SOVIET PHYSICS JETP VOLUME 13, NUMBER 1 JULY, 1961

A STUDY OF LOW-LYING EXCITED STATES IN Mn^{56} *AND* Ho^{166} *BY MEASURING CASCADE QUANTUM COINCIDENCES*

A. S. MELIORANSKIĬ, I. V. ÉSTULIN, and L. F. KALINKIN

Institute of Nuclear Physics, Moscow State University

Submitted to JETP editor July 17, 1960

J. Exptl. Theoret. Phys. (U.S.S.R.) 40, 64-71 (January, 1961)

The technique for measurement of the intensity of cascade γ quanta was employed to investigate the low-lying levels of the odd-odd nuclei Mn^{56} and Ho^{166}. The multipolarity of the 25- and 85-kev radiative transitions in Mn^{56} was determined. The level scheme of the strongly deformed Ho^{166} nucleus, which exhibits a rotational band, is discussed.

INTRODUCTION

SOME low-lying excited states of the odd-odd nuclei Mn^{56} and Ho^{166} have been studied in this research; these states arise in the radiative capture of thermal neutrons. The technique of measurement of the coincidences of cascade γ quanta by means of a luminescence spectrometer was employed.[1,2] The general measuring arrangements were described previously.[1] The further development of the coincidence technique used in the present research is given below.

2. NOTE ON THE TECHNIQUE OF MEASUREMENT OF CASCADE γ -QUANTUM COINCIDENCES

The technique of the measurement of multiple coincidences of γ quanta is usually applied to the detection of cascade transitions, with the aim of making clear the decay scheme. In a number of cases, this technique makes it possible to determine certain characteristics of the radiative transitions entering into the cascades.

We assume that there is a cascade of γ quanta with intensity of radiations $n_{\gamma 2}$ and $n_{\gamma 1}$, (Fig. 1). In the general case, $n_{\gamma 1} \neq n_{\gamma 2}$ because of the additional transitions to the lower excited level, or because of the internal conversion of the γ quanta entering into the cascades. In the measurement of the coincidences by a luminescence spectrometer, one of the γ rays is isolated in the control channel and the spectrum of pulses coinciding with the pulses in the control channel is measured in the other (main) channel. The ratio of the number of pluses in the main channel N_{coin}, determined from the area of the light spikes, to the number of pulses from the separated γ line in the control channel N_{cont} will be equal to

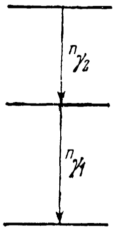

FIG. 1.

$$N_{coin}/N_{cont} = (q/n_{cont})\,\varepsilon\omega, \tag{1}$$

where q is the intensity of the cascade, n_{cont} is the intensity of the γ quanta which control the coincidences, ϵ and ω are the efficiency and the solid angle of the main channel. The quantity q, having the same dimension as n_{cont}, is determined by the intensity of the γ quanta of the upper transition $n_{\gamma 2}$ and by the total coefficient of internal conversion α of the lower transition on the electrons of the atom:

$$q = n_{\gamma_2}/(1+\alpha)_{\gamma_1}. \tag{2}$$

The value of q/n_{cont} entering into (1) will be different in the equations for the upper (3a) or lower (3b) γ quanta:

$$q/n_{cont} = 1/(1+\alpha)_{\gamma_1} \tag{3a}$$

$$q/n_{cont} = n_{\gamma_2}/n_{\gamma_1}(1+\alpha)_{\gamma_1} \tag{3b}$$

In a number of experiments in coincidence spectra, a spike appears from the characteristic x-radiation of the atom, which is connected with the internal conversion of the radiated γ quanta by the electrons of the K shell of the atom. For this spike we obtain

$$q/n_{cont} = [\alpha_K/(1+\alpha)]_{\gamma_1} W_K, \tag{4a}$$

$$q/n_{cont} = (n_\gamma \alpha_K)_{\gamma_2} W_K/[n_\gamma(1+\alpha)]_{\gamma_1}, \tag{4b}$$

