Structure of ^{142}Sm from the decay of ^{142}Eu

G. G. Kennedy, S. C. Gujrathi, and S. K. Mark
Foster Radiation Laboratory, McGill University, Montreal, Canada
(Received 24 February 1975)

^{142}Eu has been observed to have two isomers with half-lives 1.22 ± 0.22 min (^{142}Eu^m) and 2.4 ± 0.2 sec (^{142}Eu^g), both of which decay by β^+ emission to states in ^{142}Sm, resulting in 32 and 8 γ transitions, respectively. On the basis of β^+ and γ ray singles and coincidence as well as conversion electron measurements, a level scheme comprising 20 excited states with deduced J^π assignments has been constructed. Among the levels, a 5^- and a 7^- state at 2347.9 and 2372.0 keV, respectively, have been identified as two-quasiparticle neutron states. The half-life of the 2372.0 keV level has been measured to be 170 ± 2 ns using the β^+-γ delayed coincidence technique. The β^+ end-point energy measurements yielded decay energies $Q_{EC} = 8.0 \pm 0.3$ MeV and 8.15 ± 0.10 MeV for ^{142}Eu^g and ^{142}Eu^m, respectively.

RADIOACTIVITY ^{142}Eu^{m,g} from ^{144}Sm$(p, 3n)$; measured $T_{1/2}$, E_γ, I_γ, I_{ce}, E_{β^+}, γ-γ coin, γ-γ, β-γ delay, deduced Q_{EC}. ^{142}Sm deduced levels, J, π, $T_{1/2}$, logft, ICC, γ multipolarity. Enriched targets, Ge(Li), Si(Li), plastic, NaI(Tl) detectors.

I. INTRODUCTION

This work is part of a systematic study of the nuclei in the region with $Z > 50$ and $N < 82$. The nuclei in this region have their valence protons and neutrons filling the shell model orbitals $1g_{7/2}$, $2d_{5/2}$, $3s_{1/2}$, $2d_{3/2}$, and $1h_{11/2}$. The presence of the $1h_{11/2}$ orbital in this group results in the existence of negative parity isomeric states in many of the nuclei. This is particularly true in the odd-odd $N = 79$ isotones which have been observed[1-3] to have low-lying high spin isomers which decay by β emission directly to states in the even-even daughters. ^{142}Eu is an odd-odd nucleus in this isotone series whose decay to the even-even ^{142}Sm has not been well studied.

In 1965 Malan, Munzel, and Pfenning,[4] after bombarding enriched ^{144}Sm with 40 MeV deuterons and chemically separating the Eu fraction, observed a 1.2 ± 0.2 min activity and assigned it to ^{142}Eu. In 1972 Habs *et al.*[5] performed in-beam ^{144}Sm$(\alpha, 6n+\beta)$ and ^{144}Sm$(\alpha, 5n+p)$ reactions, observed the β^+ decay of ^{142}Eu, and proposed a partial decay scheme of ^{142}Eu involving five γ transitions and four excited states in ^{142}Sm. In 1973 Oelert[6] performed (p, t) reaction studies on samarium isotopes and reported levels in ^{142}Sm at 0 (0^+), 768 ± 15 (2^+), 1785 ± 15 (4^+), 2040 ± 20 (2^+), and 2358 ± 20 keV.

II. EXPERIMENTAL METHODS

The ^{142}Eu activity was produced in the McGill sychrocyclotron by the $(p, 3n)$ reaction on 96% enriched ^{144}Sm targets in the form Sm_2O_3. A pneumatic target transport system[7] capable of moving the targets from inside the cyclotron to the counting area in 2 s was used. Various forms of targets were used depending on the nature of the experiment. In general targets for γ-ray measurements were sealed in thin beryllium or aluminum tubing, and for electron measurements targets were evaporated onto thin aluminum or beryllium foils.

Typical irradiation time was 0.1 to 2 s. In the initial experiments involving the ^{142}Eu activities, the bombarding energy was 35 MeV which is below the $(p, 4n)$ reaction threshold ($Q \approx -37$ MeV). At this bombarding energy other activities produced in the target material were ^{140}Pm^{m,g} (5.95 min and 9.1 s), ^{141}Pm (20.6 min) through $(p, \alpha xn)$ reactions, ^{142}Sm (70 min), ^{143}Sm^{m,g} (65 s and 8.8 min) from (p, pxn) reactions, and ^{143}Eu (2.6 min), ^{144}Eu (10.2 s) from (p, xn) reactions. The decay properties of ^{141}Pm, ^{142}Sm, and ^{143}Sm^{m,g} (Refs. 8, 9, and 10, respectively) are already known while those of ^{140}Pm^{m,g}, ^{143}Eu, and ^{144}Eu (Refs. 1, 11, and 12, respectively) were studied thoroughly in our laboratory and their effects in the present investigation were accounted for. The final bombarding energy was chosen to be 42 MeV. At this energy interference from ^{143,144}Eu was found to be greatly reduced; however, a small amount of the new isotope ^{141}Eu was produced. The decay properties of the latter are being thoroughly studied.

γ rays were detected using two Ge(Li) detectors of volume 55 and 60 cm^3 and resolutions 2.0 and

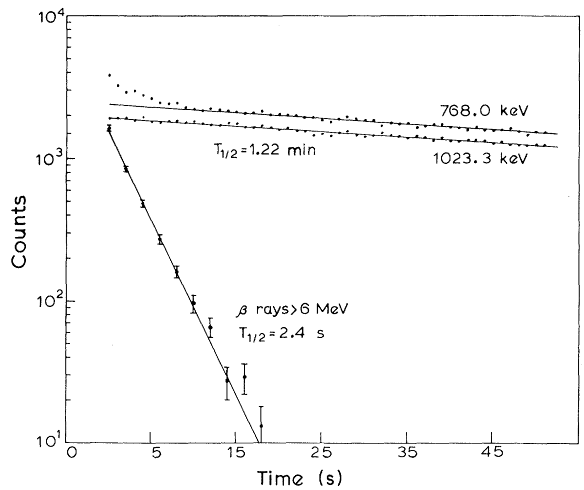

FIG. 1. Decay curve of positron activity of energy above 6 MeV and the 768.0 and 1023.3 keV γ-ray photopeaks from the decay of ^{142}Eu. The 768.0 keV line showed a two-component decay of half-lives 2.4 s ($^{142}Eu^g$) and 1.22 min ($^{142}Eu^m$).

