Isomerism in ^{148}Pr and the low-lying levels of ^{148}Nd

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(Received 28 June 1985)

The decay of ^{148}Pr to levels of ^{148}Nd has been studied using sources produced by the ^{235}U(n,*f*) reaction followed by on-line mass separation, and by the ^{148}Nd(n,p) reaction using an enriched ^{148}Nd target. Strong evidence is presented to support the previously proposed existence of a 2.27±0.05 min low-spin (1^-) isomer and a 1.95±0.08 min high-spin (4^-) isomer in ^{148}Pr. The presence of levels at 301.7(2^+), 752.3(4^+), 916.9(0^+), 999.3(3^-), 1023.0(1^-), 1171.0(2^+), 1241.6(5^-), 1248.7(2^+), and 1279.7(6^+) keV in ^{148}Nd is also supported.

I. INTRODUCTION

Recent investigations of the decay of ^{148}Pr to levels of ^{148}Nd have not been wholly conclusive either as to the presence of isomerism in ^{148}Pr or to the low-lying level structure of ^{148}Nd. In initial studies of ^{148}Pr decay, the presence of a strong 301-keV γ ray with a 2.3-min half-life was established.[1,2] The presence of additional γ rays was revealed in subsequent investigations by Skarnemark *et al.*,[3] who used fast chemical separations to isolate Ce and Pr nuclides from fission products, and by Yamamoto *et al.*,[4] who produced ^{148}Pr by the ^{148}Nd(n,p) reaction. As can be seen in Table I, where relative intensity values of a number of intense γ rays from previous publications are shown, significant intensity differences exist, particularly between sources produced from fission products and sources produced by the (n,p) reaction. The intensity differences are seen to be particularly sharp for the 450- and 615-keV transitions, which have been shown by Coulomb excitation[6–8] and two-nucleon transfer reactions[9,10] to be the 4_1^+ to 2_1^+ and 0_2^+ to 2_1^+ transitions, respectively. These differences were accounted for by Ikeda *et al.*, who measured a 2.0±0.1 min half-life for the decay of the 450-keV γ ray in sources produced by rapid chemical separation of Pr from fission products and attributed that feeding to the presence of a high spin isomer.[11] They proposed a structure for ^{148}Pr that includes a low spin 1^- isomer with a half-life of 2.27±0.04 min and a high spin 4^- isomer with a 2.0±0.1 min half-life. More recently, however, Karlewski *et al.*[12] reported only a single 2.3-min half-life from studies of sources produced by on-line separation of fission products. Moreover, the low-lying level structures of ^{148}Nd proposed by several of the investigators are not in good agreement. We have, therefore, studied the decay of ^{148}Pr produced both by mass separation of $A=148$ nuclides and by the bombardment of enriched ^{148}Nd with 14.1-MeV neutrons. The results of these studies are reported in this paper and clearly support the presence of isomerism in ^{148}Pr and resolve several of the inconsistencies in the low-lying level structure of ^{148}Nd.

II. EXPERIMENTAL PROCEDURES AND DATA ANALYSIS

The mass separation experiments were carried out at the on-line mass separator TRISTAN located at the high flux beam reactor at Brookhaven National Laboratory. The experimental setup has been described in detail in three other publications reporting the study of ^{148}Ba decay, ^{148}La decay, and ^{148}Ce decay.[13–15] In these experiments, fission products were ionized on a Re surface that is quite efficient for Ba and also produces[16] some Pr. Thus, most of the ^{148}Pr produced in these measurements is formed in the decay of 0^+ 56 s ^{148}Ce. In the study[15] by Aras *et al.* of the decay of ^{148}Ce to levels of ^{148}Pr, the lowest level fed (ground state or isomer) appears to be a 1^- level. For the studies of ^{148}Pr decay, sources were collected at the beam deposit point on a Mylar tape, moved to a shielded location while the 0.6 s ^{148}Ba, 1.5 s ^{148}La, and much of the 56 s ^{148}Ce decayed away, and then moved to a position for study. In the study position, a variety of small- and large-volume Ge detectors were employed to follow the decay of ^{148}Pr and record $\gamma\gamma t$ coincidences.

In Fig. 1 are shown the decay curves for the 301- and 450-keV rays. Our values of 2.25±0.08 min for the 301-keV γ ray and 2.02±0.09 min for the 450-keV γ ray are in excellent agreement with the 2.27±0.04 min and 2.0±0.1 min, respectively, reported[11] by Ikeda *et al.* The relative intensity values are reported in Table I for a counting period of 7 min without correction for isomerism.