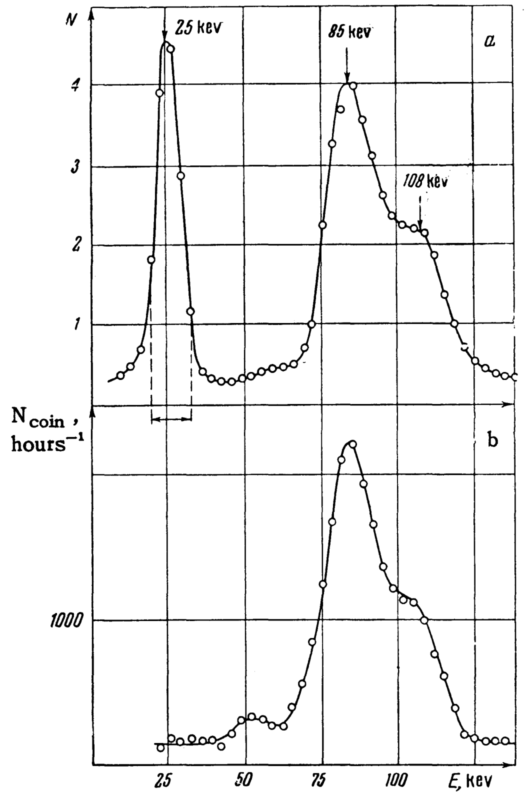

FIG. 2. Spectra from γ ray pulses of the reaction $Mn^{55}(n, \gamma)Mn^{56}$; a – in one channel; b – in coincidence with the line of 25 kev.

respectively, in place of (3a) and (3b). Here W_K is the yield of the K fluorescence.

Experimentally, the ratio N_{coin}/N_{cont} is determined; then q/n_{cont} is found from (1) and the result is compared with the theoretical values for the cases a) and b) in the case of different multipolarity radiative transitions. By the suitable analysis, it is possible in certain cases to find the succession of the radiative transitions, to find the intensity of the γ transitions, and to determine the coefficients of internal conversion and the multipolarity of the radiative transitions under consideration. Examples of the use of these techniques are contained in the succeeding sections of this paper, in which we report the results of experiments with Mn^{56} and Ho^{166}.

For an exact determination of the ratio q/n_{cont}, it is necessary to make use of the correct values of N_{cont}, ϵ, and ω. The number of pulses N_{cont} includes only a part of the pulses incident on the "slit" of the amplitude analyzer of the control channel and produced by the controlling γ lines. To determine N_{cont}, the pulse spectrum is divided into components by filtering the radiation.[1] The procedure used to determine the efficiency of the spectrometer according to the light spike ϵ was described by us earlier.[3] To find the solid angle ω, experiments were made with a compound of Te^{123m} (E_γ = 159 kev), which was identical in form with the target, with the compound located at the place of the target with a distance of 30 cm between the source and the collimator of the γ rays; in the second case, the solid angle was computed. For the determination of the multipolarity of the γ transition, use was made of the theoretical values[4–6] of the coefficients of internal conversion of γ quanta on atomic electrons.

The measurement of the coincidence spectrum was combined with measurements of the spectrum in one of the channels with the aim of determining the absolute intensities expressed in γ quanta per captured neutron.[3]

2. EXPERIMENTS WITH Mn^{56}

The spectrum of the γ rays with energies up to several hundred kev, emitted in the radiative capture of thermal neutrons in Mn^{55}, was measured by a number of authors.[7–10] However, the maximum in the spectrum which appears in the region of energies 80 — 110 kev was attributed in these works to one γ line with energy of either 85 kev[10] or 105 kev,[7,9] while the γ line with energy of 105 kev was assumed to be connected with the transition from the second excited level to the ground state of Mn^{56}. The γ quanta with energy 25 kev, which correspond to a transition from the first excited level, were recorded only in the work of D'Angelo.[10]

