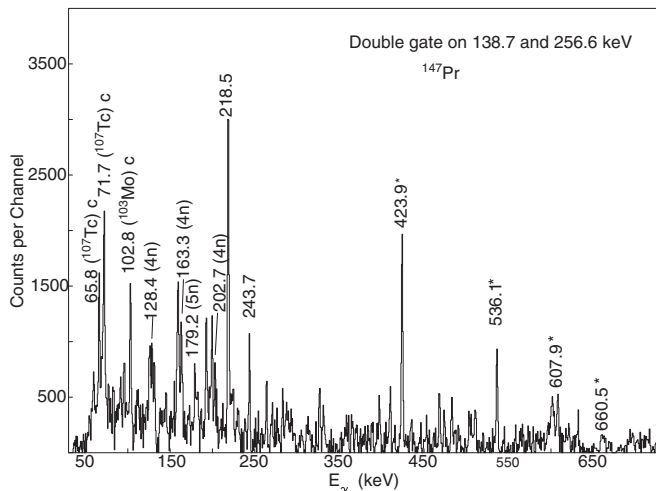


FIG. 10. Partial γ -ray coincidence spectrum by gating on 138.7- and 256.6-keV transitions in ^{147}Pr from ^{252}Cf SF data. In the spectrum, transitions belonging to Y fission partners are indicated with neutron evaporation numbers. The * indicates new transitions.

Fig. 9 (155-, 290-, 343-, 360-, 435-, and 443-keV) could not be placed in the level scheme for lack of coincidence data.

Previously, internal conversion coefficient of the 138.7-keV transition was not measured in β decay [19]. In the current work, α_{exp} of the 138.7-keV transition can be measured from the intensities of the 138.7-, 218.5-, and 243.7-keV transitions in the 256/424 double gate with the internal conversion of the relevant transitions included. The α_{exp} value obtained is 0.15(3), which is consistent with a theoretical $E1$ transition (0.10) but not $M1$ (0.51) or $E2$ (0.67). Thus, band (1) is proposed to have a negative parity and the bandhead could be either the 362.3- or the 385.1-keV level. From the comparison with the negative-parity bands in ^{145}La [21,22] and ^{149}Pm [23], the 256.6-keV γ ray is more likely to be a transition decaying from $15/2^-$ to $11/2^-$. Previously, the ground-state, 2.7-, 27.9-, and 93.2-keV levels were tentatively assigned to $3/2^+$, $5/2^+$, $7/2^+$, and $5/2^+$, respectively, in β -decay work [19], according to the decay pattern. The 218.5- and 269.1-keV transitions were assigned as $M1$ and $E1$, respectively, according to internal conversion measurement [19]. Assigning $11/2^-$ to 385.1-keV level, the 246.4-keV level is proposed to be $9/2^+$. The 362.3-keV level is then $7/2^-$ because the $11/2^-$ level decays to this state. Note that $11/2^-$ and $7/2^-$ are the lowest two negative levels (<250 keV) in the particle-plus-triaxial rotor model (PTRM) calculation in Ref. [19]. In contrast, the adopted levels in Ref. [24] tentatively assigned the ground-state, 2.7-, 27.9-, 93.2-, and 362.3-keV states to $5/2^+$, $3/2^+$, $5/2^+$, $7/2^+$, and $5/2^-$, respectively, based on the PTRM positive-parity calculation in Ref. [19]. However, this $5/2^-$ assignment does not agree with the lowest negative-parity levels, as already noted. Thus, considering both the negative- and positive-parity calculations, we agree with the spins and parities assigned in Ref. [19] and not with Ref. [24] for the lowest states.

E. ^{148}Pr

The new level scheme for ^{148}Pr is shown in Fig. 11. In this case, all transitions are newly identified. The new transitions are seen in the mass-Z-gated spectrum of ^{148}Pr (Fig. 12).

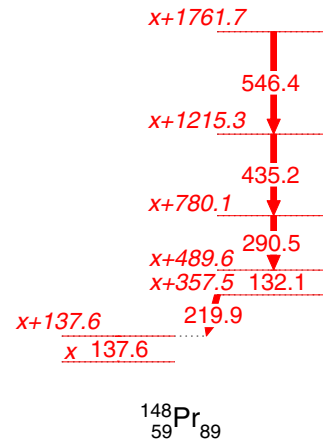


FIG. 11. (Color online) The new level scheme of ^{148}Pr in the present work. Relative intensities could not be extracted because of the very strong 219.8-keV transition in ^{149}Pr .

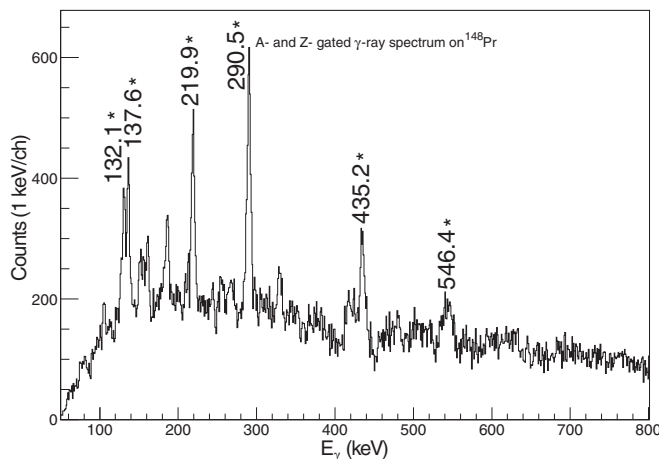


FIG. 12. Partial ^{148}Pr mass- and Z-gated γ -ray spectrum obtained from $^{238}\text{U} + ^9\text{Be}$ -induced fission data. The * indicates new transitions.

None of transitions from the β decay of ^{148}Ce [20,25,26] are observed in this work. A partial coincident γ -ray spectrum from the ^{252}Cf data is shown in Fig. 13. In this spectrum with gates on 132.1- and 290.5-keV transitions, one can clearly see the 137.6-, 219.9-, 435.2-, and 546.4-keV new transitions and the Y partner transitions. The order of these new transitions is placed based on the intensities and the similarity to ^{150}Pr . In ^{252}Cf SF data, the intensity ratios of 137.6/132.1 and 219.9/132.1 decrease about 80% as the time coincidence window decreases from 500 to 8 ns. In contrast, the ratio of the 132.1-, 290.5-, 435.2-, and 546.4-keV transition intensities remain almost the same. Thus, the 219.9- and 137.6-keV transitions are placed at the bottom and a lifetime of the order of 100 ns is proposed for the level which the 132.1-keV transition feeds. This is consistent with the nonobservation

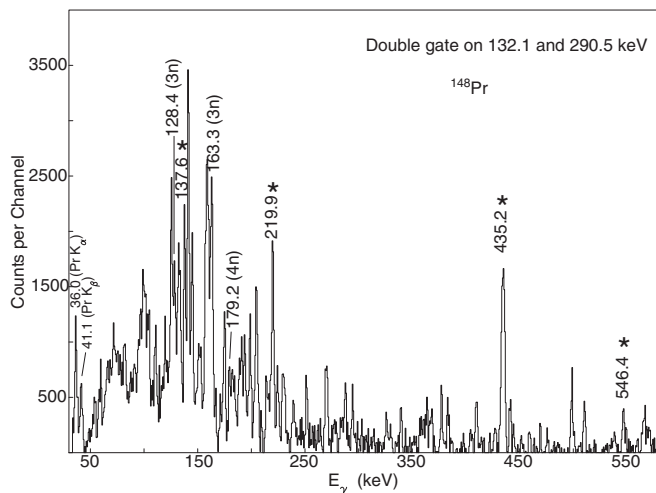


FIG. 13. Partial γ -ray coincidence spectrum by gating on 132.1- and 290.5-keV transitions in ^{148}Pr from ^{252}Cf SF data. In the spectrum, transitions belonging to Y fission partners are indicated with the corresponding number of evaporated neutrons. The * indicates new transitions.

of the 219.9-keV transition in coincidence with 290.5 keV in the prompt γ -ray spectrum obtained using the (A, Z) gate, where the prompt γ rays are sensitive only to states with lifetimes shorter than ~ 2 ns. In addition, spectra obtained in A/Z coincidence with 219.9 keV suggest the existence of another band consisting of 219.9- and 329-keV transitions. However, we cannot confirm this cascade in SF data. Triple gates (137.6-132.1-290.5- and 219.5-132.1-290.5-keV) show no evidence for the strong 105-, 121-, 195-, or 289-keV transitions seen in β decay. Thus, we conclude none of the low-spin (1,2) states seen in β decay are fed by the cascade seen in Fig. 12. This cascade could feed the 2-min 4^- isomer at 77 keV [26].

