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Excited states of the ^{150}Pm odd-odd nucleus

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The knowledge of excited states in the odd-odd ^{150}Pm, completely unknown until recently, is important both for understanding double β decay of ^{150}Nd and for nuclear structure studies in mass regions with a quantum phase transition. A large number of excited states have been determined for the first time in this nucleus by measuring spectra of the ^{152}Sm(d,α) direct reaction at 25 MeV with the Munich Q3D spectrograph and by γ-ray spectroscopy with the $(p, n\gamma)$ reaction at 7.1 MeV at the Bucharest tandem accelerator. Some of these levels correspond to peaks recently observed with the (^{3}He,t) reaction at 140 MeV/u.

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Experimental information concerning excited states in the odd-odd nucleus ^{150}Pm was completely absent until very recently. The Evaluated Nuclear Structure Data File (ENSDF) database [1,2] specifies only a ground state of possible spin and parity 1^- beta decaying with a half-life of 2.68 hours. This situation is rather astonishing for a nucleus lying close to the valley of stability, which can be reached by a variety of nuclear reactions with different stable targets that surround it.

The knowledge of the excited states in ^{150}Pm is very important for some topical nuclear structure issues. One of these is related to the fact that they are intermediate states in the double β decay ($\beta\beta$) of ^{150}Nd to ^{150}Sm, a process that can take place with the emission of either two neutrinos (2ν) or zero neutrinos (0ν). ^{150}Nd is considered one of the best candidates in experimental searches for the controversial zero-neutrino $\beta\beta$ decay ($0\nu\beta\beta$) which, if measured, would confirm the Majorana nature of neutrinos, a long-standing debate in both nuclear and particle physics [3]. Calculations of the $\beta\beta$-decay (both 0ν and 2ν) half-lives imply summing over states in the intermediate nucleus ^{150}Pm [4]. While the $2\nu\beta\beta$ process proceeds by 1^+ intermediate states, the $0\nu\beta\beta$ decay can proceed through intermediate states with different spins of both parities ([4,5] and references therein). It is therefore of major interest to have a detailed knowledge of the excited states of ^{150}Pm.

In addition, this nucleus lies in a very interesting transitional region. It is in the middle of the 50–82 proton shell ($Z = 61$) and near the $N = 90$ neutron number ($N = 89$). The nuclei with $N = 90$ were found with properties close to those predicted for the X(5) symmetry [6], which is the critical point of the phase-shape transition between spherical (vibrator) and deformed (rotor) nuclei. ^{150}Nd is actually considered as the best empirical example known today of X(5) symmetry [7]. ^{150}Pm can be regarded as consisting of one proton and one neutron hole coupled to the ^{150}Nd core; therefore, its structure together with that of its odd-A neighbors is important for the study of nuclear quantum phase transitions.

The experiments reported in this article were performed in order to provide information on the excited states of this odd-odd nucleus. While these studies were in an advanced stage, information on excited states of ^{150}Pm was reported in Ref. [5] as a result of a study with the (^{3}He,t) reaction at 140 MeV/u.

The $^{152}Sm(d,\alpha)^{150}Pm$ *reaction.* The reaction was performed with a 25 MeV deuterium beam from the Munich tandem accelerator. The reaction products were analyzed with the Munich Q3D spectrograph [8] and detected and identified with the 1-m-long cathode-strip focal-plane detector [9]. The opening slits of the magnetic spectrograph were ±21 mm (horizontal) and ±24.5 mm (vertical). The beam current was about 300 nA, and the target was 98.3% enriched Sm_2O_3 54 μg/cm^2 thick deposited on a 7 μg/cm^2 carbon foil. Energy calibrations were performed with the ^{142}Nd(d,α)^{140}Pr and ^{140}Ce(d,α)^{138}La reactions measured with the same settings of the magnetic spectrograph. The calibration targets were of comparable thicknesses, 54 μg/cm^2 (NdO_3) and 81 μg/cm^2 (CeO_2), also on 7 μg/cm^2 carbon foils. Figure 1 shows the spectra measured under these conditions, with the three targets, at the laboratory angle of 30°. For the energy-calibrating reactions we used levels in ^{140}Pr and ^{138}La final nuclei that are well known [2]—labeled with their energy in keV, uncertainty, and spin and parity values in the figure. From Fig. 1 one notices the following: First, the rather large density of levels populated in ^{150}Pm at low excitation energies compared with the other two nuclei. Second, the very low cross sections of the ^{152}Sm(d,α)^{150}Pm reaction (note the very different times needed to collect the spectra in Fig. 1, with similar target thicknesses and beam currents). While the cross sections for the energy-calibrating reactions are in the range of several tens of μb/sr for the strongest peaks seen in Fig. 1, the cross sections for our reaction are at least one order of magnitude smaller (around 6 μb/sr for the strongest peaks in Fig. 1). Under these conditions, spectra at only two angles could be measured (at 20° and

