PHYSICAL REVIEW C VOLUME 4, NUMBER 3 SEPTEMBER 1971

Decay of ^{152}Nd and the Isomers of ^{152}Pm†

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(Received 18 March 1971)

The radiations associated with the decay of 11.4-min ^{152}Nd and its 4.1-min ^{152}Pm daughter have been studied with Ge(Li), NaI(Tl), and anthracene detectors in both singles and coincidence configurations. A tentative decay scheme for ^{152}Nd involving allowed β decay to the 4.1-min isomer of ^{152}Pm (1^+) ($\log ft = 4.8$) and to an excited 1^+ level 294.6-keV higher ($\log ft = 4.2$) is presented. The 4.1-min level undergoes β decay to 10 levels in ^{152}Sm which have been previously established in decay studies of ^{152}Eu, and from Coulomb excitation and reaction studies. A new level in ^{152}Sm has been placed at ≈1081 keV. The total β-decay energy is nearly the same as the measured β end-point energy, 3.6 ± 0.2 MeV.

Evidence is presented for the existence of two previously unreported high-spin isomers of ^{152}Pm having half-lives of 7.5 ± 1.0 min and ≈18 min. A decay scheme is proposed for the 7.5-min isomer ($4^{\pm}$) of ^{152}Pm including 16 known ^{152}Sm levels and new levels at 1081, 1804, and possibly 1941 keV. At least 40% of the β transitions decay to the 1804-keV level with a $\log ft$ of ≈5.7 which suggests hindered allowed or first-forbidden decay. The observation of a 1.8-MeV β group in coincidence with an intense 1437-keV γ transition which deexcites the 1804-keV level establishes the total β-decay energy for 7.5-min ^{152}Pm as 3.6 ± 0.1 MeV. The ≈18-min isomer ($\geq 6^{\pm}$) of ^{152}Pm appears to populate a new level at 2172 keV and possibly the 1941-keV level in ^{152}Sm.

I. INTRODUCTION

A new isotope of Nd, 11.5-min ^{152}Nd, was prepared by Hoffman, Lawrence, and Daniels[1] in 1969 by the ^{150}Nd$(t, p)^{152}$Nd reaction. A 4-min Pm activity was identified as its daughter and evidence was found for a longer-lived, higher-spin ^{152}Pm activity which did not grow from ^{152}Nd but was formed directly by the ^{150}Nd$(t, n)^{152}$Pm reaction. Reports[2-4] of a 5- to 7-min half-life for a ^{152}Pm isotope formed by the (n, p) reaction in ^{152}Sm may actually have been the result of observations of a composite source of ^{152}Pm isomers in varying relative intensities. Recently, Wakat and Griffin[5] have reported isolation of the 11-min ^{152}Nd and its 4-min daughter from the products of thermal-neutron fission of ^{235}U. Presumably, only the low-spin ^{152}Pm isomer would be present in significant intensity in fission-product sources. Both high- and low-spin ^{152}Pm isomers would be produced in the triton bombardments of ^{150}Nd, and, practically speaking, only isotopes of Pr, Nd, and Pm with mass numbers between that of the target, A, and $A+2$ will be formed. For this reason, the chemical separations are easier than those involving fission products, and the interference from the complex radiations of other Pm isotopes is minimized although ^{151}Nd and ^{151}Pm are still present in high intensity. ^{151}Nd is particularly troublesome, since its half-life is nearly the same as that of ^{152}Nd, and incidental to the study of ^{152}Nd, the half-life of ^{151}Nd was redetermined to be 12.4 ± 0.2 min.

In the present study, detailed examinations of the radiations of ^{152}Nd and its 4.1-min ^{152}Pm daughter were made, and comparisons of these spectra with spectra of purified (Nd-free) Pm sources showed the existence of a 7.5-min ^{152}Pm isomer formed by the ^{150}Nd$(t, n)^{152}$Pm reaction. In the course of γ-γ coincidence measurements, evidence was found for the existence of another high-spin isomer of ^{152}Pm with a half-life of ≈18 min.

II. EXPERIMENTAL METHODS

The sources of ^{152}Nd and of ^{152}Pm were separated from the products of triton bombardment of 2- to 5-mg oxide targets of ^{150}Nd enriched to 95%. Tritons with selected energies between 9 and 12 MeV and beam currents of 1–2 μA were obtained from the Los Alamos tandem Van de Graaff accelerator. The chemical purification of Nd and Pm was based on an adaptation of standard column procedures[6,7] for the separation of individual rare earths. Following dissolution of the target and an initial precipitation of $Nd(OH)_3$ with NaOH, the sample was adsorbed on a 4-mm-i.d. × 12-cm resin column (BioRad AG-50W, X4, 400 mesh and finer) and eluted with 0.5 M, pH = 3.86 ammonium α-hydroxyisobutyrate. Liquid sources of the Nd and Pm fractions, collected directly from the column, were used for some γ spectra, while for β or low-energy γ measurements, oxalate sources (≤ 1.4 mg/cm^2) were precipitated.

The γ-ray spectra were observed with Ge(Li) detectors: a 7-mm × 1-cm-diam planar detector with a 10-mil Be window for detection of low-energy photopeaks, and two ≈25-cm^3 trapezoidal coaxially drifted detectors. β spectra were measured with a 3.2-cm × 5.1-cm-diam anthracene detector. For γ-γ and γ-β coincidence experiments, these detectors and a 3-in. × 3-in.-diam NaI(Tl) detector were used in various combinations with the axes at 180° to each other. A "crossover" coincidence technique was used in which the bipolar outputs from Tennelec 203BLR linear amplifiers were fed to Hamner *N*-685 "jitter-free" single-channel analyzers set to encompass the appropriate energy range. The outputs of the *N*-685 (any necessary small time-delay adjustments can be made in this unit) were then fed to a Hamner *N*-681 fast-coincidence circuit with the resolving time set to ≈0.1 μsec. The variation in "crossover" point with energy was observed with an oscilloscope, and timing adjustments were made if necessary to be certain that the energy range to be observed would be in coincidence with the energy of the particular gate region to be used. In addition, the time alignment was checked with appropriate standards to insure that correct γ-ray intensities were obtained when operating in the coincidence mode. Either a RIDL 400- or a Scipp 1600-channel analyzer was used.

III. RESULTS

A. ^{152}Nd-^{152}Pm(4.1 min)

1. *Half-Lives and Mass Assignments*

The half-lives of ^{152}Nd and its Pm daughter were determined by following the β decay of Nd sources freshly purified from the products of 9- or 10-MeV triton bombardments of ^{150}Nd. In order to eliminate interference from 12-min ^{151}Nd ($E_{\beta\,max}$ ≈2.1 MeV),[8] the output from the anthracene detector was fed to a single-channel analyzer set to accept only pulses from β radiation greater than ≈2.3 MeV. The decay of this radiation was recorded with a 400-channel analyzer operated in the multiscale mode with time intervals initially set at 50 sec. Although the total β-decay energy for ^{152}Nd is estimated[9-11] to be from 0.85 to 1.21 MeV, ^{152}Pm is estimated[9-11] to have a total decay energy of 3.50–3.95 MeV, so its growth into ^{152}Nd and subsequent decay should be clearly visible. Figure 1 shows the growth of ^{152}Pm into freshly separated ^{152}Nd. Least-squares analysis of the data from three such experiments gave half-life values of 11.4 ± 0.2 min for ^{152}Nd, and 4.1 ± 0.1 min for ^{152}Pm.