Measurements were carried out in the research reported here on the energy and absolute intensities of soft γ quanta of the reaction $Mn^{55}(n, \gamma)Mn^{56}$, and the coincidences between them. The very soft region of the spectrum is shown in Fig. 2. The measurements were made with the aid of a single-crystal luminescence spectrometer. Light spikes from γ quanta with energies of 25 ± 2 kev are seen in this spectrum, and the complicated character of the maximum in

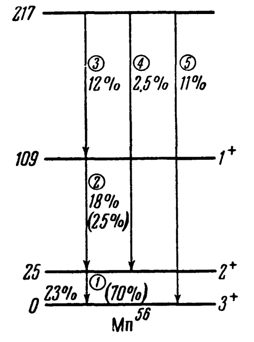

FIG. 3. Scheme of the low-lying levels of Mn^{56}. The intensities of transitions (radiative and total) are indicated in percent per captured neutron.

Table I. Gamma lines of the reaction $Mn^{55}(n, \gamma)Mn^{56}$

No. of line	Energy of gamma line, kev	Intensity of the gamma line, per cent per captured neutron	Concurrent lines, kev	
1	25±2	23±3	85, 108,	>6200
2	85±2	18±2	25, 108,	
3	108±3	12±2	25, 85,	
4	190±4	2.5±0.5	**	
5	217±4	11±2		
6	280±5	8±3*	85, 108	

*The intensity of the γ line with energy 280 kev was determined from $\gamma\gamma$ coincidences.

**The spectrum of the γ quanta that coincide with the γ lines of 25 kev was measured in the energy region up to 140 kev.

the region 85 — 110 kev is apparent. As measurements of the absorption of gamma rays in different filters have shown, this maximum consists of light spikes from γ quanta with energies of 85 ± 2 and 108 ± 3 kev. In addition to those previously known, a low-intensity γ line with energy 190 ± 4 kev was also found. Data on the energies and intensities of γ lines are given in Table I.

Gamma quantum spectra coinciding with the gamma lines of 25 and 85 kev and with the sum of the lines of 85 and 108 kev were measured. In the measurement of coincidences with γ quanta with energies of 85 kev, the γ line of 108 kev was filtered by lead, in which the first of the γ quanta mentioned were weakly absorbed. In addition to coincidences between soft γ lines, the spectrum of soft γ quanta coinciding with hard γ rays whose energies were close to the binding energy of the neutron was measured. This experiment confirmed that the γ lines discovered corresponded to transitions between the lower excited states.

Data on $\gamma\gamma$ coincidences for Mn^{56} are also given in Table I. The spectrum of γ quanta coinciding with the γ lines of 25 kev was studied in the region of energies below 140 kev. In the analysis of the results, it was noted that the ratio of the areas of the light spikes from γ quanta with energies of 108 and 85 kev, which appear in coincidences with γ lines of 25 kev (Fig. 2b), is equal, within the limits of error of the experiment, to the ratio of the areas of the spikes from these same γ lines in the spectrum measured on a single-crystal spectrometer with the same crystal (respectively, 0.60 ± 0.01 and 0.63 ± 0.04). This means that the γ line with energy 108 kev is practically completely caused by a transition from the third excited level to the second (Fig. 3). The equality of the areas of the S light spikes from γ quanta of 85 and 108 kev in the coincidence spectrum with the sum of these γ lines ($S_{85}/S_{108} = 1.02 \pm 0.05$) also bears witness to this fact. The upper limit of the intensity of the γ quanta, which is associated with the possible transition from the second excited level (109 kev) to the ground state, does not exceed 1.3 per cent for one captured neutron.

