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GAMMA-RAY CASCADES IN THE $Rh^{103}(n, \gamma)Rh^{104}$ *REACTION*

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A double-crystal γ-γ coincidence scintillation spectrometer was used to study γ-ray cascades in the $Rh^{103}(n,\gamma)Rh^{104}$ reaction with thermal neutrons. A scheme of low-lying excited levels and the appropriate transitions is constructed for the odd-odd Rh^{104} nucleus. The multipolarities of several 35—133 keV γ transitions are determined. Possible spin and parity assignments for states with excitation energies up to 900 keV are discussed.

1. INTRODUCTION

THE γ radiation from the reaction $Rh^{103}(n,\gamma)Rh^{104}$ has been investigated with both magnetic [1,2] and single-crystal scintillation spectrometers. [3,4] In [1,2] hard γ rays were detected, indicating the existence of excited states up to 1.6 MeV. The low-energy region of the γ spectrum was not measured in [1] and was not resolved in [2]; transitions from low-lying levels were not observed.

In an earlier paper, [3] which was supported by Draper's data, [4] we reported intense soft γ rays with $E_\gamma < 250$ keV emitted by Rh nuclei in thermal-neutron capture. These γ rays represent transitions between low-lying excited states, whose energies could not be established on the basis of the data then available. In the study of the reaction $Rh^{103}(d,p)Rh^{104}$ by Cohen et al [5,6] the energy levels of Rh^{104} were also not identified.

In the present work we have studied the low-lying states of the odd-odd nucleus Rh^{104}. A two-crystal coincidence scintillation spectrometer [7] was used to measure γ transitions in the radiative capture of thermal neutrons by Rh^{103}. The experimental technique has been described in [8]. Our treatment of the data has enabled us to reach qualitative conclusions, as well as some quantitative conclusions; we determined the γ cascade sequences and the γ intensities and internal conversion coefficients. [8,9] From these investigations we determined new low-lying Rh^{104} states and the multipolarities of several γ transitions. We also constructed a scheme of Rh^{104} levels up to 1 MeV and transitions between these levels.

2. MEASUREMENTS OF GAMMA-RAY SPECTRA

Our target was 22 mg of sponge rhodium forming a disk of 20 mm diameter packed in aluminum foil. The neutron source, as in our earlier work, was the heavy-water reactor of the U.S.S.R. Academy of Sciences. [10] In measurements of γ rays with $E_\gamma < 300$ keV the scintillation spectrometers included NaI(Tl) crystals 10—20 mm thick and 30 mm in diameter; for $E_\gamma > 300$ keV the corresponding dimensions were 40 mm and 40 mm.

In experiments where one of the coincidence-spectrometer channels was used as a one-crystal spectrometer, the energies and intensities of individual γ lines were determined or the total intensities of γ-line groups with close energies. These measurements (Table I) agree in the main with earlier results [3,4] and refine the energies and intensities of individual γ lines. We determined for the first time the intensities of a K x-ray line (20 keV) and of γ lines with $E_\gamma > 220$ keV. Results obtained with the one-crystal spectrometer are denoted with a single asterisk in Table I.

In the coincidence measurements the control channel of the spectrometer was adjusted for separate spectral regions corresponding to the most intense γ lines: I — 20 keV, II — 51 keV, III — 98 keV, IV — 133 keV, V — 168 keV, VI — 184 keV, VII — 220 keV, VIII — hard γ rays close to the neutron binding energy. In order to obviate a possible influence of neighboring γ lines the middle of the slit was sometimes shifted with relation to the maximum of a given photopeak. The

Table I. Gamma rays from the reaction $Rh^{103}(n,\gamma)Rh^{104}$

E_γ, keV	Intensity n_γ (%) per captured neutron	Spectral regions with which clear coincidences occur (Fig. 1)	γ rays coinciding with the given line (E_γ, keV)
20±2	36±6*	I — VIII	51, 88, 98, 133, ~ 183
35±3	~0.5**	V, VI	
51±2	11±1.5*	I, IV — VIII	133, 168, 220, 340, 450—600
88±3	~1.3**	I, V, VI	
98±3	13±2 }16±2*	I, III — VIII	98, 133, 176, 210, (340)
99±3	3±1**		
133±3	5.5±1.3** }9±1.5*	I — III, VIII, VII	51, 98, (140, 160—190, 220)
135±3	3±1**		
140±4	~0.5**		
168±5	4.5±5*,**	II, VII	51, 88, (~135, 176)
176±7	2±0.5**	III, V	98
183±7	~3** }16±2*	I, V, VI, VIII	35, 88, (~135)
184±5	13		
205±7	2.5±1*,**		
220±5	6.5±1.5** }10±2*	II, III, V — VIII	}51, 98, 140, (168, 184), ~225
230±5	1±0.4**		
(250±10)	~2*		
275±5	3±1*,**	V, VIII	
320±7	7±1.5*	VIII	
(350±10)	~4*		
440±10	8±2*	VIII	

