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First identification of high-spin states in the odd-odd neutron-rich nucleus ^{152}Pr

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The odd-odd neutron-rich nucleus ^{152}Pr has been studied from the spontaneous fission of ^{252}Cf with Gammasphere. A high-spin level scheme of ^{152}Pr has been established for the first time. Angular correlation and internal conversion coefficient measurements are used to determine the transition multipolaries. The possible configurations of the band head have been discussed based on systematics and Total Routhian Surface calculations.

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Neutron-rich lanthanide nuclei with $A \approx 150$ are in a transitional region where a change from spherical to prolate shapes occurs. They are also close to the octupole deformation region centered on $Z = 58$, $N = 88$ [1]. Recently, high-spin states in ^{151,153}Pr have been identified where octupole correlations were also observed [2]. In the same paper, the previous level scheme of ^{151}Pr in Ref. [3] was re-assigned to ^{150}Pr. Based on the result in Ref. [3], Rzączca-Urban *et al.* re-investigated the high-spin structure of ^{149}Pr by using two fission sources, ^{248}Cm and ^{252}Cf, finding a small electric dipole moment in ^{149}Pr [4] which can be caused by octupole deformations. Three $N = 93$ isotones, ^{151}Ce, ^{153}Nd, and ^{155}Sm, have been extensively studied by measuring delayed gamma-rays and conversion electrons from the thermal-neutron induced fission of ^{239}Pu and prompt and delayed gamma-rays from the spontaneous fission of ^{252}Cf [5]. The authors have performed quasiparticle-rotor-model (QPRM) calculations with a reflection-symmetric core and reproduced the level structures of these three isotones very well. Their results indicate that these three $N = 93$ isotones do not have octupole-deformed cores so that their dipole moments and hence their $E1$ transition strengths stem from the polarizing effect of the unpaired neutron. Therefore, it is of great interest to extend the nuclear structure to ^{152}Pr, an odd-odd, $N = 93$ isotone.

Previously, fourteen low-lying excited levels in ^{152}Pr were identified in the beta-decay of ^{152}Ce [6] where an isomer at 114.8(2) keV was found with a half-life of 4.1(1) μs. The configurations of the ground state of ^{152}Pr were discussed in the reports of the beta-decay of ^{152}Pr to ^{152}Nd [7–10] with different assignments. However, no high-spin level has been observed in ^{152}Pr before the present work. Here, we report a high-spin level scheme of ^{152}Pr.

The present data were collected by measuring prompt gamma-rays emitted from a ^{252}Cf spontaneous fission source of 62 μCi α activity with the Gammasphere detector array at the Lawrence Berkeley National Laboratory. A total of 5.7×10^{11} triple- and higher-fold γ-ray coincidence events were obtained, and these data were analyzed with the RadWare software package [11]. Taking advantage of this high statistics data set and a newly developed program [12] for angular correlation analysis, we are able to assign spins to some levels in this high-spin level scheme of ^{152}Pr.

To find the transitions belonging to ^{152}Pr, we double-gated on transitions in its fission partners, yttrium isotopes. Figure 1 shows a spectrum gated on the 989.9- and 911.4-keV transitions in ^{97}Y [13] which is the strongest fission partner of ^{152}Pr. In Fig. 1, three new transitions of energies 142.3, 221.9, and 296.4 keV are seen along with the known transitions in ^{97}Y and ^{150,151,153}Pr [2, 3]. One more important feature is the presence of the 36.0- and 41.1-keV peaks which are the combination of $K_{\alpha 1}$ (36.026 keV) and $K_{\alpha 2}$ (35.550 keV) x rays and the combination of $K_{\beta 1}$ (40.748 keV), $K_{\beta 2}$ (41.764 keV), and $K_{\beta 3}$ (40.653 keV) x rays of Pr [14], respectively. Thus, these 142.3-, 221.9-, and 296.4-keV transitions should belong to one or more Pr isotopes. Figure 2 (a) shows the coincidence spectrum gated on the new 142.3- and 221.9-keV transitions, where newly observed transitions are indicated with an asterisk. Figure 2 (b) shows the coincidence spectrum gated on the new 142.3- and 291.9-keV transitions which supports the proposal that the new 291.9-, 358.4-, 420.8-, 479.1-, 534.6-keV transitions compose another band in this new Pr isotope. In both spectra, the 36.0- and 41.1-keV Pr x-rays and the strong transitions in $^{96-99}$Y are observed. A new level scheme of a single Pr isotope has been established as a result of the present work as shown in Fig. 3.

