Near-yrast structure of ^{149}Pr

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The neutron-rich nucleus ^{149}Pr has been studied by means of prompt and delayed γ-ray spectroscopy using the EUROGAM2 and Gammasphere arrays of Ge detectors. New spins have been assigned to a previously reported band and it is interpreted as having a $h_{11/2}$ proton structure, from a comparison with quasiparticle-rotor model calculations. The strength of octupole correlations in odd-Z nuclei of the region is discussed.

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The $h_{11/2}$ proton orbital plays an important role in generating octupole correlations in the region of the neutron-rich lanthanide nuclei. Previous studies in the region have shown a decrease in octupole correlations in the neutron-rich cesium isotopes, when compared to their even-Z, Ba and Xe neighbors [1–3]. We have proposed [4] that the decrease in the ^{141,143,145}Cs isotopes may be due to blocking of the contribution of the $\pi(h_{11/2}, d_{5/2})_{3^-}$ coupling to octupole correlations in this region, a hypothesis that needs further investigation.

The strength of the $\pi(h_{11/2}, d_{5/2})_{3^-}$ coupling depends on the population of both $\Delta j = \Delta l = 3$ orbitals and on their relative positions. An experimental determination of these two parameters in odd-Z lanthanides should help with a better theoretical understanding of octupole correlations and the underlying single-particle structure of odd-Z nuclei in the region and, eventually, the origin of the apparent lowering of octupole correlations in the Cs nuclei. It is of interest to also study the strength of $E1$ transitions, especially at neutron numbers with $N > 88$, where strong quadrupole deformation appears. The odd-Z nucleus $^{149}_{59}$Pr, which has 90 neutrons, is a good candidate for such studies, extending our investigations of odd-Z, $N = 90$ isotones [4,5] to higher proton numbers.

Excited levels of ^{149}Pr have been previously studied by γ-ray spectroscopy, following the β decay of the ground state of ^{149}Ce [6,7] and the spontaneous fission of ^{252}Cf [8–11], and in the ^{150}Nd(d,^{3}He)^{149}Pr transfer reaction [12]. In β-decay works a level at 57.7(3) keV has been reported. Because the likely spin of the ground state of ^{149}Ce is $(3/2^-)$ [13], the spin of the 57.7-keV level in ^{149}Pr should not be higher than 7/2. The $T_{1/2} = 22.9(18)$-ns isomer, reported in Ref. [8] at 58.5(3) keV, is likely to be the same level as the 57.7-keV level seen in β-decay studies [6,7].

In Ref. [9] a cascade of γ rays feeding the 58-keV level was found and assigned to ^{149}Pr. Later however, this same cascade was reassigned to ^{151}Pr [10,11], and a new cascade was proposed on top of the 58-keV level in ^{149}Pr [10,11], with a bandhead spin of $(11/2^-)$. This spin assignment disagrees with results from the β-decay studies just mentioned. Such a high spin would be consistent with transfer-reaction data [12] reporting L(d,^{3}He) = 4 for the ground state of ^{149}Pr and therefore suggesting a spin $7/2^+$ or $9/2^+$ for the ground state. On the other hand, in a recent evaluation of ^{149}Pr [13], a ground-state spin and parity of $(5/2^+)$ are suggested, based on shell-model predictions. The $(5/2^+)$ assignment for the ground state would exclude a spin and parity of $11/2^-$ for the 58-keV level, from half-life arguments.

Another argument against the $11/2^-$ spin for the 58-keV level is given by the systematics of the difference, ΔE_{h-d}, of excitation energies of the $11/2^-$ and $5/2^+$ levels with $\pi h_{11/2}$ and $\pi d_{5/2}$ parentages, respectively, which is shown in Fig. 1 for the odd-Z lanthanides. ΔE_{h-d} is a rather regular function of the neutron number for the Eu, Pm, and La isotopes. For the Pr isotopes ΔE_{h-d} is known at $N = 82$ and 88. The data for ^{147}Pr have been taken from Ref. [18] because the excitation scheme of ^{147}Pr reported in [10] has since been assigned to ^{144}La [29]. By using these two data points, and extrapolating to $N = 90$, a value of $\Delta E_{h-d} \approx 200$ keV is obtained for ^{149}Pr, significantly higher than the 58 keV suggested in [10,11].

