INTENSITIES OF GAMMA TRANSITIONS TO THE GROUND ROTATIONAL BAND IN NEUTRON RESONANCES OF THE $Gd^{155}(n, \gamma)Gd^{156}$ *REACTION*

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The relative values of the intensities of γ transitions to the ground rotational band are measured for 20 resonances in the $Gd^{155}(n, \gamma)Gd^{156}$ reaction with a two-crystal scintillation spectrometer. At the measurement accuracy attained in the present experiments, the resonance intensity distribution is consistent with a Porter-Thomas distribution with $\nu = 1$ channels. However, the possibility remains that it consists of two-groups of such distributions with various mean intensity values.

1. INTRODUCTION

IT has been noted in several papers [1-4] that in prolate even-even nuclei (Gd^{156}, Gd^{158}, Hf^{178}) the E1 transitions from the state formed during capture of a thermal neutron to a rotational band near the ground state have very low intensities compared with transitions to more excited states. It has been assumed in these investigations that this fact is due not to ordinary fluctuations of the transition matrix elements, but to some additional selection rule. Groshev et al [1] considered the application of l-selection, and Draper [2] and Bartholomew [3] the application of K-selection to the considered E1 transitions.

Let us consider the application of K-selection to E1 transitions in Gd^{156} (8.44 MeV) and Gd^{158} (7.84 MeV). The initial states of these nuclei for neutron capture have assignments 1^- and 2^- (according to Bartholomew [5], upon capture of a thermal neutron both nuclei probably have an assignment 2^-), and in the first-excited levels $J = 2^+$ and $K = 0$. E1 transitions should be observed at these levels. However, for the initial states $J = 2^-$, $K = 2$ they should be K-forbidden. For transitions to the levels of the γ-vibration band ($J^\pi = 2^+, 3^+$; $K = 2$) this forbiddenness is lifted, and we actually see that the 7.37-MeV transition in Gd^{156} and the 6.74-MeV transition in Gd^{158} are in the capture of thermal neutrons 30 and 200 times more intense, respectively, than the transitions to the ground rotational band. Thus, when a neutron is captured at different neutron resonances, the transitions to the levels of the ground rotational band from the initial states $J^\pi = 1^-, 2^-$; $K = 1$ should be more intense than from the states $J^\pi = 2^-$, $K = 2$.

It must be borne in mind that when some forbiddenness appears, the measured distribution of the partial widths will be the sum of two broad distributions (of the Porter-Thomas type with $\nu = 1$) with different average values of $\Gamma_\gamma(E_\gamma)$.

In the present paper we make an attempt to find the change in the partial radiation width for the 8.44-MeV transition in Gd^{156} in neutron capture by different neutron resonances of Gd^{155}. This transition is convenient because it can be readily separated from the other transitions. The nearest transition has an energy 7.37 MeV [1].

2. EXPERIMENTAL PROCEDURE

The measurement was carried out with the aid of a gamma spectrometer, constructed for addition of coincidences, which was used to separate the 8.44-MeV gamma rays and in addition made it possible to measure the background due to gamma rays of other energies. The relative intensity of the 8.44-MeV gamma transition was obtained from the ratio of the areas under the resonant peaks of the partial-cross section curve at $E_\gamma = 8.44$ MeV and the curve of the total radiation cross section.

The measurements were made with a neutron beam from a linear electron accelerator [6] of 6.68-meter base and neutron pulse duration 0.6 μsec. The time selection of the gamma-ray pulses was with a 2048-channel time analyzer [7] with channel widths 0.36 and 1.46 μsec. Thus, the best resolution amounted to 0.09 μsec/m.

Two NaI crystals, one 100 mm in diameter and 54 mm long and the other 80 mm in diameter and 80 mm long, with FÉU-49 photomultipliers, were used in the gamma spectrometer. The crystals were protected on the sample side against scattered neutrons by plates 15 mm thick of B_4C with small amount of paraffin added.