To assign the mass number to the Pr isotope, we calculated the ratios, $R\big(119.4(^{98}\mathrm{Y})/122.3(^{96}\mathrm{Y})\big)$, of the transition intensities in ^{96}Y and ^{98}Y obtained by double-gating on transitions in ^{150,151,153}Pr and also on the new transitions. We also computed the ratios

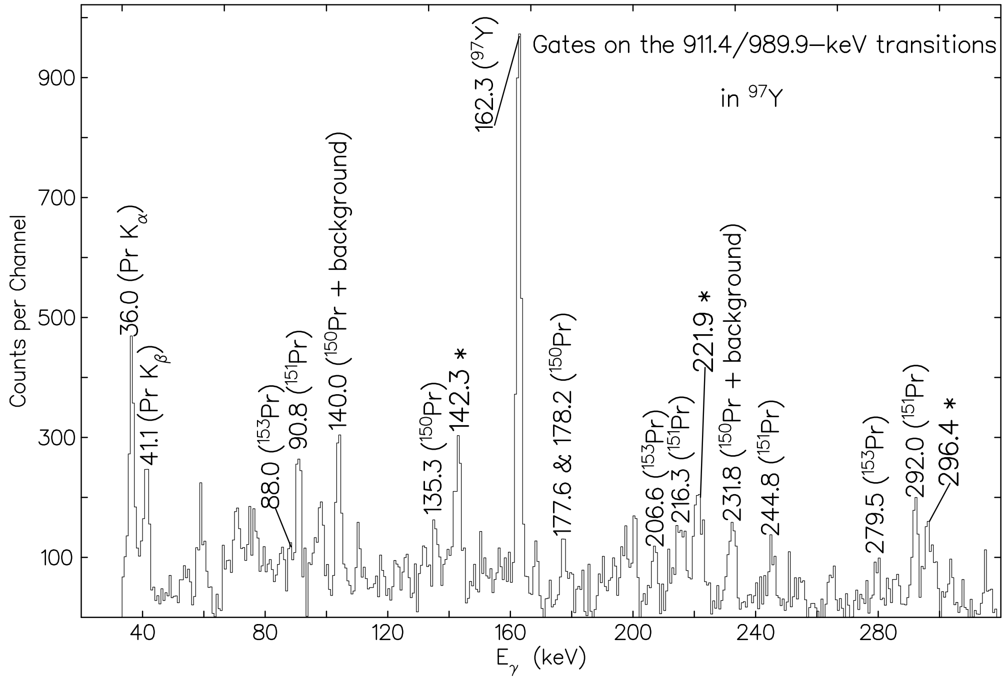

FIG. 1: Coincidence spectrum gated on the 989.9- and 911.4-keV transitions in ^{97}Y. Three new transitions of energies 142.3, 221.9, and 296.4 keV are marked with an asterisk.

