RESONANCE SCATTERING BY Sn^{116} *AND* Cu^{65} *NUCLEI OF GAMMA RAYS FROM SOLID AND LIQUID SOURCES*

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The resonance scattering of 1.29- and 1.114-MeV γ quanta by Sn^{116} and Cu^{65} nuclei was investigated using liquid and solid sources of In^{116m} and Ni^{65}. The attenuation of the effect was found to be 0.055 and 0.040 for the liquid sources and 0.050 and 0.024 for the solid sources, for Sn^{116} and Cu^{65}, respectively.

IN studying resonance scattering of γ quanta by nuclei, one determines the energy lost to the nuclear recoil by using the effect of Doppler broadening of the line, for example as the result of the preceding β and γ cascades. For this it is necessary that the lifetime of the excited state be much less than the time between collisions of the recoil nuclei with the surrounding atoms of the source material. This condition is satisfied when one uses gaseous sources, with which most experiments are done. Furthermore, in this case the computation of the energy distribution of the emitted quanta (the "microspectrum") is considerably simplified, which is of importance for the determination of the lifetime of the excited state of the nucleus.

In liquid or solid sources the time between collisions is of order 10^{-13}—10^{-14} sec. The interaction of the recoil nuclei with the surrounding atoms leads to a change of the "microspectrum" and consequently to a reduction of the resonance effect.

Studies made recently[1-3] have shown that the resonance effect in solid or liquid sources can be observed if the lifetimes of the excited nuclear states are $\leq 10^{-12}$ sec. By studying the attenuation of the resonance effect in liquid and solid sources one cannot only arrive at conclusions about the molecular interactions in the source material, but one can also determine the lifetimes of high-lying excited states, as was done, for example, in the work of Dzhelepov et al.[2]

In our earlier experiments[4,5] we studied the resonance scattering of 1.29 and 1.114 MeV γ quanta by Sn^{116} and Cu^{65} nuclei, using gaseous sources of In^{116m} and Ni^{65} in the compounds $InCl_3$ and $NiCl_2$. The lifetimes of these excited states were determined by the "self-absorption" method, and were found to be $(6.4 \pm 2.7) \times 10^{-13}$ and $(6.5 \pm 1.6) \times 10^{-13}$ sec. The present work is a study of the resonance scattering of γ quanta by Sn^{116} and Cu^{65} nuclei in liquid and solid sources.

EXPERIMENTAL PROCEDURE

A source of In^{116m} ($T_{1/2}$ = 54 min) was gotten from thermal neutron irradiation of 10 mg of metallic indium enriched to 99.6% in In^{115}, placed in a quartz ampoule of volume ~ 1 cm^3. The irradiation was done in a neutron flux of 1.8×10^{13} cm^{-2} sec^{-1} at the reactor of the Nuclear Physics Institute of the Uzbek Academy of Sciences. The irradiation time was 3 hours. The liquid source of In^{116m} was gotten by irradiating an ampoule containing a solution of In^{116} in HNO_3. The activities of the In^{116m} sources at the start of the measurements were ~ 0.9 and 1.7 Cu.

The Ni^{65} isotope ($T_{1/2}$ = 2.56 hr) was obtained by irradiating $NiCl_2$. The irradiation time was ~ 8 hours. The liquid source was prepared by irradiation of a solution of $NiCl_2$ in water. The initial source activity was about 0.3 Cu. The $NiCl_2$ was made from nickel enriched to 77.8% Ni^{64}. During irradiation the samples were contained in quartz ampoules.

Figure 1 shows the experimental arrangement. The dimensions of the tin and cadmium scatterers (for comparison) were $30 \times 30 \times 1.5$ cm^3, those of copper and iron were $26 \times 26 \times 1$ cm^3.

Considerable effort was devoted to reducing the nonresonant radiation in the energy region under study, which is produced by the background, by Rayleigh scattering of the γ quanta, by pileup of pulses due to Compton scattering of the γ quanta by the scatterer, etc.

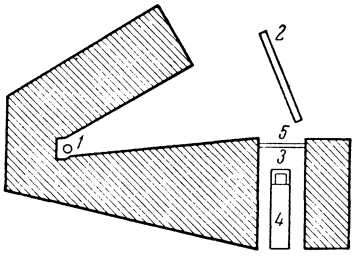

FIG. 1. Experimental arrangement: 1 – source, 2 – scatterer, 3 – crystal, 4 – photomultiplier FÉU-12B, 5 – lead filter.