G. ^{149}Pr

The new level scheme for ^{149}Pr is shown in Fig. 14. In this case, the 58.5- and 86.5-keV transitions were previously observed in the β decay of ^{149}Ce [27,28]. Band (1) in Fig. 14 was previously reported in Ref. [4]. In Fig. 15, previously

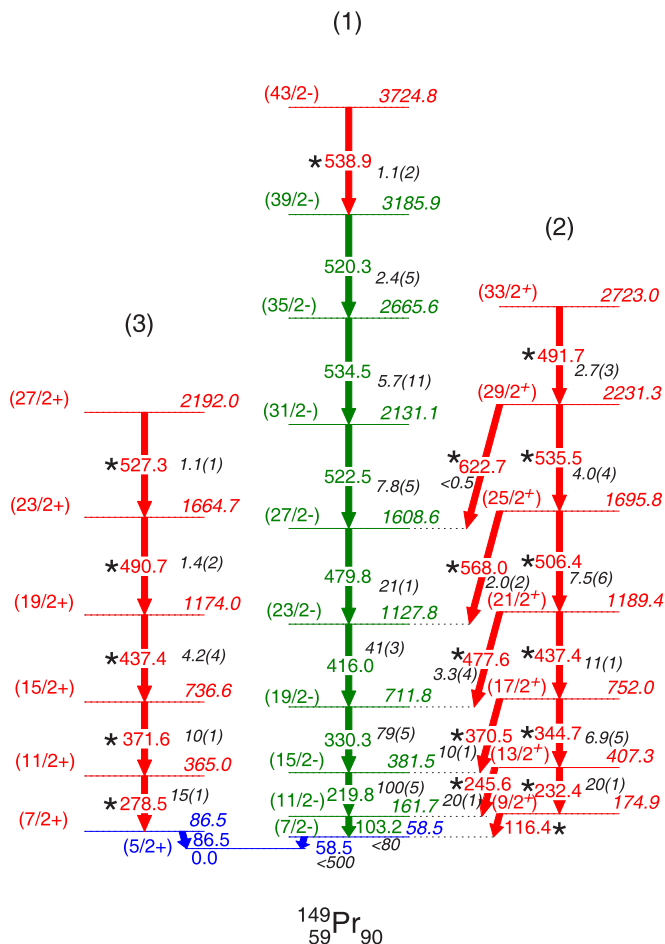


FIG. 14. (Color online) The new level scheme of ^{149}Pr in the present work. The 86.5- and 58.5-keV transitions and levels previously reported in β -decay work are labeled in blue. Those reported by Hwang *et al.* [4] are labeled in green, the 103.2- to 520.3-keV transitions in band (1). New transitions and levels are labeled in red and with an asterisk. The intensities in black to the right of the γ -ray energies are relative to 100 for the 219.8-keV transition.

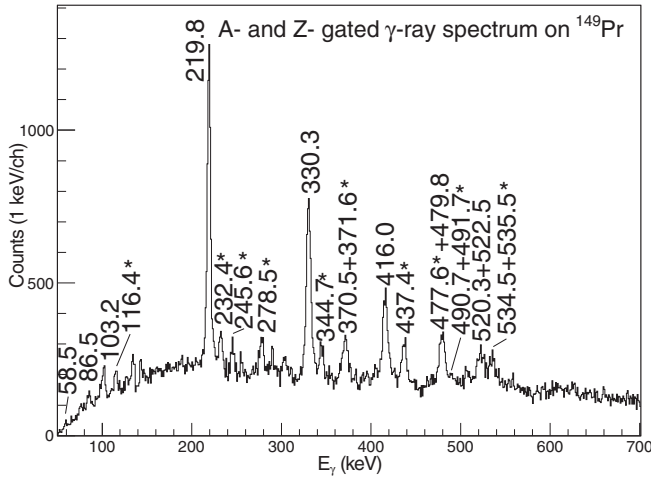


FIG. 15. Partial ^{149}Pr A- and Z-gated γ -ray spectrum obtained from $^{238}\text{U} + ^9\text{Be}$ -induced fission data. The * indicates new transitions.

reported band (1) transitions and new transitions in bands (2) and (3) are seen in the (A, Z)-gated spectra. These spectra were important in guiding SF γ -ray coincidence spectra analysis to identify the new band (3). These two new bands (2) and (3) are established in the present work by observing the coincidence between the γ rays in these bands and the 86.5- or 58.5-keV transition in ^{252}Cf SF data. A partial coincident γ -ray spectrum is shown in Fig. 16(a). In this spectrum with a gate on two new transitions in band (3), one can clearly see the 86.5-keV transition, three other new transitions, and Y partner transitions. Another partial coincident γ -ray spectrum is shown in Fig. 16(b). In this spectrum with gate on two new transitions in band (2) one can clearly see the 58.5- and

103.2-keV transitions, six other new transitions, and Y partner transitions. By gating on these new transitions and analyzing the relative γ -transition intensities, these two new bands are proposed for ^{149}Pr . The ^{252}Cf data also shows some weak evidence for the coincidences between the 103.2- and 232.4-, 219.8-, and 344.7-keV transitions, respectively. The possible low-energy 13.2 (174.9 to 161.7)- and 25.8 (407.3 to 381.5)-keV transitions are not indicated in the level scheme in Fig. 14.

Spins and parities of levels in band (1) were tentatively assigned in Ref. [6] by an internal conversion coefficient measurement and theoretical calculations. Those results are adopted in this paper. Based on the regular energy spacings and γ -ray intensities, the new level at 3724.8 keV is assigned as $43/2^-$.

The total internal conversion coefficient of the 86.5-keV transition in ^{149}Pr was measured from the intensity ratio between 86.5- and 278.5-keV transitions in the coincident spectrum gated on 371.6- and 437.4-keV transitions above them. The value was obtained to be 1.63(22), and is in agreement with the theoretical calculated value [29] of 1.96 for a $M1$ transition but not with 3.58 for an $E2$ transition.

Quasiparticle-rotor model (QPRM) calculations [6,30] suggest a $\pi 5/2[413]$ configuration for the ^{149}Pr ground-state level. The lowest three excited level energies at 86.5, 365.0, 736.6 keV of band (3) in ^{149}Pr are also reasonably consistent with the QPRM calculations of $7/2^+$, $11/2^+$, and $15/2^+$ for the states at 87, 342, and 708 keV, respectively, in Ref. [6]. Therefore, the spins and parities of excited states in band (2) are tentatively assigned as $7/2^+$, $11/2^+$, $15/2^+$, $19/2^+$, $23/2^+$, and $27/2^+$ in the present work.

Spins and parities of the levels in band (2) are tentatively assigned in Fig. 14 based on the structure similarity to the $h_{11/2}$ signature $s = +i$ octupole bands “(1)” and “(2)” in Ref. [22]. When octupole deformation or octupole correlations

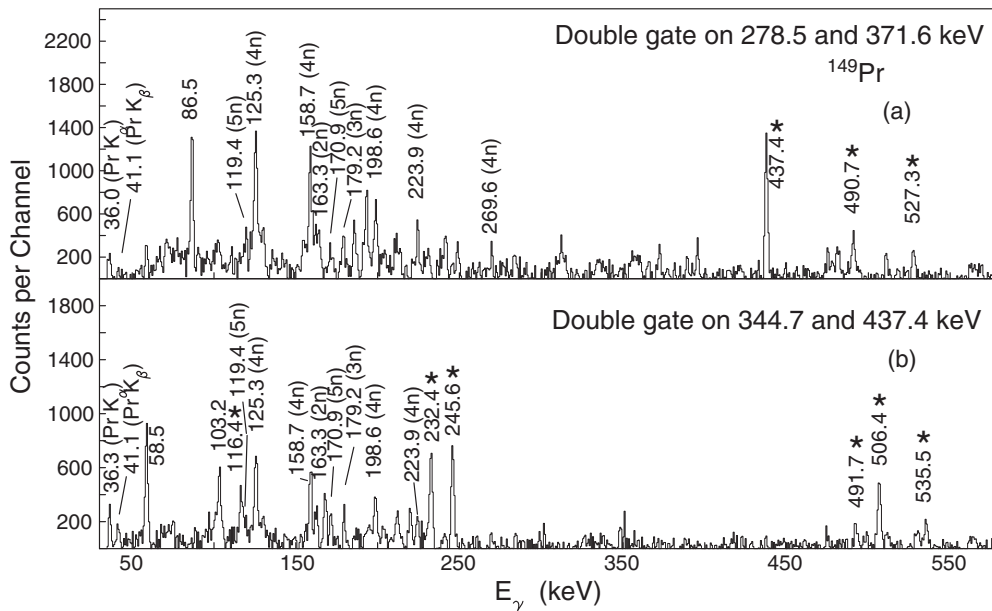


FIG. 16. Partial γ -ray coincidence spectra (a) by gating on 278.5- and 371.6-keV transitions, and (b) by gating on 344.7- and 437.4-keV transitions in ^{149}Pr from ^{252}Cf SF data. In the spectrum, transitions belonging to Y fission partners are indicated with neutron evaporation numbers; specifically, $5n$, $4n$, $3n$, $2n$ correspond to $^{98,99,100,101}\text{Y}$, respectively. The * indicates new transitions.