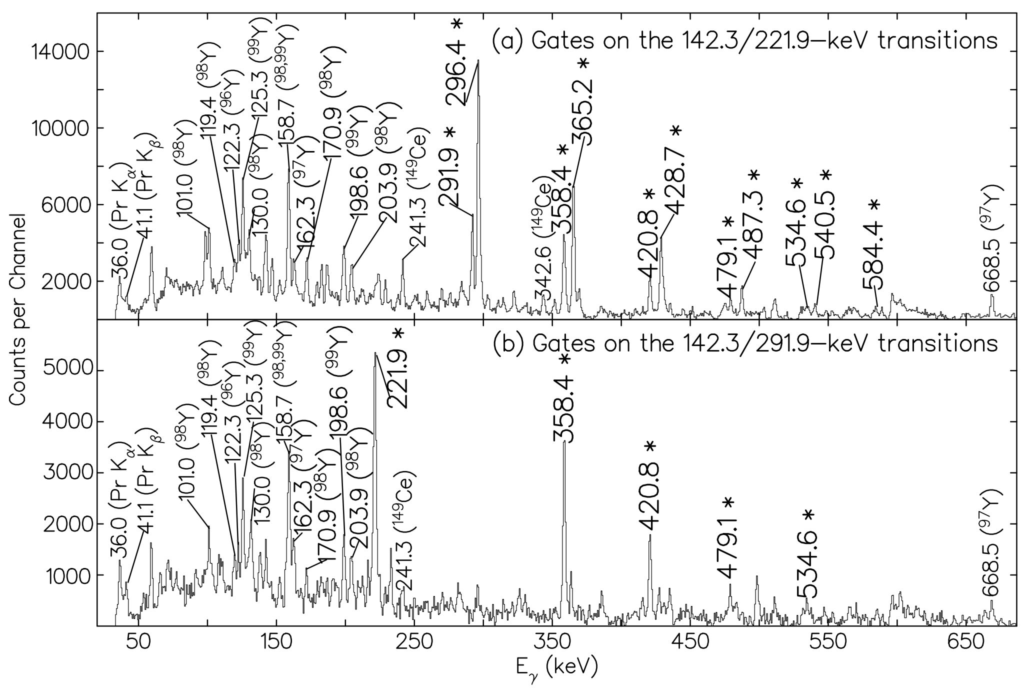

FIG. 2: Coincidence spectra gated on the new 142.3- and 221.9-keV transitions, and the 142.3- and 291.9-keV transitions. All new transitions are marked with an asterisk. Some labeled peaks are contaminants present in the spectrum because of the overlap in the energy of the gate with specific transitions in other nuclei, like the 142.2-keV transition in ^{149}Ce [15].

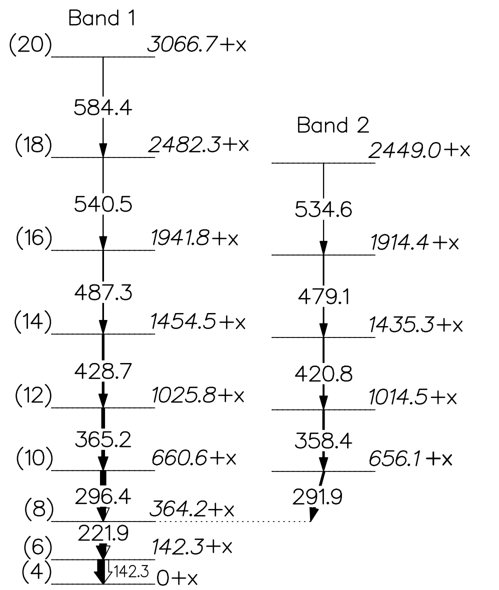

FIG. 3: Partial high-spin level scheme of ^{152}Pr established in the present work. Energies are in keV. The relative width of the arrow is proportional to the corresponding relative γ-ray intensity. Intensity uncertainties range between about 5% for the strong transitions and 20% for the weak transitions. Uncertainties of transition energies are about 0.3 keV. The band-head energy is labeled as 0+x because we cannot determine whether the present level scheme is built on the ground state or an isomer. The spin assignments are tentative and we cannot determine the parity in this work (see text for more details).

