GAMMA RAYS FROM RADIATIVE CAPTURE OF FAST NEUTRONS IN MANGANESE AND COPPER

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The spectra of γ rays emitted in radiative capture of thermal and fast neutrons are measured with a single-crystal scintillation γ spectrometer. The probability of emission of 8-MeV γ quanta is from 4 to 5 times smaller for fast neutron capture in copper than for thermal neutrons. The γ-ray spectrum in manganese is practically undeformed.

INTRODUCTION

SEVERAL investigations have shown [1-6] that the spectra of radiative capture gamma rays depend on the energy of the absorbed neutron. In those cases when gamma-ray spectra are investigated following capture of neutrons in individual resonances, such changes are due essentially to fluctuations of the partial radiation widths $\Gamma_{\gamma i}$. For example, it is shown in [5] that the probabilities for the deviation of $\Gamma_{\gamma i}$ from the mean value are quite appreciable.

At higher neutron energies (> 50 keV) one measures as a rule the radiative-capture gamma-ray spectra averaged over many resonances, and the fluctuations of the partial gamma widths are not noticeable. However, since the total radiative capture cross section consists in this case of a sum of cross sections with different values of the orbital angular momentum, we can expect the spectrum of the radiative capture gamma rays to vary with the ratios of these cross sections.

We have measured the yields of radiative capture gamma rays for different neutron energies in manganese and in a natural mixture of copper isotopes.

EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. The neutron source was an electrostatic Van de Graaff accelerator in conjunction with the T (p, n) He^3 reaction. The thickness of the target corresponds to a loss of 120 keV for 1-MeV protons. The gamma ray detector was a single-crystal scintillation gamma spectrometer with NaI(Tl) crystal (diameter 40 mm and h = 40 mm). The copper and manganese samples were in the form of rings with outside diameter 120 mm, inside diameter 40 mm, and thickness 20 mm. The samples were covered

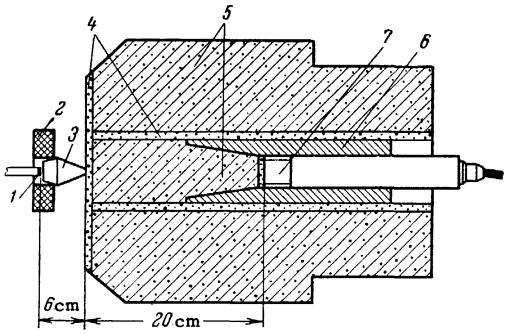

FIG. 1. Experimental setup: 1—target, 2—sample, 3—bismuth cone, 4—B_4C layer, 5—paraffin + B_4C, 6—lead, 7—detector.

with a 3 mm layer of B_4C to decrease the effect of background neutrons.

The measurements were made at several values of the proton energy: 1.95, 1.71, 1.49, 1.39, 1.25, and 1.17 MeV, corresponding to the following energy intervals of the incident neutrons: 580—240, 420—150, 290—65, 220—35, 120—30, and < 50 keV. The widths of these intervals were determined by the geometrical dimensions of the samples and the thickness of the target.

Under similar measurement conditions, when the neutron shield of the detector is in the direct vicinity of the target and of the samples, there is special danger of scattered neutrons. To estimate the contribution of these neutrons to the observed effect, we measured the spectrum of scattered neutrons with a helium (He^3) chamber, and also compared the relative radiative capture cross sections, which were determined from the induced activity in $Cu^{63,65}$, Mn^{55}, and Al^{27}. An analysis of these data has shown that for the employed samples the radiative capture of scattered neutrons is less than 5% for Cu^{63} and Cu^{65} and 50% for Mn^{55} (the last figure is accurate to about 10%).

The pulse-height distributions were regis-

tered with a 256-channel pulse-height analyzer[7]. The stability of the spectrometer energy scale was monitored by continuously flashing the photomultiplier cathode with a pulsed light source (energy resolution ~3%, amplitude ~10 MeV), the amplitude of which was determined from the gamma rays of a Po—α-Be source. The background amplitude distributions were measured without the sample. The effect/background ratio ranged for the copper samples from 2:1 to 1:1, depending on the neutron energy. The analogous ratio for manganese ranged from 1:1 to 0.7:1.

The apparatus spectra of the thermal-neutron radiative-capture gamma rays were measured under the same geometric conditions, but with the samples placed in a paraffin block. The effect/background ratio was more than 10 in this case.

Each pulse-height distribution was normalized to the number of captures in the samples, which was determined from the gamma rays of the induced activity both in copper and in manganese. The spectra were then averaged over energy intervals 0.5 MeV wide.

MEASUREMENT RESULTS AND DISCUSSION

Copper. Figure 2 shows the apparatus spectra of the gamma rays of radiative capture in copper.

