MEASUREMENT OF γ-γ COINCIDENCES IN THE REACTION $Ag^{107}(n,\gamma)Ag^{108}$

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A two-crystal scintillation spectrometer was used to measure γ-γ coincidences in the reaction $Ag^{107}(n,\gamma)Ag^{108}$. The energies and intensities of γ lines up to 640 keV were determined. The level scheme of Ag^{108} up to 720 keV and transitions between the levels are discussed.

INTRODUCTION

MAGNETIC spectrometers have been used to measure the γ spectrum in the radiative capture of thermal neutrons by a natural mixture of silver isotopes.[1] The detection of γ quanta with energies 7.27—6.94 MeV has indicated the existence of excited levels of Ag^{108}, where the binding energy of the last neutron is greater than in Ag^{110}. We have used single-crystal scintillation spectrometers to investigate γ emission from a separated isotope in the reaction $Ag^{107}(n,\gamma)$.[2,3] Intense soft γ quanta ($E_\gamma < 310$ keV, $n_\gamma > 10\%$ of the number of γ quanta per captured neutron) were observed, corresponding to transitions between low-lying excited states of Ag^{108}. The tables of Dzhelepov and Peker[4] give the possible excited levels of Ag^{108}, based on the energies of proton groups in the reaction $Ag^{107}(d,p)Ag^{108}$, which was investigated by Buechner et al.

In the present work γ-γ coincidences in the reaction $Ag^{107}(n,\gamma)Ag^{108}$ were measured using the experimental technique which we have described previously[5,6] and which is entirely similar to that employed in [7]. We present here our experimental results, propose a scheme of low-lying Ag^{108} levels and transitions between these levels, and discuss the degree of agreement with other investigations.[1-3]

EXPERIMENTAL RESULTS

The 111.6-mg target to be irradiated with neutrons was prepared out of metallic silver enriched to 99.1% Ag^{107}. NaI(Tl) crystals 10—40 mm high were used in the scintillation spectrometer. Curve a in Fig. 1 is the spectrum of pulses in a single-crystal scintillation spectrometer produced by γ rays from the $Ag^{107}(n,\gamma)$ reaction; the radiation was absorbed in a combined filter consisting of 2 mm lead, 0.5 mm tin, and 0.1 mm zinc. The clear lines of this spectrum agree with our earlier work[2] with regard to both energies and relative intensities. Additional weak 46- and 152-keV γ lines were observed in the single-crystal spectrum, as well as a more intense 22-keV peak which we attribute to K radiation. These differences resulted from diminished and refined corrections for absorption mainly in the target, which was only one-fifth as thick as previously. In measurements with characteristic filters the 80-keV γ quanta were found to lie between the K absorption edges of Pt and Au, 78.4 and 80.7 keV, respectively. The average energy of this line was taken as 79.6 + 1.1 keV, but for convenience it will hereafter be called the 80-keV line.

In the single-crystal spectrum we cannot resolve close lines or discriminate weak lines. A large number of new γ lines were discovered in γ-γ coincidence measurements performed with a two-crystal spectrometer[8] whose control channel was set for one of the pronounced peaks in the single-crystal pulse spectrum. Window widths in the separate experimental runs are indicated at the top of Fig. 1. We also measured coincidences with γ quanta close to the neutron binding energy in Ag^{108}.

The spectrum of coincidences with 80-keV quanta (region 2 in Fig. 1) exhibits γ peaks at 40, 83, (114), 134, (162), 184, and 214 keV (curve f in Fig. 1 is a typical coincidence spectrum); also 260, 300, 378, 440, 515, 565, and 635 keV (the coincidence spectrum measured with a NaI(Tl) crystal 40 mm high is represented by the uppermost curve in Fig. 2). Here and subsequently parentheses enclose the γ lines that were not determined with complete reliability because of low intensity or closeness to other lines. The coincidence spectra clearly revealed a 22-keV peak of K radiation resulting from the internal conversion