Assignment of the 4.1-min Pm activity to mass 152 was made primarily on the basis of the observation in its decay of the known[8] 122- and 245-keV γ rays, which deexcite levels in ^{152}Sm at 122 and 366 keV. Masses >152 should not be produced in significant amounts, and none of the lower masses has a similar level spacing. Furthermore, the 4.1-min activity was not produced in similar bombardments of ^{148}Nd. The assignment of the 11.4-min neodymium activity to ^{152}Nd could then be made on the basis of its genetic relationship to 4.1-min ^{152}Pm. Sources of ^{151}Nd, prepared by thermal-neutron bombardment of ^{150}Nd, showed completely different γ spectra from ^{152}Nd. The β decay of the ^{151}Nd was observed with a β proportional counter, and the resultant half-life of 12.4 ± 0.2 min is somewhat different from ^{152}Nd.

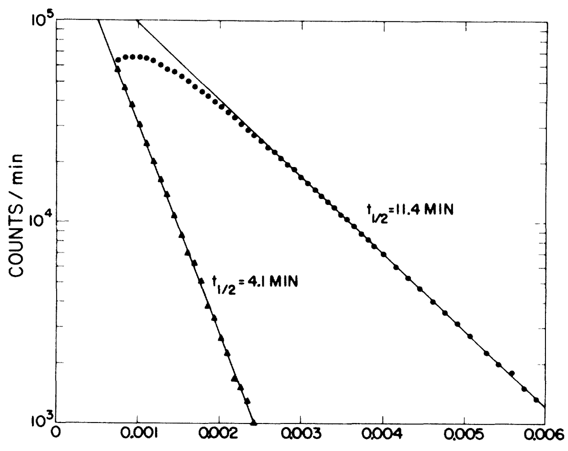

FIG. 1. Growth and decay of ^{152}Pm β radiation >2.3 MeV in a freshly purified Nd source. Purification of Nd from Pm is taken as zero time. (●), gross activity minus background; (▲), difference between gross activity and extrapolated intensity of 11.4-min ^{152}Nd activity.

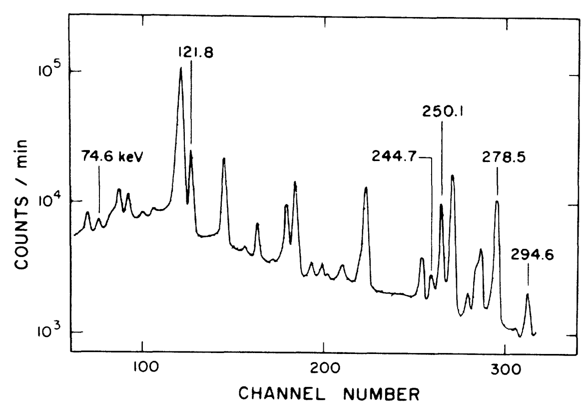

FIG. 2. Low-energy γ spectrum of Nd + Pm source measured with an ≈25-cm^3 Ge(Li) detector for 10 min starting ≈13 min after separation of Nd from Pm. Energies of ^{152}Nd photopeaks are shown. Photopeaks at 121.8 and 244.7 keV are attributed to 4.1-min ^{152}Pm, while unlabeled photopeaks are from other isotopes of Nd and Pm.

2. Radiations

The β-ray spectra of ^{152}Nd-^{152}Pm(4.1 min) equilibrium sources were examined with the anthracene detector, and from Fermi-Kurie plots of the data from several experiments, $E_{\beta\,max}$ was found to be 3.6 ± 0.2 MeV. (In addition to calibrating the anthracene detector with standard β sources, a direct comparison was made with a ^{106}Ru-^{106}Rh source, $E_{\beta\,max} = 3.53$ MeV.[8]) The 3.6-MeV β group must be associated with the decay of the 4.1-min ^{152}Pm daughter activity, since Q_β is expected to be ≈ 4 MeV, while that of ^{152}Nd is expected to be ≈ 1 MeV. It was impossible to determine the energies of the ^{152}Nd β groups because of interference from 12-min ^{151}Nd which has β energies ranging from 1.2 to 2.1 MeV.[8]

Comparison of the γ spectra of ^{152}Nd-^{152}Pm sources with sources of ^{152}Pm, free of ^{152}Nd, permitted the assignment of six γ rays to the decay of ^{152}Nd itself. Figure 2 shows the ^{152}Nd portion of the spectrum of a Nd-Pm source observed with a 25-cm^3 Ge(Li) detector. Two other low-energy photopeaks at 16.8 and 28.5 keV were observed with the planar Ge(Li) detector (resolution = 1.3 keV at 122 keV). The energies and intensities of the ^{152}Nd γ rays are given in Table I. Similar data for the γ rays attributed to the 4.1-min ^{152}Pm daughter (see Fig. 3) are given in Table II.

A γ-γ coincidence experiment was performed using the two 25-cm^3 Ge(Li) detectors. The 122-keV γ transition was used as a gate, and low-intensity peaks at 245, 689, 696, 842, $\approx$920 (?), $\approx$928, 960 (complex), and 1321 keV were observed in the coincident spectrum.

B. ^{152}Pm(7.5 min)

1. Half-Life and Mass Assignment

Comparisons of the γ-ray spectra of the ^{152}Nd-^{152}Pm equilibrium sources, with spectra of Pm sources free of Nd, showed many γ rays in common, but the separated Pm sources also showed several additional photopeaks, including rather intense 1097- and 1437-keV γ rays (Fig. 3). Measurements of the decay of these photopeaks gave a half-life value of 7.5 ± 1.0 min. The low-energy spectrum (Fig. 4) showed the same 121.8- and 244.7-keV photopeaks as the 4.1-min ^{152}Pm (Fig. 2) but the 244.7-keV peak was relatively much more intense.

The 7.5-min Pm activity has also been assigned to mass 152 because of the observation in its decay of many of the same γ rays found in the decay of the 4.1-min ^{152}Pm whose energies are the same as those known to depopulate established levels[12-21] in ^{152}Sm. Among these are the 121.8-, 244.7-, and 340.2-keV transitions which deexcite the 2^+, 4^+, and 6^+ members[17-19] of the ^{152}Sm ground-state rotational band. Again, the 7.5-min activity was not produced in triton bombardments of ^{148}Nd. This activity is not the daughter of ^{152}Nd (0^+), since its relatively intense 1097- and 1437-keV photopeaks were not observed in the equilibrium ^{152}Nd-^{152}Pm sources. A comparison of the upper limit of 0.007 for the intensity of the 1437-keV transition in 4.1-min ^{152}Pm with the value of 0.161 obtained for 7.5-min ^{152}Pm (see Table II) establishes that $\leq 4\%$ of the 7.5-min activity can be formed by an isomeric transition from 4.1-min ^{152}Pm. Presumably, the 7.5-min activity is a higher-spin isomer of ^{152}Pm which is confirmed by its excitation of high-spin levels in ^{152}Sm.

2. Radiations

Measurements of the half-lives and intensities of the photopeaks observed in spectra of Pm sources chemically separated from Nd were compared with those from spectra of the Nd-Pm equilibrium sources. Figure 3 shows such a comparison for the higher-energy portion of the spectra. The numerous unmarked photopeaks in the spectrum from the Nd-Pm equilibrium sources are due to

TABLE I. Summary of γ-ray data for ^{152}Nd.