The method of analysis of the results of $\gamma\gamma$ coincidences, described in the previous section, was used for the determination of the total conversion coefficients of γ transitions with energies of 25 and 85 kev. The experimental values obtained from Eqs. (3), and the theoretical total conversion coefficients for the K, L and M shells are given in Table II.[4-6] The experimental data for the radiative transition with 85 kev energy can be made to agree with theoretical values under the assumption either of a transition of the M2 type, or of a mixture of the multipoles M1 + E2. We can eliminate the first possibility because of the too long lifetime of the excited state in this case, a result which contradicts experiment.[10] Thus the transition with energy of 85 kev is a mixture of the multipoles M1 + E2 (admixture of radiation of the type E2 is 45 per cent) and consequently does not change the parity of the states. To the level with

Table II. Multipolarity of transitions for Mn^{56}

Transition energy, kev		25			85			
Conversion coefficient $1+\alpha$	Theory	$E1$ 3,36	$M1$ 2.37	$E2$ 79.7	$E1$ 1,05	$M1$ 1,05	$E2$ 1,83	$M2$ 1,55
	Experiment	3,0±0,2			1,4±0,2			
Multipolarity of transition		$99M1+1E2$			$55M1+45E2$			
Reduced probability	$B(M1)\cdot 10^5$, $e^2\cdot b$,	0.83			0,3			
	$B(E2)$, $e^2\cdot b^2$	1.4			4			

energy 109 kev there is a direct transition of the type E1 from the initial state of Mn^{56} with characteristics 2^- or 3^- (the first is more probable), which is realized in the capture of a thermal neutron.[11] Thus the states of 109 and 25 kev have positive parity.

The presence in the spectrum of an intense γ line with energy 25 kev gives evidence that the corresponding transition can only be dipole, since in the case of higher multipolarities it would have been practically completely converted. The measured value of the total internal conversion coefficient (Table II) is close to the theoretical value for the transition of type E1. However, the parities of the ground and first excited states are identical, and there cannot be such a transition between them. The experimental value of $(1 + \alpha)$ for 25 kev exceeds the theoretical value for the transition M1, which compels us to regard this transition as a mixture of the multipoles M1 + E2. The strong difference in the conversion coefficients for transitions of such multipolarities makes it possible to determine a small admixture of radiation of the type E2, amounting to (0.8 ± 0.3 per cent).

The results of the study of $\gamma\gamma$ coincidences confirm the scheme of γ transitions between the lower levels of Mn^{56} given in reference 8. The values of the multipolarities of γ transitions with energies of 25 and 85 kev do not contradict the results of D'Angelo,[10] who measured the lifetimes of the first three excited levels of Mn^{56}, nor of the research of reference 12 on the study of the radiation of Cr^{56}. In using the results of reference 10 in conjunction with our data on the conversion coefficients and mixtures of multipolarities (Table II), the experimental values of the reduced probabilities of transitions M1 and E2 with energies of 25 and 85 kev were computed (see Table II). The reduced probability of the transition M1 with energy 25 kev was computed with an accuracy of ± 25 per cent, and the others with ± 50 per cent. Transitions of the type M1 were retarded by a factor of 10 — 40 relative to single-particle transitions, while those of type E2 were accelerated by two or three orders of magnitude.

3. EXPERIMENTS WITH Ho^{166}

Soft γ quanta produced in the reaction $Ho^{165}(n, \gamma)Ho^{166}$ with energies of 120 and 140 kev were discovered by Sklyarevskiĭ et al.[13] and by Draper.[14] In the present work, the connection between these γ quanta and the levels of Ho^{166}, which are populated in the β decay of Dy^{166}, was studied.[15,16] One could expect the appearance of a band of rotational levels, since the odd-odd nucleus Ho^{166} is located in a region of strongly deformed nuclei.

In the investigation of the radiative capture of thermal neutrons, a target of Ho_2O_3 was used with a weight of 70 mg and in the shape of a disc 20 mm in diameter. Possible impurities of other rare-earth elements required additional checks of the purity of the target material. As a criterion, we had the γ radiation, and also the energy and peak form of the K-shell x-radiation which arises in the exposure of the specimen to the neutrons. The Dy impurity amounted to (2 ± 0.5) per cent. A small peak with energy 180 kev, which appears in the spectrum of a single channel, was connected with the Dy impurity, which was observed by its induced activity with a period of 1.25 min. About one quarter of the neutrons captured in the target were in the Dy fraction, a fact which complicated the identification of the low-intensity γ lines.