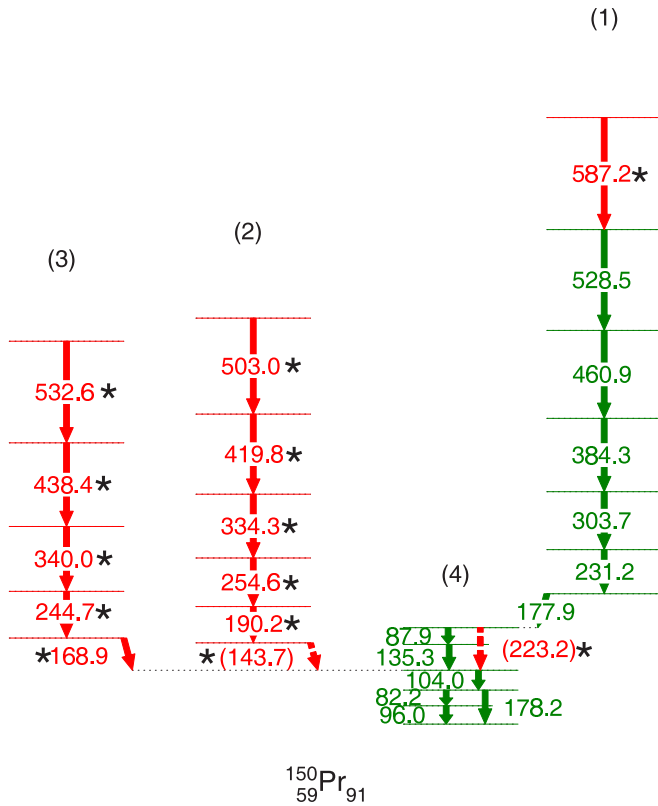


FIG. 17. (Color online) The new level scheme of ^{150}Pr in the present work. Transitions and levels previously reported by Hwang [4,5] are labeled in green (the 96.0- to 528.5-keV cascade transitions). New ones are labeled in red and with an asterisk.

are strong, one expects a symplectic quantum number $s = i$, two bands of opposite parity with the spin shown in Fig. 14, and strong $E1$ transitions between the two bands as found in Ref. [31]. Note that QPRM calculation in Ref. [6] indicates that this band is unlikely to be another signature of band (1). Further analysis is included in the discussion part.

H. ^{150}Pr

The new level scheme for ^{150}Pr is shown in Fig. 17. Bands (1) and (4) were previously assigned to ^{150}Pr in Refs. [4,5] from the SF of ^{252}Cf . In this earlier work, the relative yield ratios of partner Y isotopes were measured [5]. The transitions previously assigned to ^{150}Pr along with several new ones are shown in the (A,Z)-gated spectrum (Fig. 18). Figure 19(a) shows a coincidence spectrum double gated on the new 190.2- and 254.6-keV transitions. Figure 19(b) shows a coincidence spectrum double gated on the new 244.7- and 340.0-keV transitions. The previously known γ transitions of 96, 82.2, and 104.0 keV of ^{150}Pr and the γ transitions in the partner Y isotopes can be seen in these spectra. Therefore, these new transitions are assigned to ^{150}Pr in the present work. The newly observed 334.3-, 419.8-, and 503.0-keV transitions are coincident with the new 190.2- and 254.6-keV transitions in Fig. 19(a). Also, the new 438.4- and 532.6-keV transitions are coincident with the new 340.7- and 244.7-keV transitions in Fig. 19(b). By using these coincidence relationships in multiple

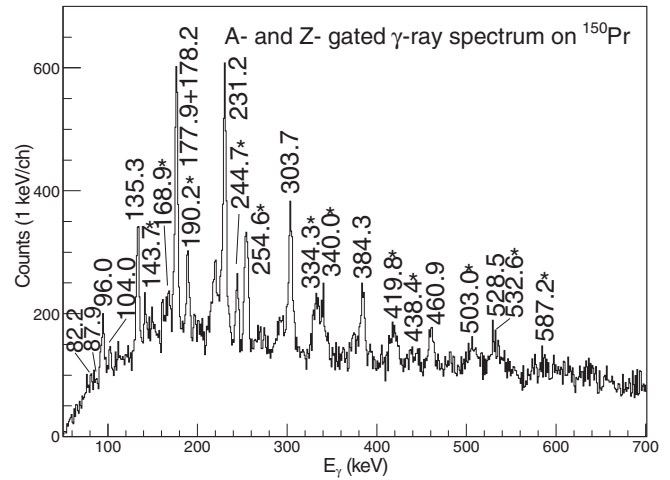


FIG. 18. Partial ^{150}Pr mass- and Z-gated γ -ray spectra obtained from $^{238}\text{U} + ^9\text{Be}$ -induced fission data. The * indicates new transitions.

gates, bands (2) and (3) were found, as shown in Fig. 17. The 143.7-keV transition is dashed because the intensity is weaker than that of the 190.2-keV transition.

I. ^{151}Pr

The new level scheme for ^{151}Pr is shown in Fig. 20. The ^{151}Pr A- and Z-gated spectra obtained from $^{238}\text{U} + ^9\text{Be}$ -induced fission are shown in Figs. 21(a) and 21(b), respectively. Bands (1) and (2) in Fig. 20 were assigned previously to ^{151}Pr in Ref. [5]. In this earlier work, the relative yield ratios of partner Y isotopes were measured. However, bands (1) and (2) were assigned to ^{152}Pr by Malkiewicz *et al.* [8]. The previously reported [5] γ transitions in bands (1) and (2) are confirmed from the mass and Z-gated spectrum in Fig. 21(a). In the present work, the 204.2- and 41.9-keV transitions in Ref. [5] are replaced with the new 214.6- and 52.3-keV transitions in bands (1) and (2) of Fig. 20. Also, a possible new 143.1-keV transition is added. Previously, bands (3) and (4) were assigned to ^{152}Pr in Ref. [7].

