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Possible octupole correlation in ^{147}Pr and $\pi h_{11/2}$ bands in ^{149,151}Pr

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Neutron-rich ^{147,149,151}Pr nuclei, produced in the spontaneous fission of ^{252}Cf, were studied using the Gammasphere array. Possible parity doublets in ^{147}Pr with $N=88$ and $\pi h_{11/2}$ bands in ^{149,151}Pr are proposed. These new data on the level structures of odd Pr isotopes suggest that octupole correlations may also be present in the neutron-rich $^{147}_{59}\mathrm{Pr}_{88}$ nucleus such as those observed in $^{146}_{58}\mathrm{Ce}_{88}$, and also that the $h_{11/2}$ bands in the ^{149,151}Pr track in energy the yrast bands in ^{148,150}Ce. The backbending related to the breaking of the neutron $i_{13/2}$ pair is observed at $\hbar\omega\approx 0.27$ (MeV) for the proton $h_{11/2}$ band of ^{149}Pr.

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The neutron-rich nuclei with $N\approx 88$ and $Z\approx 56$ show strong octupole correlations. The reinforcement of the gaps predicted in the single particle orbitals at $\beta_3\approx 0.10$ to 0.16 for $Z=56$ and $N=88$ are responsible for this region of octupole correlations. Strong octupole correlations are observed in $^{142-146}$Ba($Z=56$) [1–3], ^{145,147}La($Z=57$) [4,5], and ^{144,146}Ce($Z=58$) [6–8] isotopes but not in Cs($Z=55$) [9]. Therefore, a search for the possible octupole correlations in Pr($Z=59$) may be useful for mapping out the systematics in this region. If octupole deformation is present, parity doublet bands should be observed. Since strong octupole correlations have been established in the ^{146}Ce nucleus, the ^{147}Pr nucleus with $N=88$ is a good candidate for observation of parity doublet bands. These two nuclei are very similar to the ^{144}Ba and ^{145}La nuclei with $N=88$, respectively, where clear octupole correlations are observed [2–6]. In the present work, we investigated the level scheme of ^{147}Pr to look for the similarities between ^{147}Pr and ^{145}La, where possible parity doublets were observed [4,5].

A ^{252}Cf source of strength 28μCi was sandwiched between two Ni foils of thickness 11.3 mg/cm^2 and then sandwiched between 13.7 mg/cm^2 thick Al foils and placed at the center of Gammasphere. This experiment was carried out with 72 Compton-suppressed Ge detectors. The data were recorded in an event-by-event mode. Three-dimensional histograms (cubes) of triple coincidence events (with the three γ-ray energies as axes) were then constructed and analyzed using the RADWARE software [10]. The width of the coincidence time window was about 1 μs, but narrower time gates could be implemented in software at the cube generation stage. Most of the data analysis presented below was performed on a cube with a 100 ns wide coincidence requirement. The experiment was carried out for a period of three weeks. During the second and third weeks, two of the Ge detectors were replaced with Si and XPGE detectors.

The new γ transitions in Pr were discovered by gating on the γ transitions in the partner Y fragments. The 58.5 keV transition (58.2, 58.0, and 57.7 keV in Refs. [11,12]) and 104.5 keV transition in ^{149}Pr [13] were identified from ^{149}Ce β decay. The 220.3 keV transition (220.0 keV in Ref. [11]) in ^{149}Pr was identified in the reaction ^{150}Nd(d,^{3}He)^{149}Pr. The transition of energy 103.2(5) keV which we observed may be the same as the 104.5(3) keV transition observed in β-decay studies [13]. The positions of the 104.5 keV and 220.3 keV transitions were not previously known in the level scheme of ^{149}Pr [11,13]. In the present work, the 58.5, 103.2, and 220.3 keV cascade are observed on the basis of the coincidence relation. Several new transitions are observed to be in coincidence with these transitions. The newly established level scheme of ^{149}Pr is shown in Fig. 1(a). The 96.0(5) keV transition in ^{151}Pr (96.8 keV in Ref. [14]) was discovered in studies of β decay of ^{151}Ce. Gating on this transition in ^{151}Pr and another transition in the partner Y isotope, one sees several new γ transitions belonging to ^{151}Pr as shown in Fig. 1(b).