Energy (keV)	γ-ray intensity Relative	Absolute[a]	Assumed multipolarity	Transition intensity
16 ±0.5	0.25±0.06	0.077	$E1$	0.62
28.6±0.2	0.04±0.02	0.012	$M1$	0.15
74.6±0.2	0.04±0.02	0.012	$E1$	0.02
176 ±2	≤0.07	≤0.02	$M1$	≤0.03
250.1±0.2	0.68±0.03	0.21	$E1$	0.21
278.5±0.2	1.00	0.31	$E1$	0.31
294.6±0.2	0.12±0.01	0.04	$M1$	0.04

[a]The relative γ-ray intensities were converted to absolute intensities on the basis of the experimentally determined absolute intensity of 0.31 for the 278.5-keV γ ray.

TABLE II. Summary of γ-ray data for ^{152}Pm.

Energy (keV)	Transition intensity [a] 4.1-min ^{152}Pm Relative	Absolute	7.5-min ^{152}Pm Relative	Absolute
121.8 ± 0.1 [b]	1.00	0.274	1.00	0.944
137 ± 1 [c]	...	...	(0.006)	(0.005)
231 ± 1 [c]	...	...	(0.013)	(0.012)
244.7 ± 0.1 [b]	0.062 ± 0.013	0.017	0.63 ± 0.03	0.59
340.2 [d]	...	...	0.30 ± 0.1	0.28
361.3 ± 0.2 [c]	...	...	(0.003)	(0.003)
432.0 ± 0.2	...	...	0.014 ± 0.003	0.013
656.2 ± 0.5 [e]	masked	...	0.029 ± 0.005	0.027
689.0 ± 0.3 [e]	0.023 ± 0.010	0.006	0.015 ± 0.003	0.014
696.5 ± 0.2	0.098 ± 0.015	0.027 [f]	0.027 ± 0.002	0.025
781.1 ± 0.3	...	...	0.035 ± 0.004	0.033
811 ± 1	0.036 ± 0.015	0.010	0.028 ± 0.005	0.026
814 ± 1	0.027 ± 0.010	0.007 [f]	0.020 ± 0.004	0.019
818 ± 1	≤0.014	≤0.004 [f]	masked	...
841.7 ± 0.3	0.116 ± 0.010 [g]	0.032	0.043 ± 0.006	0.041
853.5 ± 0.5	0.056 ± 0.015	0.016 [f]	...	...
867.7 ± 0.5	...	...	0.016 ± 0.004	0.015
901 ± 1	...	...	0.017 ± 0.004	0.016
920.0 ± 0.3	0.037 ± 0.015	0.010	0.026 ± 0.005	0.025
926.5 ± 0.4	0.033 ± 0.015	0.009	...	...
≈962 (complex)	0.32 ± 0.05 [g]	0.088	0.080 ± 0.010	0.076
1004.5 ± 0.5	...	...	0.031 ± 0.010	0.029
1021.6 ± 0.2	...	...	0.011 ± 0.004	0.010
≈1081	0.04 ± 0.01 [g]	0.011	0.006 ± 0.002	0.006
1085.9 ± 0.4	≤0.016	≤0.004 [f]	0.013 ± 0.005	0.012
1097.0 ± 0.2	...	...	0.235 ± 0.025	0.222
1112.2 ± 0.4	...	...	0.034 ± 0.008	0.032
1194 ± 1	...	...	0.018 ± 0.006	0.017 [f]
1214 ± 1	...	...	0.018 ± 0.006	0.017
1233.8 ± 0.7 [c]	...	...	(0.004)	(0.004)
1250.3 ± 0.3	...	...	0.008 ± 0.004	0.008
1293 ± 1	0.015 ± 0.005	0.004	≤0.007	≤0.007 [f]
1298 ± 1	0.047 ± 0.010	0.013	...	...
1321.2 ± 0.5	0.037 ± 0.010	0.010	≤0.016	≤0.015
1389 ± 1	0.014 ± 0.010	0.004	0.006 ± 0.003	0.006 [f]
1406.2 ± 0.5	...	...	0.005 ± 0.003	0.005
1437.5 ± 0.3	≤0.007	≤0.002 [f]	0.161 ± 0.015	0.152

[a] Our absolute efficiency calibration is estimated to be accurate to ±10%, while relative efficiencies are estimated to be accurate to ±5%. Quoted errors are based on statistical considerations only.

[b] These $E2$ transitions have been corrected for internal conversion; total conversion coefficients of 1.15 and 0.11 for the 122- and 245-keV transitions, respectively, were obtained by interpolation in the tables of Ref. 22.

[c] These transitions have been attributed principally to the 18-min isomer of ^{152}Pm, and the intensities have been corrected to the end of bombardment using an 18-min half-life. These intensities were derived from 9-MeV triton bombardments. The 137-keV photopeak was masked in singles spectra so its intensity relative to the 231-keV photopeak was derived from spectra gated by the 340- and 1437-keV photopeaks (Table III).

[d] The 340-keV photopeak is masked in singles spectra by the strong 340.1-keV transition from ^{151}Pm, but its energy in coincidence spectra appears to be consistent with the value of 340.2 keV given in Ref. 19. Its intensity was derived relative to the 245-keV photopeak from coincidence spectra gated by the 122-keV photopeak (Table III).

[e] These transitions are reported in Ref. 16 to have $E0+E2$ multipolarity, and the intensities have been corrected for internal conversion according to the experimentally determined conversion coefficients given in Ref. 16.

[f] These transitions have not been placed in the respective level schemes.

[g] These intensities were corrected for the contribution from ^{151}Nd.

^{151}Nd; those in the spectrum from separated Pm sources are mostly from 28-h ^{151}Pm with a small contribution from 2.7-h ^{150}Pm. After subtraction of the contribution from the other Pm isotopes and 4.1-min ^{152}Pm, more than 25 γ transitions were attributed to the decay of the 7.5-min ^{152}Pm. A summary of the energy and intensity data for these photopeaks is given in Table II.

Some γ-γ coincidence experiments were performed using the 25-cm^3 Ge(Li) detector gated by pulses from the NaI(Tl) detector. The results are summarized in Table III.

In order to determine the end-point energy of the more intense β groups of the 7.5-min ^{152}Pm without interference from the β radiation from the 4.1-min activity, the β-ray spectrum was gated by the 1437-keV photopeak detected in the NaI(Tl) crystal. A β end-point energy of 1.8 ± 0.1 MeV was observed.

An experiment using the same arrangement was performed in an attempt to measure a possible delay between the β radiation and the 1437-keV γ ray. The output of a single-channel analyzer set to admit only pulses from β radiation less than ≈ 2 MeV was used as the start pulse for an ORTEC 437 time-to-amplitude converter. The output from another single-channel analyzer set to correspond to γ radiation in the 1.35- to 1.55-MeV range was used as the stop pulse. The output from the TAC was then fed to a 400-channel analyzer. Time intervals corresponding to 2.3, 21, and 222 nsec per channel were used. In all cases the signal from the 1437-keV photopeak appeared in the same position as a prompt signal from a ^{60}Co standard and had the same width, ≈ 14 nsec. Therefore, within the limitations of the measurement, any delay of the 1437-keV transition is less than 20 nsec.