2.1 keV [full width at half-maximum (FWHM)] for a 1.3 MeV γ ray. A 0.5 cm^3 Ge(Li) x-ray detector was used to detect low-energy γ rays. Positrons were detected with a 4 cm diam by 5 cm long plastic scintillator while conversion electron measurements were performed with a 3 mm thick Si(Li) detector. Standard modular electronics coupled with an on-line PDP-15 computer were used for data acquisition and analysis.

III. EXPERIMENTAL RESULTS

A. Half-life measurements and activity assignments

The time decay of β^+ and γ radiations was studied using plastic and Ge(Li) detectors. The decay of several intense photopeaks confirmed the existence of the previously reported 1.2 min isomer of ^{142}Eu. The half-life has been remeasured accurately as 1.22 ± 0.02 min. γ ray spectra also showed the existence of several peaks decaying with a 2.4 s half-life. The decay of the β^+ activity of energy >6 MeV showed a clear single component of 2.4 ± 0.2 s as shown in Fig. 1. This 2.4 s activity has been assigned to a new isomer of ^{142}Eu for the following reasons. It is produced in abundance at the same bombarding energy as the 1.22 min isomer of ^{142}Eu. The 768.0 keV γ ray which represents the $2^+ \rightarrow 0^+$ transition from the first excited state in ^{142}Sm shows a composite decay with half-lives 2.4 s and 1.22 min (Fig. 1). Moreover, the 1.22 min and 2.4 s activities begin to appear in the spectra at bombarding energies

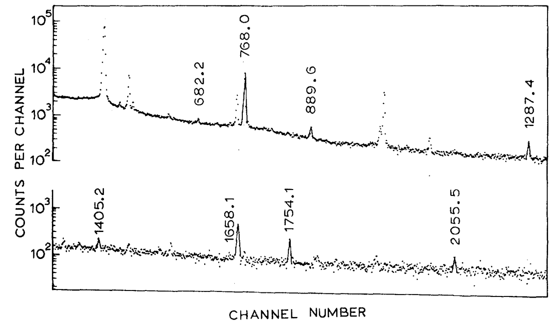

FIG. 2. A typical γ-ray spectrum taken from 2 to 6 s after the end of irradiation of enriched ^{144}Sm. Only the $^{142}Eu^g$ γ rays have been labeled. The unlabeled peaks are from the decay of $^{142}Eu^m$ and ^{143}Eu.

greater than 30 MeV, which is slightly higher than the Q value (−27 MeV) for the $(p, 3n)$ reaction.

Figure 2 shows the γ-ray spectrum recorded during the time interval from 2 to 6 s following irradiation. Only those peaks which possess the 2.4 s half-life are labeled and are assigned to $^{142}Eu^g$. Figure 3 shows the γ-ray spectrum collected from 30 s to 4.5 min after the end of irradiation. The photopeaks with a decay period of 1.22 min are labeled and assigned to $^{142}Eu^m$. The energies and relative intensities of all the γ rays of $^{142}Eu^g$ and $^{142}Eu^m$ are listed in Tables I and II, respectively.

B. Coincidence measurements

Coincidence experiments were performed on the decay of the 1.22 min isomer of ^{142}Eu. In the γ-γ coincidence measurements two Ge(Li) detectors were placed face to face with a 1.2 cm graded Pb shield between them. The sources were placed off the axis of the detectors to reduce the contribution of annihilation γ rays. The coincidence resolving time was 60 ns. Low energy coincidence events were studied by replacing one of the large volume Ge(Li) detectors with the Ge(Li) x-ray spectrometer. Digital gates were set on all the γ-ray peaks and on the Compton background near each peak. The gated spectra were collected and analyzed by the computer-controlled data acquisition system. In each experiment approximately 90 bombardments were made and each target was counted for a 4 min period.

A strong coincidence between Sm L x rays and the intense 556.6, 768.0, and 1023.3 keV γ rays was observed. The x-ray spectrum in coincidence with the 556.6 keV peak is displayed in the lower half of Fig. 4. For comparison the x-ray spectrum taken in the singles mode is shown in the upper part of Fig. 4. Some of the typical gated

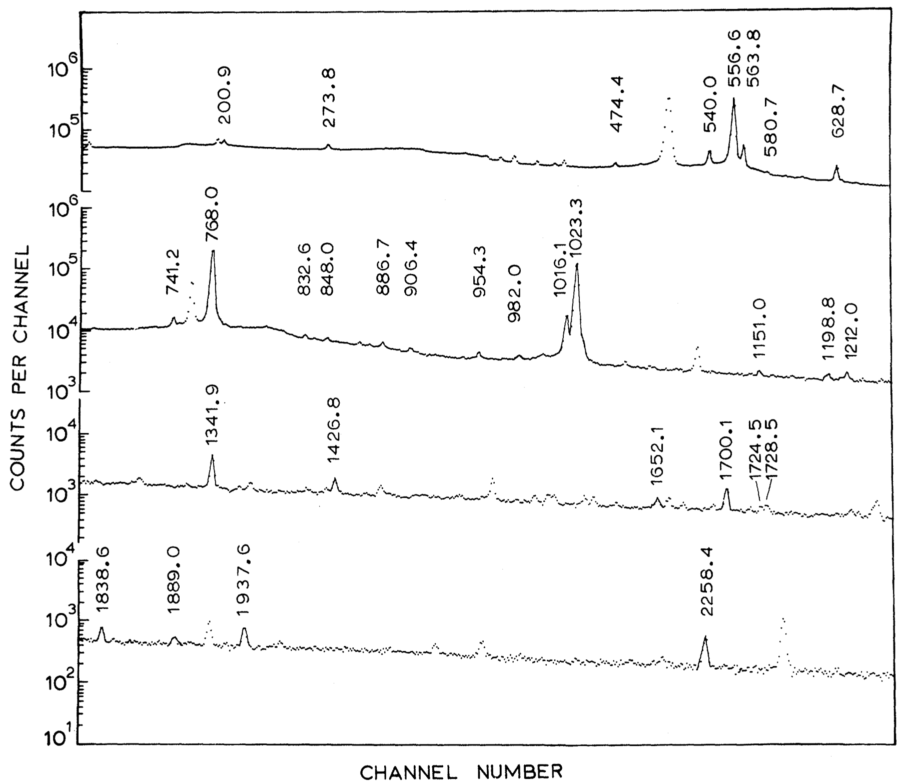

FIG. 3. A typical γ-ray spectrum taken from 0.5 to 4.5 min after the end of irradiation of enriched ^{144}Sm. Only the ^{142}Eu^m γ rays have been labeled. The unlabeled peaks are from the impurities listed in Sec. II.

spectra obtained with large volume detectors and corrected for Compton background in the gates are shown in Fig. 5. The results are tabulated in Table III.