In general, the binary spontaneous fission (SF) yield is maximized at the 3n or 4n channel. In the coincidence spectrum with the double gate on the 135.3 and 231.2 keV transitions in ^{151}Pr as shown in Fig. 2(a), the γ transitions in ^{99}Y (125.1 keV) with 2n emission and ^{98}Y (101.0 and 119.4

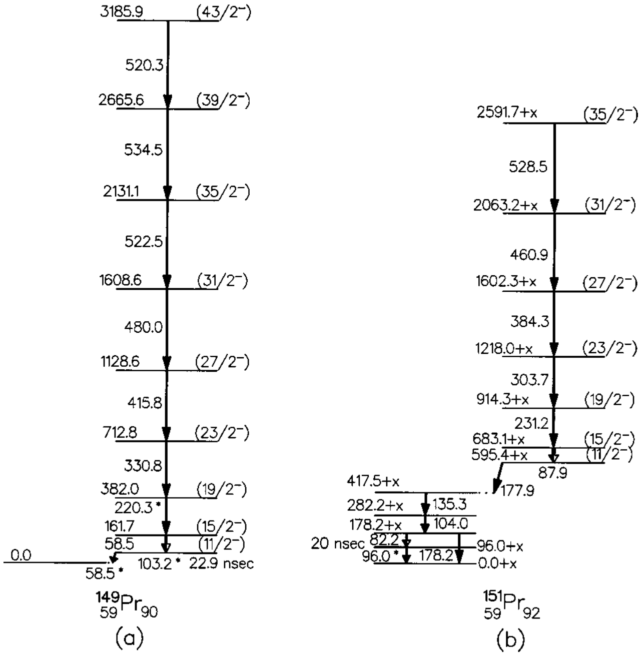

FIG. 1. Level schemes of (a) ^{149}Pr and (b) ^{151}Pr established in the present work. An asterisk represents previously known transitions.

keV) with $3n$ emission show up clearly but the γ transitions such as 163.4 keV in ^{101}Y with $0n$ emission are not seen as expected. The relative yield ratio of ^{98}Y (119.4 and 101.0 keV transitions) with $3n$, and ^{99}Y (125.1 keV transition) with $2n$, extracted from Fig. 2(a) is approximately 1. The yield for the $3n$ SF channel may be larger because some isomeric states are present in ^{98}Y. In the $4n$ ^{97}Y channel, the first excited state is an isomeric state with a half-life of 1.2 sec and the transition from the decay of the isomer is not observed in the present work. In the coincidence spectrum with the double gate on the 220.3 and 415.8 keV lines in ^{149}Pr [Fig. 2(b)], the transitions in ^{99}Y with $4n$ emission are the strongest and the 119.4 keV transition in ^{98}Y with $5n$ emission is weak because of ^{98}Y's isomeric states. The 101.0, 130.0, and 158.3 keV transitions in ^{98}Y are doublets with 103.0(^{149}Pr), 128.3(^{101}Y), and 158.6(^{99}Y) keV transitions as shown in Fig. 2(b). The relative yields for ^{98}Y (119.4 and 101.0 keV lines) with $5n$, ^{99}Y (125.1 keV line) with $4n$, ^{100}Y (95.5 keV line) with $3n$, and ^{101}Y (128.3 keV line) with $2n$ emission are 78.3, 329.0, 105.7, and 64.1, respectively. These yields, corrected for the detector efficiency and internal conversion, were extracted from the spectrum in Fig. 2(b). The yield of the ^{98}Y isotope may be larger because of some isomeric states. These yield distributions of the partner Y isotopes support the mass assignments of the observed bands to ^{149}Pr and ^{151}Pr.