In a separate set of experiments using the 14.1-MeV neutron source at the Lawrence Livermore National Laboratory, ^{148}Pr was produced by the ^{148}Nd(n,p)^{148}Pr reac-

TABLE I. Intensities (except for Ikeda *et al.*, Ref. 11, these intensities are given for unspecified mixtures of the low- and high-spin isomers) of selected ^{148}Nd γ rays following ^{148}Pr decay or (n,n′γ) reactions.

$E_\gamma(J^\pi)$	Skarnemark *et al.* (Ref. 3) (n,f)	Yamamoto *et al.* (Ref. 4) (n,p)	Taylor and Singh (Ref. 5) (n,p)	Karlewski *et al.* (Ref. 12) (n,f)	This work (n,f)	This work (n,p)	Ikeda *et al.* (Ref. 11) (n,f) Low spin	Ikeda *et al.* (Ref. 11) (n,f) High spin	Demidov *et al.* (Ref. 19) (n,n′γ)
301(2^+)	100	100	100	100	100	100	100	100	100
450(4^+)	5.3	17.3	17.3	5.4	4.2	19	0.3	52	22
489(5^-)		6.0	3.2			4.3	0.6		4.0
522		0.6	1.6			2.5		1.8	
615(0^+)	5.4	1.6	2.0	4.2	3.8	2.6	3.7		4.1
697(3^-)	10.9	13.4	11.0	10.4	9.0	11.2	6.7	42	10
721(1^-)	8.3		1.0	9.0	5.3	2.8	7.0		3.9
869(2^+)	7.5	5.2	6.2	6.6	7.8	5.6	6.1		6.3
1023(1^-)	9.0	4.7	6.2	8.9	7.3	4.4	7.8		5.3
1106(3^+)		1.2	1.4		1.3	1.1		8.2	0.4
1248(2^+)	6.6	5.5	6.3	7.0	8.4	4.6	5.3		4.4
1357	10.4	6.2	7.5	10.2	11.1	4.7	9.0		1.1
1381	4.7	2.6	2.9	4.3	4.3	2.0	3.7		1.0
1556(3^+)		1.0	2.3			1.7		9.8	0.7

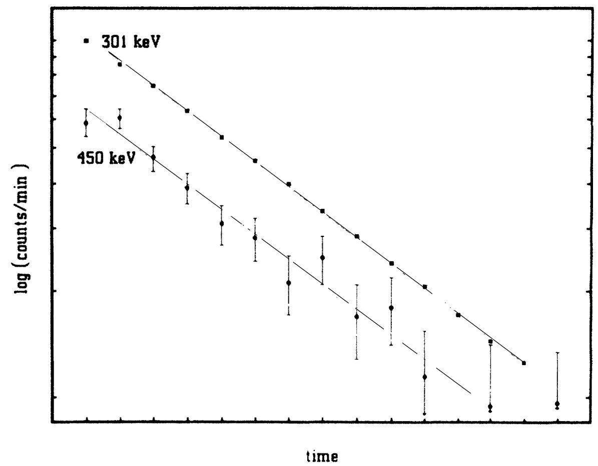

FIG. 1. Decay curves for the 301- and 450-keV γ rays. The peak areas were taken from 15 sequential 32 s spectra beginning 32 s after the end of sample collection. The half-life of 2.02±0.09 s for the 450-keV peak does not include the last two data points.

tion. A rapid pneumatic transfer system was used to permit counting of the samples to begin 30 s following the end of irradiation. Singles and two detector $\gamma\gamma t$ coincidence data were collected using 60-cm^3 Ge detectors positioned 5 cm from the source. The relative intensities for an 8-min counting period without correction for isomerism are reported in Table I. The intensity data from the (n,p) sources also require the presence of two isomers, as the intensity for the 450-keV γ rays is the largest listed.

The wide variation in the intensity of the 450-keV 4^+ to 2^+ transition relative to the intensity of the 301-keV 2^+ to 0^+ transition as a function of production method is readily accounted for by the presence of isomers with spins of 1^- and 4^-. In the (n,p) reaction, the production ratio of the two isomers will be governed by the l values of the incoming neutron and outgoing proton and the γ ray cascade from the resultant excited nucleus. Owing to the larger l value required to populate the 4^- isomer, a significantly larger yield of the 1^- isomer would be expected. In sources produced in fission, the isomer ratio will depend upon how the Pr is separated. In our experiments with the TRISTAN mass separator system, most of the Pr is the decay product of 0^+ ^{148}Ce which will populate the 1^- isomer almost exclusively. What little high-spin isomer is present is a consequence of direct separation of Pr, which has been shown to occur in earlier experiments.[16] In experiments where direct chemical separation of Pr is made, the relative yield of the high spin isomer will reflect the independent fission yield of Pr relative to the cumulative chain yield. In an early experiment where Pr was milked from Ce that had been separated from fission products, very little high-spin Pr would be expected, and no 450-keV γ ray intensity was reported.[17]