In the above experiments it was found that the 511 keV peak in coincidence with the intense γ rays was much weaker than expected (see Fig. 5). In addition, other γ rays appeared more weakly in coincidence with the intense γ rays than one would expect from their singles intensities. This clearly indicated the presence of a long-lived state in ^{142}Sm. Indeed, as will be shown in Sec. V, the 2372.0 keV level in ^{142}Sm has been found to have a half-life of 170 ± 2 ns. In order to facilitate the construction of the energy level scheme, the prompt and delayed γ-ray spectra were studied in γ-γ and β^+-γ experiments. A wide gate in the region 550–1040 keV including all the intense γ rays was set using a 7.6×7.6 cm NaI(Tl) detector while the coincidence spectra were recorded in various time bins using Ge(Li) detectors. The peaks not seen in the prompt spectrum were found in the delayed spectrum. The prompt and delayed γ-ray spectra were also studied in coincidence with β^+ rays > 2 MeV. Most of the γ rays which are found in delayed coincidence in the γ-γ coincidence experiment were found in prompt coincidence with β^+ rays. The only γ rays seen in delayed coincidence with the positrons are at 556.6, 563.7, 768.0, 1016.1, and 1023.3 keV. Therefore, these five γ rays are the only ones which follow the deexcitation of the delayed state.

TABLE I. Energies and relative intensities of γ rays from the 2.4 s ^{142}Eu^g. ΔA = uncertainty in the last digit of A.

E_γ (keV)	ΔE_γ	I_γ [a]	ΔI_γ
682.2 [b]	7	5.5	8
768.0	2	100	
889.6	3	13.3	12
1287.4	3	13.7	12
1405.2 [b]	4	7.1	8
1658.1	5	13.0	30
1754.1 [b]	4	13.0	10
2055.5	10	4.9	6

[a] Relative to an intensity of the 768.0 keV γ ray = 100.
[b] γ rays not placed in the decay scheme.

TABLE II. Energies and relative intensities of γ rays from the 1.22 min $^{142}Eu^{m}$. ΔA = uncertainty in the last digit of A.

E_γ (keV)	ΔE_γ	I_γ [a]	ΔI_γ
200.9	5	1.1	2
273.8	5	1.2	2
474.4	5	0.75	10
540.0	2	5.0	4
556.6	2	86.6	30
563.7	2	8.3	4
580.7	4	0.44	10
628.7	2	4.1	2
741.2	2	1.7	2
768.0	2	100	
832.6 [b]	2	0.42	9
848.0	3	0.40	8
886.7	2	0.69	7
906.4	3	0.50	12
954.3	2	0.58	8
982.0	5	0.24	5
1016.1	2	11.0	6
1023.3	2	92.0	30
1151.0	3	0.35	7
1198.8	3	0.39	10
1212.0 [b]	3	0.47	10
1341.9	2	2.98	14
1426.8	3	0.78	15
1652.1	3	0.29	6
1700.1	3	0.83	7
1724.5	4	0.12	4
1728.5 [b]	3	0.20	5
1838.6	3	0.44	5
1889.0	4	0.15	3
1937.6	3	0.51	6
2258.4	2	0.64	6

[a] Relative to an intensity of the 768.0 keV γ ray = 100.
[b] γ rays not placed in the decay scheme.

C. β end-point measurements

To determine the end-point energies of the β^+ rays a plastic scintillation spectrometer consisting of E and ΔE detectors of design similar to that described by Beck[13] was used. The energy calibration was achieved by using ^{58}Cu, ^{62}Cu, ^{64}Ga, ^{66}Ga, ^{92}Tc, and ^{144}Eu sources. The spectra were corrected for summing, back-scattering, and resolution distortions following the method given in Refs. 13 and 14.

Figure 6 shows the Fermi-Kurie analysis of the β^+-ray spectrum of $^{142}Eu^{g}$ along with those of ^{58}Cu, ^{64}Ga, and ^{92}Tc. The maximum end-point energy for $^{142}Eu^{g}$ was found to be 7.0 ± 0.3 MeV. As will be discussed in Sec. IV this β^+ group directly feeds the ground state of ^{142}Sm giving Q_{EC} as 8.0 ± 0.3 MeV. Since the mass excess of ^{142}Sm is known to be -78.92 ± 0.02 MeV[3] the mass ex-

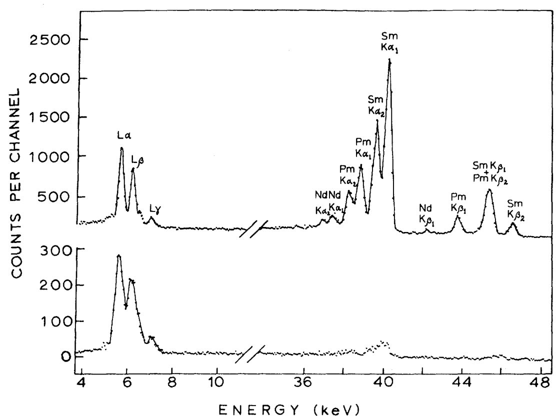

FIG. 4. Low-energy spectra taken with a Ge(Li) x-ray spectrometer. The upper part shows the singles measurement while the lower spectrum was obtained in coincidence with the 556.6 keV γ ray.