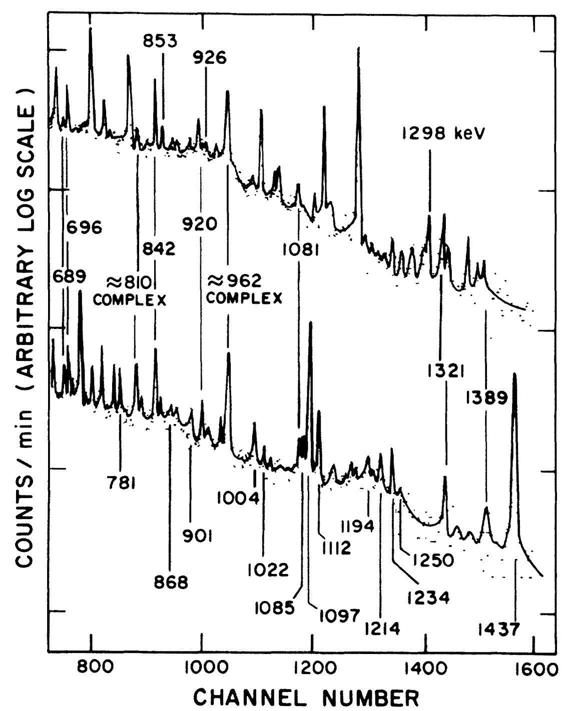

FIG. 3. The upper curve presents the high-energy γ spectrum of a purified Nd source plus the Pm daughters, including ^{152}Nd and its 4.1-min ^{152}Pm daughter (midtime of count ≈ 18 min after separation from Pm). The lower curve shows the γ spectrum of a purified Pm source, including 7.5-min ^{152}Pm but relatively little of the 4.1-min isomer (midtime of count ≈ 5.5 min after separation from Nd, 25.9 min after the end of bombardment). Photopeaks common to both spectra are indicated. (The solid line is only intended as a visual aid; the energies and intensities of the photopeaks were determined by analysis of many such spectra.)

C. ^{152}Pm(≈ 18 min)

In the γ-γ coincidence measurements of separated Pm sources the spectra gated by the 122-, 340-, and 1437-keV photopeaks showed γ rays of 137 and 231 keV (Table III). Figure 5 shows the γ spectrum in coincidence with the 1437-keV photopeak. The 231-keV transition in both singles and coincidence spectra decayed with a half-life of 18 $\pm$ 3 min. The 137-, 361-, and 1234-keV photopeaks (Table II) appeared to decay with a somewhat shorter half-life which suggests contributions from both 7.5- and 18-min components. The 18-min activity was not present in spectra observed after triton bombardment of ^{148}Nd and consequently cannot be associated with the decay of

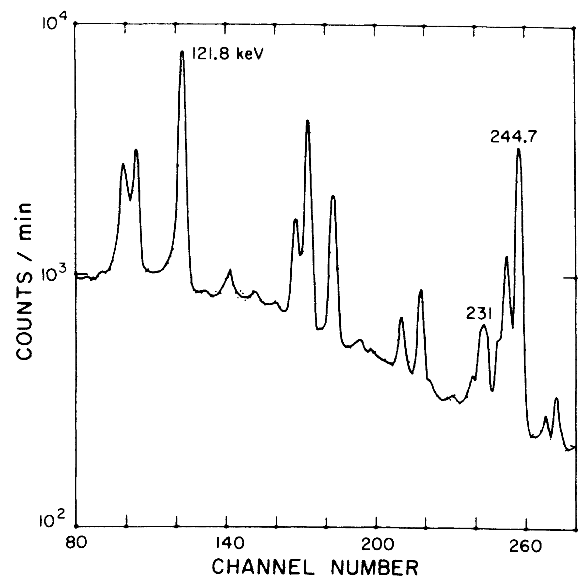

FIG. 4. Low-energy portion of the same γ spectrum for the purified Pm source shown in Fig. 3.

^{149}Pm or ^{150}Pm. It seems unlikely that this activity could be an isomer of ^{151}Pm, since Q_β is only ≈ 1.2 MeV[8] and the observed 1.437–0.231-MeV coincidence would require a very highly excited isomeric state in ^{151}Pm. We have attributed the 18-min activity to another isomer of ^{152}Pm which ultimately decays to ^{152}Sm levels also populated by the 7.5-min ^{152}Pm. The yields of the γ transitions attributed to the 18-min isomer were higher when triton energies of 11 MeV rather than 9 MeV were used, but they were still of very low intensity. This suggests a higher-spin assignment for the 18-min than for the 7.5-min isomer. In addition, the half-lives of some photopeaks, such as 1437 keV, appeared to be longer than 7.5 min in the 11-MeV bombardments, indicating additional feeding by the 18-min activity.

IV. DECAY OF ^{152}Nd

A preliminary decay scheme for ^{152}Nd incorporating all of the observed γ rays is shown in Fig. 6. Although we do not know which of the isomeric states of ^{152}Pm is the ground state, the 4.1-min level has been taken as zero energy in this discussion. [The 4.1- and 7.5-min isomers are believed to be within ≈ 100 keV of each other (see Sec. VI) so our estimates of Q_β would not be appreciably changed.] The transition intensities were calculated from the results given in Table I together with appropriate conversion coefficients[22] for the multipolarities indicated in Fig. 6. The multipolarities have not been measured, so these assignments are only tentative and have been chosen to be consistent with the level scheme. However,

TABLE III. γ-γ coincidence data for 7.5- and 18-min ^{152}Pm.

Energy (keV)	Relative photopeak intensity[a] 122-keV gate	340-keV gate	1437-keV gate
122[b]	···	0.94	0.91
137	0.016	0.013	0.010
231	0.024	0.031	0.022
245[b]	1.00	1.00	1.00
340	0.47	···	···
≈367	···	≈0.01[c]	≈0.03[c]
1097	0.58	0.79	···

[a] The intensities of the 137- and 231-keV photopeaks were corrected to end of bombardment using an 18-min half-life; the other intensities were corrected using a 7.5-min half-life.

[b] The intensities of these $E2$ transitions have been corrected for internal conversion.

[c] Spectra gated by the 340- and 1437-keV photopeaks appeared to show excess 367-keV photopeak over that attributable to summing of the 122- and 245-keV γ transitions.

with these assumptions it appears that there is little or no direct β decay to the 16- or 44.6-keV levels.

The intensity of the 279-keV γ ray relative to the 3.6-MeV β group in 4.1-min ^{152}Pm was determined by comparing the γ intensity with the β-disintegration rate of the same Nd-Pm equilibrium source. The β-disintegration rate was obtained with the anthracene detector by counting β rays with energies greater than 2.2 MeV. The efficiency for detection of the 3.5- to 3.6-MeV β groups was determined by counting a ^{106}Ru-^{106}Rh standard ($E_\beta = 3.1$–3.55 MeV, $\approx 80\%$) of known disintegration rate. In duplicate experiments, values of 25.6 and 23.7%, giving an average of 24.7%, were obtained for the intensity of 279-keV γ rays to β rays in the 3.5- to 3.6-MeV β groups. According to the decay scheme of Fig. 7, the intensity of the 3.5- to 3.6-MeV β groups is $\approx 80\%$, and, therefore, the $I_{279\,\gamma}/I_{\Sigma\beta\,^{152}Pm} = 20\%$. Since, within our limits of detection, all of the ^{152}Nd decays to 4.1-min ^{152}Pm, the intensity of ^{152}Nd in a source in transient equilibrium is

$$\left(\frac{d}{m}\right)_{^{152}Nd} = \frac{\lambda_{^{152}Pm} - \lambda_{^{152}Nd}}{\lambda_{^{152}Pm}} \left(\frac{d}{m}\right)_{^{152}Pm} = 0.64\left(\frac{d}{m}\right)_{^{152}Pm}$$