Then band (3) was assigned to ^{151}Pr and band (4) to ^{153}Pr from the SF work of ^{248}Cm and ^{252}Cf [8]. Now band (3) and band (4) in Fig. 20 are assigned to ^{151}Pr in the present work because the 142.3-, 221.3 + 221.9-, 296.4-, 291.9-, 365.2-, and 358.4-keV transitions are seen in the ^{151}Pr mass and Z-gated spectra in Figs. 21(a) and 21(b). The 221.3- and 221.9-keV transitions were reported earlier as one 221.9-keV transition [7]. Later, the 142.3-keV transition in Ref. [7] was separated into 142.1- and 141.6-keV transitions in Ref. [8]. The 221.9-keV transition in Ref. [7] was separated into 221.8- and 221.0-keV transitions in Ref. [8]. In this paper, a shift of about 0.6 keV of the 221.9-keV peak has been confirmed by comparing the gates between bands (3) and (4), for example, double gates on 296.4 and 356.2 keV in band (3), 291.9 and 358.4 keV in band (4), triple gates on 296.4, 356.2, and 428.7 keV in band (3), and 291.9, 358.4, and 420.8 keV in band (4). However, no visible energy difference of the 142.3-keV transition is seen when comparisons are set between any of

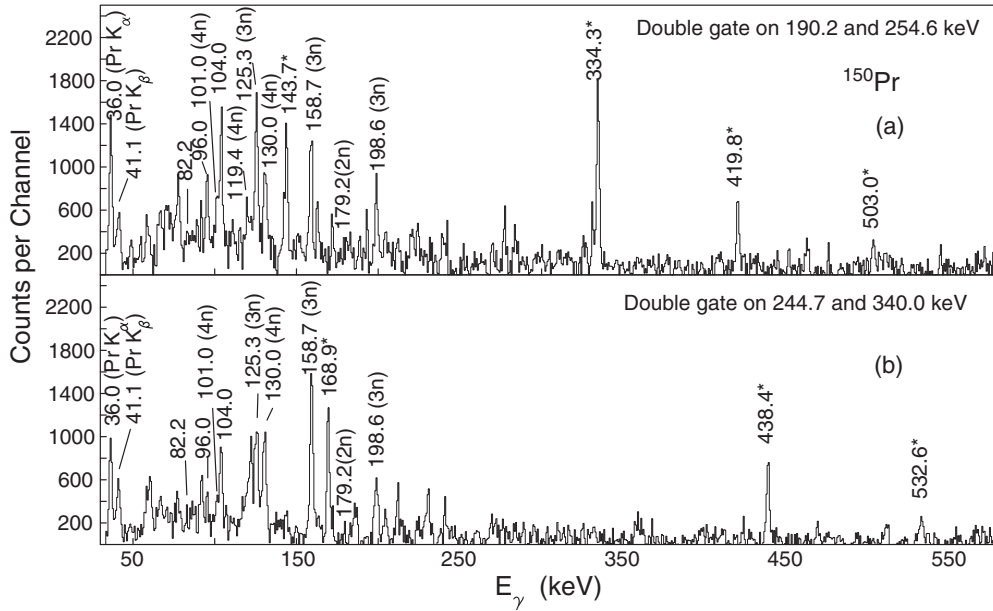


FIG. 19. Partial γ -ray coincidence spectra (a) by gating on 190.2- and 254.6-keV transitions, and (b) by gating on 244.7- and 340.0-keV transitions in ^{150}Pr from ^{252}Cf SF data. In the spectrum, transitions belonging to Y fission partner are indicated with neutron evaporation numbers; specifically, $4n$, $3n$, $2n$ correspond to $^{98,99,100}\text{Y}$, respectively. The * indicates new transitions.

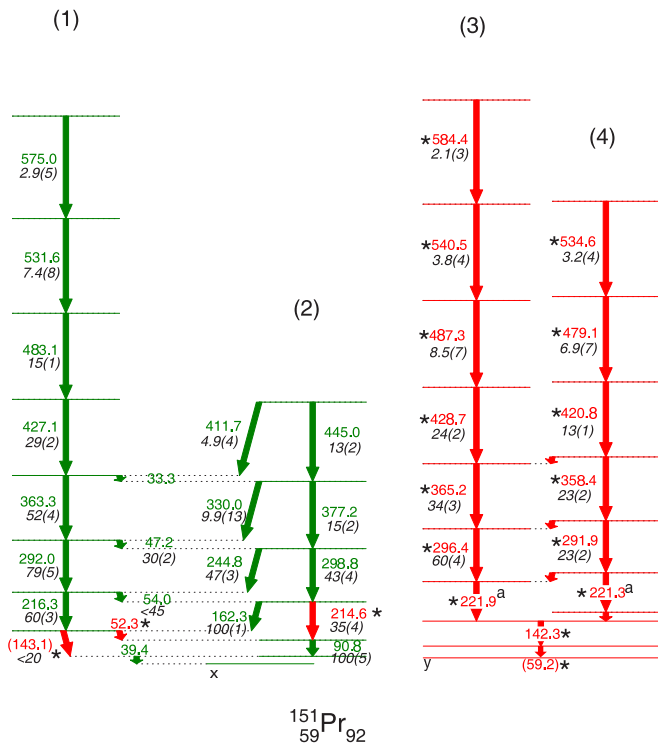


FIG. 20. (Color online) The new level scheme of ^{151}Pr in the present work. Transitions and levels in bands (1) and (2) previously reported by Hwang *et al.* [5] are labeled in green. New levels and transitions are labeled in red and with an asterisk. The $221.9 + 221.3$ -keV transitions, superscript “a”, have the normalized intensity of 100. Bands (3) and (4) are shown in red with other new transitions because both bands now feed a single 142.3-keV transition. Band (3) was assigned to ^{151}Pr and band (4) to ^{153}Pr in Ref. [5]. The γ -ray intensities are relative to 100 for the 162.3-keV transition.

the gates in bands (3) and (4). Thus, two different 221.9- and 221.3-keV transitions are proposed, but there is only one 142.3-keV transition in the level scheme. In the present work, all of bands (1), (2), (3), and (4) are definitely assigned to ^{151}Pr , as shown Fig. 20. Further analysis about the mass assignment are presented in the $^{152,153}\text{Pr}$ and discussion sections.

Figure 22(a) is a coincidence spectrum from ^{252}Cf SF data by gating on 216.3- and 292.0-keV transitions showing the new 52.3- and 143.1-keV transitions. The peak around 40 keV is an overlap of a 39.4-keV γ transition and 41.0-keV Pr x ray. Therefore, the energy of the 39.4-keV transition has a relatively large uncertainty and might range from 39 to 42 keV. If the

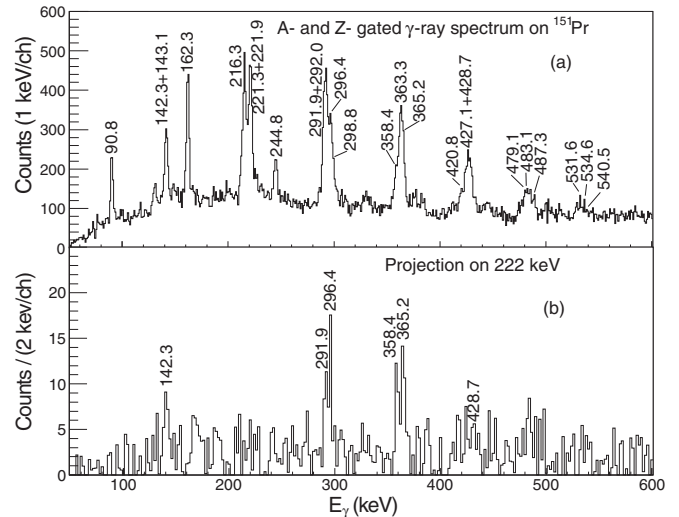


FIG. 21. Partial ^{151}Pr mass- and Z-gated γ -ray spectra obtained from $^{238}\text{U} + ^9\text{Be}$ -induced fission data. Part (a) is single γ -ray spectrum. Part (b) is a gated spectrum on the 222-keV transition.

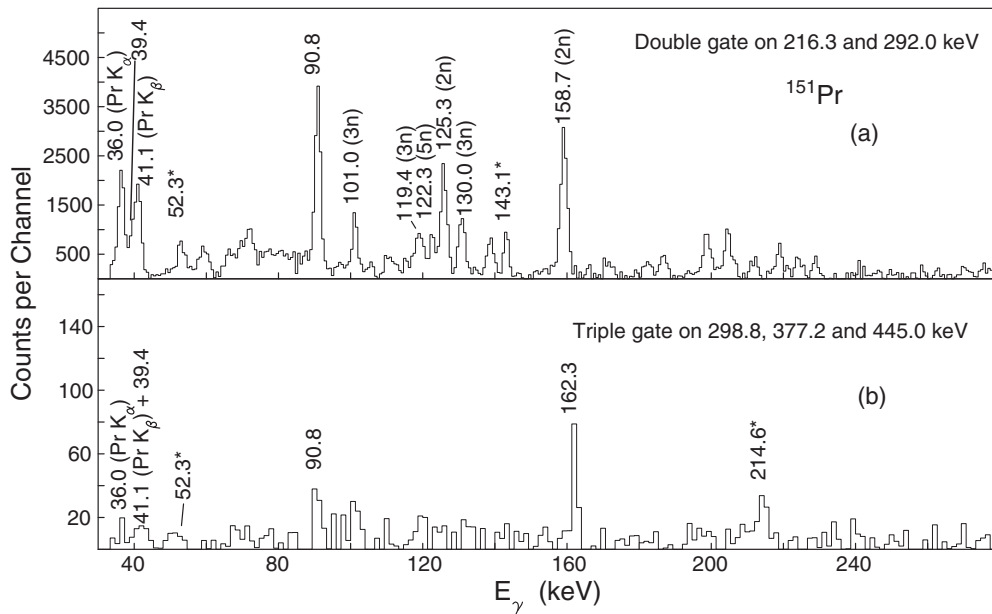


FIG. 22. Partial γ -ray coincidence spectra (a) by gating on 216.3- and 292.0-keV transitions, and (b) by gating on 298.8-, 377.2-, and 445.0-keV transitions in ^{151}Pr from ^{252}Cf SF data. In the spectrum, transitions belonging to Y fission partner are indicated with neutron evaporation numbers, specifically, $5n$, $3n$, $2n$ correspond to $^{96,98,99}\text{Y}$ respectively. The * indicates new transitions. Note the keV/channel in panel (a) differs from that in panel (b).