To clarify the uncertainties in the level scheme of ^{149}Pr and to determine the energy difference between the $11/2^-$ and $5/2^+$ levels, we have reinvestigated this nucleus using another fission source. In this work we report on a measurement of γ rays from spontaneous fission of ^{248}Cm, performed using the EUROGAM2 array of anti-Compton spectrometers [30], equipped with four additional low-energy photon spectrometers (LEPS) [31]. We have also used high-fold coincidence γ-ray data from a measurement of the spontaneous fission of a ^{252}Cf source using the Gammasphere array. More details on this experiment can be found in [32].

In Fig. 2 a γ-ray spectrum double-gated on the 219.7- and 416.0-keV lines of a three-dimensional histogram is shown, which was sorted from triple γ-ray events in the ^{248}Cm fission data set. In the spectrum all the lines previously assigned to ^{149}Pr in [10] from the fission of ^{252}Cf are present. We note that energies of the low-energy transitions reported in Ref. [10] are about 0.3 keV higher than those seen in our work. In Fig. 2 there is a 300.0-keV line from the complementary ^{96}Rb [33] isotope, expected to be the most abundant fission-fragment partner to ^{149}Pr in fission of ^{248}Cm, and some weak, unidentified lines.

Coincidences with the complementary Rb isotopes in Fig. 2 are weak but the spectra measured by LEPS,

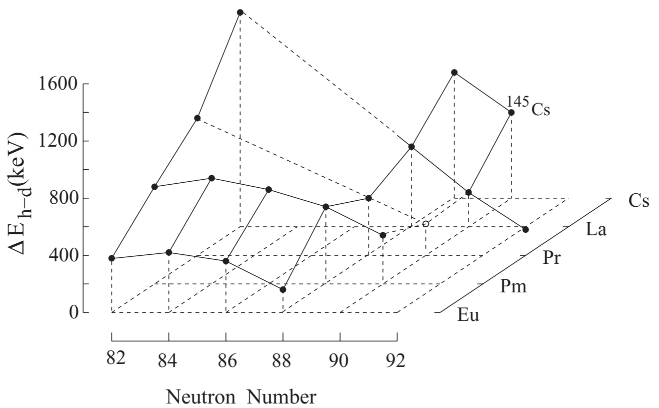

FIG. 1. Differences between excitation energies of $11/2^-$ and $5/2^+$ levels in odd-Z, neutron-rich lanthanide nuclei. The data are taken from Refs. [2,4,5,14–28].

shown in Fig. 3, support the assignment of the discussed cascade to a Pr isotope. In the spectrum shown in Fig. 3(a), which is doubly gated on the 219.7- and 416.0-keV lines, one can see the 58.1- and 102.6-keV lines of this cascade and the 35.9-keV, K_α and 40.7-keV, K_β x-ray lines of Pr.

Figure 4 shows a γ-ray spectrum double-gated on the 219.7- and 330.3-keV lines in the ^{252}Cf fission data set. In the spectrum, besides lines from the previously mentioned cascade, there are lines from the ^{98,99,100,101}Y. A weighted-average mass of the complementary yttrium isotope, estimated using the observed γ-ray intensities of various yttrium isotopes as weights, is $\langle A(Y)\rangle = 99.2(4)$. As around 3.8 neutrons are emitted, on average, following the fission of ^{252}Cf, the cascade can be assigned to ^{149}Pr, as proposed in [10].

In Fig. 5 we show the level scheme of ^{149}Pr obtained in this work, which, in addition to the data reported in [10], includes spin and parity assignments for the excited levels, as described in the following. The half-life of the 58.1-keV level was measured at 26(4) ns, using the ^{252}Cf fission data. The "time walk" effect, estimated by gating on the nearby background, has been subtracted. The obtained half-life is consistent with the literature value [8].

In Fig. 3(b) we show a summed double-gated LEPS spectrum, with the first gate set on the 102.6-keV line and the second gate on the 219.7-, 330.3-, and 416.0-keV lines. In the spectrum one observes the 58.1-keV line of ^{149}Pr and

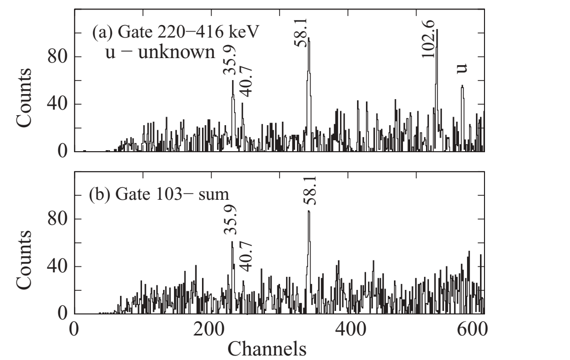

FIG. 3. LEPS γ spectra gated on (a) 219.7- and 330.3-keV and (b) 102.6- and 219.7-keV lines in ^{248}Cm data. See text for details on the sum in panel (b).