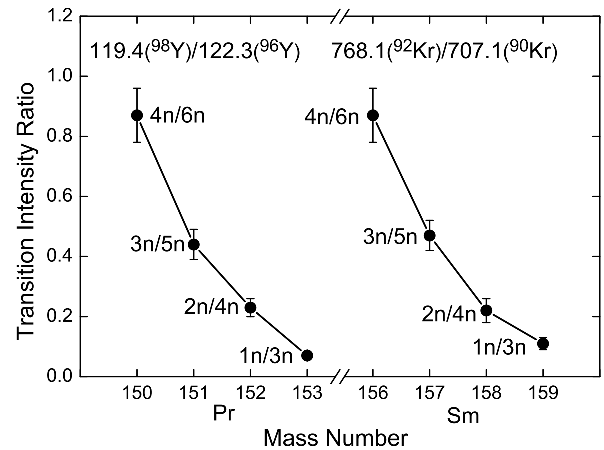

FIG. 4: Transition intensity ratios $R\big(119.4(^{98}\mathrm{Y})/122.3(^{96}\mathrm{Y})\big)$ in different Pr gates and $R\big(768.1(^{92}\mathrm{Kr})/707.1(^{90}\mathrm{Kr})\big)$ in $^{156-159}$Sm gates. The $R(4n/6n)$ value for ^{150}Pr is normalized to the corresponding $R(4n/6n)$ value for ^{156}Sm for the sake of comparison. xn corresponds to the x neutron channel. Data are taken from the present work for ^{152}Pr and Ref. [2] for others.

,$R\big(768.1(^{92}\mathrm{Kr})/707.1(^{90}\mathrm{Kr})\big)$, obtained by double-gating on the known transitions in $^{156-159}$Sm. These two sets of ratios are shown in Fig. 4. For comparison, the R values of ^{96,98}Y are normalized to the $R(768.1/707.1)$ value in ^{156}Sm. Based on the similar behavior of these two curves and the known level schemes of ^{150,151,153}Pr, we conclude that the new transitions belong to ^{152}Pr. A high-spin level scheme of ^{152}Pr has been established for the first time.

Angular correlations for a few cascades in band 1 (the yrast band) in Fig. 3 were measured by using the technique described in Ref. [12]. The measured coefficients, A_2^{exp} and A_4^{exp}, are summarized in Table I. By comparing these coefficients with the theoretical A_2 and A_4 values for a pure quadrupole $\rightarrow$ quadrupole cascade [16], we propose that all the transitions involved in these angular correlation measurements have an $E2(\Delta I = 2)$ character, based on the fact that $M2$ transitions are not observed in general in the spontaneous fission of ^{252}Cf. The total internal conversion coefficient (α_{T}) of the 142.3-keV transition was measured to be 0.78(9). Comparison with the theoretical values for an $E1$, $M1$, or $E2$ transition [17], respectively, shows that the 142.3-keV is of pure $E2$ character. If the spin-parity of the level (labeled as 0+x keV in Fig. 3) fed by the 142.3-keV transition is known, then we will be able to assign the spins and parities to the levels in band 1 by assuming that the other higher levels are depopulated by $E2$ transitions.

We are also interested in the electromagnetic properties of the 291.9-keV transition that links bands 1 and 2, because band 2 may be a good candidate to form a set of parity doublet bands with band 1. The measured A_2 values for the cascades including the 291.9-keV transition have large errors. The values are positive even if you take into account their large uncertainties. Therefore, the multipolarity of this transition cannot be $E1$ because $A_2^{\mathrm{th}} = -0.071$ for an $E1 \rightarrow E2$ cascade (here, we assume that all other involved transitions have an $E2$ character). We are even unable to determine whether this transition is a pure $E2$ or $M1/E2$ type from A_4^{exp} because of the larger uncertainties in A_4^{exp}. The likely multipolarity of the 291.9-keV transition is purely $E2$ or $M1/E2$ based on the measured A_2 alone and high-spin features of these involved levels. Thus, the levels in band 2 are proposed to have the same parity as those in band 1, if one assumes that the higher cascade transitions in band 2 are of $E2$ character.