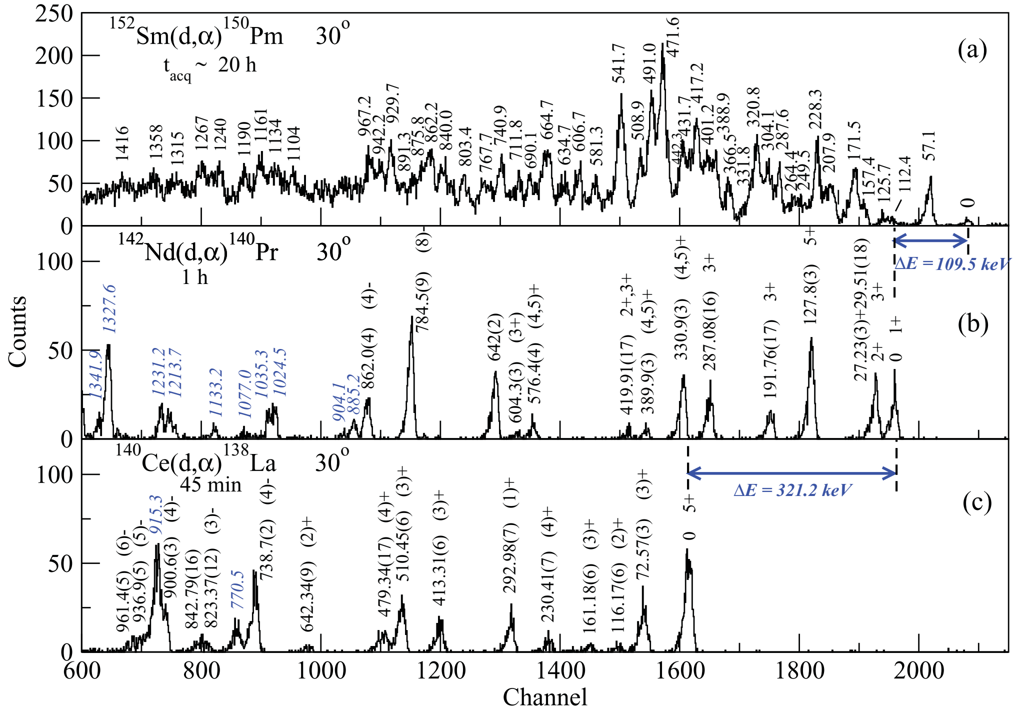

FIG. 1. (Color online) Spectra at 30° for reactions ^{152}Sm(d,α)^{150}Pm (a), ^{142}Nd(d,α)^{140}Pm (b), and ^{140}Ce(d,α)^{138}La (c), measured with same magnetic setting. The collection times of the spectra (taken with comparable beam intensities) are indicated in the upper-left corner of each spectrum. For the two calibration reactions (lowest spectra), the well-known levels [2] are marked with their energy in keV, uncertainty, and spin and parity, while the energies written with (blue) italics mark levels seen for the first time in this study. Ground-state-energy differences between these reactions are also highlighted by the double arrows.