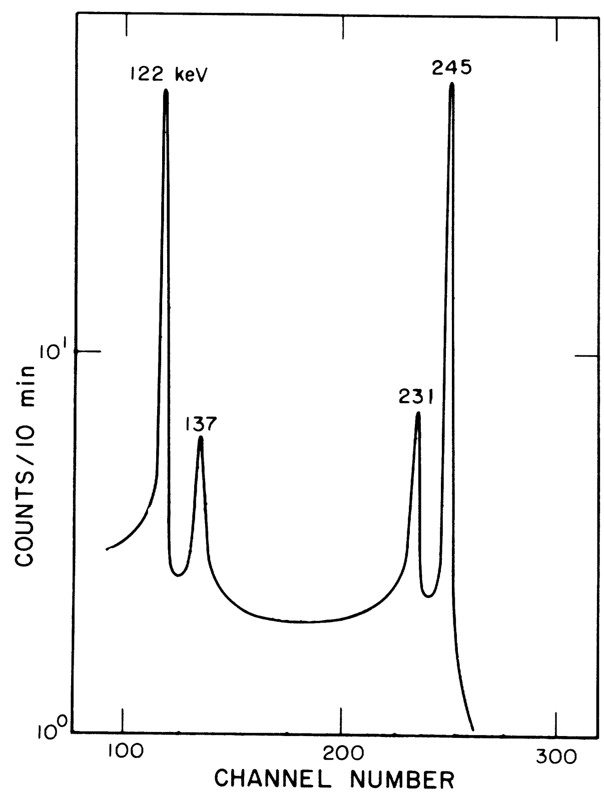

FIG. 5. ^{152}Pm γ spectrum gated by the 1437-keV photopeak (midtime of count ≈ 15 min after separation from Nd).

and therefore, $(I_{279\,\gamma}/I_\beta)_{^{152}\mathrm{Nd}} = 0.20/0.64 = 0.31$. Our measurements were made ≈40 min after initial separation from Pm, so the equation for transient equilibrium is applicable, since $e^{-\lambda_{^{152}\mathrm{Pm}} t}$ is ≤1.5% of $e^{-\lambda_{^{152}\mathrm{Nd}} t}$.

If one assumes Q_β for ^{152}Nd to be 1.0 MeV,[9-11] log*ft* values of 4.8 and 4.2 can be calculated for the β transitions to the 0- and 294.6-keV levels of ^{152}Pm. These values clearly indicate allowed β decay, and permit the assignment of $I^\pi = 1^+$ to these levels. Several low-lying orbitals are available from which 1^+ levels can be constructed. The lowest-energy Nilsson level assignments for the 61st proton and the 91st neutron results in a 1^+ state with the configuration $\frac{3}{2}^+[651]_n\,\frac{5}{2}^+[413]_p$. The β decay of ^{152}Nd to this state, involving the conversion of a $\frac{3}{2}^+[651]$ neutron to a $\frac{5}{2}^+[413]$ proton, would be severely hindered. However, the asymptotic quantum number assignments for this $\frac{3}{2}^+$ orbital are not unique, because of interaction with other $\frac{3}{2}^+$ orbitals such as the $\frac{3}{2}^+[402]$; in fact, recent calculations of single-particle levels in a deformed Woods-Saxon potential[23] indicate that the latter component predominates when the deformation parameter, β, ≳0.3. β decay involving this component would be considerably less hindered.

Combination of the low-lying $\frac{5}{2}^-[532]_p$ and $\frac{3}{2}^-[521]_n$ orbitals gives 1^+ as the excited state and 4^+ as the lower-energy state. Such a 1^+ level could be populated by somewhat hindered allowed β decay. Another possibility for the construction of a 1^+ level involving the $\frac{3}{2}^-[541]_p$ and $\frac{5}{2}^-[523]_n$ orbitals would result in hindered allowed β decay.

The 294.6-keV transition must be $M1$ or $M1+E2$ if the 1^+ assignments for the 0- and 294.6-keV levels are correct. On the basis of relative intensities, the 250.1- and 278.5-keV transitions may be hindered $E1$ transitions. (Single-particle estimates would indicate they should be ≈100 times as intense as the 294.6-keV transition.) This is consistent with assignments of 0^-, 1^-, or 2^- for the 16- and 44.6-keV levels. A possible 44.6-keV transition was masked by K x radiation from Pm. The existence of a level at ≈119 keV was postulated to accommodate the weak 74.6-keV transition. An upper limit to the intensity of a possible 176-keV γ transition was estimated after correction for a rather large contribution from ^{151}Nd. The reduced transition probability for the 176-keV transition relative to the 294.6-keV transition is most consistent with an $M1$ assignment. Then the 119-keV level must have positive parity and the 74.6-keV transition is most likely $E1$. The intensities given in Fig. 6 are based on these assignments and give a reasonable intensity balance. It would appear that the level at 119 keV is not appreciably populated by direct β decay, and therefore must have a spin greater than 1; 2^+ is the most likely assignment, and can be readily constructed from low-lying Nilsson orbitals, such as $\frac{7}{2}^+[404]_p + \frac{3}{2}^+[651]_n$. Possible transitions of 103 and 119 keV to the 16- and 0-keV levels, respectively, are masked by radiations from ^{151}Nd.

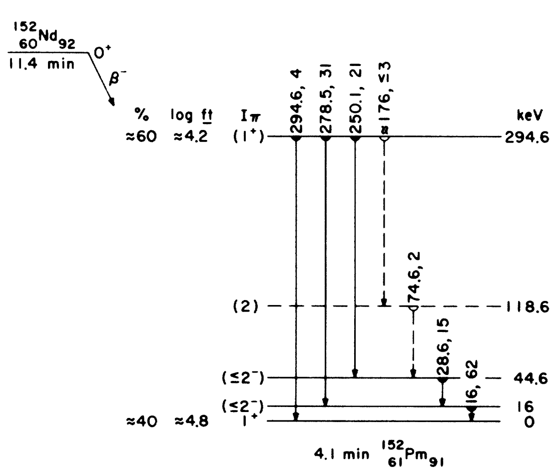

FIG. 6. Proposed decay scheme for 11.4-min ^{152}Nd. The open semicircles with dashed lines indicate doubtful transitions. Since it is not known which isomeric state of ^{152}Pm is the ground state, energies are given relative to the 4.1-min (1^+) ^{152}Pm state as zero.

V. DECAY OF 4.1-min ^{152}Pm

Figure 7 shows a partial decay scheme for 4.1-min ^{152}Pm formulated from our experimental results together with information concerning the ^{152}Sm levels obtained from decay[8,12-16] of ^{152}Eu, Coulomb excitation experiments,[17-19] ^{150}Sm(t, p)-^{152}Sm reactions,[20] and ^{152}Sm(p, p') studies.[21] The intensity of the 121.8-keV γ transition relative to total 4.1-min ^{152}Pm β transition was determined in the same experiments described in Sec. IV. Values of 27.9 and 26.8%, for an average of 27%, were obtained. From the intensities of the γ transitions as placed in Fig. 7, it was calculated that ≈70% of the β transitions proceed to the ground state, and ≈10% feed the 121.8-keV level. Thus the measured β end-point energy of 3.6 is very nearly the energy of the ground-state transition, and Q_β is then 3.6 ± 0.2 MeV for 4.1-min ^{152}Pm.