Note: a single asterisk denotes results obtained with the one-crystal spectrometer; two asterisks pertain to the two-crystal spectrometer. Insufficiently reliable results are bracketed.

following energy regions corresponded more exactly to the different experimental runs:

Experimental run:	I	II	III	IV
Energy region, keV:	12.5—27.5	42—61	87—107	127—143
Experimental run:	V	VI	VII	VIII
Energy region, keV;	160—172	184—196	215—242	$(6.0-6.8)\cdot 10^3$

These energy regions are denoted in Fig. 1 and Table I by the corresponding Roman numerals I—VIII.

Typical spectra are shown in Fig. 1. Curve 1, obtained with the one-crystal spectrometer, is the spectrum of γ rays from $Rh^{103}(n,\gamma)Rh^{104}$ absorbed in a combined absorber of lead, tin, and zinc. Curve 2 is the spectrum of coincidences with hard γ rays (region VIII). Curve 2 exhibits all peaks seen on curve 1; therefore the corresponding γ rays result from transition between the lower excited states.

The spectrum of coincidences with region VII (220 keV) is shown by curve 3, which reveals changed intensity ratios of the peaks compared with curve 1, and especially a drastic reduction of the 184-keV peak. Curve 4 (coincidences with region VI) shows even greater changes of ratios between peaks and also reveals weak 35- and 88-keV lines that do not appear in spectrum 1, where they were suppressed by neighboring strong peaks. In selecting coincidences with region V the slit of the control channel received pulses from 168- and 184-keV γ rays in approximately equal numbers. This was taken into account in interpreting the coincidence spectra of this experimental run. The spectra of coincidences with regions V and VI resemble each other. In the spectrum of coincidences with region IV (curve 5) the 51- and 98-keV photopeaks are most distinct. It is noteworthy that in coincidences with region III, when the control channel was adjusted for the 98-keV photopeak, the spectrum also exhibited a very intense peak of 98 keV (curve 6) within error limits. In coincidences with region II (curve 7), corresponding to 51-keV lines, a reliable peak at 168 keV is observed, which in spectrum 1 is only a small bump on the 184-keV peak. Coincidences with K x rays (not shown in Fig. 1) reveal the peaks of γ rays in cascade with intense x-ray transitions.

Our method of treating the measurements of γ-γ coincidences has been described in [8,9]. Some of the results are given in Table I, where γ intensities obtained from coincidence measurements are denoted by two asterisks. The number of γ lines with E_γ up to 300 keV is seen to exceed greatly the number of distinct peaks in the one-crystal spectrum. A more detailed analysis showed that the half-widths of the 133-, 184-, and 220-keV peaks appreciably exceed the corresponding half-widths of single γ lines. The complex character of these peaks is thus shown.

Further refinements were obtained from the coincidences. Weak 35-, 88-, 140-, 168-, 176-, and 205-keV lines were discriminated in the coincidence spectra because intense nearby masking peaks were greatly diminished. The doublet character of the 98-keV peak has already been men-