30°) within the allocated beam time. Angular distribution measurements within reasonable beam times could not be planned yet, therefore the only information extracted from these measurements was the level excitation energies. The peaks corresponding to these energy levels are shown in Fig. 1 with the energies, taken from weighted averages of the values at the two angles, listed in Table I. The full width at half maximum (FWHM) energy resolution of the spectra was about 13 keV, comparable with that of about 11 keV for the Nd target and of 14–15 keV for the Ce (thicker) target. We note that, for the three reactions (a) ^{152}Sm(d,α)^{150}Pm, (b) ^{142}Nd(d,α)^{140}Pm, and (c) ^{140}Ce(d,α)^{138}La, the measured ground-state-energy differences (at 30°) are $\Delta E_{\text{a-b}} = 109.5\,(11)$ keV, and $\Delta E_{\text{b-c}} = 321.2\,(10)$ keV (see Fig. 1). While the first value agrees within errors with the value 104.5 (210) keV expected on the basis of the Q values from mass tables [10], the second

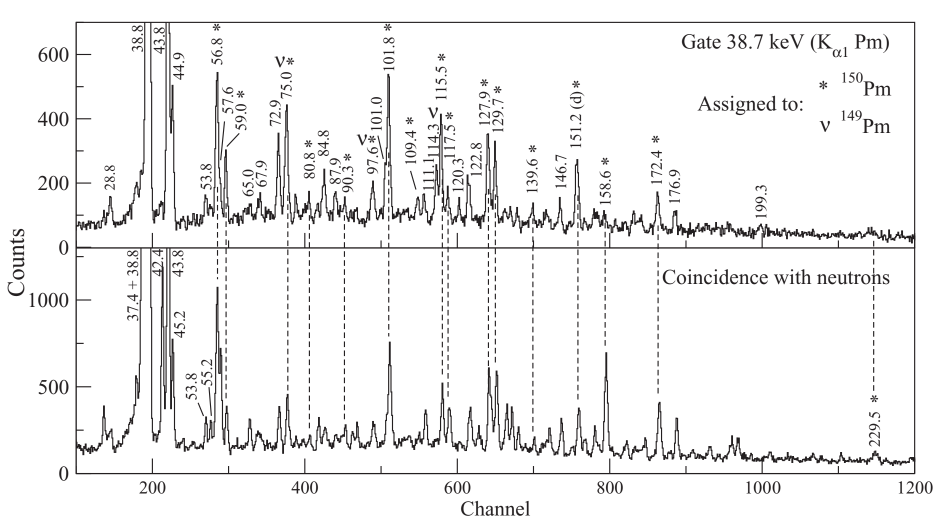

FIG. 2. γ-ray spectra gated by the 38.7 keV $K_{\alpha 1}$ x-ray of Pm (upper graph) and by neutrons (lower graph). γ rays assigned to ^{150}Pm and placed into a level scheme are marked by an asterisk.

TABLE I. Energies of excited states of ^{150}Pm, as observed in the present experiments (first two columns) compared to the peaks assigned in the recent (^{3}He,t)-reaction study [5]. The uncertainties in the excitation energies are below 0.2 keV for the $(p, n\gamma)$ case, and 10 keV for the (^{3}He,t)-reaction case [5].

E_x (keV)			E_x (keV)		
$(p, n\gamma)$	(d,α)	(^{3}He,t) [5]	$(p, n\gamma)$	(d,α)	(^{3}He,t) [5]
0	0	0		491.0 (17)	
56.8	57.1 (7)			508.9 (15)	500
115.8	112.4 (11)	110		541.7 (21)	
127.9	125.7 (10)			581.3 (13)	590
129.7				609.7 (7)	
158.6	157.4 (13)			634.7 (18)	
172.3	171.5 (8)			664.7 (13)	670
196.5		190		690.1 (19)	
208.0	207.9 (15)			711.8 (8)	
219.9				740.9 (5)	730
225.9				767.7 (18)	
229.5	228.3 (15)			803.4 (11)	
244.4				840.0 (16)	
(247.2)	249.5 (10)			862.2 (8)	860
258.5	264.4 (6)			875.8 (12)	
281.7		280		891.3 (12)	900
288.8	287.6 (10)			929.7 (7)	
293.9				942.2 (7)	
	304.1 (6)			967.2 (7)	
319.2	320.8 (7)				1000
326.0				1104 (2)	
330.0	331.8 (11)			1134 (2)	1140
369.3	366.5 (10)			1161 (2)	
	388.9 (22)	400		1190 (2)	
	401.2 (12)			1240 (2)	1230
	417.2 (6)			1267 (2)	1270
	431.7 (15)			1315 (2)	1320
	442.3 (8)			1358 (2)	1370
	471.6 (7)			1416 (2)	1400