The log*ft* value of ≈6.5 for β decay of 4.1-min ^{152}Pm (1^+) to the 0^+ ground state of ^{152}Sm indicates that the allowed β transition is rather highly hindered. If the configuration for the 1^+ level is $\frac{5}{2}^+[413]_p$ coupled with $\frac{3}{2}^+[651+402]_n$ as discussed in Sec. IV, perhaps the hindrance may be attributed to a larger contribution from the $\frac{3}{2}^+[651]$ neutron state to the ground-state configuration of ^{152}Sm.

The energies, spins, and parities of the levels at 121.8, 366.5, 685, 811, 963.5, 1042, 1293, and 1511 keV in ^{152}Sm have been well established by decay studies of ^{152}Eu, and in Coulomb-excitation and reaction studies. We identify the 1298- and 1443-keV levels of Fig. 7 with the 1298- and 1440-keV levels seen only in the (p, p') studies.[21]

On the basis of our coincidence results and the energy sum, a new level has also been placed at 1081 keV. This is not the same as the 1086-keV level (2^+) observed in other studies, since a 1081-keV, but not the 1086-keV, γ ray is observed in the decay of 4.1-min ^{152}Pm. (However, the 1086-keV γ ray is observed in the decay of 7.5-min ^{152}Pm, Table II.) The intensity of the $\approx$960-keV γ ray depopulating this level was obtained after correcting the intensity of the complex 962-keV photopeak for the contribution from the 963-keV transition out of the 963.5-keV level, using the relative-intensity data[15] for ^{152m}Eu for the 963- and 842-keV transitions. The new level at 1081 keV is deexcited to the 0^+ and 2^+ members of the ground-state rotational band, and most probably has an assignment of $1^{\pm}$ or 2^+. Any of these assignments would be consistent with the direct β population ($\log ft \approx 6.9$) of the state from a 1^+ parent.

The known 4^+ level at 366.5 keV cannot be fed directly by β decay from the low-spin ^{152}Pm, and the observation of the 244.7-keV γ ray which deexcites this level indicates that it must be populated by γ transitions from higher-energy levels. Among these are the 926.5-, 675-, and 444-keV transitions. The 444- and 675-keV transitions are masked by ^{151}Nd, but we have estimated their intensities from other studies.[13-16] An intensity balance of 1.3% into the level vs $\approx$1.7% out is then obtained, which is probably within our limits of error, although there may still be other weak transitions feeding the level.

Although we might expect the known 0^+ level at 685 keV to be populated by β decay, the 563-keV γ transition which deexcites the level is again masked by ^{151}Nd so we cannot determine its intensity accurately, but it is less than $\approx$0.3%. The $\log ft$ for β decay to this level is then $\geqslant$8.3. This seems like an extremely high value, but considering that the $\log ft$ value for β decay to the ground state is $\approx$6.5, it does not seem unreasonable that the β decay to the collective 0^+, β-vibrational state is hindered by another factor of 50 to 100.

The 689-keV γ ray which deexcites the known 811-keV (2^+) level was observed in the γ singles spectrum of 4.1-min ^{152}Pm and in coincidence with the 122-keV photopeak. The intensities of the 444- and 811-keV transitions relative to our measured 689-keV transition intensity were calculated from the ^{152}Eu decay data.[13-16] This leaves most of our observed intensity of the 811-keV γ ray unaccounted for.

The 841.7-keV γ transition deexcites the known 1^- level at 963.5 keV, and the intensity of the 963-keV ground-state transition is calculated from the decay data[15] for 9.3-h ^{152m}Eu. The $\log ft$ value of $\approx$7.0 for β decay to this level is consistent with the level assignments.

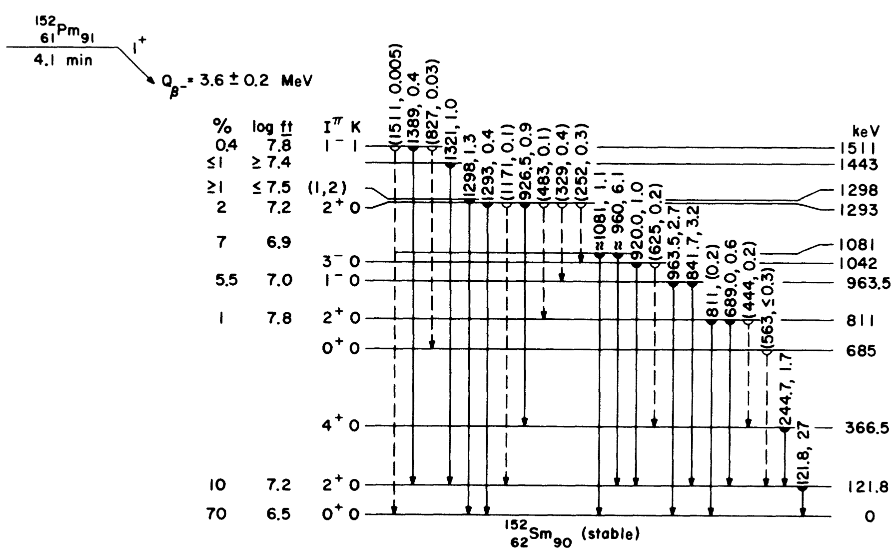

FIG. 7. Proposed decay scheme for 4.1-min ^{152}Pm. Transitions with energy values in parentheses were not observed, but have been reported previously as occurring between the indicated levels. Intensities given in parentheses for undetected γ transitions were calculated from observed intensities of other transitions from the same level and previously reported relative intensities. Intensities given in parentheses for some detected transitions were calculated by division of our measured intensities according to previously reported relative intensities.

The observation of a 920-keV photopeak seems to indicate excitation of the 1042-keV level, assigned[13, 16, 18, 21] as 3^-. There should be essentially no direct β population of this level, so again it must be fed from higher-energy levels by γ transitions which we have been unable to detect; the known 252-keV transition populating the level is not intense enough to account for all the population.

The level at 1293 keV, populated by the decay of ^{152g}Eu, is reported[16] to decay via 251.7-, 329.4-, 482.8-, 926.2-, 1171.0-, and 1292.6-keV transitions and was given an assignment $I^{\pi}K = 2^+0$. Of these, we see only the 926.5- and 1292.6-keV transitions; the others are either too weak or masked by other photopeaks.

The level at 1298 keV is presumably the same as that observed at 1298 keV in the (p, p') studies.[21] The 1298-keV γ ray was not observed to be in coincidence with the 122-keV γ ray (Sec. III A 2), and therefore, it presumably deexcites the 1298-keV level. Aquili, Cesareo, and Giannini[13] and Riedinger, Johnson, and Hamilton[16] saw a relatively strong 1299-keV γ transition in the decay of ^{152g}Eu, but did not place it in their level schemes for ^{152}Sm. It probably represents the transition deexciting this same level in ^{152}Sm. The level must have a spin of 1 or 2, since it populates the ground state, but we do not have enough information to make a parity assignment.

The observation of a 1321-keV photopeak in coincidence with the 122-keV transition is consistent with its depopulation of the 1443-keV level. This level has been seen previously in the (p, p') studies,[21] and no spin or parity assignments were made.

The level at 1511 keV was observed in the decay of ^{152m}Eu (0^-), and in the (p, p') studies, but not in the decay of ^{152g}Eu (3^-). We see a 1389-keV γ ray which presumably deexcites this level, but the associated[15] 1511-, 827-, and 700-keV transitions are all less than 7% of the intensity of the 1389-keV transition and therefore are too weak for us to observe. The log*ft* value for β population of this 1^- level from ^{152}Pm is ≈ 7.8.