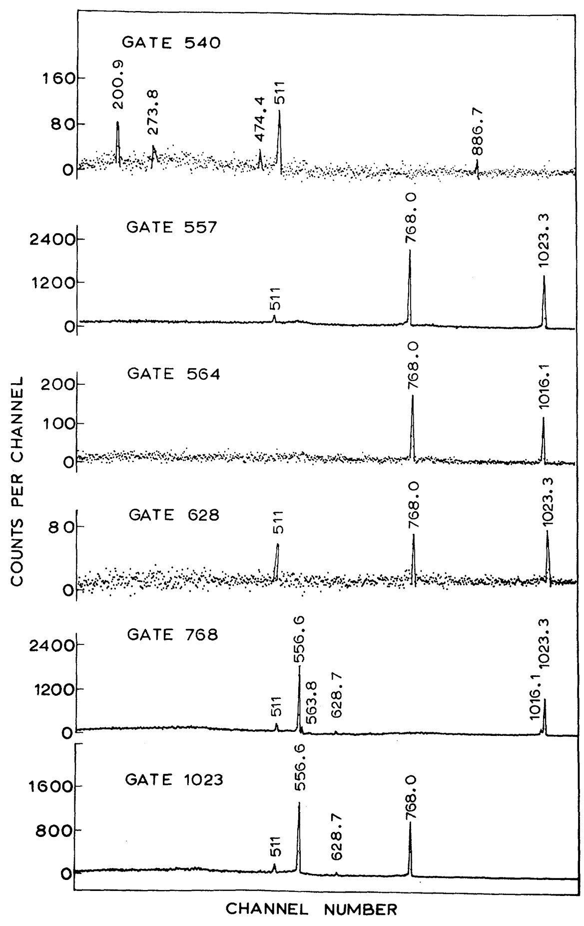

FIG. 5. γ-γ coincidence spectra with gates set on the 540.0, 556.6, 563.8, 628.7, 768.0, and 1023.3 keV peaks. Background coincidences have been subtracted.

TABLE III. γ-γ coincidence results. Brackets indicate probable coincidences.

Gating γ ray (keV)	Coincident γ rays (keV)
200.9	273.8, 511.0, 540.0
273.8	200.9, 511.0, 540.0, 741.2
474.4	511.0, 540.0
540.0	200.9, 273.8, 474.4, 511.0, 886.7
556.6	Sm L x rays, 511.0, 768.0, 1023.3, 1724.5
563.7	Sm L x rays, 511.0, 768.0, 1016.1
628.7	511.0, 768.0, 1023.3, (1151.1), (1889.0)
741.2	273.8, 511.0
768.0	Sm L x rays, 511.0, 556.6, 563.7, 628.7, 1016.1, 1023.3
848.0	(511.0)
886.7	511.0, 540.0
906.4	511.0, (628.7)
954.3	(511.0)
1016.1	Sm L x rays, 511.0, 563.7, 768.0
1023.3	Sm L x rays, 511.0, 556.6, 628.7, 768.0
1151.0	(511.0), (628.7)
1341.9	511.0
1426.8	511.0
1700.1	511.0
1838.6	(511.0)
1889.0	(511.0)
1937.6	511.0
2258.4	511.0

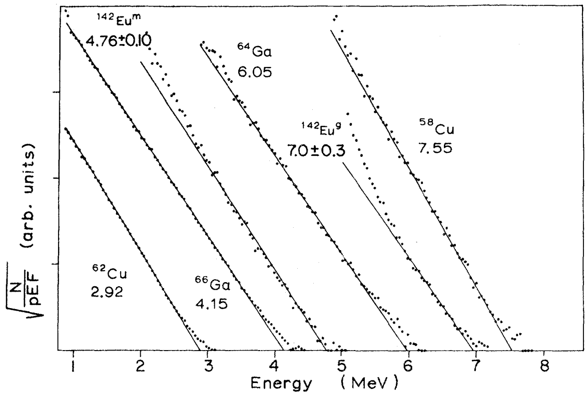

FIG. 6. Fermi-Kurie plots of ^{142}Eu^m and ^{142}Eu^g recorded with $E + \Delta E$ plastic scintillator detector system along with the ^{58}Cu, ^{64}Ga, ^{66}Ga, and ^{62}Cu sources used as calibrations.

cess of ^{142}Eu^g is therefore -70.92 ± 0.30 MeV. This mass excess is to be compared with the values -71.42 MeV predicted by Garvey *et al.*,[15] -72.71 MeV predicted by Zeldes, Grill, and Simievic,[16] and -71.04 MeV predicted by Myers and Swiatecki.[17]

From the decay scheme of ^{142}Eu^m (see Fig. 9) the most intense β^+ group is expected to feed the 2372 keV delayed state ($T_{1/2} = 170$ ns). Therefore, the β^+-ray spectrum was studied in delayed coin-

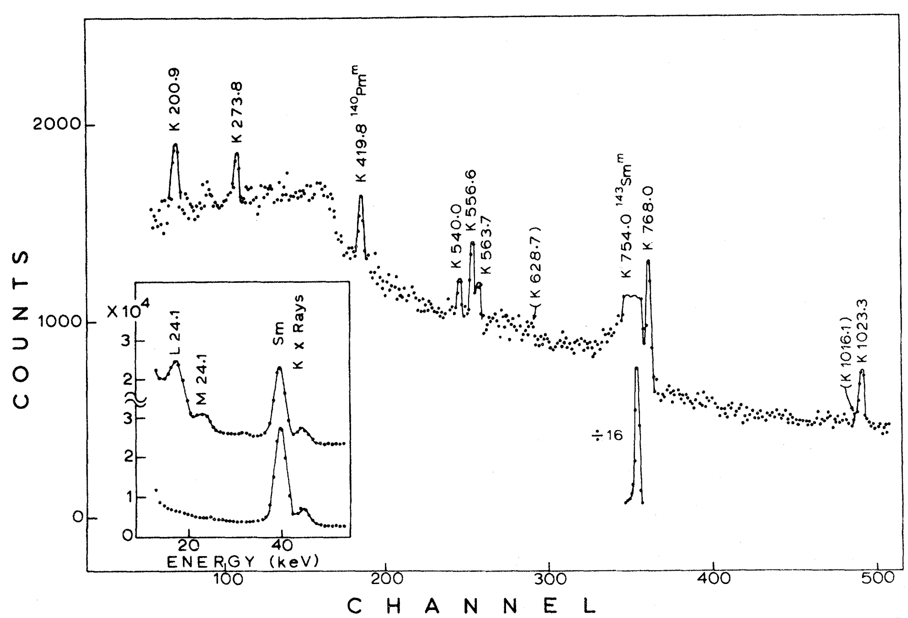

FIG. 7. Conversion electron spectrum recorded with a cooled Si(Li) detector in coincidence with the Sm K x rays detected in a thin NaI(Tl) detector. In the inset the upper part shows the direct low-energy electron spectrum while the lower part was obtained with a 2 mg/cm^2 thick Al absorber between the source and the detector.

TABLE IV. K conversion coefficients (α_K) and multipolarity assignments for transitions in ^{142}Sm.