To reduce the natural background, the detector (a NaI(Tl) crystal 4 cm in diameter and 4 cm high, with an FÉU-12B photomultiplier) was shielded on all except the front side by a thickness of 25 cm of lead. For an energy around 1 MeV, the counting rate in one channel did not exceed 1.2 pulses per minute. To shield the detector from quanta scattered by the Compton effect, a lead filter was placed in front of the crystal. The choice of filters was made from measurements of the intensity of the scattered radiation as a function of time for filters of different thicknesses, using a source of In^{116m} with an initial activity of ~ 1 Ci. It was found that summing of pulses was negligible for a filter thickness of 0.8 cm. In this case the intensity of the scattered radiation dropped in accordance with the halflife of the isotope.

Elastic Rayleigh scattering of the γ quanta by Cu and Fe nuclei is negligible. The cross section for this process can be computed from data in the literature;[6,7] it is $\bar{\sigma} = (2.7 \pm 0.4) \times 10^{-29}$ cm^2, which is ~ 60 times less than the cross section for resonance scattering of 1.114-MeV quanta by Cu^{65} nuclei. These same data give a cross section of $(8.0 \pm 1.8) \times 10^{-29}$ cm^2 for the Rayleigh scattering by Sn. The Rayleigh scattering is important only in this last case. In both cases this type of elastic scattering was reduced to a minimum by choosing the scattering angle to be 120°.

The resonance effect was studied using an AI-100 hundred-channel pulse height analyzer. The magnitude of the effect was determined by analysis of the spectra of scattered radiation from resonance (tin or copper) and nonresonance (cadmium and iron) scatterers.

During the measurements over the energy interval 0.5—1.6 MeV, the following spectra were taken: a) background; b) background with scatterers present; c) scattered radiation when source is present without scatterer; d) scattered radiation from solid or liquid sources with scatterers of tin, cadmium, copper and iron. Since the Rayleigh scattering is large for the transition $In^{116} \rightarrow Sn^{116}$, to insure identical scatterers of tin and cadmium under nonresonant conditions, a scattered spectrum was taken with a source of Co^{60} with an activity of 0.25 gram-equivalent of Ra.

The initial counting rates for each scatterer were compared using a calibrated intensity meter, which fixed the activity of the sources and their time variation. For more accurate calculations of the intensity of the direct beam, at the end of each series we took a spectrum of the source placed several meters from the detector. The total intensity of the radiation incident on the scatterer could be calculated simply from these data using the known lifetimes of the isotopes and the time of the measurements.

In computing the average resonant scattering cross section, we took account of absorption of quanta in the scatterer and the angular distribution of the scattered quanta. For Cu^{65} at a scattering angle of 120°, this correction does not exceed 9%.

The solid angle from source to scatterer was computed by integrating over the surface of the scatterer. The solid angle from scatterer to detector and the efficiency of counting of γ rays by the crystal were determined experimentally.

RESULTS AND DISCUSSION

Figures 2 and 3 show spectra of the scattered radiation, taken with sources of In^{116m} and Ni^{65}. The average values of the resonance scattering by Sn^{116} and Cu^{65} nuclei are given in the table. The quantity $P_l(E)$, the fraction of quanta of the incident radiation in a 1 eV interval at the

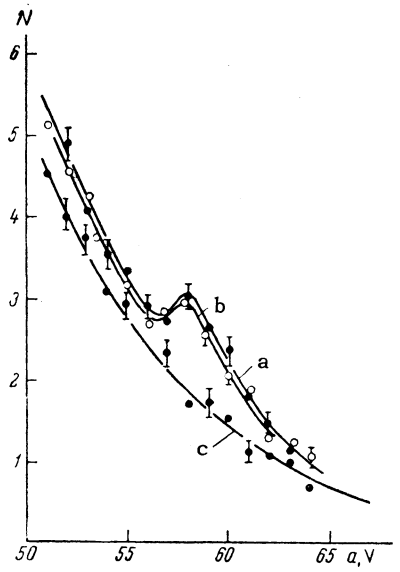

FIG. 2. Resonance scattering by Sn^{116}. Spectrum of scattered radiation from: a) liquid source, tin scatterer; b) solid source, tin scatterer; c) solid source, cadmium scatterer. The abscissa is the pulse height a, the ordinate N gives the number of pulses.

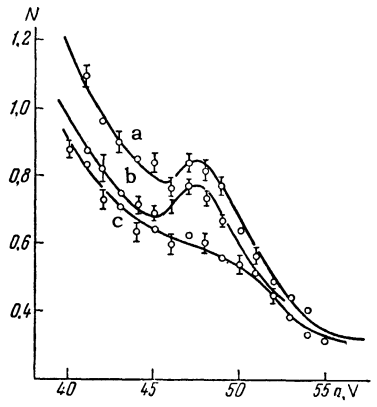

FIG. 3. Resonance scattering by Cu^{65}. Spectrum of scattered radiation from: a) liquid source, copper scatterer; b) solid source, copper scatterer; c) solid source, iron scatterer.

resonance energy, can be computed from the relation

$$\bar{\sigma} = (g_2/g_1)\,(\lambda^2/4)\,\Gamma_\gamma P_l(E),$$

where Γ_γ is the natural width of the level. The attenuation of the resonance effect is

$$A = P_l(E)/P(E),$$

where P(E) is found from the energy distribution of the γ quanta from a gas source.