In Table III we give the energy and intensity of the γ quanta involved in the reaction $Ho^{165}(n, \gamma)Ho^{166}$. In previously published researches, the γ lines 1 and 2 were not shown. The intensity of the γ lines 3 and 4 found in the present work differs somewhat from the result of Sklyarevskiĭ et al.[13] and, in particular, of Draper,[14] whose data on the γ line with energy 121 kev are inaccurate. The peak with energy 47 ± 2 kev is demonstrated by the K-shell x-radiation of the Ho atom. The intensity of this radiation, which is shown in the table, has been adjusted for the x-radiation of Dy (a correction of the order of 7 per cent is obtained by recalculation of the data of references 13 and 14).

Table III. Lines of the reaction $Ho^{165}(n, \gamma)Ho^{166}$

No. of line	Energy of γ line, kev	Intensity, in percent per captured neutron	Coincident γ lines kev	Multipolarity of the γ transition
X	47±2	58±12	X, 121, $>$1750	
1	56—66	19±5*	121	$M1$
2	82±2	2.5	X, $>$1750	$M1$
3	121±3	16±2	X, $>$1750	$E2$
4	140±3	22±3	—	$E1+M2$

*Strong conversion, the total intensity of the transition is shown.

Four different series of measurements of coincidences were carried out with x-radiation by γ lines of 121 and 140 kev, and also with hard γ quanta with energy of 1.75 Mev, which are generated in the target under the action of the neutrons. In these experiments, no coincidences were found with γ quanta of energy 140 kev, which indicates the long lifetime of the level with which the transition under consideration is realized, in accord with the work of Alexander and Bredel.[17] The gamma transition with energy 140 kev can lead either to the ground state of Ho^{166} or to the first excited state with energy 54.2 kev,[16] since it was not possible to find coincidences with these γ quanta, because of their appreciable conversion on the atomic electrons. Alexander and Bredel[17] determined the coefficient of internal conversion of the γ quanta with energy of 140 kev on the K shell of the atom, the value of which ($\alpha_K \approx 0.4$) indicates two possible variants of multipolarity: E2 or E1, with 5 per cent addition of M2. Such a strongly retarded E2 transition ($\tau = 2.14 \times 10^{-4}$ sec[17]) is scarcely probable, but E1 transitions with a retardation factor as large as $10^6 - 10^9$ are known. The intensity of the transition also supports a multipolarity of the E1 type. Therefore, it is more probable to regard the γ transition with energy of 140 kev as a mixture transition, which contradicts the assumption that it leads to the ground state. Apparently, there exists a level in the Ho^{166} nucleus with excitation energy 194 kev with the characteristic 3^+ (see Fig. 4). In this case, the absence of γ transitions to the second excited level and to the ground state is satisfactorily explained.

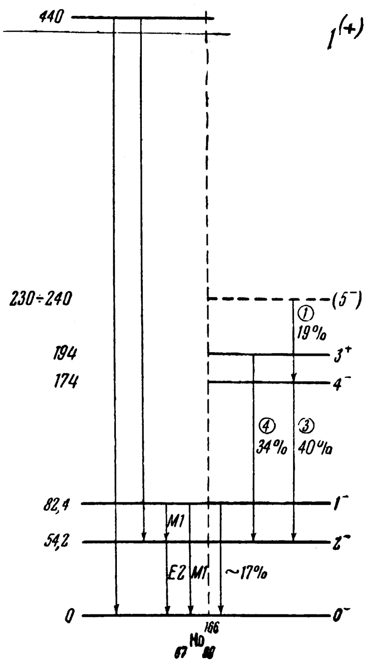

FIG. 4. Level scheme of Ho^{166}. On the left are the levels which appear in the decay of Dy^{166}.[16] On the right are those of the reaction Ho(n, γ). The total intensity of transitions is shown in per cent per captured neutron.