the 35.9- and 40.7-keV x-ray lines, which originate from the internal conversion of the 58.1-keV line. Using the intensities of these lines, we estimate that the experimental K-conversion coefficient for the 58.1-keV line is $\alpha_K = 0.9(4)$. This value is consistent only with the 58.1-keV transition being $E1$ in nature, as theoretical conversion coefficients for $E1$, $M1$, and $E2$ transitions with this energy are 0.92, 5.3, and 4.6 [34], respectively.

Figure 6 shows a γ-ray spectrum doubly gated on the 330.3- and 416.0-keV lines of ^{149}Pr in the ^{252}Cf fission data set. The intensity of the 219.7-keV line is taken here as a reference, and we neglect any internal conversion for this transition, as α_{tot} can be at most 0.14 (the value for a 220-keV, $E2$ transition in a praseodymium isotope [34]). With this assumption we obtain $\alpha_{tot} = 1.7(6)$ and $\alpha_{tot} = 2.2(6)$ for the 58.1- and 102.6-keV lines, respectively. These coefficients indicate that the 58.1- and 102.6-keV transitions have $E1$ and $M1$ or $E2$ multipolarities, respectively, because theoretical α_{tot} values [34] at 58.1 keV are 1.1, 6.2, and 15.9 for $E1$, $M1$, and $E2$ multipolarities, respectively, and at 102.6 keV are 0.23, 1.03, and 1.13 for $E1$, $M1$, and $E2$, respectively.

To assign spins to excited levels in ^{149}Pr we have adopted spin $(5/2^+)$ for the ground state [13] and assumed that spins are increasing with excitation energy, as commonly observed in fission fragments [35]. The most likely spin and parity of the 58.1-keV level is $7/2^-$, due to the $E1$ multipolarity of the 58.1-keV line. A negative parity is also assigned to the

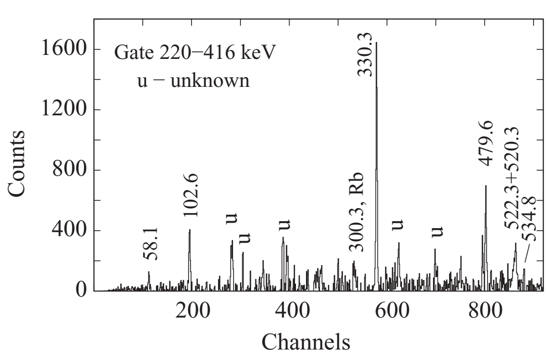

FIG. 2. A γ spectrum doubly gated on 219.7- and 416.0-keV lines in the ^{248}Cm fission data.

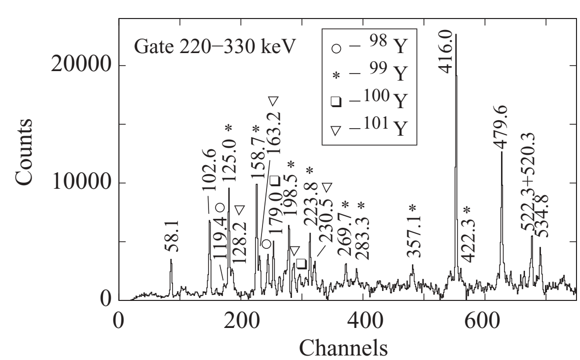

FIG. 4. A γ spectrum doubly gated on 219.7- and 330.3-keV lines in ^{252}Cf fission data.