39.4-keV transition is the same as the 38.9-keV one reported in β -decay work [26], bands (1) and (2) would decay to the ground state. However, because the energy of this transition has a large uncertainty, an x -keV level is used in Fig. 20. The 143.1-keV transition is much weaker than the 90.8-keV one and is bracketed in the level scheme. Figure 22(b) is a coincidence spectrum from ^{252}Cf SF data triple gated on 298.8-, 377.2-, and 445.0-keV transitions. The 204.2-keV transition is not

seen compared to 214.6 keV in this gate, which suggest some contamination at 204.2 keV in the spectrum of the previous work (Ref. [5]). Thus, the 204.2-keV transition is replaced with the 214.6-keV one in the present work.

Figure 23(a) is a coincidence spectrum from ^{252}Cf SF data by gating on 221.9-, 296.4-, and 365.2-keV transitions. The 428.7-, 487.3-, 540.5-, and 584.4-keV transitions in band (3) can be seen. Figure 23(b) is a coincidence spectrum from ^{252}Cf

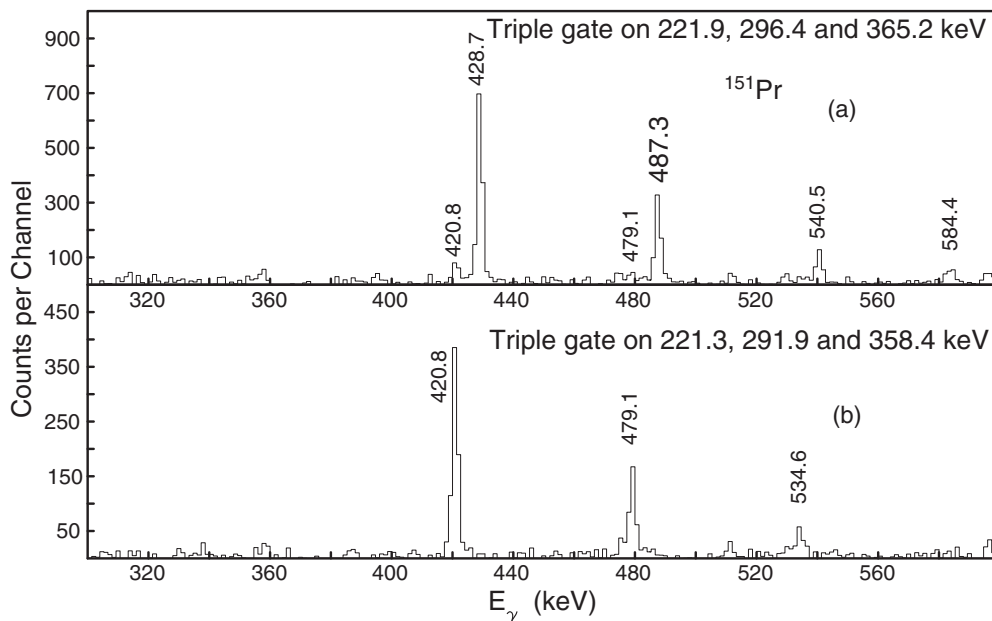


FIG. 23. Partial γ -ray coincidence spectra (a) by gating on 221.9-, 296.4-, and 365.2-keV transitions and (b) by gating on 221.3-, 291.9-, and 358.4-keV transitions in ^{151}Pr from ^{252}Cf SF data.

Sf data by gating on 221.3-, 291.9-, and 358.4-keV transitions. The 420.8-, 479.1-, and 534.6-keV transitions in band (4) can be seen. The ^{252}Cf SF data also show coincidence of the 296.4- and 358.4-keV transitions, as well as the 365.2- and 420.8-keV transitions, but interband transitions linking bands (3) and (4) are not observed in the current work. These coincidences indicate the existence of a very low-energy transition to lift up band (4) in ^{151}Pr .

The analysis result for γ transition intensities are also labeled in the level scheme. The intensities have been separated into two parts. The intensities of transitions in band (1) and band (2) are normalized to that of the 162.3-keV transition and those in band (3) and band (4) are normalized to the summation of the 221.9- and 221.3-keV transition intensities.

Previously, internal conversion measurements established the 47.2- and 54.0-keV transitions as $E1$ and the 90.8-keV one as $M1$ [5]. The value of the 90.8-keV transition was obtained from the 90.8- and 292.0-keV transition intensities in the coincidence spectrum gated on 216.3 and 363.3 keV in Ref. [5]. This measurement did not include the contribution of the 47.2-keV transition. If this contribution is taken into account, the internal conversion value will increase by a factor of $\sim 20\%$, which will make it closer to the theoretical $M1$ value. Those corrections can be seen in the erratum Ref. [32]. The branching of the 143.1-keV transition is very small [see Fig. 22(a)] and does not change the result much. The α_{exp} value of 54.0 keV was obtained from the 54.0-, 162.0-, and 204.0-keV transition intensities in the 292.0- and 363.3-keV double gate in Ref. [5]. This measurement is also questionable because the 204.0-keV transition is not confirmed in the current work. The peak around 54.0 keV in the 292.0- and 363.3-keV double gate is an overlap of the 52.3- and 54.0-keV transitions. Thus, the intensity as well as the α_{exp} value of the 54.0-keV transition cannot be accurately obtained in the present work. The α_{exp} value of the 52.3 keV can be obtained from the 52.3- and 90.8-keV transition intensities in the 216.3- and 292.0-keV double gate. The value is 3.5(9), which lies between the theoretical value of $E1(1.4)$ and $M1(8.3)$. However, the 216/292 gate might be interfered by the 214.6-keV transition so that the error of the α_{exp} value of the 52.3 keV would be much higher.

J. ^{152}Pr

The new level scheme for ^{152}Pr is shown in Fig. 24. All levels and transitions are newly established in the present work except for the 114.8- and 98.1-keV transitions, which were identified in ^{152}Ce β decay [33]. Figure 25 shows the ^{152}Pr A- and Z-gated single γ spectrum from $^{238}\text{U} + ^9\text{Be}$ -induced fission data, illustrating the evidence for the mass assignment for these three new bands. All the strong transitions in these three bands can be seen. As can be seen from the figure, the 221.3-, 221.9-, 358.4-, and 365.3-keV transitions are not seen in the $A = 152$ spectrum (Fig. 25) as compared to $A = 151$ gated spectra [Figs. 21(a) and 21(b)]. This confirms that 142.3-221.9-296.4- (^{151}Pr) and 142.3-221.3-292.0-keV cascades do not belong to ^{152}Pr , as previously reported in Ref. [7], but in ^{151}Pr and the latter does not belong to ^{153}Pr , as recently reported [8]. The position of the 162.3-keV transition in ^{151}Pr

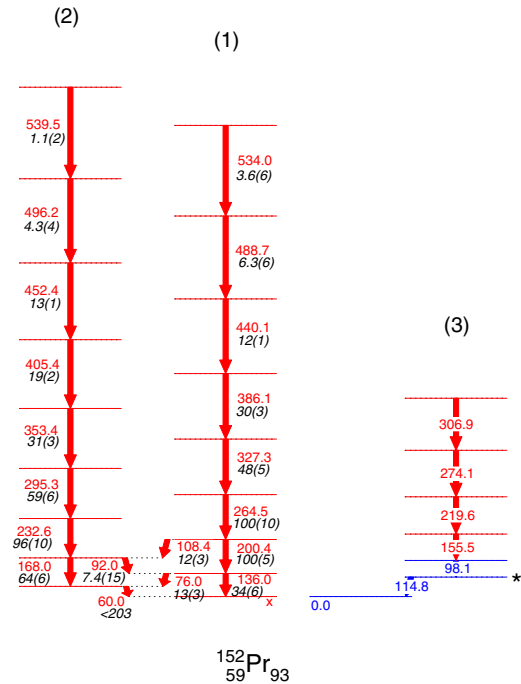


FIG. 24. (Color online) The level scheme of ^{152}Pr in the present work. The 114.8- and 98.1-keV transitions and levels previously reported in β decay work are labeled in blue. All others are new ones labeled in red. * This level is an isomer with a lifetime of 4.1 μs according to the measurement in Ref. [33]. The γ -ray intensities are relative to 100 for the 200.3-keV transition.