Inasmuch as the 450-keV γ ray is populated by the decay of both the low-spin and high-spin isomers, the measured half-life of 2.02 min will represent some average between the two half-lives of the two isomers. Likewise, all of the decay of the high-spin isomer must pass through the 301-keV γ ray, making it also an average between the two true values. An estimate of the branching from a 1^- nuclide to the 4^+ level of the even-even daughter may be drawn from the decay scheme of 1^- ^{146}Pr. In that decay, the relative intensity of the 4^+ to 2^+ transition is 0.68 relative to 100 for the 2^+ to 0^+ transition. On the other hand, for the decay of 1^- ^{150}Pm decay to ^{150}Sm, the relative intensity[18] of the 4^+ to 2^+ transition is 1.1. We therefore estimate that at least 1% of the decay of the low spin isomer feeds through the 4^+ to 2^+ transition. The fraction of the decay of the 4^- isomer that passes through the 4^+ to 2^+ transition varies much more widely as a function of Q_β and the specific levels involved. It is as low as 5% where the 4^- parent decays predominantly to the 3^- level in the daughter that in turn decays largely to the 2^+ level, to as much as 85% where there is little direct β feeding to the lowest 3^- level. If we estimate that the 1^- isomer has a 1% branch through the 4^+ to 2^+ transition and that the 4^- isomer has a 50% branch through the 4^+ to 2^+ transition, then the half-life of the low spin isomer is raised to 2.27 min and the half-life of the high spin isomer is lowered to 1.95 min.

The results of the coincidence study were used to construct the partial level scheme for ^{148}Nd shown in Fig. 2. This level scheme differs from those presented by Taylor and Singh[5] and by Ikeda *et al.*[11] in several small, but significant, points. In particular, Taylor and Singh[5] place the 489-keV γ ray as populating the 301-keV level from a level at 790 keV. Our coincidence data indicate that the 489-keV γ ray is in coincidence with both the 450- and 301-keV γ rays. As is seen in Table I, the 489-keV γ ray

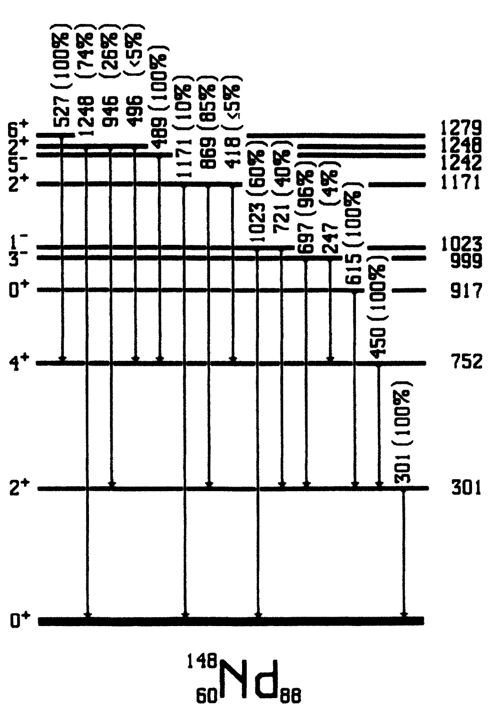

FIG. 2. Low-lying levels of ^{148}Nd fed in the decay of ^{148}Pr isomers as proposed in this work.

is not observed in the fission product ^{148}Pr which is dominated by the decay of the low-spin isomer, thereby suggesting its placement in the decay scheme of the high-spin isomer. In recent studies of the ^{148}Nd(n,n$'\gamma$) reaction, Demidov *et al.*[19] have placed the 489-keV γ ray in a similar position. They measured the angular correlation of the 489-keV γ ray and deduced a quadrupole-dipole mixing ratio of 0.03 ± 0.02 and suggested spin and parity of 5^- for the 1241-keV level. Such an assignment would be consistent with our intensity values, which indicate feeding by the high-spin isomer, and support an assignment of 4^- for the spin and parity of the high-spin isomer.