A block diagram of the electronic apparatus is shown in Fig. 1. For each gamma quantum registered in the crystal, there are two signals from the photomultipliers: fast and slow. The fast pulse is fed to a coincidence circuit (CCA or "Apple tree" installation). The slow pulses are amplified and fed to an addition circuit (which operates in this case also as a pulse mixer). Following the addition circuit, the pulses are analyzed in a single-channel pulse-height analyzer (AADO-1), with amplitude window set to separate the pulses corresponding to gamma rays with $E_\gamma = 8.44$ MeV. The standard pulses from the AADO-1 are fed to the 2048-channel time analyzer.

However, along with the pulses corresponding to gamma rays with $E_\gamma = 8.44$ MeV, the addition circuit delivers background pulses due to the superposition of pulses from lower-energy gamma quanta belonging to one or two neutron-capture acts that are close in time. The amplitudes of these pulses can be equal to the amplitude of the pulses corresponding to $E_\gamma = 8.44$ MeV. To find the background due to the superposition of the pulses in the addition circuit, a control circuit is

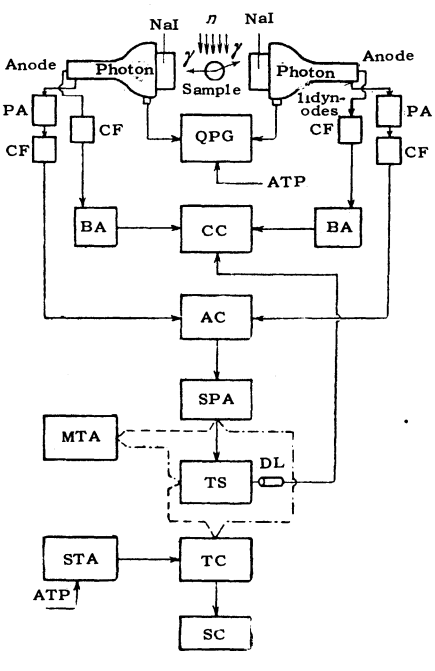

FIG. 1. Block diagram of the electronic apparatus. PA – preamplifier, CF – cathode follower, QPG – quenching pulse generator, ATP – accelerator triggering pulse; BA – broadband amplifier, CC – coincidence circuit, AC – addition circuit, CPA – single-channel pulse height analyzer; MTA – multi-channel time analyzer, TS – triggering system, DL – delay line, STA – single-channel time analyzer, TC – transmission circuit, SC – scaler circuit.

used, in which the pulses from the coincidence circuit and from the single-channel pulse-height analyzer are made to coincide. Consequently, the control circuit registers the fact that the pulse with amplitude corresponding to $E_\gamma = 8.44$ MeV, analyzed in the AADO-1, is due to the addition of two pulses, which have arrived from both channels. The resolution time of the coincidence circuit is chosen in this case equal to the resolution time of the addition circuit. Pulses from the control circuit are fed to a single-channel time analyzer, which transmits only those pulses which are within the limits of the specified time interval (corresponding to a certain chosen neutron resonance of Gd^{155}), and then to the scaler.

The signal due to the gamma rays and the fast neutrons, produced at the instant when the electron pulse is produced in the accelerator, is quenched by applying to the control electrode of the photomultiplier a negative pulse of 60–80 volts and 10–15 μsec.

The background of the measurements of the partial cross section at $E_\gamma = 8.44$ MeV consisted of two components. One was due to scattering of the neutrons incident on the sample and the structural elements of the gamma spectrometer. This background was measured by replacing the investigated gadolinium specimen with an equivalent scatterer. The second component of the background was due to the fact that along with the weak 8.44-MeV gamma line there are emitted many gamma rays in cascades with total energy equal to the neutron binding energy, 8.53 MeV. This component is small in the region between the resonances and is appreciable in the resonances of the investigated sample. Two variants are possible:

1. Two or more gamma quanta belonging to one cascade fall into one or both crystals and, after releasing all their energy, produce in the addition circuit a pulse of amplitude close to that of the pulse from the single 8.44-MeV gamma quantum. When the gamma quanta enter into both crystals, this case is registered by the control circuit. If all gamma quanta of the cascade fall in one crystal, then it is impossible to distinguish such a case from the 8.44-MeV gamma quantum. The number of such cases can be determined from the registered number of cases when gamma quanta have fallen in both crystals.