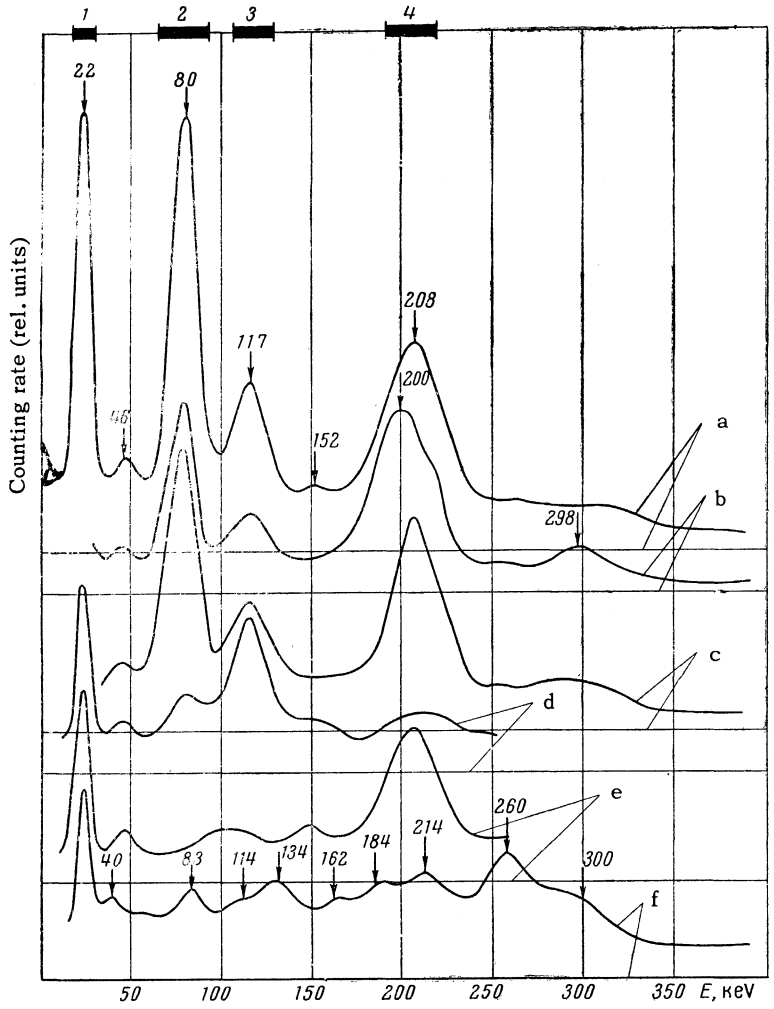

FIG. 1. Typical spectra of γ rays from Ag^{108}. a – single-crystal spectrum of γ rays absorbed in a filter consisting of 1 mm Pb, 0.5 mm Sn, and 0.1 mm Zn. Coincidence spectra discriminated in control channel: b, c – hard γ rays close to the neutron binding energy; d – region 4; e – region 3; f – region 2.

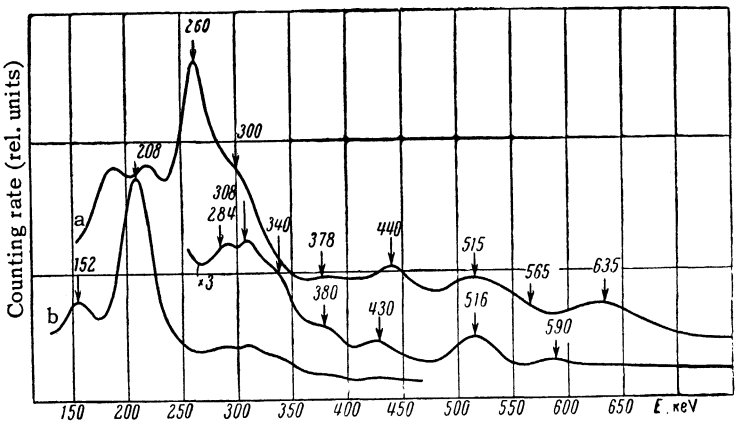

FIG. 2. Spectra of coincidence with (a) 80-keV γ rays [using NaI(Tl) crystal 40 mm high], and (b) 117-keV γ rays [using NaI(Tl) crystal 10 mm high].

of mainly low-energy γ quanta. The K conversion coefficient α_K was thus determined experimentally.[5] The value of α_K obtained for 40-keV γ quanta depends somewhat on its value for 83-keV quanta:

$$\alpha_K(40) = 5.5 \pm 2.5 - (0.94 \pm 0.09)\,\alpha_K(83). \qquad (1)$$

The experimental value given by (1) prevents the assignment of E2 or higher multipolarity to the 40-keV transition. If the 83-keV transition is of dipole character, the 40-keV transition is most probably M1.