We also differ with Ikeda *et al.*[11] regarding the placement of a 0^+ level at 723 keV that deexcites to the 301-keV level by a 422-keV γ ray. Demidov *et al.*[18] did not observe this γ ray in the (n,n$'\gamma$) experiments while clearly observing the 615-keV γ ray that deexcites the well-established 0^+ level at 916 keV. In our sources produced by mass separation following fission, no peak could be observed at 422 keV after the decay of the 421-keV γ ray from 56 s ^{148}Ce decay. We show in Fig. 3 portions of the γ-ray spectrum of ^{148}Pr decay covering various periods of time after the end of the beam deposition period. In the sources produced by the (n,p) reaction, interference arises from a strong 423.6-keV γ ray in the decay of 2.8 min ^{145}Ce that is produced by the ^{148}Nd(n,γ)^{145}Ce reaction. Our coincidence data suggest that if such a γ ray is present, it lies higher in the decay scheme, as a gate on the 422 region shows both the 301- and 450-keV peaks. Like Ikeda *et al.*,[11] we also place the 522-keV γ ray in the decay scheme of the high-spin isomer, but the coincidence data indicate that it feeds a level at 1858 keV that deexcites by 1556- and 1106-keV rays. That level is observed by Taylor and Singh,[5] Ikeda *et al.*,[11] and by Demidov *et al.*,[19] and given a 3^+ assignment by Demidov *et al.* We observe that level only very weakly in our (n,f) experiments, and it is not observed in (n,f) experiments by Karlewski *et al.*[12]

Demidov *et al.*[19] also place a 6^+ level at 1279 keV that deexcites to the 4^+ level at 752 keV by a 527-keV γ ray. The 527-keV γ ray is below our detection limits in the (n,f) produced sources, even with mass separation, but is observed with half the intensity of the 522-keV line in our (n,p) produced sources. These data are consistent with the 6^+ assignment of Demidov *et al.*[19] and a 4^- assignment for the spin and parity of the high spin ^{148}Pr isomer. Above 1400 keV all of the data appear to support levels at 1659, 1683, 1687, and 1858 keV with a number of other levels not consistently supported by all of the data.

The resulting levels of ^{148}Nd below 1400 keV are shown in Fig. 4 along with the levels of the $N=88$ isotones. The $N=88$ levels have often been considered as borderline between the prolate deformed structure associated with nuclides that have $N\geq90$ and the transitional nuclides just above the $N=82$ closed shell. As can be seen in Fig. 4, however, these $N=88$ structures vary quite strongly as Z changes. Of particular interest are the 1^- and 3^- levels that rise monotonically and dramatically as Z increases and the 0^+ levels which show a minimum at $Z=64$. Moreover, the second 2^+ level, typically associated with asymmetric collective excitation, lies well above the 0_2^+

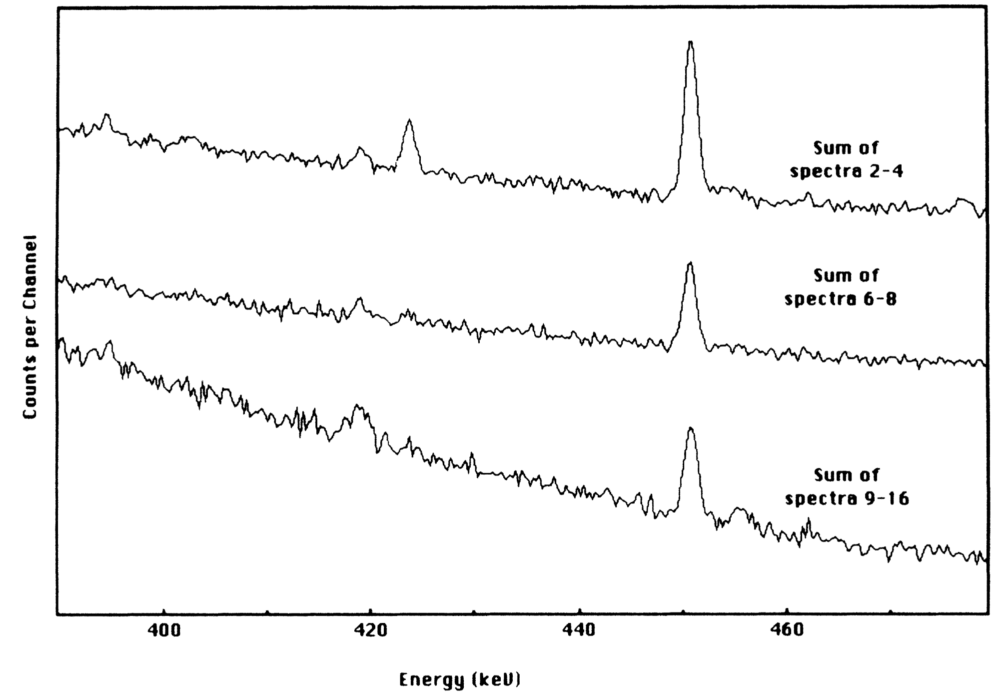

FIG. 3. Portions of the spectra of the decay of ^{148}Pr isomers showing the decay of peaks near 420 and 450 keV. The upper spectrum covers the period from 32 s until 128 s after movement of the tape, the middle spectrum covers the period 160 s and 256 s after movement of the tape, and the lower spectrum covers the period between 256 s and 512 s after movement of the tape. The peak at 421 keV is attributed entirely to the decay of 56 s ^{148}Ce, as it decays away much faster than the 450-keV γ ray.