One notices no overlap between these new transitions in ^{152}Pr identified here and those seen in the beta-decay of ^{152}Ce [6]. This is reasonable because levels in ^{152}Pr populated in the beta-decay of the even-even ^{152}Ce nucleus cannot have spins larger than three when the ground sate spin of ^{152}Pr is either 3 or 4 [7–10]. The levels observed in the spontaneous fission of ^{252}Cf have usually high spins. However, it is impossible for us to know

TABLE I: Angular correlation coefficients A_2 and A_4 measured in the present work. The theoretical A_2 and A_4 values for a pure quadrupole → quadrupole cascade are included.

Cascade (keV)	$A_2^{\rm exp}$, $A_4^{\rm exp}$	$A_2^{\rm th}$, $A_4^{\rm th}$
428.7 → 365.2	0.17(4), 0.01(6)	0.10, 0.0
365.2 → 296.4	0.16(4), 0.04(6)	0.10, 0.0
365.2 → 221.9	0.17(5), 0.01(7)	0.10, 0.0
296.4 → 221.9	0.10(2), 0.03(4)	0.10, 0.0

whether the 142.3-keV transition decays to the ground state of ^{152}Pr or an isomer from the present experimental results. An isomeric state of half life 4.1(1) μs at 114.8(2) keV was observed previously [6]. Unfortunately, its half life is beyond our time window which is $\sim$1 μs. Therefore, we propose tentatively that the yrast band with a $\Delta I = 2$, $E2$ cascade is built on the 0+x-keV level. Moreover, the collective feature of this cascade is emphasized by its very regularly increasing transition energies with spins.

The level scheme of ^{152}Pr in Fig. 3 shows typical features of a rotational band. Mantica *et al.*[18] showed that the quadrupole deformation, β_2, increases gradually from about 0.12 in ^{145}Pr to 0.20 in ^{149}Pr. ^{152}Nd, a neighboring even-even core, is strongly deformed with $\beta_2 \approx 0.32$ [19]. So a relatively large $\beta_2 \geq 0.2$ is expected in ^{152}Pr. Calculations based on the cranked shell model have been performed here for ^{152}Pr. Collective rotation was investigated by means of Total Routhian Surface (TRS) calculations in a three-dimensional deformation space of β_2, γ, and β_4 (for more details, see Refs. [20]). The present calculations give a nearly constant β_2 of 0.25 and $\gamma \approx 0°$ up to $\hbar\omega = 0.50$ MeV.

Two-quasi-particle coupling in an odd-odd nucleus is established from the single-particle orbitals observed experimentally of the neighboring odd-mass isotopes (for protons) and isotones (for neutrons). An extensive examination of two-quasi-particle coupling configurations for the ground and isomeric states in ^{154}Pm ($Z = 61$), an $N = 93$ isotone, was performed in Ref. [22]. Based on their method, an attempt is made here to assign a two-quasi-particle configuration and thus spin-parity to the 0+x-keV level of the level scheme shown in Fig. 3.

The single particle orbital for the 59th proton in ^{152}Pr near the Fermi surface at a deformation of $\beta_2 \approx 0.25$ seems to be $\pi 3/2^-[541]$. Note that the authors in Refs. [9, 10] proposed the proton in ^{152}Pr to occupy the $5/2^-[532]$ Nilsson orbital, whose corresponding state is yet to be observed experimentally, based on their assumption of the spin-flip transition. TRS calculations also support the $\pi 3/2^-[541]$ assignment, instead of $5/2^-[532]$ which is predicted to be located about 850 keV higher than the $\pi 3/2^-[541]$ orbital. In our recent report on high-spin states in ^{151,153}Pr [2], their high-spin level schemes were proposed to be built on a $3/2^-$ state ($\pi 3/2^-[541]$), consistent with the spin-parity assignment for the ground state of ^{151}Pr in Ref. [23] from the beta-decay of ^{151}Ce