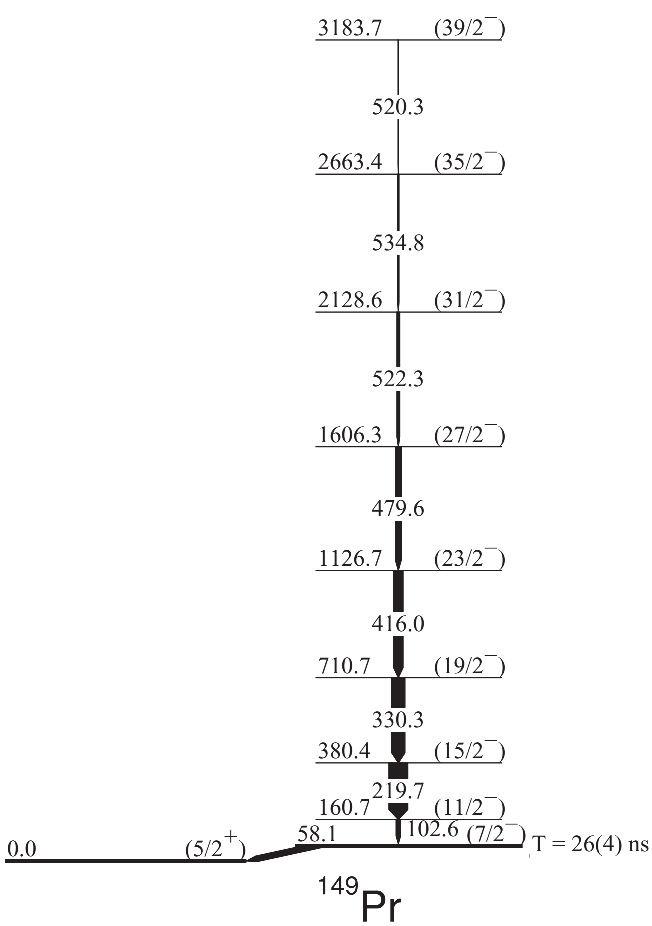

FIG. 5. Level scheme of ^{149}Pr, as obtained in this work.

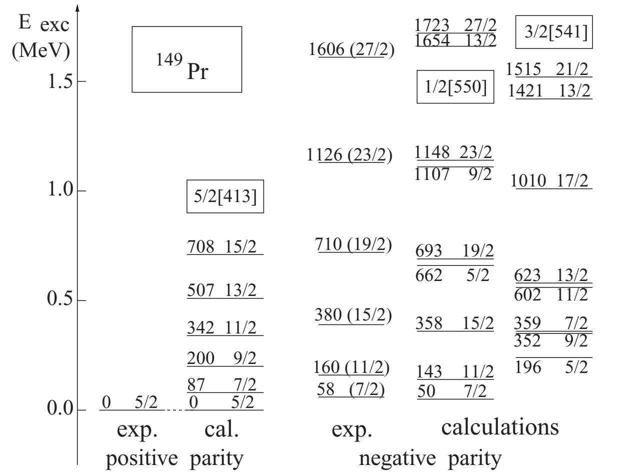

FIG. 7. Experimental and calculated excitation energies in ^{149}Pr. See text for further explanation.

160.7-keV level, due to $M1$ and/or $E2$ character of the 102.6-keV line. The regular band on top of the 58.1-keV level closely resembles $\Delta I = 2$ rotational bands built on the $7/2^-$ levels in the nearby nuclei ^{145}Cs [4], ^{147}La [5], ^{149}La [14], and ^{151}Pm [23]; therefore we propose that it is also of the same nature. The excitation energy of the $11/2^-$ level in ^{149}Pr is now proposed to be at 160.7 keV and is consistent with that expected from the systematic trend shown in Fig. 1.

In ^{149}Pr the valence proton is expected to populate the 3/2[541] proton orbital originating from the $\pi h_{11/2}$ shell [36]. To verify this expectation we performed quasiparticle-rotor model (QPRM) calculations for ^{149}Pr using the codes GAMPN, ASYRMO, and PROBAMO [37]. Deformation parameters of $\epsilon_2 = 0.20$ and $\epsilon_4 = -0.02$ were used along with Coriolis attenuation parameters of $\xi = 0.50$ and 0.45 for the positive- and negative-parity states, respectively. Standard values of the κ and μ parameters, for the ls and l^2 terms, have been used [38] (see also Refs. [39]).