value deviates by about 20 keV from the expected value of 299.0 (70) keV, suggesting that the Q value of reaction (c) should be corrected by about that quantity. Table I shows that all peaks identified in the (^{3}He,t) reaction study, except for the peak at 1000 keV, correspond within their 10 keV uncertainty [5] to peaks identified in our (d,α) reaction study; the latter showing many more levels below 1 MeV excitation. Some of the peaks identified at higher excitation energies (between 1100 and 1416 keV, see Fig. 1) with the (d,α) reaction very likely correspond to unresolved multiplets, because their average width is around 19 keV—but one again notices a good correspondence with peak structures observed in Ref. [5].

The $^{150}Nd(p,n\gamma)^{150}Pm$ *reaction.* The (p,n) reaction was performed with a proton beam of 7.1 MeV from the Bucharest tandem accelerator. This energy was chosen such as to keep the contribution of the $(p, 2n)$ channel (threshold energy 6.52 MeV) at a negligible level. The target was a self-supported foil 0.6 mg/cm^2 thick. In order to minimize the background created by the stopped beam, a beam dump was adapted to the reaction chamber so that the beam was stopped 50 cm behind the target. The intensity of the beam was kept around 15 nA in order to limit the counting rates in the detectors. In a first experiment, an array of one high-purity Ge (HPGe) planar detector and seven 50% HPGe detectors were used. However, it turned out that most of the γ rays from levels populated in ^{150}Pm had low energies, below 200 keV, where the large-efficiency detectors had low efficiency. Therefore, in a second experiment, the detection system contained four planar detectors and five of the large HPGe detectors, as well as a 1 liter NE215 scintillator detector for neutrons. The coincidences between all these detectors were recorded online, and in the offline processing $\gamma\gamma$ and neutron-γ coincidence matrices were built. The results based on the coincidences between the four planar detectors will be presented below. The large HPGe detectors helped rather little in improving the statistics in the interesting low-energy region, while contributing with an increased background due to the β decay of the collected ^{150}Pm nuclei to ^{150}Sm.

Figure 2 shows γ-ray spectra highlighting most of the transitions that were assigned to, and placed into, the level scheme of ^{150}Pm. The upper panel displays the spectrum coincident with the $K_{\alpha 1}$ x-ray of Pm at 38.7 keV. Many low-energy transitions from this spectrum, except for a few weak lines known to belong to the ^{149}Pm nucleus [1,11] (the just-opened $2n$ channel), have also been seen in the n-γ coincidence spectrum (lower panel), and therefore clearly belong to the ^{150}Pm nucleus. There is a large number of γ-rays