The first excited state at 58 keV in ^{149}Pr was identified from β decay of ^{149}Ce. In our previous work [15], the band built on the 95.5 keV transition was, tentatively, assigned to ^{149}Pr due to the observation of a weak γ-ray peak at 58.2 keV in the coincidence spectrum double gated with 135.3 and 231.2 keV transitions as shown in Fig. 13 in Ref. [15]. But in the present work, we found clearly that the 58.2 keV transition is not related to the band built on the 95.5 keV transition as shown in Fig. 3. When a double gate is set on the 58.2 and 104.0 keV transitions, none of the γ transitions of the band built on the 95.5 keV transition as shown in Fig. 13 in Ref. [15] are observed in the coincidence spectrum but the band built on the 58.5 keV level in ^{149}Pr is seen. Therefore we can exclude the possible existence of the 58.2 keV level below the 95.5 keV transition. As shown in Fig. 2(a), in the coincidence spectrum with a double gate on the 135.3 and 231.2 keV transitions, the 128.3 and 163.4 keV transitions belonging to ^{101}Y are very weak (if present at all), as expected for a $0n$ ^{151}Pr channel. These transitions in ^{101}Y are too weak to be from the $2n$ partner of the previously assigned ^{149}Pr. Note the clear presence of these ^{101}Y transitions in the coincidence spectrum $(2b)$ gated on the γ transitions of the correctly assigned ^{149}Pr. Therefore the mass of the band in Fig. 1(b) is assigned as ^{151}Pr on the basis of the known transition of 96.0 keV in ^{151}Pr.

The new level scheme of ^{151}Pr is shown in Fig. 1(b). The order of γ transitions is determined by comparing the relative intensities of γ transitions in coincidence spectra. In the coincidence spectrum with the double gate on the 178 keV region, all the transitions except 96.0 and 82.2 keV in ^{151}Pr are observed. Also, when a double gate on the 178 keV peak and another transition in the band was set, we observed a transition at 178 keV. We conclude that the 178 keV transition is a doublet. We assigned a 178.2 keV transition as a cross over transition as shown in Fig. 1(b). The 87.9 keV transition is observed as shown in the coincidence spectrum gated on the 135.3 and 231.2 keV transitions in Fig. 2(a). The position of the 87.9 keV transition in the level scheme is not clear because of the low detection efficiency $[\varepsilon(87.9\ \mathrm{keV})/\varepsilon(150\ \mathrm{keV})\approx 0.2]$ and large conversion co-

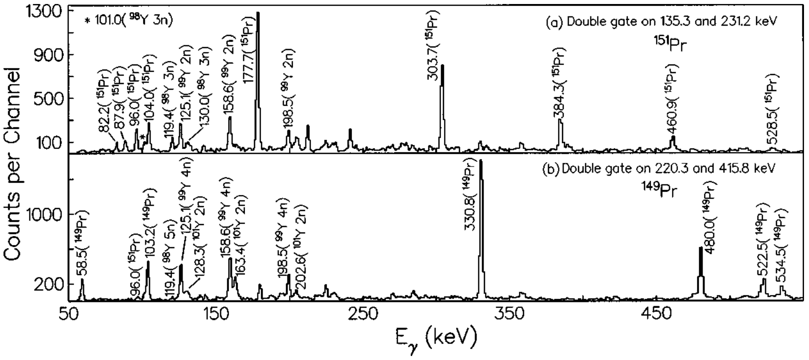

FIG. 2. Partial coincidence spectra double gated on (a) 135.3 and 231.2 keV transitions in ^{151}Pr and (b) 220.3 and 415.8 keV transitions in ^{149}Pr.

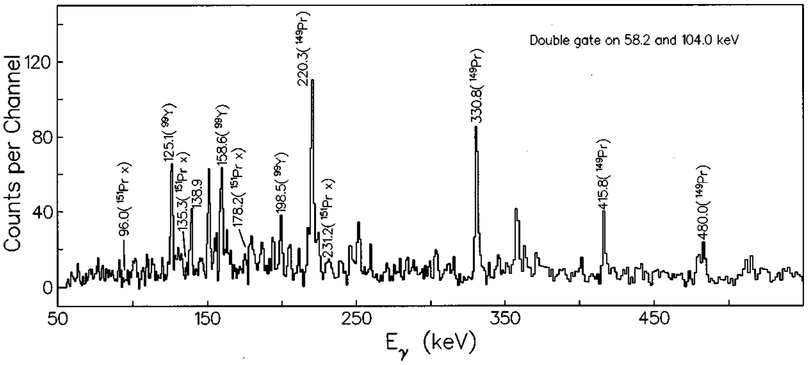

FIG. 3. Partial coincidence spectrum double gated on 58.2 and 104 keV transitions.