The coincidences with 117-keV γ quanta (region 3 in Fig. 1) revealed γ lines at 46, 152, 208, (234), 284, 308, 340, 380, 430, 516, and (590) keV (curve e in Fig. 1 and curve b in Fig. 2). In this part of the work the experimental value of α_K was determined for 46-keV quanta, as well as the total

Table I. Conversion coefficients of γ transitions

E_γ, keV	Conversion coefficients	Experiment		Theory			
		Value	γ line in coincidence	*E*1	*M*1	*E*2	*M*2
46	α_K	9.3±2,0	117	1,17	3.35	10.0	~50
	$1+\alpha$	26±7	117	2,41	5,00	25,7	~75
	$\alpha_K/(1+\alpha)$	0.36±0,08	*X*	0,486	0.67	0.383	0,68
117	$1+\alpha$	1,7±0,2	~200 and 117	1.1	1.27	1,86	3,48
	α_K	0,4±0.2	~200	0,088	0.234	0,654	2,0

conversion coefficient α, which was obtained by the method described in [6].

The experimental results are given in Table I. Coincidences of 46-keV quanta with region 1 (22 keV) were also observed, thus enabling the determination of $\alpha_K/(1+\alpha)$, which is given in the third line of Table I. A comparison of the experimental and theoretical values [9] given in this table shows that the 46-keV transition is of E2 character. The maximum possible M1 admixture is 20%, so that the E2 character is dominant.

It is difficult to interpret the spectrum of coincidences with region 4 (~200 keV), which contains several γ lines. However, this run revealed new lines at (180) and 322 keV; these appear to be in cascade with the intense 200-keV line which coincides with neither 80 keV nor 117 keV. The photopeak areas at 117 keV (coincidences with region 4) and 208 keV (coincidences with region 2) were used to determine the total internal conversion coefficient of 117-keV γ quanta, which is given in Table I. By analyzing the intensity of K radiation observed in coincidences with 200-keV (curve d in Fig. 1) we obtained a relationship between the K conversion coefficients of 80- and 117-keV quanta. According to the investigation of isomeric Ag^{108m} decay in [10] the 80-keV transition is of E1 character, which does not conflict with our result, particularly that derived from the total K intensity in the single-crystal spectrum. Therefore the coincidences with 200-keV γ quanta yielded an experimental value of α_K for 117-keV quanta (the last line of Table I). To determine the multipolarity of this transition we used the experimental values of both α_K and $1+\alpha$. A combined analysis taking into account the sensitivity of the techniques to multipolarity derives the experimental value 0.7 ± 0.2 if the effect for an E2 transition is taken as unity. At the same time the theoretical value for an M1 transition is 0.47. Therefore pure M1 and E2 assignments are rejected for 117 keV, to which we can assign the mixture M1 + E2 with nearly equal components.

Curves b and c in Fig. 1 are the spectra of coincidences with γ quanta having energies close to the binding energy (7.27 MeV) of the last neutron in Ag^{108}. In these runs direct transitions from the initial state induced by thermal neutron capture, went to 1.2—1.5 MeV (curve c) or to 0.5—0.7 MEv (a run with a narrower control channel window, curve b); lower-lying levels also resulted from the decay of these states. The same γ lines were observed as in the single-crystal spectrum (Fig. 1) but with changed relative intensities. Curve b shows that the intensities of 200 ± 4 and 295 ± 6 keV increased relative to 80 and 117 keV. The 200- and 295-keV quanta are evidently emitted directly in radiative transitions from states arising through direct transitions, whereas the 80- and 117-keV lines represent subsequent cascade transitions.