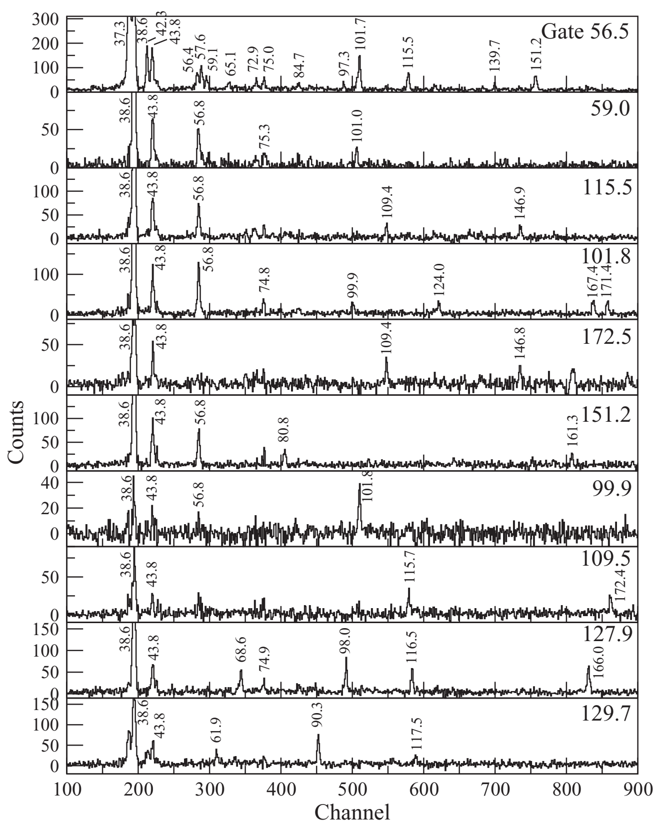

FIG. 3. Gated γ-ray spectra obtained from a symmetric $\gamma\gamma$-coincidence matrix constructed for the four planar detectors (see also the level scheme shown in Fig. 4).

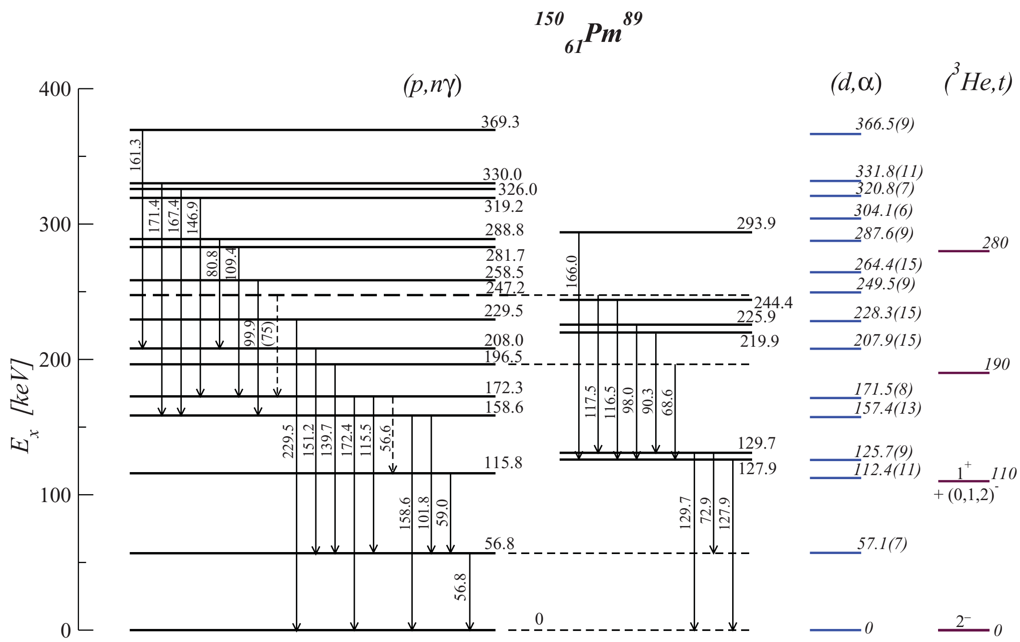

FIG. 4. (Color online) Low-excitation level schemes (below 370 keV), as obtained from the present $(p, n\gamma)$ and (d,α) reactions (present work), compared to the levels seen in the recent study with the $(^3\mathrm{He},t)$ reaction [5].