VI. DECAY OF HIGH-SPIN ISOMERS OF ^{152}Pm

Figure 8 shows a tentative decay scheme for the high-spin isomers of ^{152}Pm. The spins, parities, and energies of the ^{152}Sm levels at 121.8, 366.5, 706.7, 811, 963.5, 1023, 1042, 1086, 1126, 1234, 1372, 1530, and 1580 keV have been fairly well established from decay studies[8, 12–16] of ^{152}Eu and from reaction studies.[17–21] We believe the levels at 1388, 1443, and 1777 keV are probably the same as those observed at 1385, 1440, and 1775 keV in the (p, p') studies.[21] On the basis of our coincidence studies and energy sums, we have placed

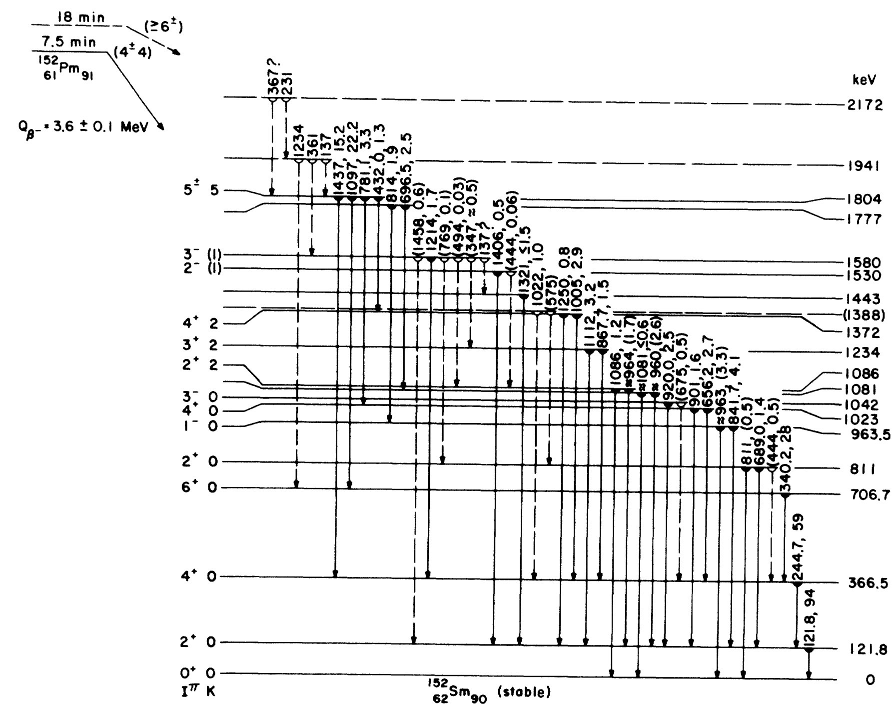

FIG. 8. Proposed decay scheme for the 7.5- and ≈18-min isomers of ^{152}Pm. The relative energies of these isomers are not known.

new levels at 1081, 1804, 1941, and 2172 keV. The levels at 121.8, 366.5, 811, 963.5, 1042, 1081, and 1443 keV are also populated by the decay of the low-spin isomer of ^{152}Pm.

The fact that we observed a 1.8 ± 0.1-MeV β group in coincidence with the 1437-keV photopeak which deexcites the level at 1804 keV establishes the total β-decay energy for 7.5-min ^{152}Pm as 3.6 $\pm$ 0.1 MeV. Since Q_β for the 4.1-min, low-spin isomer of ^{152}Pm was found to be 3.6 ± 0.2 MeV (Sec. V), it is impossible to determine from the energy measurements which isomer is the lower-energy state of ^{152}Pm. It would appear that their energies are within 100 keV of each other. As stated in Sec. III B 1, a limit of $\leq 4\%$ could be set for the amount of the 7.5-min isomer that could be produced by a possible isomeric transition from the 4.1-min isomer. However, since the purified Pm fraction is always a mixture of the isomers, it was very difficult to set a meaningful limit on the amount of the low-spin isomer that might grow from the 7.5-min isomer. From the observation of the decay of the 853- and 1298-keV transitions in separated Pm samples, we estimate that no more than $\approx 10\%$ of the 4.1-min activity can be formed in this way.

Assignments of $3^\pm$ for the 7.5-min ^{152}Pm can probably be ruled out because the lifetimes of the γ transitions would be so short that isomeric transition would be expected to be the predominant mode of decay. Assignments of $4^\pm$ would probably be consistent, since the possible $E3$ or $M3$ transitions might be somewhat hindered. Spins of ≥ 5 are probably ruled out, since some spin-3 levels in ^{152}Pm appear to be fed directly by β decay with logft values of 7 to 8. As mentioned previously (Sec. IV), 4^+ states can be made by appropriate coupling of the neutron and proton levels which probably contribute to the 1^+ levels in ^{152}Pm fed by the β decay of ^{152}Nd. A 4^- state can also be composed of the low-lying $\frac{5}{2}^+[413]_p$ and $\frac{3}{2}^+[521]_n$ levels, but it would be the higher-energy state.

Although we were not able to determine the absolute γ-transition intensities for the 7.5-min isomer, if its spin is 4, there should be no detectable direct β feeding of the 122-keV or ground-state levels of ^{152}Sm, and the total γ intensity feeding the ground state was therefore normalized to 100%. The intensity of the γ transitions feeding the 122-keV level is $\approx 80\%$, while the intensity of the 122-keV transition deexciting the level is 94%. This discrepancy is probably due in part to experimental errors in determining the γ intensities, and to the corrections which had to be made for the 4.1-min isomer which contributes much more to the 122- than to the 244-keV transition. In addition, there are at least two γ transitions having a total intensity of $\approx 4\%$ which we have not been able to place in the decay scheme, and there may be others which we have not been able to detect because of interference from other isotopes present.

With the present assignment of $4^\pm 4$ for 7.5-min ^{152}Pm, the β transition to the well-established 4^+0 level at 366 keV is K forbidden by at least 4 units and would therefore be expected to have a logft value 8 units higher than normal, or a logft of at least 12, corresponding to a β intensity of $< 10^{-3}\%$. Again, we attribute the discrepancy in the intensity balance for this level (54 vs 59%) to errors in our γ intensities and to possible undetected transitions.

The β transitions to the established levels at 811, 963, 1086, and 1530 keV would have $\Delta I = 2$ and therefore should have logft values $\gtrsim 9$ and intensities $\leq 0.5\%$. β decay to the levels at 1022 and 1042 keV would be K forbidden by 4 and 3 units, respectively, and β feeding should be $< 0.1\%$. Since we observe considerable γ decay from all of these levels, they are probably populated by γ transitions from higher-energy levels, but we have been unable to identify many of them.

A logft value of 7.6 can be calculated for the β transition to the 1234-keV level if one assumes no other appreciable γ population of the level. The value is consistent with β population of this 3^+ $(K = 2)$ level by allowed or first forbidden β decay with K forbiddenness of 1. Similar arguments can be made for the possible allowed or first forbidden β transitions to the 1372- and 1580-keV levels. The calculated logft values of 7.7 and ≤ 7.4 appear to be somewhat low for transitions which are forbidden by 2 units in K.

The level at ≈ 1777 keV may be deexcited by 696- and 814-keV γ transitions to the 1081- and 963-keV levels. The level was not seen in the decay of the low-spin isomer, and may be directly fed by β decay of the high-spin isomer since we have not found evidence of γ population from higher-energy levels.