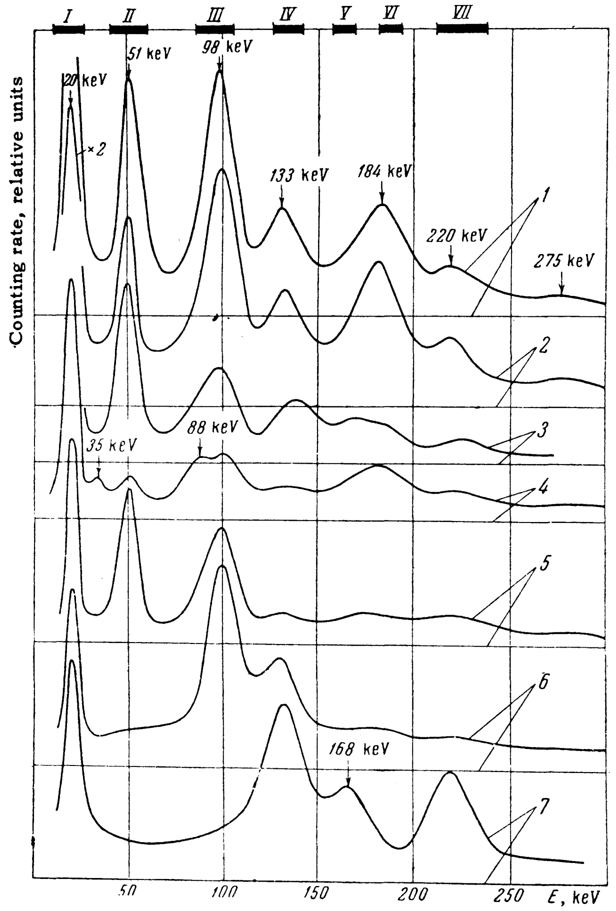

FIG. 1. Typical spectra of γ rays from the reaction Rh^{103} $(n, \gamma) Rh^{104}$. Curve 1 – spectrum, obtained with the one-crystal spectrometer, of γ rays absorbed in 1mm Pb + 0.5 mm Sn + 0.2 mm Zn. Coincidence spectra: curve 2 – coincidences with region VIII, 3 – with region VII, 4 – with region VI, 5 – with region IV, 6 – with region III, 7 – with region II.

tioned; in Table I the two energies 98 and 99 keV comprising the peak have been given for convenience. Lines with energies around 133 keV are observed in coincidences with 51- and 98-keV γ rays (curves 7 and 6 in Fig. 1). However, the curves show that these γ rays do not coincide with each other in time. There are therefore two γ lines at ~ 133 keV in different cascades; their energy difference in Table I is also largely arbitrary. Similar considerations have indicated the complex character of the 184- and 220-keV peaks.

A definite γ-transition scheme is required if γ-line intensities are to be determined from γ-γ coincidences. Therefore a scheme was constructed and intensities were calculated concurrently. The data in Table I correspond to the scheme shown in Fig. 2. The sums of individual γ intensities obtained by the coincidence method are in good agreement with the intensities of γ groups obtained from one-crystal spectra.

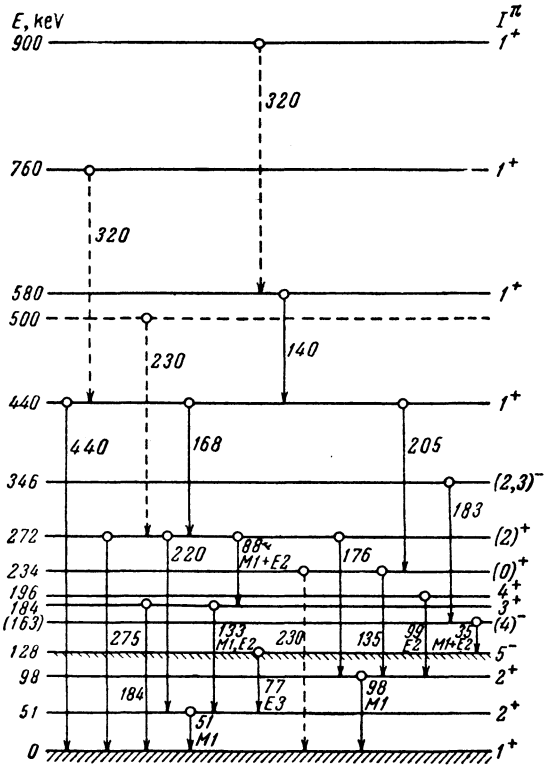

FIG. 2. Lowest levels and transitions in Rh^{104}.

3. THE MULTIPOLARITIES OF SEVERAL TRANSITIONS

The intense emission at 20 ± 2 keV (Table I) in the one-crystal spectrum can be assigned to the characteristic K x-ray emission of the Rh atom in connection with internal conversion. The coincidence spectra (Fig. 1) also exhibit a K peak which can be used in conjunction with the γ photopeaks to determine internal conversion coefficients.

We first considered the multipolarity of the 51-keV emission due to a ground-state transition from the first excited level of Rh^{104}. The multipole character M1 has customarily been assigned to this radiative transition,[11] but a recent publication has attributed electric dipole character.[12] In the present work the multipolarity of the 51-keV quanta was determined more accurately by measuring the activity of Rh^{104m} with a 4.3-min half-life, consisting of 51-keV γ rays and K x rays. The experiments furnished two different methods of determining internal conversion coefficients, giving the total (α) and the K conversion (α_K) coefficients.