that may be assigned in this way to decay levels of ^{150}Pm, and not all of them could be placed into a level scheme. Some of the γ rays were placed into a level scheme based on their intensities and the observed coincidence relations. Examples of γ-ray-gated spectra obtained from a symmetric $\gamma\gamma$-coincidence matrix of the four planar detectors are shown in Fig. 3, while the corresponding constructed level scheme is shown in Fig. 4. The established levels of ^{150}Pm are also listed in Table I. A discussion of several issues related to the constructed level scheme is in order here. As seen in Fig. 2, there is a multiplet of γ rays with energies around 57 keV. Careful gating on these γ rays revealed the following: A 57.7 keV γ ray is coincident with the x-rays of Nd (therefore it belongs to an Nd nucleus), and also with γ rays of 56.4, 57.7, and 65.0 keV (all seen in Fig. 2). On the other hand, gating on the 38.7 keV x-ray of Pm shows that there are two lines, 56.8 and 59.0 keV, belonging to Pm. The 59.0 keV line is coincident with the 56.8 keV line, and a 101.8 keV line is also coincident with 56.8 keV line (Fig. 2). This leads to the construction of the lowest part of the level scheme, with three levels at 56.8, 115.8, and 158.6 keV (Fig. 4). Note that the 56.8 keV level was also observed in the (d,α) reaction as 57.1 (7) keV (Fig. 1 and Table I). The 115.8 keV level approximately corresponds to a level seen in the (d,α) reaction at 112.4 (11) keV. Other levels were added to the level scheme (Fig. 4) based on $\gamma\gamma$ coincidence relations (some of them shown in Fig. 3) or other arguments. The 229.5 keV level was added as decaying to the ground state because there is a clear transition with that energy in the neutron-coincidence spectrum (Fig. 2) and additional support is the existence of a level seen in the (d,α) reaction at 228.3 (15) keV. The two strong γ-ray transitions of 127.9 and 129.7 keV seen in both spectra of Fig. 2 were included into the level scheme as due to two levels decaying to the ground state. For the 129.7 keV level, support is given by its decay to the 56.8 keV level and possible feeding from another level, tentatively placed at 247.2 keV (Figs. 3 and 4). The 127.9 keV level is fed by the 196.5 keV level through a 68.6 keV transition. There is a level at 125.7 (0) keV seen in the (d,α) reaction, and it approximately corresponds in energy to the doublet 127.9–129.7 keV assigned in the (p, n) reaction. As seen in Fig. 1, the doublet 112.4–125.7 keV seen in (d,α) is rather weakly excited, so that actually it has been difficult to decide whether there are only two or more levels around those energies. A strong peak was observed in the $(^3\mathrm{He},t)$ reaction [5] at 110 (10) keV, which is predominantly due to a 1^+ level, but it has contributions from transferred ℓ values, indicating the possible existence of at least one more level. Therefore, around the 120 keV excitation there seems to exist two or three closely lying levels. In the (p, n) reaction results, the levels at 196.5 and 281.7 keV correspond to the 190 and 280 keV peaks, respectively, seen in the $(^3\mathrm{He},t)$ reaction [5].

Spin and parity values of levels in ^{150}Pm shown Fig. 4 are from the recent work [5] and are known only for the ground state, assigned as 2^-, and for the multiplet around 110 keV that contains one 1^+ state, one 0^-, 1^-, or 2^- state, and possibly a third, 2^+ or 3^+ state. An attempt at measuring γ-ray multiplicities during the $(p, n\gamma)$ experiment was made by positioning one of the planar detectors at three angles. However, the γ-ray angular distribution results for these low-energy transitions were rather inconclusive. This is probably due to large uncertainties in the detector efficiency as a function of angle, which is caused by the irregular geometry of the absorbing walls of the beam-dumping system whose use was necessary (measuring with a thin-walled spherical chamber was impossible due to very high background caused by the beam that was stopped near the target).

In conclusion, excited states in the odd-odd ^{150}Pm nucleus, which was completely unknown until very recently, were determined with two experiments of good energy resolution: a $(p,n\gamma)$ reaction at 7.1 MeV incident energy, and a (d,α) reaction at 25 MeV incident energy with a 13 keV FWHM resolution for the α-particle spectra. About 20 excited states were assigned in the first reaction up to an excitation energy of 370 keV, and 48 in the latter up to 1416 keV, with generally good agreement between the two reactions. Some of the levels seen in these studies correspond to peaks observed in the recent (^{3}He,t) reaction study [5]. The results show that this nucleus is characterized by a rather large density of levels at low excitation energies, and this can be significant for the calculations of the $\beta\beta$ decay half-lives of ^{150}Nd. Because of the very low cross sections for the population of these levels in the (d,α) reaction, and the low energies of the γ transitions assigned to the decay of the lowest-excited levels as evidenced in the (p,n) reaction, the determination of spin and parity values of levels in this nucleus remains a delicate problem, and new experiments should be performed with this purpose.

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