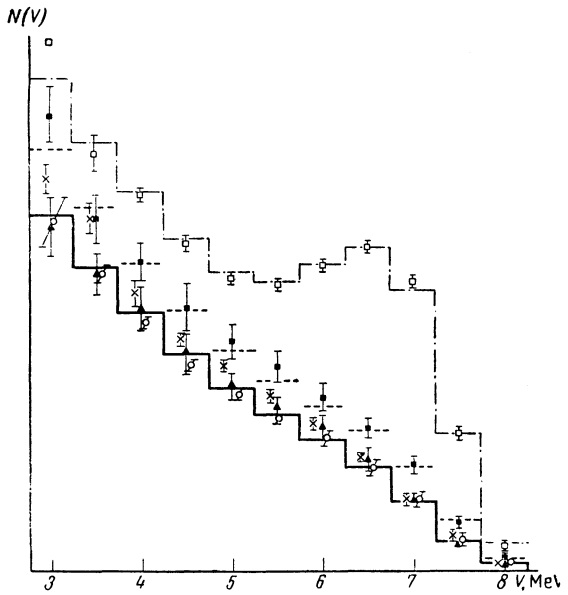

FIG. 2. Apparatus spectra of radiative-capture gamma rays in copper for neutrons of different energies: □—thermal, ■—< 50 keV, ▲—220-35 keV, o—420-150 keV, ×—580-240 keV. Histograms—pulse-height distributions obtained by multiplying the obtained gamma-ray spectra by the spectrometer sensitivity matrix L(E, V), for thermal neutrons—dash dot line, for neutrons with energy < 50 keV—dashed line, for energies 50-500 keV—continuous line. (Errors—mean-square.)

The apparatus spectra for the capture of fast neutrons in different energy intervals coincide, within the limits of measurement errors, with the exception of the spectrum obtained at < 50 keV. The apparatus spectrum of the gamma rays from radiative capture of thermal neutrons contains appreciably more gamma rays with energy close to the neutron binding energy. Since all the spectra were normalized to the same number of captures in the samples, we have, apart from some constant A, which depends on the geometrical conditions of the experiment, on the absolute value of the neutron flux, etc.,

$$N(V) = A \sum N(E) L(E, V) \Delta E, \qquad (1)$$

where N(E)—number of gamma quanta with energy E in the interval ΔE per neutron capture in the sample, L(E, V)—spectrometer sensitivity matrix, and N(V)—measured amplitude distribution of the pulses, normalized to the same number of captures in the sample.

In using the function N(E) for the thermal neutrons, the constant A was determined from the published data[8]. This normalization turned out to be possible, since the measured values of N(V) in the pulse-height region above 5.5 MeV are in splendid agreement in form with the calculation based on formula (1).

Figure 3 shows in histogram form the N(E)E spectra for capture of fast neutrons, obtained by successive approximation with allowance for the constant A. The error in the obtained number of gamma quanta increases with decreasing energy of the interval. In the thermal spectrum, the reliability of the data for ϵ_γ > 7 MeV was determined essentially by the accuracy of the intensities of the

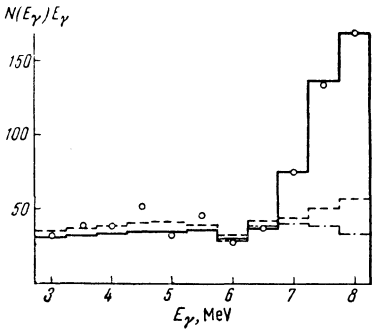

FIG. 3. Histograms of gamma-ray spectra for radiative capture of neutrons in copper: continuous line—thermal neutrons, dashed line—neutrons with energy < 50 keV, dash-dot line—neutrons with energy 50-500 keV, circles—thermal neutrons from [8]. The ordinates represent the number of gamma quanta per 100 captures in an energy interval 0.5 MeV wide, multiplied by the average energy of the given interval (in MeV).

7.91, 7.63, and 7.29 MeV lines, given in [8], while below 7 MeV the error can reach 20%. In the spectra for the radiative capture of fast neutrons we can assume on the average that the error is ~ 20%. Inasmuch as $\int N(E)\,EdE$ should be equal to the excitation energy of the nucleus, and the intensities of the gamma quanta with energies 3—7 MeV remain practically constant, it must be assumed that either the intensity has increased by several times in the gamma-quantum energy region < 3 MeV, or that some systematic error has crept into normalization of the gamma ray spectra for radiative capture of fast neutrons. The latter can be estimated by assuming that the gamma-ray spectrum for the capture of fast neutrons has the same form as the analogous spectrum for the capture of thermal neutrons in the energy region below 3 MeV. Such an assumption necessitates that the spectra of the gamma rays for fast neutrons (Fig. 3) be multiplied by approximately 1.4.