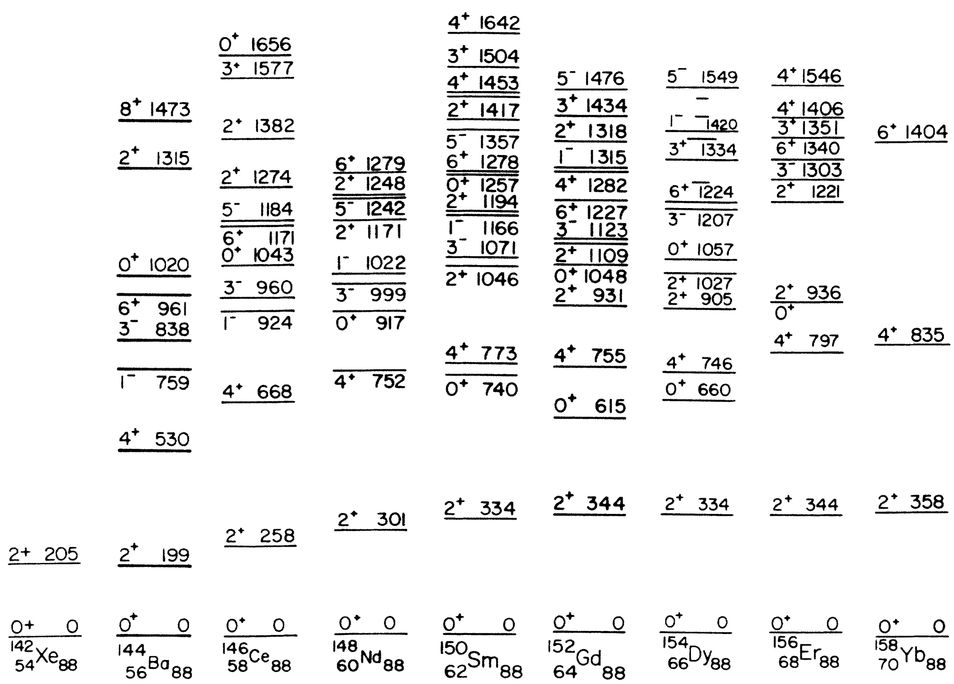

FIG. 4. Systematics of the $N=88$ isotones across the $Z=64$ subshell. The level of ^{142}Xe is from Ref. 20, the levels of ^{144}Ba are from Ref. 21, and the levels of ^{146}Ce are from Ref. 22 ; the other data are from Ref. 18.

and 4_1^+ levels at low Z and moves down in energy monotonically as Z increases.

Recently Casten[23] showed the great utility of plotting the ratio of the first 4^+ energy to the energy of the first 2^+ level against the product of the number of protons N_π times the number of neutrons N_ν beyond the nearest double shell closure. This minimum in the energy of the first 2^+ level structure as well as the minimum of the ratio of the energy of the $4^+/2^+$ levels which falls at $Z=56$ produces an interesting bulge in these systematics. In the $N=90$ nuclides, the minimum $4^+/2^+$ ratio falls much higher at $Z=60$. In addition, the shift from shell to deformed structure falls along a different curve for these nuclides with $Z<64$ as compared to the nuclides with $Z>64$ and $N>90$. Moreover, Leander et al.[24] recently argued that the nuclides around ^{145}Ba may show octupole or cluster structures.[25] We suggest that this bulge is, in fact, associated with a small separate deformed area that arises from octupole or cluster structure.

We conclude by noting that our data combined with all of the existing data strongly support the presence of two isomers in ^{148}Pr, probably 1^- and 4^- as proposed by Ikeda et al.[11] Strong evidence also exists, again from all of the data, to support the levels shown in Fig. 3 below 1400 keV. With the ^{148}Nd level structure now more clarified, the $N=88$ isotones offer a rich opportunity for systematic tests of nuclear structure models of transitional nuclides over large changes in the underlying core structure.

The authors wish to express their appreciation to the U. S. Department of Energy for support of this work under Contracts DE-AS05-79ER10494, DE-AC02-76CH00016, and W-7405-ENG-48.

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