Transition energy E_γ (keV)	Experimental α_K	Theoretical α_K from Hager and Seltzer (Ref. 18) $E1$	$E2$	$E3$	$M1$	$M2$	Multipolarity assignment
200.9	0.194 ± 0.060	0.0357	0.1490	0.544	0.2050	1.0800	$E2, M1$
273.8	0.103 ± 0.040	0.0158	0.0578	0.189	0.0889	0.3850	$E2, M1$
540.0	0.0156 ± 0.0031	0.0031	0.0087	0.0219	0.0154	0.0467	$M1$
556.6	0.0020 ± 0.0004	0.0029	0.0080	0.0201	0.0143	0.0428	$E1$
563.7	0.0110 ± 0.0032	0.0028	0.0078	0.0194	0.0138	0.0412	$E2, M1$
628.7	0.0069 ± 0.0062	0.0022	0.0060	0.0143	0.0105	0.0301	$E1, E2, M1$
768.0	0.0037	0.0015	0.0037	0.0084	0.0065	0.0172	$E2$
1016.1	0.0008 ± 0.0016	0.0009	0.0020	0.0042	0.0033	0.0081	$E1, E2$
1023.3	0.0018 ± 0.0003	0.0009	0.0020	0.0041	0.0032	0.0080	$E2$

cidence with γ rays of energy 550-1070 keV. The Fermi-Kurie plot is shown in Fig. 6. The end-point energy was found to be 4.76 ± 0.10 MeV and therefore a Q_{EC} of 8.15 ± 0.10 MeV was deduced for ^{142}Eu^m.

D. Conversion electron spectroscopy

In order to determine the multipolarities of the γ transitions the internal conversion electron spectrum of ^{142}Eu^m was studied with a cooled 3 mm thick by 14 mm diam Si(Li) detector having resolution 2.7 keV at an electron energy of 624 keV. Because of the high positron background, relatively small conversion coefficients for the intense γ rays, and the short half-life, the conversion electron spectrum was studied in coincidence with the Sm K x rays detected in a 1 cm thick by 5 cm diam NaI(Tl) detector placed at 180° with respect to the Si(Li) detector. The system was calibrated with standard sources such as ^{113}Sn, ^{133}Ba, ^{137}Cs, ^{139}Ce, and ^{207}Bi. A typical electron spectrum from ^{142}Eu^m is shown in Fig. 7. The K 420.0 and K 754.0 peaks are due to ^{140}Pm^m (Ref. 8) and ^{143}Sm^m (Ref. 9), respectively. The low-energy electron spectrum was measured without x-ray coincidence. The results are displayed in the inset of Fig. 7 where the upper part shows the L and M conversion peaks corresponding to the 24.1 keV transition while the lower spectrum in which these peaks disappear was taken with a 2 mg/cm^2 aluminum absorber between the source and detector. The K conversion coefficients (α_K) were obtained from the relative intensities of electrons and γ rays by assuming pure $E2$ multipolarity for the 768.0 keV transition ($2^+ \to 0^+$). A small enhancement of electron peak intensities due to possible coincidences between the K-capture x rays and conversion electrons was taken into account using the established decay scheme of ^{142}Eu^m (see Sec. IV). The multipolarities of various transitions were obtained by comparing the experimental α_K values with the theoretical ones[18] and are tabulated in Table IV.

IV. DECAY SCHEMES

The decay schemes of the 2.4 s and 1.22 min isomers of ^{142}Eu based on the above measurements are shown in Figs. 8 and 9, respectively. The indicated Q_{EC} values are deduced from the β^+ end-point measurements in the present investigation. The errors in the measured Q_{EC} values prohibit the determination of the ordering of the isomers. However, the 2.4 s isomer has been assigned as ^{142}Eu^g and the 1.22 min isomer as ^{142}Eu^m from the systematics and similarity of the decay schemes of neighboring odd-odd $N = 79$ nuclei, namely, ^{138}Pr (Ref. 2) and ^{140}Pm (Ref. 1).

A. Decay of 2.4 s ^{142}Eu^g

The decay scheme of ^{142}Eu^g shown in Fig. 8 is based purely on γ-ray energy sums as coincidence

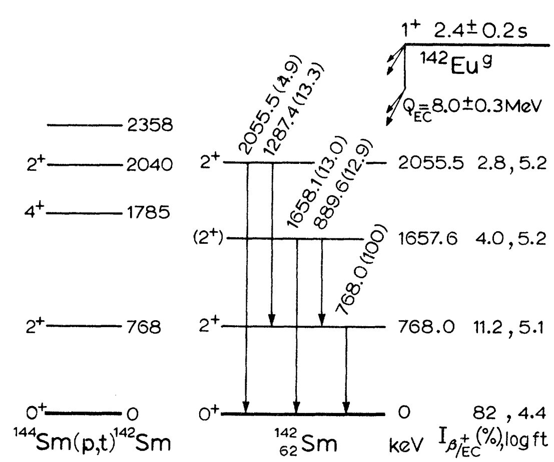

FIG. 8. Decay scheme of 2.4 s ^{142}Eu^g. The levels in ^{142}Sm obtained from ^{144}Sm(p, t) reactions are also shown for comparison.

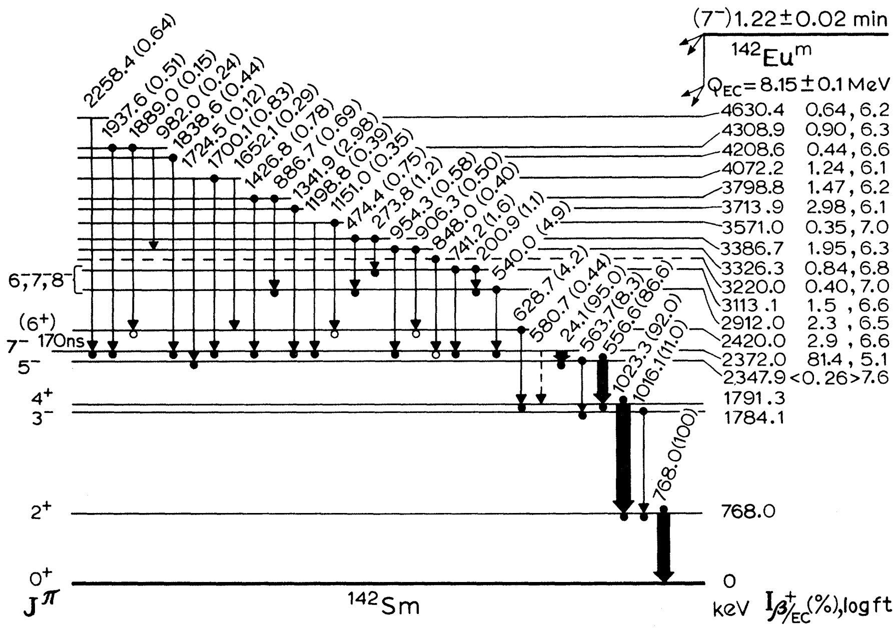

FIG. 9. Decay scheme of 1.22 min ^{142}Eu^m. Open circles denote probable coincidences while a dotted line indicates that the placement of the transition is tentative.