2. The second variant is analogous to the first, but the gamma quanta belong here not to one but to different cascades which are close in time. The addition of the amplitudes of the pulses that travel in one or both channels is due to the finite resolution of the path. The resultant pulse amplitude be-

Isotopic composition	Chemical composition	Weight, grams	Diameter of sample, mm	N, at. Gd/cm^2
Natural mixture of isotopes	Gd_2O_3	88.91	100	$4.35 \cdot 10^{21}$
Gd^{155}	Gd_2O_3	1.414	50	$4.426 \cdot 10^{20}$

yond the addition circuit can in this case exceed the amplitude corresponding to the neutron binding energy.

It is easy to show that for identical crystals in both channels the background due to the superposition of pulses from the gamma quanta belonging to one or two cascades that are close in time can be obtained by doubling the number of events registered by the control circuit.

Measurement of the background was made in two stages. Simultaneously with measuring the partial cross section at $E_\gamma = 8.44$ MeV we measured the coincidence background and superpositions in the time interval containing the chosen Gd^{155} resonance, and also determined the ratio of the effect to the background for this resonance. During the measurements this procedure was used for several Gd^{155} resonances. Measurements were then made in which the pulses from the control circuit were applied to a 2048-channel time analyzer, and the pulses from the AADO-1 were applied to a single-channel time analyzer tuned to one of the resonances. The energy dependence of the background was then determined and the effect/background ratio again monitored. From the effect/background ratio in the resonances investigated in this manner it is possible to obtain the absolute value of the background for the entire region of partial cross sections.

The table lists data on the samples used in the measurements. The main measurements in the resonant region were carried out with a sample containing a natural mixture of gadolinium isotopes, placed in a graphite container. The sample with Gd^{155} was used for measurements in the thermal region, in order to exclude the influence of Gd^{157}

Calibration against the gamma-ray energy in both channels of the gamma spectrometer was carried out with the aid of radioactive sources Co^{60} (1.17, 1.33, 2.50 MeV), Po–Be (4.43 MeV), and the gamma lines of the (n, γ) reactions on Fe (7.64 MeV) and Ni (8.99 MeV).

3. MEASUREMENT RESULTS

Figure 2 shows the plots of the number of counts per time-analyzer channel for the gamma-ray energy intervals 2.8–3.8 (curve a) and 8.4–8.8 MeV (curve b). The figure shows also the background (for E_γ from 8.4 to 8.8 MeV), measured by the method described above. Each curve is the result of averaging of several series of measurements.

Analysis of curve b (E_γ in the interval from 8.4 to 8.8 MeV) has shown that in addition to the Gd^{155} resonances there are also Gd^{157} resonances (2.9, 17.1, 25.6, 49 eV) and resonances at 22.4 eV belonging [8] to Gd^{154} and Gd^{158}.

The instability of the photomultipliers and the electronic apparatus [1)] cannot account for the presence and strength of the Gd^{157} resonances due to its 7.857-MeV gamma line. This is even less likely to cause the resonance due to even-even isotopes Gd^{154} and Gd^{158}, in which the binding energies of the last protons do not exceed 6.37 MeV. Consequently, these resonances should apparently be due essentially to the background of the gamma quanta of cascades that are close in time. However, subtraction of the background in accordance with the procedure described above did not eliminate these resonances [2)].

It can be stated that the entire effect observed in the resonance at 22.4 eV is connected with superposition of pulses from gamma quanta of different cascades. These should explain all the more the part of the area of this resonance, which remains after subtracting twice the value of the experimentally measured background. It is obvious that in the resonances of Gd^{155} and Gd^{157} there is also an unaccounted for background of the same origin.

Our calculations have shown that the background contribution to the resonance, due to the double superpositions (n_2), is determined by the area S of the resonant peak on the curve a ($S = \Sigma n_i$; n_i is the count in the time channel within the limits

1)The maximum instability, determined by the position of the peak due to the 4.43-MeV gamma rays, did not exceed 5–6%.

2)A possible cause of the inaccurate measurement of the background may be the fact that the resolution time of the coincidence circuit was set too low in our measurements. In addition, obviously, the fact that the coincidence circuit was triggered by gamma quanta with energy not lower than 800 keV has some effect.