By the first method we determined the absolute intensity of γ rays for saturated activation. There is considerable resemblance between this method and the measurement of γ-line intensities in the (n, γ) reaction from one-crystal spectra.[3] The target activity was calculated from the Rh^{104m}

Table II.

Transition energy, keV	Internal conversion coefficient	Experimental	Theoretical			Identification of transition
			$E1$	$M1$	$E2$	
51	$1+\alpha$	3.2 ± 0.5	2.0	3.4	17	$M1$
	$\alpha_K+0.36\,(1+\alpha)$	3.3 ± 0.6	1.6	3.3	15.3	

cross section (12 ± 2b) with normalization of the neutron flux by means of boron. From this we determined $1+\alpha$; experimental and theoretical values for different multipolarities are given in the first line of Table II.[13] The table also indicates our experimental errors, but since the activation cross section is known only within 17% the actual experimental error must be doubled.

The second method employed the intensities of K x rays and 51-keV γ rays from Rh. The K radiation was associated with the conversion of 51- and 77-keV (E3) γ rays[11,12] in equilibrium. This yielded the value of $\alpha_K + 0.36\,(1+\alpha)$ given in the second line of Table II.

Table II shows that the experimental results agree with the theoretical values of an M1 transition, while the theoretical values for an E1 transition lie outside the experimental error limits. Therefore a magnetic dipole character was attributed to the 51-keV transition. The half-life $T_{1/2} = (2.6 \pm 0.2) \times 10^{-9}$ sec given in [14] also agrees best with the M1 character. This transition is retarded by a factor of about 40 compared with single-particle transitions, whereas the factor would be 3×10^3 for an E1 transition. It must also be added that an assumption of E1 character for the 51-keV transition would necessarily entail additional E1 transitions between the lowest excited levels.

We shall now discuss the intensity of K x rays in coincidence spectra from the $Rh^{103}(n,\gamma)$ reaction. In the measurements of coincidences with ~ 133-keV quanta (region IV, curve 3 in Fig. 1) the coefficient α_K for a 98-keV transition is determined after taking account of the conversion of 51-keV quanta. Quadrupole and higher multipoles are rejected by this calculation. The experimental errors do not permit a final decision between E1 and M1 transitions. Additional arguments supporting the magnetic dipole character of 98-keV γ rays were obtained from measurements of coincidences with "hard" γ rays (VIII, curve 2), since in these experiments the 98-keV intensity increased somewhat instead of decreasing compared with the 51-keV intensity. (The reduced 51-keV intensity in this case can be attributed to the exclusion of the branch passing through the isomeric state Rh^{104m}.) The 98-keV transition is probably associated with levels of the same parity as the 51-keV transition.

The K emission detected in measurements of coincidences with 98-keV γ rays (III, curve 6) results from the internal conversion of 98-, 99-, and 135-keV γ rays. In these experiments the relation between the K conversion coefficients of 99- and 135-keV γ rays is obtained if the value of $\alpha_K(98)$ is taken for an M1 transition:

$$\alpha_K(99) + (1.21 \pm 0.17)\,\alpha_K(135) = 2.0 \pm 0.6. \qquad (1)$$

The experimental value (1) uniquely determines the E2 character of 99-keV quanta. E1 multipolarity is rejected for the 135-keV transition.

The spectra of coincidences with 51-keV γ rays (II, curve 7) revealed only weak K radiation, with a corresponding increase in the experimental error. From the computed value of α_K for 133-keV γ rays, despite the large errors, we can exclude E1 and M2 transitions (which are associated with parity change). Thus the 133-keV transition can be of either M1 or E2 character.