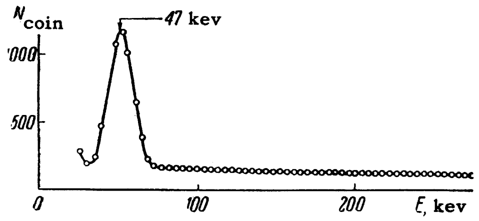

FIG. 5. Spectrum of pulses, which coincides with the gamma lines of 121 kev in the reaction Ho(n, γ).

In the measurement of coincidences with γ quanta of energy 121 kev there is a peak of energy 47 ± 2 kev, within the limits of error of experiment, which corresponds to K radiation of Ho, and no other γ lines are observed. The results of one of many similar experiments are shown in Fig. 5. In picking out the coincidences with the x radiation, coincidences are also observed with γ quanta of energy 121 kev. Thus the γ quanta with energy of 121 kev are found in a cascade with strongly converted γ lines (we denote them by y), whose conversion coefficient on the electrons of the K shell of the atom is $\alpha_K \geq 10$. A similar estimate eliminates the possibility of transitions E1 and E2, but permits a multipolarity of the type M1 with energy of 56 — 65 kev, or of type M2 with energy 56 — 120 kev. If the energy of the transition under consideration, $E_y = 47 \pm 2$ kev, is identical with the energy of the K radiation, then this multipolarity can only be E1.

The intensity of the cascade from the lines y and 121 kev is determined from Eq. (1):

$$(q/n_{121})_{\text{exp}} = 0{,}34 \pm 0{,}06. \qquad (5)$$

This value was compared with the theoretical, obtained from (4), for various assumptions on the multipolarity of the radiative transitions under consideration. If the γ transition with energy 121 kev is considered as the upper transition [case (4a)], then the estimate of the multipolarity of the transition y, which corresponds to the value (5), contradicts the estimate of the multipolarity according to α_K. Therefore, case (4a) is rejected. Similar analysis for γ quanta with energy of 47 kev leads to the same conclusion. The given analysis did not consider the possibility of the transition 0 — 0. However, introduction of an excited level with spin 0 makes it necessary to forbid also a series of transitions between the lower excited levels of Ho^{166}, which are realized in the reaction (n, γ), and in the decay of Dy^{166}. More justifiable is the conclusion that the lower transition has the energy 121 kev [case (4b)]. Making use of the experimental value of (5) from an expression similar to (4b), we determine the total intensity of the transition y: $n_y = 19$ per cent for a single captured neutron with a multipolarity of the γ quanta with energy 121 kev of the type M1 or E2. The multipolarity of the γ quanta with energy 121 kev is found from the intensity of the x radiation (Table III) with account of the internal conversion of these γ transitions on the K shell of the atom, where the choice of the multipolarity E2 is preferable.

The intense cascade of lines y and 121 kev can lead to the ground state or to the lowest excited level. We assume that the cascade leads to the second excited level (Fig. 4). In this case, the absence of coincidences between the lines 121 and 82 kev (Fig. 5) should have sufficed to account for the low intensity of the direct transition (of the order of 5 per cent) in comparison with the intensity of the cascade transition from the level with energy 82.4 kev. But the low intensity of the direct transition contradicts the results of the study[15,16] of the radiation of Dy^{166}. In the transition of the cascade to the ground state, it is advantageous to introduce new levels of Ho^{166} with the quantum characteristics 1^- or 2^- which could also be populated in the β decay of Dy^{166}. We would expect transitions here from the 121-kev level not only to the ground state, but also to the first two levels. The scheme of γ transitions shown in Fig. 4 is free of the foregoing contradictions. In this scheme, the transition with energy 121 kev is accomplished from the level with energy 174 kev. For the level with energy 230 — 240 kev, the characteristic 5^- is chosen, which guarantees the transition to the level 174 kev with the suppression of the other transitions.