experiments were not feasible due to the short half-life and relatively weak γ-transition intensities. The levels of ^{142}Sm from recent ^{144}Sm(p, t) reactions[6] are also shown for comparison. The presence of a rather strong 511.0 keV peak decaying with the 2.4 s half-life suggested the existence of an intense β^+ branch to the ^{142}Sm ground state. In order to determine the ground state β^+ feeding, the ^{142}Eu sources were enclosed in a copper absorber so that all the positrons were stopped. The relative intensity of the 2.4 s component of the 511.0 and 768.0 keV peaks was extracted and after correction for detector efficiency, absorption, and annihilation in flight it was determined that $I(\beta^+)/I(768.0) = 8.4 \pm 1.1$. Using theoretical EC/$\beta^+$ ratios[3] the ground state feeding was determined as 82%. The log*ft* values for other levels were deduced from the γ-ray intensity balance. The intensity of the unplaced γ rays is not accounted for in the indicated log*ft* values.

The first excited state in ^{142}Sm is known to be at 768 keV and accounts for the observed 768.0 keV γ ray. The other two levels at 1657.6 and 2055.5 keV are based on energy sums. The allowed nature of the β transitions to the 0^+ ground state and the 2^+ first excited state in ^{142}Sm fixes the spin and parity of ^{142}Eu^g as 1^+. Similarly, the 1657.6 and 2055.5 keV levels are fed by allowed transitions and they in turn decay by γ emission to 0^+ and 2^+ levels in ^{142}Sm. Therefore a 1^+ or 2^+ spin assignment for both of them seems most reasonable. However, we prefer a 2^+ assignment for both of them for the following reasons. A 2^+ state at 2040 ± 20 keV is seen in the ^{144}Sm$(p, t)^{142}$Sm reaction and could well be the 2055.5 keV level of this work. The 1657.6 keV level is at the position expected for the two-phonon 2^+ state. From systematics and theoretical considerations a 1^+ level is not expected at excitation energy as low as this.

Systematics of second 0^+ levels in this region[19] suggests that such a level in ^{142}Sm should be found near 1400 keV. If such a level is populated in the decay of ^{142}Eu^g it should decay by γ emission only to the 768.0 keV 2^+ level. Amongst unplaced γ rays the 682.2 keV is the most likely candidate giving a level at 1450.2 keV. However, this level is not shown in Fig. 8 because of lack of further supporting evidence.

B. Decay of 1.22 min ^{142}Eu^m

The first excited state is known at 768.0 keV while the levels at 1791.3 and 2347.9 keV are firmly established from the prompt cascade relationship of the intense 768.0, 1023.3, and 556.6 keV γ rays. The 1023.3 keV transition must be placed below the 556.6 keV transition for intensity balance and because the 1023.3 keV γ ray is in coincidence with the 628.7 keV transition while the 556.6 keV γ ray is not. Similarly, the noncoincidence of the 563.7 and 1016.1 keV γ rays with the intense 556.6 and 1023.3 peaks along with the cascade relationship of the 563.7, 1016.1, and 768.0 keV γ rays leads to a level at 1784.1 keV in ^{142}Sm. These results are consistent with the observation of a 4^+ level at 1785 ± 15 keV in the (p, t) reaction work.[6]

A level at 2420.0 keV has been proposed, as the 628.7 keV γ ray was found in prompt coincidence with only the 1023.3 and 768.0 keV transitions. As only Sm L x rays are observed in prompt coincidence with the intense cascade of 556.6-1023.3-768.0 keV, a level within 47 keV (Sm K-shell binding energy) above the 2347.9 keV level is expected. The energy of this level has been assigned as 2372.0 keV from the following considerations. Among the γ rays so far unplaced there are four pairs of energies, namely, 906.3-954.3, 1151.0-1198.8, 1652.1-1700.0, and 1889.0-1937.6 keV with a common energy difference of about 48 keV. Also, three low-energy members of these pairs show a probable coincidence with the 628.7 keV peak while no coincidence was observed among themselves. Therefore a level at 2372.0 keV is proposed and the above-mentioned pairs are shown to decay to the 2372.0 and 2420.0 keV levels from the 3326.3, 3571.0, 4072.2, and 4308.9 keV levels. From the low-energy L and M conversion electron peaks a transition of 24.1 ± 0.3 keV was deduced and agreed very well with the expected transition between the 2372.0 and 2347.9 keV levels.

The Sm L x rays and the 556.6-1023.3-768.0 keV cascade were found to be in delayed coincidence with the β rays confirming the delayed nature of the 2372.0 keV level. Other prompt and delayed coincidence results are also in agreement with this assignment. The dotted 580.7 keV transition between the 2372.0 and 1791.3 levels should be considered tentative only.

The levels at 3220.0, 3713.9, 4208.6, and 4630.4 keV decay by single γ transition and are proposed because the γ rays from these levels appeared in delayed γ-γ and prompt β-γ coincidence spectra. Similarly, from a variety of coincidence results it was evident that the rest of the unplaced γ rays must originate from levels above the delayed level. Therefore the levels at 2912.0, 3113.1, 3386.7, and 3798.8 keV are proposed which account for the coincidence properties of the 200.9, 273.8, 474.4, 540.0, 741.2, 886.7, and 1426.8 keV γ rays.