The K radiation was strong (by comparison with the γ lines) in the coincidence spectra obtained from experimental runs V and VI (curve 4 in Fig. 1). In these experiments the relation between the α_K coefficients for 35- and 88-keV γ rays was obtained after making small corrections for the conversion of 51- and 98-keV radiation:

$$\alpha_K(35) + (4.6 \pm 0.37)\,\alpha_K(88) = 23 \pm 6. \qquad (2)$$

The experimental value (2) imposes certain limitations on $\alpha_K(35)$ and $\alpha_K(88)$ and therefore on the multipolarities of these transitions. The 35-keV γ rays can be of either the type M1 + E2 or E2, while the 88-keV transition cannot be of M2 or higher multipole order. The area of the 35-keV peak observed in coincidences permits a further refinement of the multipolarity determination, assuming the transition scheme shown in Fig. 2. As has been shown in earlier work,[9] the ratio of the number of coincidences to the number of pulses in the control channel makes it possible to determine the intensity $n_\gamma(183)$ of the upper transition and the total internal conversion coefficient α of the lower radiative transition. The experimental result is

$$n_\gamma(183)/(1+\alpha)_{35} = 0.254 \pm 0.094. \qquad (3)$$

The analysis of the experimental value (3) indicates a magnetic dipole character for the 35-keV transition, with the possible E2 admixture not exceeding 25%. From (2) we find that the multipolarity of the 88-keV transition is E2 or M1 + E2 with a permissible M1 contribution up to 80%.

In conclusion we summarize the γ transitions for which multipolarities were determined: 35 keV (M1 + E2), 51 keV (M1), 88 keV (M1 + E2 or E2) 98 keV (M1), 99 keV (E2), 133 keV (M1 or E2), and 135 keV (M1 or E2).

4. EXCITED LEVELS AND TRANSITIONS IN Rh^{104}

The measured coincidence spectra discussed in the preceding sections enable us to construct the scheme of the lowest excited levels of Rh^{104}.

It has been shown that 51-keV γ rays coincide with 133-, 168-, and 220-keV γ rays (regions II, IV, V, and VII). It has also been observed that 168- and 184-keV quanta coincide with 88 keV. These facts make it possible to establish two new Rh^{104} excited states at 184 and 272 keV, with transitions to and from these levels (the left-hand side of Fig. 2). By analyzing the experimental data in the manner described in [9] we obtained the γ intensities n_γ (Table I) with account of branchings at the given levels. Any other ordering of the γ transitions or other versions of the scheme lead either to values of n_γ conflicting with those determined from the one-crystal spectra, or to inconsistency of the results in the different sets of γ-γ coincidences. Levels with the excitation energies 440, 580, 760, and 900 keV are reached by direct transitions from the initial state that arises in neutron capture.[2] Our measurements have refined the energies of these levels.

The coincidences with 98-keV γ rays (III) revealed another chain of transitions not leading to the 51-keV level. The intensity $n_\gamma(135)$ of the observed 135-keV line was determined both from coincidences with 98 keV and by "inverse measurements" from the 98-keV photopeak in coincidences with region IV of spectrum 1. The intensity of the upper, 99-keV transition, was found from coincidences with region III. The total relative intensity of the lower, 98-keV, transition, with account of internal conversion, is twice as great as the probability that the isomeric state Rh^{104m} is formed. Also, as indicated in the preceding section, the 98-keV radiative transition is probably associated with levels of positive parity.

The totality of the foregoing arguments leads to the conclusion that the transition chain in question is associated with the ground state rather than with the isomeric state. We have therefore introduced a new 98-keV level, from which a ground-state transition is made (Fig. 2). A satisfactory ordering of the γ transitions observed in coincidences with 98-keV γ rays is attained by introducing an additional 234-keV level. At the same time we attain a simple explanation of the weak 176- and 205-keV transitions (the right-hand side of Fig. 2) observed in the control experiment, which is performed with a NaI(Tl) crystal 40 mm thick having enhanced sensitivity to the indicated γ rays.

The interpretation of coincidences with 215—234-keV γ rays (VII, curve 3 of Fig. 1) encountered difficulties associated mainly with the existence of γ lines in the selected spectral region of the control channel. A 230-keV peak could not be accounted for by a transition between any of the previously assumed levels, and a 500-keV level was arbitrarily introduced. In the aforementioned control experiment registering coincidences with 98-keV quanta the coincidence spectrum included unresolved γ lines at ~ 200—250 keV. Calculations showed that the 98-keV peak observed on curve 3 of Fig. 1 can be accounted for by coincidences with these γ lines, which evidently represent transitions between high-lying levels. A ground-state transition from 234 keV was not observed, although there are no arguments against its occurrence. A strong 320-keV line was found in the one-crystal spectra; Fig. 2 shows probable positions for this line as a transition between levels known from measurements with "hard" γ rays. These transitions evidently appear in the spectra of coincidences with 51 and 98 keV. Their designation in Table I as a ~ 340-keV line results possibly from errors in the energy calibration.