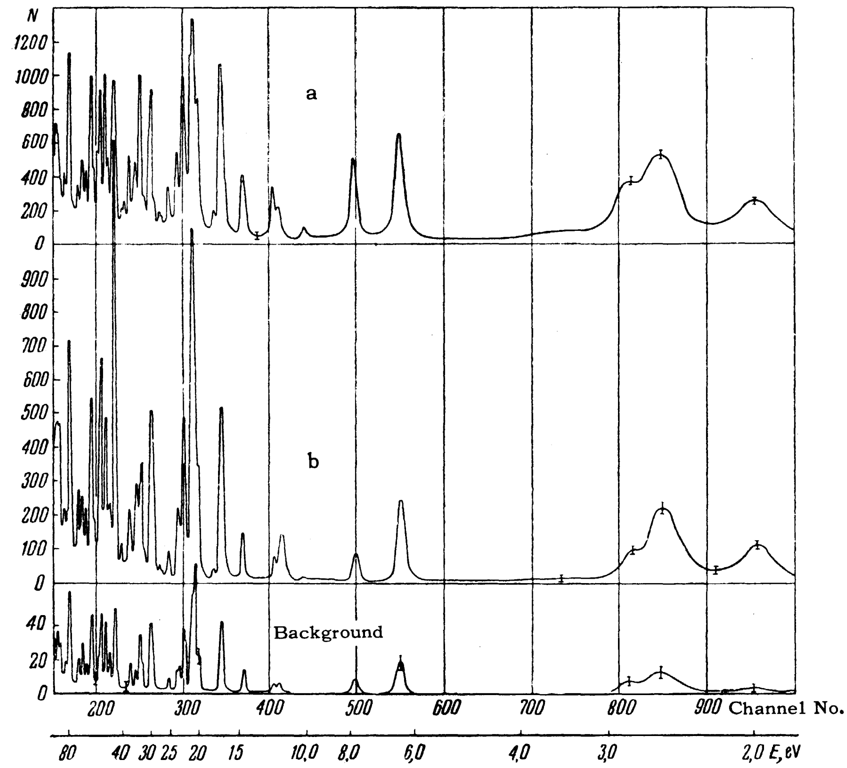

FIG. 2. Total number of counts N for the intervals of energy of gamma rays: a – 2.8 – 3.8 MeV, b – 8.4 – 8.8 MeV, and background in the energy interval 8.4 – 8.8 MeV.

of the resonance) and by some function $g(\tau/T)$ of the ratio of the resolution time τ to the resonance width T in the flight-time scale:

$$n_2 = C\, g(\tau/T) \sum n_i.$$

After estimating the value of τ, we have found that we can assume $g(\tau/T) \sim 1/T$ for almost all the investigated resonances. Therefore, in order to find the part of n_2 unaccounted for in the measurements we can use the relation

$$n_2^{\text{unac}} = CT^{-1} \sum n_i.$$

The value of the constant C was determined from the condition of the equality $n_2^{\text{unac}} = S - S_{\text{scat}} - 2S_b$ for the resonance at 22.4 eV, and was then used to determine n_2^{unac} in all the other investigated resonances[3)].

In those cases when the Gd^{155} resonances merged with the resonances of the other isotopes, we calculated from curve a the value of $S - S_{\text{scat}}$ pertaining to Gd^{155} (on the basis of measurements with the separated isotopes). It is obvious that the procedure of finding and subtracting n_2^{unac} should lead to the vanishing of part of the area due to the Gd^{157} resonances and the even-even isotopes from the peaks of the curve b, which represent mixtures of resonances. The sum of the resonances at 20.8 eV could not be processed by this method, and the relative intensity of the 8.44-MeV gamma transition obtained for them is a lower estimate.

In measurements with the Gd^{155} sample, the background was measured only at the point 0.0384 eV, in which the overwhelming part of the effect was due to the Gd^{155} resonance at 0.0268 eV [9]. The determination of the true background was made difficult by the fact that there was no resonance to "vanish" upon subtraction of the superposition background. Therefore to calculate the superposition background at the thermal point, we used for this resonance the resonance Gd^{155} at 6.49 eV, the area of which turns out to be vanishingly small in measurements with natural Gd after subtracting n_2^{unac}.