The results of the calculations are shown in Fig. 7. Calculated levels are normalized to the zero energy of the $5/2^+$ ground-state level, for which calculations predict a $\pi 5/2[413]$ dominant configuration, with an amplitude of 95%. The $7/2^-$ level is calculated at 50 keV above the ground state with the $\pi 1/2[550]$ dominant configuration (with an amplitude of 91%). The levels of this band mix strongly with those of the band based on the nearby $\pi 3/2[541]$ orbital. The favored branch of the negative-parity band is reproduced well. The calculated unfavored levels (both positive and negative) are strongly nonyrast, which explains their nonobservation in the experiment. The $3/2^-$ level of the 1/2[550] configuration is calculated about 30 keV above the $5/2^+$ ground state. In this case both $3/2^-$ and $7/2^-$ levels should likely form isomers, which have not been observed. It is then likely that in reality the $3/2^-$ level is located above the $7/2^-$ level. The candidate is

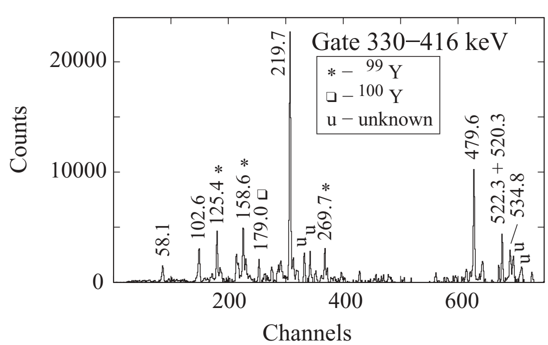

FIG. 6. A γ-ray spectrum doubly gated on 330.3- and 416.0-keV lines in ^{248}Cm fission data.

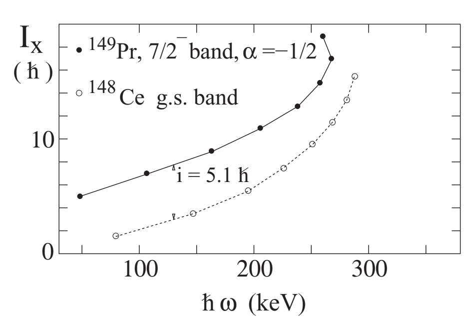

FIG. 8. Total aligned angular momentum in the $(7/2^-)$ band of ^{149}Pr.

the 86.3-keV level strongly populated in β decay of the $(3/2^-)$ ground state of ^{149}Ce [6,7].

The $\pi 1/2[550]$ configuration for the negative-parity band is supported by the total aligned angular momentum in this band, shown in Fig. 8, which was calculated by assuming $K = 1/2$. Relative to the ground-state band of ^{148}Ce, the signature $\alpha = -1/2$ branch has $5.1\hbar$ of the aligned angular momentum, which in this region is consistent only with the bandhead being of a $\pi h_{11/2}$ origin.

It is interesting that the reflection-symmetric QPRM calculations reproduce well the excitation energies in ^{149}Pr, where octupole correlations should be strong. Strong octupole correlations are supported by the experimental half-life of the $7/2^-$, 58.1-keV level, which is three orders of magnitude shorter than the half-life corresponding to single-particle, calculated within QPRM. From the 22.9(18)-ns half-life [8] of the 58.1-keV level we estimate the electric-dipole transition rate $B(E1) = 2.6(2) \times 10^{-5}$ W.u. for the 58.1-keV transition. This is three orders of magnitude faster than the single-particle $B(E1)$ rates observed in the $N = 90$ isotope ^{151}Pm [23] and four orders of magnitude faster than the rate predicted by the QPRM calculations, $B(E1) = 3.0 \times 10^{-9}$ W.u. We also note that the high attenuation of the Coriolis interaction applied in this work may result from diluting the Coriolis matrix elements in the reflection-asymmetric potential [40] (and a similar effect was reported in Ref. [41]).

The $B(E1)$ rate in ^{149}Pr is about an order of magnitude slower than $B(E1)$ rates between parity doublets in ^{151}Pm [23] and in ^{153}Eu [42]. Comparing the $B(E1) > 3.0 \times 10^{-4}$ W.u. decay rate of the $7/2^-$ level in ^{151}Pm with the value in ^{149}Pr, and taking an electric-dipole moment of $Q_1 = 0.18(3)\ e$ fm in ^{151}Pm [23], we estimated the electric dipole moment in ^{149}Pr to be $Q_1 < 0.07\ e$ fm. A similar suppressing of the $B(E1)$ rate has been observed in $N = 90$ isotones ^{145}Cs [4] and ^{147}La [43]. This suppression may be caused by blocking of the $\pi(h_{11/2}, d_{5/2})_{3^-}$ octupole coupling [4]. However, it remains to be explained why $B(E1)$ rates increase in the $N = 90$ isotones at $Z > 59$. New calculations using models with octupole degrees of freedom are required to interpret new experimental data on neutron-rich lanthanides obtained recently.

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