The coincidences with regions V and VI (Fig. 1) include a 35-keV line not observed in any other experimental run, although the associated K radiation is fairly strong. We therefore have a ~ 183-keV transition in a 35—183-keV cascade not associated with the transitions to the 51- and 98-keV levels. If it is assumed that the given cascade goes to the ground state of Rh^{104}, it cannot be understood why these transitions have no connection with the previously assumed excited levels. In view of the low intensity of the cascade, one can assume preferably that it leads to the isomeric state Rh^{104m}, i.e., it goes through levels with negative parity. An analysis of the ratio between the intensity of the 35-keV peak observed in coincidences and the count in the control channel, using the same technique as in [9], yields no unambiguous conclusion regarding the γ-ray sequence in the 35—183-keV cascade. The experimental result (3) can be brought into agreement with the theory by changing within reasonable limits both the intensity of the upper transition and the multipole ratio in the M1 + E2 mixture. We shall assume that the lower, 35-keV, transition proceeds from a 163-keV level. The multipolarity M1 + E2 for 35-keV γ rays was determined from (3) in the preceding section on the basis of this assumption.

The level scheme in Fig. 2 indicates the most probable spins and parities of excited Rh^{104} states. Direct transitions of comparable intensity from the initial state arising out of neutron capture should be of E1 character like a ground-state transition. Since such transitions to 2^+ levels were not found, the initial state is most likely of 0^- character. Therefore the levels realized in the direct transitions have the probable character 1^+ as shown in the scheme. We avoided the assignment 1^+ for the other excited levels in order to forbid transitions to these levels which were not observed in [1,2]. The assignment 2^+ for the 51- and 98-keV levels was determined from the multipolarity M1 of the appropriate transitions. The 184-, 196-, and 272-keV levels have positive parity, since transitions from these levels involve no change of parity.

The selected spins were the most favorable values to account for the intensity ratios of the observed radiative transitions. Zero spin is possible for the 234-keV excited level, although this identification cannot be regarded as final.

The interpretation of excited Rh^{104} levels is hampered by the large numbers of neutrons and protons in unfilled shells. For example, the ground state must have the complex configuration $(g_{9/2})^5_{7/2} d_{5/2}$.[15] A complex configuration must also be attributed to the isomeric state. We can only mention two characteristics of the levels studied in the present work: first, the large number of levels close to the ground state and their small separations, and secondly, the difference between the chains of transitions to the first two excited levels having identical characters.

[1] G. A. Bartholomew and B. B. Kinsey, Can. J. Phys. **31**, 1025 (1953).

[2] Groshev, Demidov, Lutsenko, and Pelekhov, Atlas of Gamma-Ray Spectra from Radiative Capture of Thermal Neutrons, Pergamon Press, New York, 1959.

[3] Éstulin, Kalinkin, and Melioranskiĭ, JETP **32**, 979 (1957), Soviet Phys. JETP **5**, 801 (1957).

[4] J. E. Draper, Phys. Rev. **114**, 268 (1959).

[5] Cohen, Mead, Price, Quisenberry, and Martz, Phys. Rev. **118**, 499 (1960).

[6] B. L. Cohen and R. E. Price, Nuclear Phys. **17**, 129 (1960).

[7] A. S. Melioranskiĭ, PTÉ No. 3, 44 (1961).

[8] Melioranskii, Éstulin, Kalinkin, and Kudinov, JETP **38**, 758 (1960), Soviet Phys. JETP **11**, 548 (1960).

[9] Melioranskiĭ, Éstulin, and Kalinkin, JETP **40**, 64 (1961), Soviet Phys. JETP **13**, 43 (1961).

[10] Atomnaya Energiya **3**, 276 (1957) (Brief Communication), Soviet J. Atomic Energy, p. 1080.

[11] Jordan, Cork, and Burson, Phys. Rev. **90**, 862 (1953).

[12] Nuclear Data Sheets, National Academy of Sciences–National Research Council, 1960 (U.S. Government Printing Office, Washington, D.C.).

[13] M. E. Rose, Internal Conversion Coefficients, North Holland Publ. Co., Amsterdam, 1958.

[14] S. J. du Toit and L. M. Bollinger, Phys. Rev. **123**, 629 (1961).

[15] M. H. Brennan and A. M. Bernstein, Phys. Rev. **120**, 927 (1960).

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