efficient $[\alpha(E2)=3.41]$ which causes the large uncertainty in calculating the peak intensity. However, in the coincidence spectra with the double gates on 135.3–231.2 keV transitions, 135.3–303.7 keV transitions, 177.9–231.2 keV transitions, and 177.9–303.7 keV transitions, the 87.9 keV peak is relatively enhanced when compared to other coincidence spectra with other double gates. One of them is shown in Fig. 2(a). Therefore, the 87.9 keV transition is, tentatively, placed as connecting the 231.2 and 177.9 keV transitions in the level scheme of ^{151}Pr. In the coincidence spectrum with the double gate on 96.0 (^{151}Pr) and 125.1 keV (^{99}Y) transitions, the order of the 104.0 and 135.3 keV transitions can be clearly determined because the intensity ratio, $I(104.0)/I(135.3)$, is 2.63 for $M1$ or 2.08 for $E1$.

Two bands discovered in ^{149,151}Pr resemble the ground state rotational bands in ^{148,150}Ce as seen in the comparison of the transition energies in Fig. 4. A proton $h_{11/2}$ decoupled band was discovered in ^{147}La with $N=90$ [4,5]. Therefore the bands observed in ^{149,151}Pr can be understood as originating from the excitation or decoupling of the proton $h_{11/2}$ orbital from the core nuclei of ^{148,150}Ce. The proton $h_{11/2}$ band in ^{149}Pr shows back bending at $\hbar\omega\approx0.27$ MeV. A similar back bending in the proton $h_{11/2}$ band in ^{147}La was observed at $\hbar\omega\approx0.27$ MeV [4,5]. The cranked shell model calculations of Ref. [4] suggest that this backbending at $\hbar\omega\approx0.27$ MeV originates from alignment of the neutron $i_{13/2}$ pair, but not from the alignment of the proton $h_{11/2}$ pair which occurs at the higher rotational frequency of $\hbar\omega\approx0.40$ MeV [5].

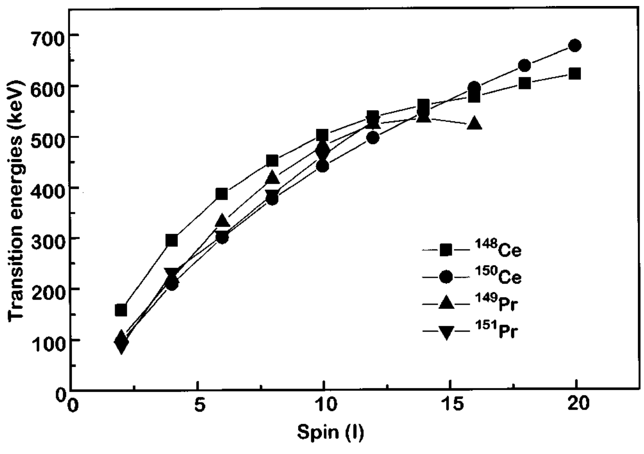

FIG. 4. Comparison of the $E2$ transition energies between the $h_{11/2}$ bands of ^{149,151}Pr and the ground rotational bands in ^{148,150}Ce.

The level scheme of ^{147}Pr as discovered in this work is shown in Fig. 5. All the levels in ^{147}Pr were identified by assigning the transitions between the lowest levels of the rotational bands on the basis of their yields relative to the partner Y isotopes as shown in Figs. 6 and 7. In Fig. 6, two coincidence spectra double gated on the 125.1 and 158.6 keV transitions in ^{99}Y, and 128.3 and 163.4 keV transitions in ^{101}Y, respectively, are shown. The 82.3, 100.3, and 153.9 keV transitions, shown in Figs. 6(a) and 6(b), are assigned to ^{147}Pr. This conclusion came from the comparison of these lines to 58.5, 103.2 (^{149}Pr), 96.0, and 135.3 (^{151}Pr) keV transitions in the coincidence spectra with double gates on the γ transitions in ^{99,101}Y. In Fig. 6(a), the $4n$ channel (58.6, 104 keV, etc., of ^{149}Pr) has the strongest yield. Since the yield functions are of Gaussian shape centered around $3.5n$ [7], one expects that the $2n$ and $1n$ channel yields are comparable to the $5n$ and $6n$ channel yields, respectively [7]. The intensity of the 100.3 keV transition in Fig. 6(a) is too small to belong to a $5n$ channel (^{148}Pr) when compared with the intensity of the 95.5 keV peak (^{151}Pr,$2n$). It could still belong to ^{148}Pr since in odd-odd nuclei, individual cascades are usually weaker than in odd-A nuclei. If this is true, the 100.3 keV transition has to be weak in both of Figs. 6(a)