(100 relative intensity) is labeled in Fig. 25. The absence of the 162.3-keV peak (the weak peak seen in the valley is at 160.5 keV) indicates that bands (1) and (2) assigned to ^{151}Pr belong there and not to ^{152}Pr , as recently reported in Ref. [8]. These facts give further evidence for the mass assignment for the four bands in ^{151}Pr in the present work. Further analysis of the mass assignments are reported in the ^{153}Pr section. The

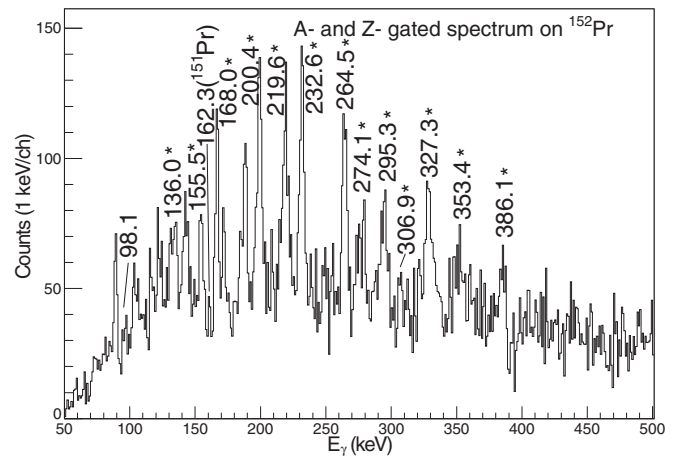


FIG. 25. Partial ^{152}Pr mass- and Z-gated γ -ray spectra obtained from $^{238}\text{U} + ^9\text{Be}$ -induced fission data. The position of the 162.3-keV transition from ^{151}Pr is also indicated to illustrate its nonobservation (see text for details). Note the absence of the 114.8-keV isomeric transition. The * indicates new transitions.

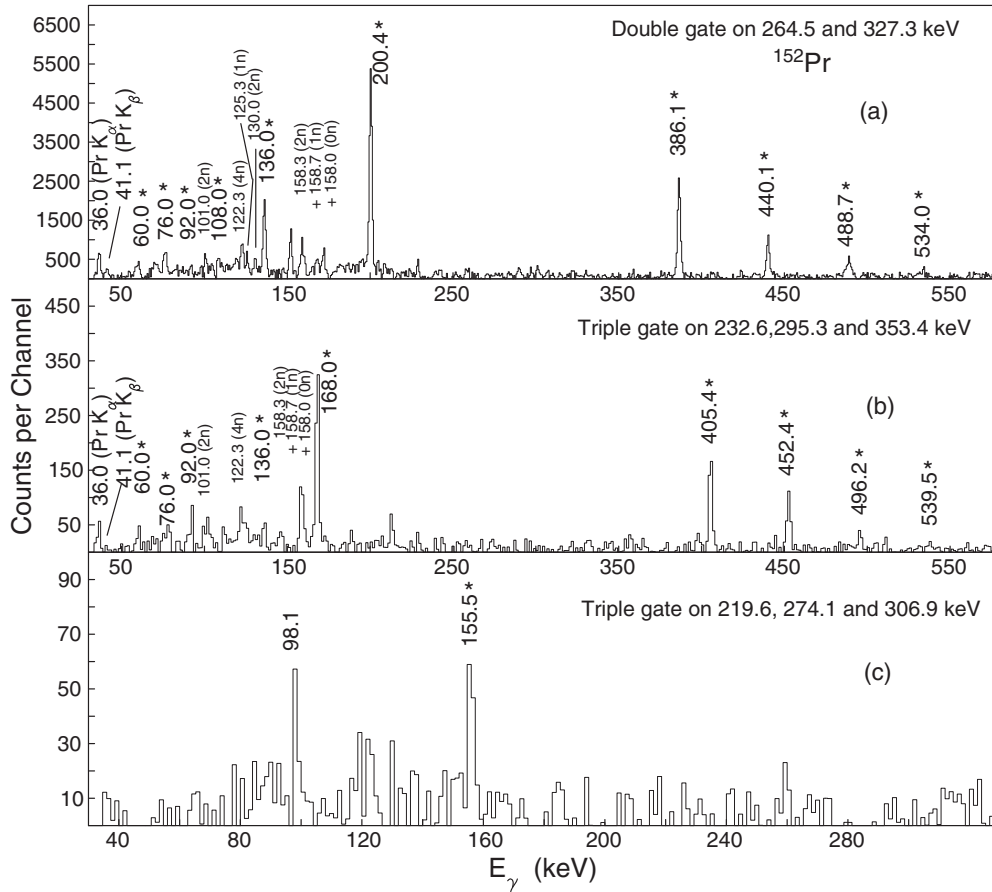


FIG. 26. Partial γ -ray coincidence spectra (a) by gating on 264.5- and 327.3-keV transitions, (b) by gating on 232.6-, 295.3-, and 353.4-keV transitions, and (c) by gating on 219.6-, 274.1-, and 306.9-keV transitions in ^{152}Pr from ^{252}Cf SF data. In the spectrum, transitions belonging to Y fission partner are indicated with neutron evaporation numbers, specifically, 2n, 1n, 0n correspond to $^{98,99,100}\text{Y}$ respectively. The * indicates new transitions.

relatively strong 90- and 188-keV peaks in Fig. 25 are not seen in any of the SF coincidence data connected to bands (1) and (2) in Fig. 24. The SF coincidence data do indicate a 188-279-322-385-keV cascade, which could form another band in ^{152}Pr .

Figure 26(a) shows a coincidence spectrum from the ^{252}Cf SF data by double gating on 264.5- and 327.3-keV transitions. The 136.0-, 200.4-, 386.1-, 440.1-, 488.7-, and 534.0-keV transitions in band (1) and 60.0-, 76.0-, 92.0-, 108.4-keV linking transitions between band (1) and band (2) can be seen. Figure 26(b) shows a coincidence spectrum from the ^{252}Cf SF data by triple gating on 232.6-, 295.3-, and 353.4-keV transitions, where 168.0-, 405.4-, 452.4-, 496.2-, and 539.5-keV transitions in band (2) and 60.0-, 76.0-, and 92.0-keV linking transitions between band (1) and band (2) can be seen. Figure 26(c) shows a coincidence spectrum from ^{252}Cf SF data by triple gating on 219.6-, 274.1-, and 306.9-keV transitions, where 98.1- and 155.5-keV transitions in band (3) can be seen. The 114.8-keV transition is not observed in the current work because the electronic coincidence time window for the ^{252}Cf fission experiment is about 1 μs , which is relatively smaller than the 4.1- μs lifetime [33] of the 114.8-keV level. For prompt- γ -ray data, the present GANIL experimental setup is sensitive only

to states with lifetimes shorter than ~ 2 ns. The result for γ transition intensities are also given in the level scheme.

K. ^{153}Pr

The new level scheme for ^{153}Pr is shown in Fig. 27. Band (1) in Fig. 27 was assigned previously to ^{153}Pr in Ref. [5], but was assigned, recently, to ^{154}Pr from the SF work of ^{248}Cm and ^{252}Cf [8]. In the earlier work, the relative yield ratios of partner Y isotopes were measured [5]. The ^{153}Pr mass and Z-gated spectra obtained from $^{238}\text{U} + ^9\text{Be}$ -induced fission are shown in Fig. 28. The previously reported γ transitions of 88.0-, 156.7-, 206.6-, 279.5-, 351.1-, 417.8-, and 477.9-keV transitions in ^{153}Pr [5] are confirmed from the mass and Z-gated spectrum shown in Fig. 28. The 142.3-, 221.3-, and 292.2-keV cascade previously assigned to ^{153}Pr by Malkiewicz *et al.* [8] is not confirmed by the mass and Z-gated spectrum in Fig. 28. The position of the 292.2-keV transition is shown in Fig. 28 to illustrate its nonobservation. Instead, a new cascade with 143.1-, 221.9-, and 297.7-keV transitions can be seen in the spectrum. Further analysis about the mass assignment is reported in the Discussion section.