The obtained changes in the spectra for radiative capture in copper can be examined from several points of view.

1. Let us discuss the influence of the isotopic effect (that is, the variation of the gamma-ray spectrum as a function of the ratio of the (n, γ) reaction cross sections in Cu^{63} and Cu^{65} as a function of the neutron energy). We present below the calculated and measured ratios of the number of captures in Cu^{63} and Cu^{65}:

Neutron energy, keV.		< 50	35—220	65—290	150—420	240—580	Thermal
Contribution of isotope Cu^{65}, %	calc.	20.0	19.3	17.3	16.5	16.7	18
	expt.	17.8±2.0	19.1±0.8	18.7	18.2±1.1	17.8±0.8	16.3±0.9

The measured ratios were obtained by the activation method using gamma rays emitted during β decay of Cu^{64} and Cu^{66}. The calculated ratios were obtained from the radiative capture group cross sections determined by V. I. Golubev and M. N. Nikolaev from the known published data. It follows from the foregoing data that the contribution to the total cross section of the isotope Cu^{65} is constant in all cases, accurate to 4%, which naturally cannot influence noticeably the form of the spectrum of the radiative-capture gamma rays.

2. The variation in the radiative-capture gamma ray spectra in copper could be attributed to the influence of p-neutrons, the capture cross section of which becomes appreciable already in the neutron energy region ~ 50 keV. But for this purpose it is necessary (see Fig. 3) that the cross section ratio $\sigma_{s,d}/\sigma_{p,f}$ be of the order of 0.3, if in the p-capture there are no transitions with gamma-ray energies corresponding to the binding energy of the neutron; otherwise the ratio $\sigma_{s,d}/\sigma_{p,f}$ should only be smaller. The radiative capture cross sections for Cu^{63} were calculated for the neutron energy regions under consideration in accordance with the statistical theory, using the penetrability coefficients from [9] at $\overline{\Gamma}_\gamma = 0.4$ eV, $\overline{D} = 2.4 \times 10^3$ eV, and $\xi = 0.05$. Figure 4 shows the results of the calculation. The obtained calculated ratios $\sigma_{s,d}/\sigma_{p,f}$ are at least three times larger than necessary to explain the decrease in the probability of emission of gamma quanta with energy > 7 MeV.

3. Kapchigashev and Popov [10] have shown that the cross section for the radiative capture of

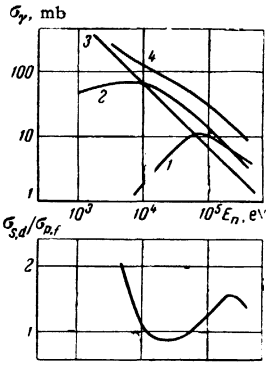

FIG. 4. Calculated radiative-capture cross sections for Cu^{63}: curves: 1—d-neutrons (σ_d), 2—p-neutrons (σ_p), 3—s-neutrons (σ_s), 4—total radiative cross section, equal to $\sigma_s + \sigma_p + \sigma_d$ ($\sigma_{s,d} = \sigma_s + \sigma_d$, $\sigma_{p,f} = \sigma_p + \sigma_f$).

thermal neutrons in Cu^{63} can be attributed to negative resonance with $E_0 = -100$ eV. This negative resonance has apparently anomalously large partial gamma widths for hard quanta [1)].

Manganese. Figure 5 shows in the form of a histogram the apparatus spectra of gamma rays from the radiative capture of neutrons of different energies in manganese. The gamma-ray spectra for the capture of fast neutrons coincide, within the limits of experimental error. Compared with the spectra due to the capture of thermal neutrons,

[1)] In a recently published paper by Bergqvist and Starfelt [11] similar data are reported for copper. In the radiative-capture gamma ray energy below 6.5 MeV, the spectra agree with those obtained in our work within 20%. At energies above 6.5 MeV, the difference is larger.

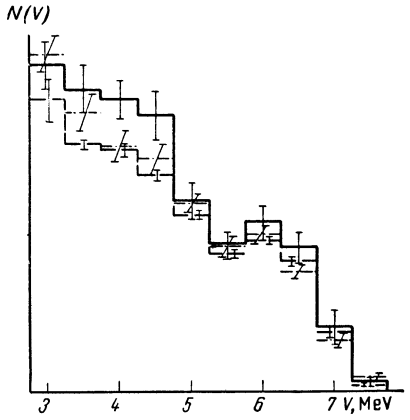

FIG. 5. Apparatus spectra of gamma rays from radiative capture in manganese, normalized to the same number of captures, for neutrons of different energies: solid line—thermal neutrons, dash-dot line—neutrons with energy 580-240 keV, dashed line—with energy 290-65 keV (mean-square errors).

we can note a weak decrease in the intensity of transitions with gamma-ray energies 4—5 MeV.

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