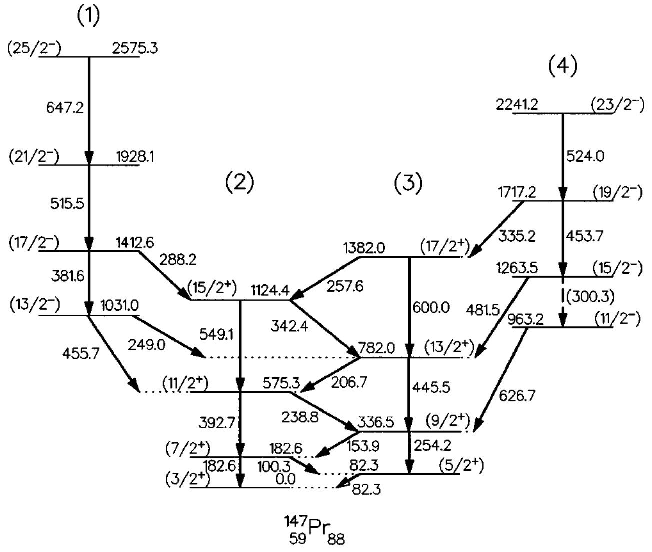

FIG. 5. Level scheme of ^{147}Pr. All the transitions are new.

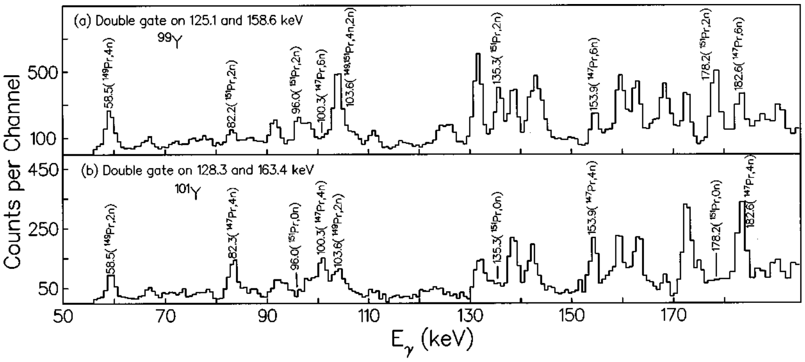

FIG. 6. Partial coincidence spectra double-gated on (a) 125.1 and 158.6 keV transitions in ^{99}Y and (b) 128.3 and 163.4 keV transitions in ^{101}Y.

and 6(b). But the 82.3 and 100.3 keV transitions are relatively strong as shown in Fig. 6(b), relative to the 103.2 keV transition in ^{149}Pr. Also, in Fig. 6(a), the 153.9 and 182.9 keV transition intensities are smaller than the 135.3 and 177.7 keV transition intensities in the $2n$ channel (^{151}Pr). The 82.2 keV transition is a doublet of energies 82.3(^{147}Pr) and 82.2(^{151}Pr) keV. Most of the intensity in this doublet is from ^{151}Pr in Fig. 6(a) and from ^{147}Pr in Fig. 6(b). From the above information of the yield variations, the observed rotational bands are assigned to ^{147}Pr with $N=88$. The very close similarity of the observed bands to those in ^{145}La with $N=88$ supports the assignment of these bands to ^{147}Pr. A similar rotational band was not observed in ^{146}La with $N=89$ [15]. The coincidence spectrum with double gates set on the 100.3 and 82.3 keV transitions in ^{147}Pr is shown in Fig. 7 in order to identify several more transitions.