The data can be used to analyze the processes of interaction of the recoil nuclei with the surrounding atoms of the source material. Ofer and Schwarzschild[1] and Ilakovac[8] have treated a simple model for the motion of the recoil nuclei. If before the first collision the nucleus traverses a path l with the constant velocity $v_{res} = E\gamma/Mc$ which is needed for establishing resonance, the time until collision will be $T = l/v_{res}$. Obviously the effect of collisions can be taken into account crudely by a factor $1-\exp(-T/\tau_\gamma)$, which appears in the resonance cross section for the case of liquid and solid sources, so that

$$P_l(E)/P(E) = 1 - \exp(-T/\tau_\gamma).$$

In this case, using the experimental values of $P_l(E)/P(E)$, we find for l the values 1.43 and 0.9 Å, for liquid and solid Ni^{65}, respectively. The value of v_{res} was taken to be 5.5×10^5 cm/sec.

For In^{116}, with $v_{res} = 3.55 \times 10^5$ cm/sec, the values of l were 1.27 and 1.14 Å for liquid and solid sources, respectively.

However, this model does not take account of the details of slowing down of the recoil nuclei. Actually the velocity of a recoil nucleus decreases continuously all along its path. This was taken into account in the paper of Cumming et al,[3] where the attenuation of the resonance effect was computed for the case of a β-γ cascade. These computations can be made for Cu^{65}, since the resonance effect is due to the transition $\beta(1.010) - \gamma(1.114)$.

The attenuation of the resonance effect as a result of gradual slowing down of the recoil nucleus can be expressed as follows:

$$A = \frac{\int_{v_{res}}^{v_{max}} \frac{f(v_0)}{v_0}\,\alpha(v_0)\,dv_0}{\int_{v_{res}}^{v_{max}} \frac{f(v_0)}{v_0}\,dv_0},$$

where $f(v_0)$ is the velocity distribution of the recoil nuclei after the decay, while

$$\alpha(v_0) = \frac{v_0}{L}\left\{\left[\tau_\gamma + \frac{L}{v_0}\right] - \left[\tau_\gamma + \frac{L}{v_{res}}\right]\exp\left[\frac{L}{\tau_\gamma}\left(\frac{1}{v_0} - \frac{1}{v_{res}}\right)\right]\right\},$$

where $l/L = p$ is the average velocity loss per collision, which is computed taking into account the masses of the recoil nuclei and the nuclei of the surrounding medium, and l is the mean free path of a recoil nucleus before collision. The value of L can be found from the relations given above, using the experimental values for $P_l(E)/P(E)$ and τ_γ. Using the value L = 12.2 Å, we get p = 0.197, l = 2.4 Å.

The corresponding value of l, if one neglects the detailed energy loss of the recoil nuclei, is 1.43 Å, i.e., 1.7 times smaller than the value of l from a detailed treatment of the slowing down of

Average cross section for resonance scattering by Sn^{116} and Cu^{65} and attenuation of the resonance effect

Transition	Liquid source			Solid source		
	$\bar{\sigma}$, 10^{-27} cm²	$P_l(E)$, 10^{-4} eV^{-1}	A	$\bar{\sigma}$, 10^{-27} cm²	$P_s(E)$, 10^{-4} eV^{-1}	A
$In^{116} \rightarrow Sn^{116}$	8.2±1.6	7.0±2.0	0.055	7.4±1.2	6.3±1.7	0.050
$Ni^{65} \rightarrow Cu^{65}$	1.58±0.26	3.36±0.26	0.040	0.97±0.18	2.05±0.60	0.024

the recoils. This comparison seems to indicate the importance of treating the mechanism of energy loss of the recoil nuclei when one calculates the mean interaction length of the recoils from the attenuation factor of the resonant scattering. One should note the large effect of the lifetime of the level on the magnitude of the attenuation. Thus, for $\tau_\gamma = 5 \times 10^{-13}$ sec, which lies within the limits of error for the determination of τ_γ by the self-absorption method, the value of L is $7.1^{+2.3}_{-1.8}$ Å.

We note that our results for Sn^{116} and Cu^{65} are in satisfactory agreement with data from other work.

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