For resonances in which an appreciable part (up to 25%) of the total width is the neutron width, we estimated the effect due to capture in the NaI crystals of neutrons scattered at resonance. Since the maximum energy of the gamma rays captured in I and Na was 6.57 and 6.95 MeV, respectively, this effect should appear only in the background of the superpositions and in curve a. The estimate was made starting from the results obtained with an equivalent scatterer, and has shown that the contribution of this effect is negligibly small.

Figure 3 shows a histogram of the distribution

3) S_{scat} and S_b are the resonance areas corresponding to the background and scattering, and included in the count of the control circuit.

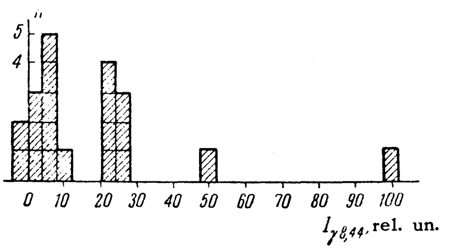

FIG. 3. Distribution of relative intensities of 8.44-MeV gamma transition in Gd^{156} in 20 resonances of the reaction Gd^{155} (n, γ) Gd^{156} (n – number of resonances).

of the intensity $I_{\gamma 8.44}$ over the twenty investigated resonances of Gd^{155}. What is striking is the gap between the small and medium values of $I_{\gamma 8.44}$, which possibly indicates the existence of two groups in the distribution of the intensity $I_{\gamma 8.44}$ for two different initial spin states.

Figure 4 shows the integral distribution of $I_\gamma/\bar{I}_\gamma$, plotted for one common average value of $\bar{I}_\gamma$. The same figure shows the integral Porter-Thomas distributions for $\nu = 1$ and $\nu = 2$ channels. It is seen that the distribution of the experimental values of $I_{\gamma 8.44}$ can be regarded as agreeing with the $\nu = 1$ curve, which in the case of the existence of two groups indicates that their average values differ little.

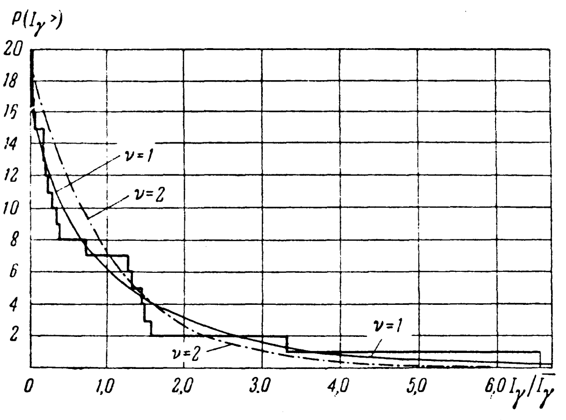

FIG. 4. Integral distribution of intensity $I_{\gamma 8.44}$. The Porter-Thomas distributions are shown for channel numbers $\nu = 1$ and $\nu = 2$.

An unambiguous conclusion that K-selection exists in this case is made impossible also by the lack of information on the spins of the investigated levels. It must be noted that the thermal point, the initial state of which [5] is 2^-, corresponds to the small values of $I_{\gamma 8.44}$ in accord with the assumed presence of K-selection.

It is necessary to take also into account the fact that the accuracy of the measurements of the small quantities $I_{\gamma 8.44}$ is in our experiment much smaller than in the case of large quantities. It can be expected that the increase in the accuracy of the measurements will make it possible to establish that the given distribution consists of two groups with essentially differing mean values $I_{\gamma 8.44}$.

Measurements of the relative intensities of the 8.44-MeV gamma transition in different resonances of the $Gd^{155}(n, \gamma)Gd^{156}$ reaction will be continued.

At present we are improving the apparatus to increase the time resolution and to eliminate the background connected with the superposition of pulses from neutron capture events that are close in time.

The idea of this measurement was suggested to us by L. V. Groshev and A. M. Demidov. We are grateful to them, and also to M. I. Pevzner for a fruitful discussion of the results. We also consider it our duty to express gratitude to V. A. Kochetkov and A. Ya. Lunin for much work which they performed.

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