The log*ft* values shown in Fig. 9 are deduced from the γ-ray intensity balance and the theoretical EC/β^+ ratios.[3]

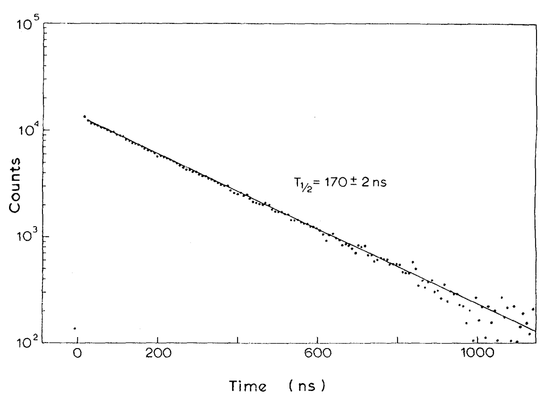

FIG. 10. β-γ delayed coincidence spectrum for the 2372.0 keV level. The random background has been subtracted.

V. DETERMINATION OF THE HALF-LIFE OF THE 2372.0 AND 2420.0 keV LEVELS

To measure the half-life of the 2372.0 keV level a standard β^+-γ delayed coincidence experiment was performed using 5 cm thick by 4 cm diam plastic and 7.6 cm thick by 7.6 cm diam NaI(Tl) detectors. The time-to-amplitude converter start pulse was generated by the β^+-ray detector in which the energy discriminator was set to accept events with energy above 2.3 MeV so as to exclude the γ-ray contribution while the stop pulse was taken from the γ-ray spectrometer whose energy window was set to accept the events from 550 to 1050 keV. The time spectrum obtained after correcting for random coincidences is shown in Fig. 10. The time spectrum was calibrated with a Tennelec precision time calibrator, having a precision of 0.2%. The count rate was kept low to reduce dead time in the time-to-amplitude converter. The residual dead-time effects were corrected for, and this correction is estimated to be accurate to ± 0.8 ns. From the average of several measurements a half-life of 170 ± 2 ns was assigned to the 2372.0 keV level in ^{142}Sm. Assuming this decays to the 2347.9 keV level by a pure $E2$ transition (see Fig. 9 and Sec. IV), the partial transition rate is 8.3 Weisskopf units.

The half-life of the 2420.0 keV level was also measured with the NaI(Tl) detector replaced by a Ge(Li) detector to select the 628.7 keV transition. Because of insufficient time resolution only an upper limit of less than 2 ns was obtained. This is consistent with the conclusion (see Table IV) that the 628.7 keV transition is $E1$, $E2$, or $M1$.

VI. SPIN AND PARITY ASSIGNMENTS

The levels at 768.0 and 1791.3 keV have been observed by Habs *et al.*[5] and identified as the 2^+ and 4^+ members of the quasirotational ground state band in ^{142}Sm. These J^π assignments are strongly substantiated by the (p, t) reaction work of Oelert.[6] They are also confirmed by the present conversion electron measurements, which indicate $E2$ multipolarity for the 768.0 and 1023.3 keV transitions. The 2347.9 keV level decays to the 1791.3 keV level (4^+) through an intense 556.6 keV $E1$ transition. The complete absence of any transition to the 768.0 keV (2^+) state clearly favors a 5^- assignment to the 2347.9 keV level. The multipolarity of the 563.7 keV γ ray is either $E2$ or $M1$ while that of the 1016.1 keV transition is $E1$, $E2$, or $M1$ (see Table IV). Therefore, the only possible spin assignment for the 1784.1 keV level is 3^-.

The spin of the 2372.0 delayed state has been assigned as 7^- because of the $E2$ nature of its decay to the 2347.9 keV 5^- state. This transition has been determined to be $E2$ from the observed ratios of the Sm L x-ray peaks (Fig. 4). More specifically, from the observed x-ray spectra of ^{142}Eu^m, the L-subshell vacancies created by the internal conversion processes were calculated assuming the theoretical intensity distribution[20] for the individual L x-ray lines, and after correcting for various effects such as the variation in detector efficiencies, absorption effects, the fluorescent yields,[21] Coster-Kronig transitions,[21] and L-shell vacancies formed in the creation of K x rays.[21] The last effect was almost negligible when the Sm L x-ray spectrum in coincidence with the 556.6 keV γ ray was used to extract the L-subshell vacancies. The deduced L-shell conversion coefficient ratios for the 24.1 keV transition were $L_{\text{I}}/L_{\text{II}} = 0.20 \pm 0.35$ and $L_{\text{III}}/L_{\text{II}} = 1.25 \pm 0.25$, in good agreement with the theoretical ratios[18] for an $E2$ transition, namely, 0.005 and 1.37, respectively. For any other multipolarity, the theoretical ratios[17] differ by an order of magnitude from the measurements. From the intensities of the L x-ray peaks, the total intensity of this 24.1 keV $E2$ transition was deduced to be 121 ± 40, which is consistent with the value 95 (see the decay scheme) obtained from intensity balance.

The 2420.0 keV state decays only to the 1791.3 keV 4^+ level by an $E1$, $E2$, or $M1$ transition (see Table IV and Sec. V) hence its spin-parity is $5^\pm$ or 6^+. The probable spin-parity of ^{142}Eu^m is 7^- or 8^- because it decays mostly to the 7^- state in ^{142}Sm and not to the 5^- state ($\log ft > 7.6$). However, it decays by β emission to the 2420.0 keV state with a $\log ft$ of 6.6 which is too low a value for a first forbidden unique transition; hence the spin of ^{142}Eu^m is 7^-. This permits the elimination of the $5^\pm$ assignment to the 2420.0 keV state leaving it with spin-parity 6^+.

The remaining levels above 2420 keV are fed by β transitions with $\log ft$ values ranging from 6.1 to 7 which implies that these levels have spins 6, 7, or 8. The multipolarity of the decays from the 2912.0 and 3113.1 keV states restricts these states to negative parity only. The 4072.2 keV level must have spin 6 or 7 since it decays by γ emission to the 5^- and 7^- states.

VII. DISCUSSION

In the shell model picture the odd proton in $^{142}_{63}$Eu$_{79}$ could be in either the $2d_{5/2}$ or $1g_{7/2}$ orbital while the odd neutron could occupy the $1h_{11/2}$ or $2d_{3/2}$ or $3s_{1/2}$ orbital. Indeed all known odd mass Eu isotopes do have a $\frac{5}{2}^+$ ground state. In most of the $N = 79$ odd mass nuclei $\frac{3}{2}^+$ appears as the ground state while the isomeric states are $\frac{11}{2}^-$. The spin of ^{142}Eu^g is 1^+ (Sec. IV) which could arise by coupling a $2d_{5/2}$ proton with a $2d_{3/2}$ neutron hole. Similarly, the 7^- spin of ^{142}Eu^m should originate by coupling a $2d_{5/2}$ proton to the $1h_{11/2}$ neutron hole. It should be noted that 1^+ and 7^- ground and isomeric states have also been observed in ^{138}Pr (Ref. 2) and ^{140}Pm (Ref. 1) where similar shell model configurations are expected and whose decay patterns are strikingly similar to that of ^{142}Eu.