The strongly coupled ground rotational band in ^{145}La has a configuration of 5/2[313] based on the $1g_{7/2}$ proton orbital. However, the ground state in ^{147}Pr has spin and parity of $3/2^+$ [10] assigned on the basis of the β decay and the 3/2[411] orbital of the $2d_{5/2}$ proton is near the Fermi surface of ^{147}Pr. Therefore the 3/2[411] configuration is assigned to the discovered rotational band in ^{147}Pr. The spins and parities of the bands 1 and 4 in ^{147}Pr are tentatively assigned on the basis of the similarity to the negative parity bands in ^{145}La. The negative parity bands 1 and 4 in Fig. 4 do not have any linking transition between them. The $B(E1)/B(E2)$ ratio of $0.33\times10^{-6}\text{fm}^{-2}$ for the 288.2($E1$) and 381.6($E2$) keV transitions is extracted from the coincidence spectrum gated on the 515.6 and 647.2 keV transitions in ^{147}Pr. Also, the $B(E1)/B(E2)$ ratio of $0.60\times10^{-6}\text{fm}^{-2}$ for 335.2($E1$) and 453.7($E2$) keV transitions is extracted from the coincidence spectrum gated on the 445.5 and 153.9 keV transitions in ^{147}Pr because the 257.6 keV transition is much weaker than the 600.0 keV transition. The $B(E1)/B(E2)$ ratios for ^{146}Ce are 0.70 $\times10^{-6}\,\text{fm}^{-2}$ [379.5($E1$)$-$367.9($E2$) keV transitions], $2.09\times10^{-6}\,\text{fm}^{-2}$ [185.5($E1$)$-$565.2($E2$) keV transitions], $0.87\times10^{-6}\,\text{fm}^{-2}$ [282.6($E1$)$-$468.1($E2$) keV transitions], and $0.78\times10^{-6}\,\text{fm}^{-2}$ [332.5($E1$)$-$614.5($E2$) keV transitions]. The $B(E1)/B(E2)$ ratios in ^{147}Pr are smaller than those in ^{146}Ce but still show definite enhancement of the $E1$ transitions.

The parity doublets are not seen in ^{147}Ce with $N=89$ [16] whereas one observes them in ^{146}Ce. This indicates that the addition of an odd neutron blocks the octupole correlations in ^{147}Ce but the addition of a proton does not change the degree of octupole correlation in ^{147}Pr. The level scheme of ^{147}Pr with $N=88$ is very similar to that observed in ^{145}La with $N=88$ where octupole correlations are observed [4,5]. Therefore, the existence of the parity doublets in ^{147}Pr can be expected since its core nucleus, ^{146}Ce, shows octupole correlations. However, parity doublets are not observed in ^{149,151}Pr. This is expected, because the core nuclei, ^{148,150}Ce, of ^{149,151}Pr do not show octupole correlations. Instead, in ^{149,151}Pr, $h_{11/2}$ decoupled bands are observed. The ^{147}La nucleus with $N=90$ exhibits the parity doublets in the high spin region similar to the weak octupole correlations in ^{146}Ba. However, octupole correlation strength in ^{147}La is weakened by the decoupling of the $h_{11/2}$ proton from the core nucleus ^{146}Ba [5]. The level structures of ^{147,149,151}Pr isotopes suggest that the presence of parity doublets in ^{147}Pr as well as the absence of parity doublets and the presence of the $h_{11/2}$ bands in ^{149,151}Pr resemble the similar effects observed in their ^{146}Ce and ^{148,150}Ce core isotopes. The back bending observed at $\hbar\omega\approx0.27$ MeV for the proton $h_{11/2}$ band of

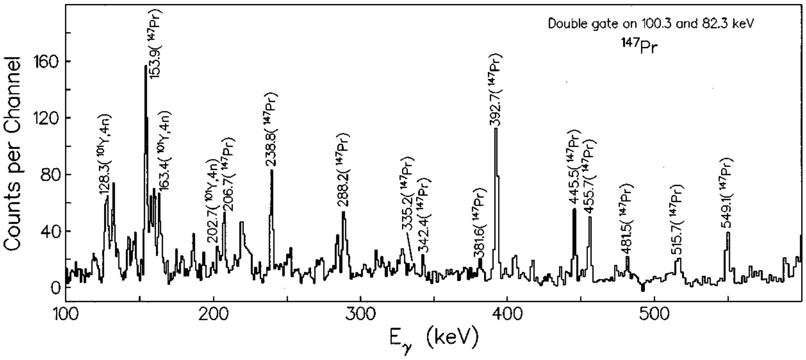

FIG. 7. Partial coincidence spectrum double-gated on 100.3 and 82.3 keV transitions in ^{147}Pr.

^{149}Pr is interpreted as the breaking of the neutron $i_{13/2}$ pair.

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