The energies and intensities of the γ lines observed in the present work are summarized in Table II. The intensities of most lines were derived from the coincidence measurements using the transition scheme discussed at the end of the present article. In determining intensities from the single-crystal spectra we considered the contributions from close lines among the coincidences. In some instances insufficient energy res-

Table II. Energies and intensities of γ lines in the reaction $Ag^{107}(n,\gamma)Ag^{108}$

E_γ, keV	Intensity n_γ, % per captured neutron	E_γ, keV	Intensity n_γ, % per captured neutron
22±1	29±4*	284±6	1,7±0,5
40±2	0,5±0,3	295±6	7±2
46±2	1,3±0,3*	300±5	4,4±0.7
79,6±1,1	23±2*	308±6	3,5±1.0
83±3	0,3±0,1	322±6	~4
(114±4)	~1	(334±6)	~3,5
117±3	9±1*	340±6	3±1
134±5	1.5±0.6	378±8	5±1,5
152±3	1,3±0,2	380±7	1,7±0,5
(162±4)	1.0±0.5	430±9	1.7±0,5
(180±5)	~0,2	440±9	4.5±1.5
184±5	3±1	(478±10)	~3.5
200±4	~20*	515±10	<7
208±4	10±2	516±10	<4
214±5	5±1.5	565±12	2,3±0.7
(230±6)	~2	(590±15)	>1
260±4	5±1	635±10	7±2

*Intensity determined from single-crystal spectra.

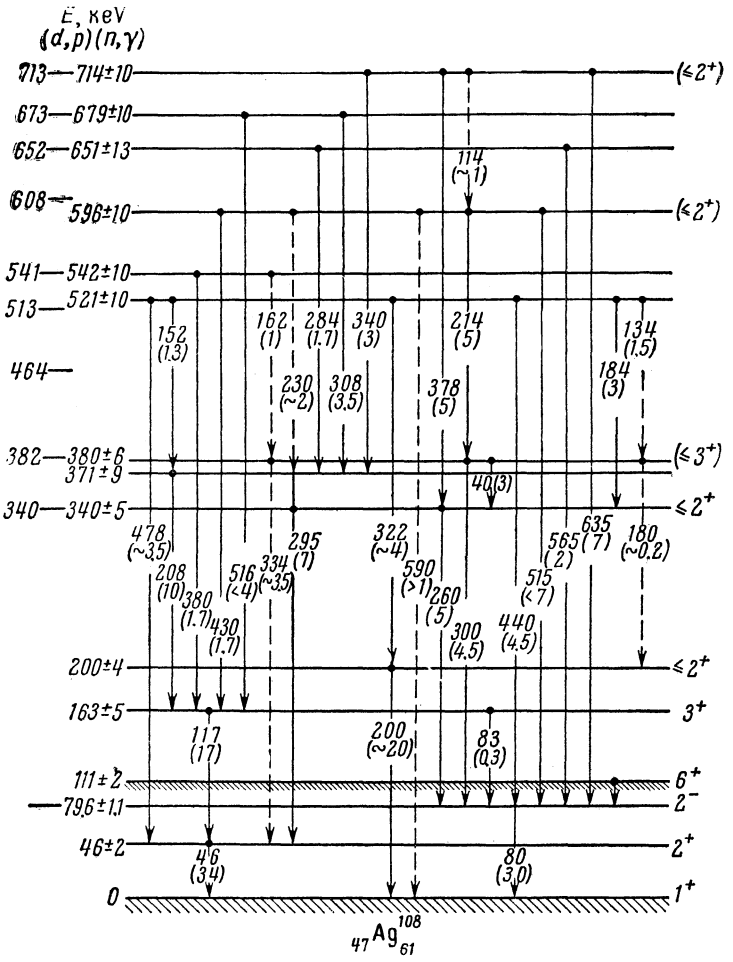

FIG. 3. Level scheme of Ag^{108}.

olution of the scintillation spectrometer prevented an exact determination of γ energies, some of which therefore appear to be identical within experimental error, although they represent different transitions in different cascades and appear in coincidences with distinctly different γ rays. Only the upper intensity limits of the 515- and 516-keV lines are given; this is associated with a possible contribution of annihilation radiation.