A new level has been placed at 1804 keV on the basis of our coincidence results (Table III) which established the 1437-, 245-, 122-keV and the 1097-, 340-, 245-, 122-keV cascades involving the ground-state rotational band. On the basis of energy differences, the level also appears to be deexcited by weak 432- and 781-keV transitions to the 4^+ levels at 1372 and 1023 keV. If there is no appreciable γ population of the 1804-keV level, a logft value of 5.7 is obtained for the β transition populating the level. This logft value indicates a hindered allowed, or possibly a first-forbidden β transition, with no K forbiddenness. In either case, the spin of the level is restricted to 3, 4, or 5 if the 7.5-min ^{152}Pm has a spin of 4. Since the level is strongly deexcited to the 6^+0 level, the spin assignment of 3 is ruled out. An assignment of 4^+ seems unlikely since the transition to the 2^+ member of the ground-state rotational band is not observed, and the experimentally observed ratio of the 1437- to 1097-keV $B(E2)$ transition probabilities is only 0.18. The observation of a very intense 1097-keV transition to the 6^+0 level rules out the 4^- assignment. Therefore, the remaining assignments of $5^\pm$ seem the most consistent with the observed γ deexcitation of the level. If the K of the level is also 5, as is indicated by the lack of K forbiddenness in the β decay to the level, one would expect the transitions to the 6^+ and 4^+ members of the ground-state rotational band to be retarded by as much as 10^8 over the single-particle estimates. This would lead to estimates as long as $\approx 10^{-6}$ sec for $M1$ transitions and $\approx 10^{-8}$ sec for $E1$ transitions. Our observation that the lifetime of the level is ≤ 20 nsec is perhaps more consistent with the 5^- assignment, but if there is much mixing with other states such a conclusion may be unwarranted.

Levels could be placed at 1941 and either 2035 or 2172 keV to account for the observation of 137- and 231-keV γ transitions in coincidence with the 1437-keV transition (Table III). The main reason for tentatively placing the level at 2172 keV is the observation of a 367-keV photopeak (probably in excess of that due to summing of the 122- and 244-keV photopeaks) in the coincidence spectra. On the basis of energy considerations, an observed 1234-keV γ ray may be the transition from the 1941- to the 707-keV (6^+0) level. The 231-keV photopeak decayed with a half-life of 18 ± 3 min, while the 137-, 361-, and 1234-keV photopeaks appeared to decay with somewhat shorter half-lives, intermediate between 7.5 and 18 min (Sec. III C). A possible explanation for these observations is the existence of an 18-min isomer of ^{152}Pm which has a spin ≥ 6 so that it does not decay entirely via isomeric transition to the 7.5-min ^{152}Pm, but decays by β transition to 1941- and 2172-keV levels in ^{152}Sm. The 2172-keV level might presumably be fed only by the 18-min isomer, and depopulated by the 231-keV transition, while the 1941-keV level might be fed by both the 7.5- and 18-min isomers, thus accounting for the observation of intermediate half-lives for the 137-, 361-, and 1234-keV transitions which deexcite it. (There may also be a 137-keV transition between the 1580- and 1443-keV levels in ^{152}Sm.) The 1214-keV transition which presumably deexcites the 1580-keV level decays with an apparent half-life of ≈ 11 min. This would be consistent with population of this level from the 1941-keV level via the low-intensity 361-keV transition. Since the 2172-keV level appears to be populated primarily by the 18-min isomer, its spin is probably 6 or higher; if the 1941-keV level is populated directly by β decay from the 7.5-min isomer, its spin should be no greater than 5.

ACKNOWLEDGMENTS

We wish to express our appreciation to the personnel of the Los Alamos Van de Graaff facility for providing the bombardments, and to Mrs. F. O. Lawrence for assistance with the chemistry and data processing. We also wish to thank Dr. J. D. Knight and Dr. C. J. Orth for many helpful discussions. The interest and support of Dr. G. A. Cowan and Dr. J. E. Sattizahn is gratefully acknowledged.

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†Work performed under the auspices of the U. S. Atomic Energy Commission.

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PHYSICAL REVIEW C VOLUME 4, NUMBER 3 SEPTEMBER 1971

Comparison of the Nuclear-Reaction Energy Scale with the Gamma-Ray Energy Scale*

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The excitation energy of the first excited state of ^{24}Mg was measured with inelastic deuteron scattering using the energy of α particles from ^{210}Po as a standard. The result is 1368.2 $\pm$ 0.5 keV. The average of recent measurements of the energy of γ rays emitted by this state gives an excitation energy of 1368.67 keV based on the electron rest-mass energy. Thus the widely used polonium calibration energy is found to be consistent with the γ-ray energy standard to within 0.04%.

I. INTRODUCTION

The purpose of this work is a direct comparison of the energy scale used for γ rays with one widely used for particle energies. γ-ray energies are based on the energy equivalent of the electron mass, usually through the energy of the ^{198}Hg(0.411 MeV) decay, whereas particle energies are based on decay energies of radioactive α emitters (usually ^{210}Po), or threshold or resonance energies. These scales are presumed to be based on absolute measurements and are usually assumed to be consistent. There is, of course, much indirect evidence that they are consistent, because energy-level differences measured with particle reactions generally agree with those deduced from the energy of the γ-ray transition between the levels. Caution must be used in making such comparisons because often the γ-ray energies are based on assumed energy-level differences which have in turn been measured against ^{210}Po, and often it is not clear what fundamental energy scale has been used in reported measurements. For these reasons it was considered desirable to make a direct comparison of the ^{210}Po α energy with the ^{198}Hg energy. Of course the ^{210}Po α energy has been measured[1] absolutely and the ^{198}Hg γ ray is presumably known to very high accuracy[2] in terms of the fundamental constants. A direct comparison is then, in a sense, a check on the accuracy of these measurements, but the present interest is verification of the consistency of energy standards used for nuclear energy measurements.

Previous work in this laboratory[3] has shown that the ^{210}Po α energy agrees with the ^{7}Li(p, n)^{7}Be threshold energy commonly used and with the absolute determination of the RaC′ decay energy. Some question remained, however, about the comparison of the γ-ray energy scale and the ^{7}Li(p, n)-^{7}Be threshold. A comparison of the energy scales may be made by measuring the excitation of a nuclear state with charged-particle analysis in terms of the ^{210}Po energy and measuring the decay γ-ray energy in terms of the ^{198}Hg decay energy.

For a precise comparison with the ^{210}Po energy an excitation energy as near 5.3 MeV as possible is desired, but γ-ray measurements become difficult above 1 MeV. A good compromise may be made using the ^{24}Mg state at 1.368 MeV. The γ-ray transition to the ground state has been very carefully measured in two laboratories. We summarize these measurements and then discuss our measurement of the excitation energy using charged-particle reactions.

In the accurate γ-ray energy measurements a secondary standard, namely a transition energy in ^{198}Hg, was used. As the ^{198}Hg transition was in turn measured[2] against the annihilation radiation, both measurements tie the ^{24}Mg γ-ray energy to the electron rest mass. Changes in the fundamental constants of physics will change the resulting value but the changes will probably be less than 0.1 keV, which is smaller than the uncertainties in the present particle energy measurements.

External conversion was used with the Chalk River iron-free β spectrometer by Murray, Graham, and Geiger[4] to compare the ^{24}Mg(1.37 MeV) γ-ray energy, directly and through four "secondary calibration standard" γ rays from ^{208}Pb and ^{60}Ni. The resulting level energy is found to be 1368.568 $\pm$ 0.044 keV. A curved-crystal spectrometer was