Habs *et al.*[5] identified the 0^+ (0), 2^+ (768.0), and 4^+ (1791.3 keV) levels as members of a ground state quasirotational band. It would be tempting to assign the 6^+ (2420.0 keV) level as the next member of this band. However, this is unlikely because, using the variable moment of inertia model[22] and the energies of the 2^+ and 4^+ levels, the calculated energy for the 6^+ member was found to be 2996 keV. Since this nucleus is fairly close to the $N = 82$ magic number, it may not be sufficiently deformed to warrant a quasirotational interpretation. The 3^- state at 1784.1 keV could be the first octupole phonon state. The 3^- phonon state in ^{144}Sm has been found[23] to lie at 1810 keV.

The 7^- state at 2372.0 keV is fed by an intense β branch of $\log ft$ 5.1 from the decay of the 7^- isomer of ^{142}Eu, which presumably has a dominant configuration of $(\pi 2d_{5/2} \times \nu 1h_{11/2}{}^{-1})$. This indicates that the probable dominant configuration for the 7^- state in ^{142}Sm is a $(2d_{3/2}{}^{-1} \times 1h_{11/2}{}^{-1})$ two-neutron hole state. Since the $3s_{1/2}$ orbit lies close to the $2d_{3/2}$ orbit, the 5^- state at 2347.9 keV is also very likely a two-neutron hole state with dominant configurations $(3s_{1/2}{}^{-1} \times 1h_{11/2}{}^{-1})$ and/or $(2d_{3/2}{}^{-1} \times 1h_{11/2}{}^{-1})$. Using harmonic oscillator wave functions with $\hbar\omega = 41 A^{-1/3}$ MeV and a neutron effective charge of $1.1e$ the $B(E2)$ value for the $(2d_{3/2}{}^{-1} \times 1h_{11/2}{}^{-1})\ 7^- \rightarrow (3s_{1/2}{}^{-1} \times 1h_{11/2}{}^{-1})\ 5^-$ transition was calculated to be 56.8 $e^2\,\text{fm}^4$. For the $(2d_{3/2}{}^{-1} \times 1h_{11/2}{}^{-1})\ 7^- \rightarrow (2d_{3/2}{}^{-1} \times 1h_{11/2}{}^{-1})\ 5^-$ transition a $B(E2)$ value of 29.7 $e^2\,\text{fm}^4$ was calculated. These values are to be compared with the experimental value of 364.2 $e^2\,\text{fm}^4$ determined from the half-life of 170 ns and the theoretical $E2$ total conversion coefficient of 1115. The large discrepancy between these calculated values and the experimental $B(E2)$ value could be due to the ^{142}Sm nucleus being slightly deformed.

This research was supported by a grant from the Atomic Energy Control Board of Canada. One of us (G. G. K.) wishes to thank the National Research Council of Canada for the scholarship awarded him during the course of this work.

---

[1] G. Kennedy, S. C. Gujrathi, and S. K. Mark, Bull. Can. Assoc. Phys. 30, 4, 19 (1974).

[2] V. S. Buttsev, Ts. Vylov, V. G. Kalinnikov, and N. A. Tikhonov, Izv. Akad. Nauk. SSSR, Ser. Fiz. 38, 63 (1974) [Bull. Acad. Sci. USSR, Phys. Ser. 38, 54 (1974)].

[3] C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (Wiley, New York, 1967), 6th ed.

[4] H. P. Malan, H. Munzel, and G. Pfenning, Radiochem. Acta 5, 24 (1966).

[5] D. Habs, H. Klewe-Nebenius, R. Lohken, S. Goring, J. Van Klinken, H. Rebel, and G. Schatz, Z. Phys. 250, 179 (1972).

[6] W. Oelert, Z. Phys. 259, 263 (1973).

[7] R. E. Turcotte, Ph.D. thesis, McGill University, 1972 (unpublished).

[8] F. Y. Yap, R. R. Todd, W. H. Kelly, Wm. C. McHarris, and R. A. Warner, Michigan State University Cyclotron Laboratory Report No. 92, 1973 (unpublished).

[9] J. F. Lemming and S. Raman, Nucl. Data B10, 309 (1973).

[10] M. K. Dewanjee and I. L. Preiss, J. Inorg. Nucl. Chem. 34, 327 (1972).

[11] G. Kennedy, S. C. Gujrathi, and P. F. Hinrichsen, Can. J. Phys. 51, 96 (1974).

[12] G. Kennedy, S. C. Gujrathi, and P. F. Hinrichsen, Bull. Am. Phys. Soc. 18, 628 (1973).

[13] E. Beck, Nucl. Instrum. Methods 76, 77 (1969).

[14] M. S. Freedman; T. B. Novey, F. T. Porter, and F. Wagner, Jr., Rev. Sci. Instrum. 27, 516 (1956).

[15] G. T. Garvey, W. J. Gerace, R. L. Jaffe, I. Talmi, and I. Kelson, Rev. Mod. Phys. 41, 4II (1969).

[16] N. Zeldes, A. Grill, and A. Simievic, K. Dan. Vidensk. Selsk. Mat.–Fys. Skr. 3 (No. 5), 113 (1967).

[17] W. D. Myers and W. J. Swiatecki, University of California Report No. UCRL-11980, 1965 (unpublished).

[18] R. S. Hager and E. C. Seltzer, Nucl. Data A4, 1 (1968).

[19] M. Sakai, Institute for Nuclear Study, University of Tokyo, Japan, Report No. INS-J-142, 1973 (unpublished).

[20] E. Storm and H. I. Israel, Nucl. Data A7, 565 (1970).

[21] W. Bambynek, B. Craseman, R. W. Fink, H. V. Freund, H. Mark, C. D. Swift, R. E. Price, and P. Venugopala Rao, Rev. Mod. Phys. 44, 716 (1972).

[22] M. A. J. Mariscotti, G. Scharff-Goldhaber, and B. Buck, Phys. Rev. 178, 1864 (1969).

[23] J. Kownacki, H. Ryde, V. O. Servejev, and Z. Sujkowski, Nucl. Phys. A196, 498 (1972).