ENERGY LEVELS OF Ag^{108}

The excited states of Ag^{108} are established by the γ-γ coincidence measurements. The ~ 80-keV level introduced in our earlier work[2] was also observed in the decay of the isomeric state Ag^{108m}.[10,11] Coincidences of several intense lines with 80-keV quanta (the γ-γ cascades) indicate excited levels at 340, 380, 521, 596, and 714 keV (Fig. 3). Coincidences with 117 keV revealed an intense 46-117-208-152 keV cascade, with the sequence of transitions determined as in [6]. In this way levels were established at 46, 163, 371, and 521 keV.

The levels at 542, 695, and 679 keV were obtained from the interpretation of other γ transitions appearing in coincidences with 117 keV. Figure 3 shows that all γ lines listed in Table II fit between the given levels. The dashed lines denote transitions that were not determined uniquely. The total relative transition intensities $n_\gamma(1+\alpha)$ (% per captured neutron) are given in parentheses. The proposed level scheme was confirmed by additional coincidence measurements in the regions of ~ 290 and ~ 330 keV.

The energy differences of hard γ quanta observed in the radiative capture of thermal neutrons by Ag[1] indicate the excited levels 190 ± 20 and 330 ± 20 keV of Ag^{108}. Excited states at 590 ± 20 and 720 ± 20 keV were also determined in this way but perhaps do not belong to Ag^{108}, since these experiments were performed with natural silver and the binding energy of the last neutron in Ag^{110} is about 500 keV smaller than the corresponding quantity in Ag^{108}. The energies of the foregoing levels were refined by our data. Direct E1 transitions from the initial $1^-(0^-)$ state[12] produced by neutron capture serve to populate levels with

characteristics $I\pi \leq 2^+$. Therefore in the measured coincidences with hard γ quanta (curve b in Fig. 1) the most intense lines at 200 and 295 keV must represent transitions from such levels, as is shown in Fig. 3.

We have previously[2] suggested the existence of 266- and 302-keV levels in Ag^{108}, which were not confirmed by the γ-γ coincidences. The Ag^{108} level scheme proposed in the present work (Fig. 3) also disagrees with that given in[4] where the levels were obtained from data on the energies of proton groups in the reaction $Ag^{107}(d,p)Ag^{108}$, assuming that the protons of maximum energy correspond to the ground state of Ag^{108}. However, we do not believe that the assumption was justified. The neutron binding energy in Ag^{108} has been given as 7.19 ± 0.01 MeV from the (d, p) reaction,[13] but E_{bind} = 7.27 ± 0.02 MeV from the (n, γ) reaction.[1] The difference between these two values lies outside the experimental error. It can be assumed that in the (d, p) reaction the proton group of maximum energy corresponds to an 80 ± 30-keV state rather than to the ground state, as in the reaction $Rh^{103}(d,p)Rh^{104}$.[14] Our results are in best agreement with the data from the (d, p) reaction if the protons of maximum energy are associated with a 79.6-keV state. The energy levels associated with the (d, p) reaction must then be computed from this state, as is shown in Fig. 3. A number of levels established reliably in the present work were not observed in the (d, p) reaction.

We consider finally the spins and parities of the excited Ag^{108} states. The transition from the isomeric state, computed from its lifetime, is probably of multipolarity $l = 4$. From the decay of the isomeric state to Pd^{108} levels and from the dipole character of the 80-keV transition we determined the most probable spins of the corresponding states (Fig. 3), in agreement with [10,11] The 46-keV level has positive parity and spin 2 or 3 (with E2 or M1 + E2 for the transition). For spin I = 3 it is difficult to explain the absence of a transition to this level from the isomeric state (hindered by a factor of more than 10^7); therefore the assignment 2^+ is preferable. It is interesting to note that the existence of transitions from the same states to levels with positive parity and to the negative-parity 79.6-keV state furnishes evidence of competition between M1(E2) and E1 transitions.

The 163-keV level is 3^+, since the 117-keV transition is of type M1 + E2. The 46- and 117-keV γ quanta were found in coincidence measurements; therefore they come from levels with lifetimes $\tau < 5 \times 10^{-8}$ sec. Thus E2 transitions from the 46- and 163-keV levels are accelerated by more than two orders of magnitude compared with single-particle transitions. The possible characteristics of the 380-keV level were determined from the multipolarity of the 40-keV transition.

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