The previously assigned 51.7-, 227.8-, and 277.7-keV transitions are not placed in Fig. 27 because these transitions

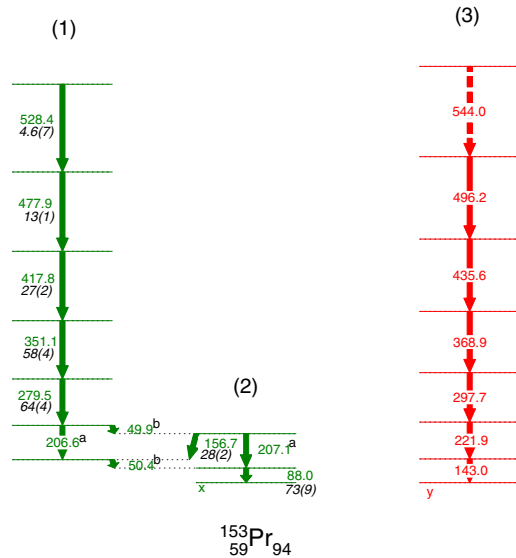


FIG. 27. (Color online) The level scheme of ^{153}Pr in the present work. Transitions and levels previously reported by Hwang *et al.* [5] are labeled in green, bands (1) and (2). New ones in band (3) are labeled in red. (a) The 206.6 + 207.1-keV transitions have the relative intensity of 100. (b) The 49.9 + 50.4-keV transition have the relative intensity of <127. The new transitions in red were too close in energy to transitions in ^{151}Pr to measure intensities.

are not clearly seen in the ^{252}Cf SF data. Furthermore, the 227.8-keV transition is not observed in the 206.6- and 969.1-keV (a fission partner ^{95}Y transition [34]) double gate and the 206.6- and 417.8-keV double gate. Thus, the previously reported 13/2 level and its three transitions are tentatively removed from the level scheme. The results for γ transition intensities are shown in the level scheme. Previous internal conversion measurements established the 50.4-keV transition as $E1$ and the 88.0-keV one as $M1$ [5]. The value of the 50.4-keV transition is questionable because the 206.6/351.1-

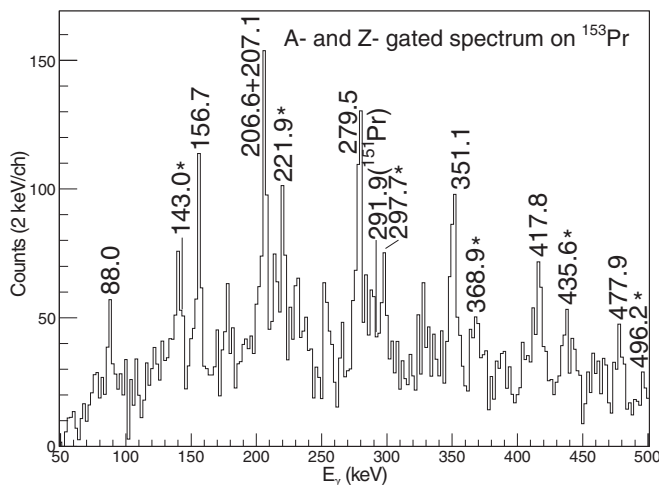


FIG. 28. Partial ^{153}Pr mass- and Z-gated single γ -ray spectra obtained from $^{238}\text{U} + ^9\text{Be}$ -induced fission data. The position of the 291.9-keV transition from ^{151}Pr is also indicated to illustrate its nonobservation (see text for details). The * indicates new transitions.

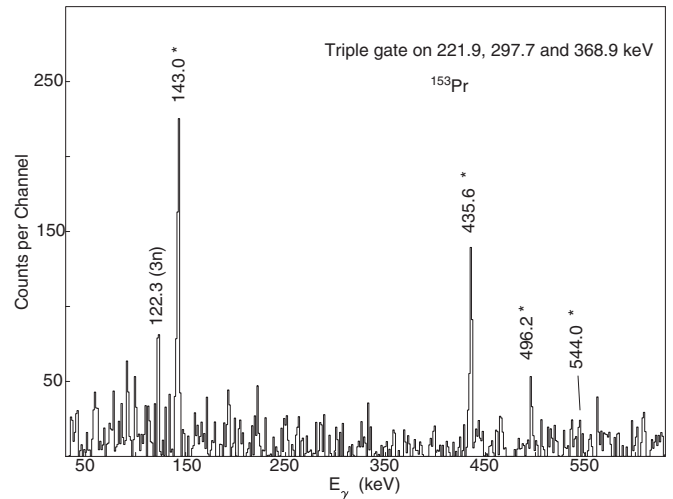


FIG. 29. Partial γ -ray coincidence spectrum by triple gating on 221.9-, 297.7-, and 368.9-keV transitions in ^{153}Pr from ^{252}Cf SF data. In the spectrum, transitions belonging to the Y fission partner are indicated with neutron evaporation numbers, specifically, $3n$ corresponds to ^{96}Y . The * indicates new transitions.

keV gate used in Ref. [5] might be interfered with by the 207.1-keV transition. If one approximately assumes the 49.9- and 50.4-keV transitions have the same α_{exp} value, the 2.3(7) value in Ref. [5] should be used, not 3.2(9) in the erratum Ref. [32] because the 227.8-keV transition is not confirmed in the current work. Figure 29 shows a coincidence spectrum from ^{252}Cf SF data by gating on the 221.9-, 297.7-, and 368.9-keV transitions. In this gate, four other γ -ray transitions in band (3) can be seen. The (A,Z)-gated spectra were important in guiding the γ -ray coincidence spectra analysis to identify new band (3).

IV. DISCUSSION

Mantica *et al.* showed that the quadrupole deformation increases gradually from ^{145}Pr to ^{149}Pr [19]. The current work implies that $^{151,153}\text{Pr}$ have similar but larger deformation than ^{149}Pr based on the decreasing $E2$ energies and $\Delta E2$ values shown for their bands (1) in Table I. A comparison of the proposed $E2$ transition energies and transition energy spacing in bands (1), (2), and (3) in $^{147,149,151,153}\text{Pr}$ is shown in Table I. The similarity of the transition energies indicates similar structures of the nuclei. Moreover, bands (1) and (3) in $^{151,153}\text{Pr}$ are almost identical both in transition energy (less than 10 keV) and intensity up to very high spins. Such kinds of almost identical bands were also observed in $^{152,154,156}\text{Nd}$ [35], $^{153,155,157}\text{Pm}$ [36], $^{156,158,160}\text{Sm}$ [37], $^{155,157,159}\text{Eu}$ [38], $^{160,162,164}\text{Gd}$ [39], respectively. This identical-bands phenomenon occurs just after the phase transition from spherical to large deformed shape as N increases from 88 to 90 in this region. $\Delta E2$ energy shrinks more in ^{149}Pr and bending takes place at high spin. In contrast, the $\Delta E2$ energies are similar and do not shrink as much in $^{151,153}\text{Pr}$, which indicates a relatively rigid rotor in these nuclei. Note that the $E2$ and $\Delta E2$ energies in bands (1), (2), and (3) in ^{150}Pr are different to indicate that band (2) has a

TABLE I. Comparison of the $E2$ transition energies in bands (1), (2) and (3) in $^{147,149,151,153}\text{Pr}$ and the transition energy difference.