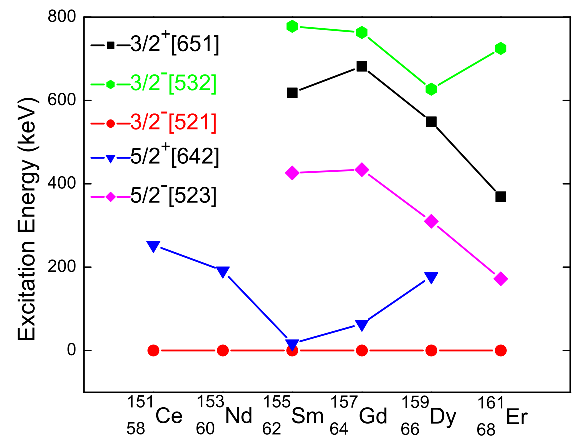

FIG. 5: (Color online) Locations of low-lying, low-energy quasi-neutron states in odd-A, $N = 93$ isotones in the $A \approx 150$ mass region. Data are taken from Refs. [5, 21].

where a possible isomeric state at 35.1 keV was found with a tentative $I = 7/2^+$.

The available single neutron orbitals for the 93rd neutron in ^{152}Pr are $3/2^+[651]$, $5/2^+[642]$, and $3/2^-[521]$ at $\beta_2 \approx 0.25$. Figure 5 presents the observed quasi-neutron states of $E < 800$ keV in odd-A, $N = 93$ isotones in this mass region. One finds that the ground states of the $N = 93$ isotones from $Z = 58$ to 68 are in the $3/2^-[521]$ Nilsson orbital, and this assignment is consistent with our TRS calculations where $3/2^+[651]$ is predicted to be the lowest for positive-parity orbitals. The $5/2^+[642]$ orbital is the second lowest orbital known experimentally so far for ^{151}Ce ($Z = 58$) and ^{153}Nd ($Z = 60$), and is predicted to be located about only 130 keV above the $3/2^+[651]$ orbital. High-spin states in both ^{151}Ce ($Z = 58$) and ^{153}Nd ($Z = 60$) have been observed to be built on the $3/2^-$ ($3/2^-[521]$) and $5/2^+$ ($5/2^+[642]$) states, respectively [5]. Therefore, it is very reasonable for the present high-spin level scheme of ^{152}Pr to be built on a state whose configuration is either $\pi 3/2^-[541] \otimes \nu 3/2^-[521]$ or $\pi 3/2^-[541] \otimes \nu 5/2^+[642]$. Based on the Gallagher-Moszkowski coupling rules [24], these two configurations give $K^\pi = 3^+$ and $K^\pi = 4^-$ to the band head.

Note that high-spin states in the favored signature sequence are easier to populate in an odd-odd nucleus. The formula, $\alpha_{\rm f} = \frac{1}{2}\left[(-1)^{j_\pi - 1/2} + (-1)^{j_\nu - 1/2}\right]$, for an odd-odd nucleus [25], gives $\alpha_{\rm f} = 0$ (even-integer spins) to both the above configurations, $\pi h_{11/2} \otimes \nu i_{9/2}$ and $\pi h_{11/2} \otimes \nu i_{13/2}$. Therefore, it is most likely for the band head to have $I = 4$, no matter what configuration it has, based on the present scenario. At present, however, its parity cannot be uniquely assigned.

In conclusion, a high-spin level scheme of ^{152}Pr has been established for the first time by studying the gamma-rays from the spontaneous fission of ^{252}Cf with the Gammasphere detector array. Angular correlation and internal conversion coefficient measurements have been used to assign $E2$ to transitions in the yrast band (band 1). No evidence for octupole correlations has been found in ^{152}Pr. Systematics and TRS calculations support the assignment of the $\pi 3/2^-[541]$ orbital to the 59th proton in ^{152}Pr, instead of the $\pi 5/2^-[532]$ orbital in the previous reports. We propose the present level scheme to be built on an $I = 4$ level without a definitely known parity and excitation energy. More work in both experiment and theory is necessary to understand the nuclear structure of ^{152}Pr well.

Acknowledgments

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