In the suggested scheme of levels of Ho^{166} (Fig. 4) there is seen a rotational band 0 (state 0^-), 54.2 kev (2^-) and 174 kev (4^-) for K = 0. The moment of inertia of this rotational band is characterized by the value $A = \hbar^2/2J = 9.20 \pm 0.07$ kev (for $B = 0.05 \pm 0.011$ kev) and is identical with the calculations of Peker[18] for odd-odd nuclei for the case K = 0 and $I_0 = 0$. The level of energy 82.4 kev, through which pass about 17 per cent of all transitions, can serve as the beginning of a new rotational band with odd spins. In the measurement of coincidences with x-radiation and hard γ quanta ($E_\gamma > 1.75$ Mev) γ quanta are observed with energy of 82.4 kev, and x-radiation not connected with the cascade of the lines y and 121 kev is observed. Evidently there is a soft γ radiation which leads to the level with energy 82.4 kev; however, we did not observe the corresponding γ quanta. The nucleus Ho^{166} has a long-lived isomeric level with spin and parity 7^- (references 19 and 20), which has an excitation energy ~ 900 kev. This state can have K = 7 and the transition from it to the observed level will be connected with the strong K forbidenness.

---

[1] Melioranskiĭ, Estulin, Kalinkin, and Kudinov, JETP **38**, 758 (1960), Soviet Phys. JETP **11**, 548 (1960).

[2] A. S. Melioranskiĭ, Приборы и техника эксперимента (Instrum. and Exptl. Techn.) in press.

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

[4] L. A. Sliv and N. M. Band, Таблицы коэффициентов внутренней конверсии гамма излучения (Tables of Internal Conversion Coefficients of Gamma Radiation) (Acad. Sci. Press, Moscow-Leningrad, 1958).

[5] M. E. Rose, Tables of Internal Conversion Coefficients, Beta and Gamma Spectroscopy, under the editorship of K. Siegbahn, Appendix IV, North Holland, 1955.

[6] M. E. Rose, Internal Conversion Coefficients (Amsterdam, 1958).

[7] M. Reier and M. H. Shames, Phys. Rev. **100**, 1302 (1955).

[8] Kennett, Bollinger, and Carpenter, Phys. Rev. Lett. **1**, 76 (1958).

[9] Urbanec, Kopecky, and Kajfosz, Czechoslovak J. Phys. **9**, 544 (1959).

[10] N. D'Angelo, Phys. Rev. **117**, 510 (1960).

[11] Groshev, Demidov, Lutsenko, and Pelekhov, Атлас спектров γ-лучей радиационного захвата тепловых нейтронов (Atlas of Gamma Ray Spectra of Radiative Capture of Thermal Neutrons) Atomizdat, 1958.

[12] Dropesky, Schardt, and Shull, Nucl. Phys. **16**, 357 (1960).

[13] Sklyarevskiĭ, Stepanov, and Obinyakov, Атомная энергия (Atomic Energy) **4**, 22 (1959).

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

[15] R. G. Helmer and S. B. Surson, Bull. Amer. Phys. Soc. **4**, 427 (1959).

[16] Geiger, Graham, and Ewan, Bull. Amer. Phys. Soc. **5**, 255 (1960).

[17] K. Alexander and V. Bredel, Nucl. Phys. **16**, 153 (1960).

[18] L. K. Peker, Izv. Akad. Nauk SSSR, Ser. Fiz. **24**, 365 (1960), Columbia Tech. Transl. p. 350.

[19] P. Baskma and H. DeWoard, Nucl. Phys. **12**, 533 (1959).

[20] Pastima, Miederna, and Smulders, Physica **25**, 671 (1959).

Translated by R. T. Beyer
11