^{147}Pr	^{149}Pr	^{151}Pr	^{153}Pr	^{149}Pr	^{151}Pr	^{153}Pr	^{149}Pr	^{151}Pr	^{153}Pr
Band (1) $E2$ (keV)				Band (2) $E2$ (keV)			Band (3) $E2$ (keV)		
	103						142	143	
256	220	216	207	232	215	207		222	222
424	330	292	280	345	299		279	296	298
536	416	363	351	437	377		372	365	369
608	480	427	418	506	445		437	429	436
660	523	483	478	536			491	487	496
	535	532	528	492			527	541	544
	520	575						584	
	539								
Band (1)				Band (2)			Band (3)		
$\Delta E2$ (keV)				$\Delta E2$ (keV)			$\Delta E2$ (keV)		
	117						80	79	
168	110	76	73	113	84		74	76	
112	86	71	71	92	78		93	69	71
72	64	64	67	69	68		65	64	67
52	43	56	60	30			54	58	60
	12	49	50	-44			36	54	48
	-15	43						43	
	19								

large deformation than bands (1) and (3). Note the $E2$ energies in band (1) of $N = 88$ ^{147}Pr in Fig. 8 are 36, 94, 120, 128, and 137 keV, respectively, larger than in band (1) of $N = 90$ ^{149}Pr , where the differences are only 4 to 53 keV between ^{149}Pr and ^{151}Pr to indicate a phase transition here too. An internal conversion measurement in Ref. [5] implied $E1$ interband transitions between band (1) and band (2) in ^{151}Pr . Therefore, there could be a small octupole deformation or correlation in ^{151}Pr and the similar cross transitions between bands (1) and (2) likewise suggest this in ^{149}Pr . QPRM calculations for $^{149,151,153}\text{Pr}$ have been discussed earlier in Refs. [6,8].

Pr nuclei in this region present serious challenges in assigning bands to particular odd- Z Nilsson orbitals. There are $K = 1/2$ orbitals of both parities and large j values near the Fermi energy. The odd-parity $K = 1/2^- [550]$ has $j = 11/2$ and the even-parity $K = 1/2^+$ orbitals are a mix of $g_{7/2}$ and $d_{5/2}$. The odd-parity $K = 1/2^-$ band will have large signature splitting, and the even-parity $K = 1/2^+$ bands can have either sign of signature splitting or near cancellation for certain admixtures.

The 368.8-, 546.3-, and 672.3-keV transitions in the new $3/2^+$ band in ^{145}Pr are similar to the first three $E2$ transitions (397, 541, and 709 keV) in ^{144}Ce . Therefore, the aligned angular momentum of this new band relative to the ^{144}Ce core is around $3.0\hbar \sim 3.5\hbar$. Such comparison indicates that the $3/2^+$ band in ^{145}Pr is possibly originated from the $\pi g_{7/2}$ orbital.

As discussed in the previous part, band (1) in ^{147}Pr is proposed to have a negative parity. The available orbital of negative parity in this region is $\pi h_{11/2}$. According to the PTRM calculations [19], the $1/2^- [550]$ band was proposed to be the low-lying negative-parity one. Note that the negative-parity band (1) in ^{149}Pr in the current work was also proposed to be $1/2^- [550]$ from previous QPRM calculation [6].

Band (2) in ^{149}Pr does not match any configurations in the previous QPRM calculations, which are mentioned here for completeness [6]. This band could form a $s = i$ octupole band with band (1) if they have the opposite parity. Note that octupole correlation is not included in the QPRM calculation in Ref. [6]. Our potential-energy-surface calculation in the present work (more details in Ref. [40–42]) shows medium octupole deformation ($\beta_3 = 0.068$) of $1/2^- [550]$ configuration [band (1)]. Although the previous QPRM calculations predicted this configuration do not have 100% amplitude (91% in Ref. [6], 77% and 81% in Ref. [30]), the octupole deformation may change the signature splitting of the $1/2^- [550]$ band (1) in ^{149}Pr . Furthermore, a small double backbending occurs in band (1) of ^{149}Pr at $\hbar\omega \sim 0.27$ MeV, while a little more distinct one occurs at about the same rotational frequency in band (2). As discussed in Ref. [4], cranked shell-model calculations [22] suggest that this backbending at 0.27 MeV originates from the alignment of a neutron $i_{13/2}$ pair and not a proton $h_{11/2}$ pair. Thus, band (2) in ^{149}Pr can also be another signature of band (1). If bands (1) and (2) in ^{149}Pr have the opposite parities, the average $B(E1)/B(E2)$ ratio would be around $0.05 \times 10^{-6} \text{ fm}^{-2}$. This value lies between the average $B(E1)/B(E2)$ ratios of the octupole bands in ^{148}Ce (0.82×10^{-6} [43]) and ^{150}Ce (0.04×10^{-6} [44]) and is smaller than that of the positive branch of octupole bands in ^{147}La (0.38×10^{-6}). These data suggest the importance of octupole correlations in ^{149}Pr as found in ^{148}Ce [39]. Note the predicted center of octupole deformation is that $Z = 56$, $N = 88$ [31], so ^{147}La with $Z = 57$ and $N = 90$ and ^{148}Ce with $Z = 58$ and $N = 90$ are close to the center and have the expected large $E1$ strength. Here ^{149}Pr with $Z = 59$ and $N = 90$ is more similar to ^{150}Ce with $Z = 58$, $N = 92$, so the $E1$ strength decreases as one moves farther away from the center of $Z = 56$ and $N = 88$.

Spin and parity assignments of the bands in ^{151}Pr and ^{153}Pr are not placed in the present work because the $E2$ transition energies in these bands are quite similar. According to the QPRM calculation in Ref. [8], $3/2^- [541]$, $1/2^+ [420]$ and $3/2^+ [422]$ are proposed to be the three low-lying states in $^{151,153}\text{Pr}$. If one assumes that the bands (1) and (2) in ^{151}Pr have the same configuration and parity, then only the theoretical prediction of the $3/2^+ [422]$ configuration in Ref. [8] can reproduce the signature splitting in bands (1) and (2). According to the statement in the previous part, the x keV level in ^{151}Pr could be the $3/2^-$ ground state. The $x + 182.5$ -keV level in band (1) in Fig. 20 would be $7/2^+$. Bands (3) and (4) in ^{151}Pr could be $1/2^+ [420]$ or $3/2^- [541]$, but $1/2^+ [420]$ is more likely, because no linking transitions are observed between bands (1,2) and (3,4) in the current work and bands (3) and (4) are more likely to decay to the 35.1 keV isomer. The y keV level could be the $1/2^+ [420]$ state. The configurations of bands in ^{153}Pr can be assigned according to the level scheme similarity to ^{151}Pr . However, such assignments cannot explain the absence of bands (2) and (4) in ^{153}Pr . Also, our potential-energy-surface calculation reported here shows octupole deformation ($\beta_3 = 0.043$) of the $1/2^+ [420]$ configuration. If bands (1) and (2) in ^{151}Pr have the opposite parity, they can form an octupole band. In the current work, band (1) is the strongest populated one. Thus, similar to

the discussion in Ref. [8], states in this band are possibly yrast and more likely to be the favored branch of the $3/2^-$ [541]. In all, similar to the discussion of ^{149}Pr , spins and parities of the bands in $^{151,153}\text{Pr}$ still cannot be firmly assigned.

Potential-energy-surface calculations show tendencies toward both octupole deformation and triaxiality. The octupole $Y_{3,0}$ deformation can give rise to parity doubling, and triaxiality can give so-called γ bands. Further theoretical and experimental work is needed.

V. CONCLUSION

In conclusion, new bands in $^{145,147-150}\text{Pr}$ have been reported; the previous questionable assignments of transitions and levels in $^{151,153}\text{Pr}$ were clarified by A - and Z -gated spectra and yield curves; a new high-spin level scheme for ^{152}Pr has been established and confirmed by mass- Z -gated spectra. Spins and parities of the levels in the new band in ^{149}Pr have been tentatively assigned. New transitions have been identified in $^{143-146}\text{Pr}$. More work on both experiment and theory is needed to understand the nuclear structure of $^{147-153}\text{Pr}$ well. The levels in $^{149,151}\text{Pr}$ are similar to octupole structures. The bands in $^{151,153}\text{Pr}$ are very similar in transition energies and $\Delta E2$, which indicates that they are relatively rigid rotors. The long multiple high-spin bands with increasing

neutron number in the Pr isotopes provide interesting tests for nuclear model calculations. The unique combination of (A, Z) identified in-beam γ rays and high-fold data from a Cf source has opened new vista to study the evolution of nuclear structure as functions of spin and isospin. Further improvements in the sensitivity for fission fragment spectroscopy are planned using the next-generation tracking detector AGATA combined with an improved VAMOS++ spectrometer at GANIL.

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