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RESONANCE SCATTERING OF GAMMA RAYS BY Cd^{114}

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The lifetime of the first excited state of the Cd^{114} nucleus (556 kev) was measured by means of gamma-ray resonance scattering using a gaseous In^{114} source in the compound $InCl_3$. The value $\tau = (1.42 \pm 0.21) \times 10^{-11}$ sec for the lifetime of the level agrees satisfactorily with the data from Coulomb excitation investigations. The relation between excitation energy and reduced transition probabilities for even-even cadmium isotopes is discussed.

1. INTRODUCTION

RESONANCE scattering of gamma rays has been used in recent years to measure short lifetimes of excited nuclear states ($\tau \lesssim 10^{-10}$ sec). The cross section for the process is proportional to the width of the excited level, so that when all other conditions are unchanged the resonance scattering intensity increases inverselv with the measured lifetime.

The widths of the lowest excited nuclear levels usually do not exceed 10^{-3} ev. The bombarding gamma rays must therefore correspond very precisely to the resonance energy of an excited state. As a source of these photons one naturally uses a radioactive isotope which decays to an excited state of the nucleus whose resonance excitation is under investigation. However, this is not a sufficient condition for obtaining photons of the required energy. The energy of a gamma ray emitted by a nucleus at rest is always somewhat smaller than the energy of the corresponding excited state, because a part of the transition energy is transformed into kinetic energy of the recoiling atom or molecule. A portion of the energy of an absorbed gamma ray also is converted into recoil energy of the absorbing nucleus. While such reductions of the gamma-ray energy are relatively small, they are always much greater than the excited level width. For the observation of resonance scattering the gamma energy must be increased to compensate the losses incurred through the recoils of both the emitting and absorbing nuclei. Various compensation methods based on the Doppler effect have been discussed in reviews by Dzhelepov[1] and by Metzger.[2]

The present investigation is concerned with the resonance scattering of 556-kev gamma rays emitted in $In^{114} \rightarrow Cd^{114}$ decay, by Cd^{114} nuclei. The method of cascade transitions[3] was used to compensate recoil losses. In In^{114} decay the 556-kev gamma ray is preceded by the emission of a 334-kev neutrino and a 772-kev gamma ray. After emission of the neutrino and first photon a recoiling Cd^{114*} nucleus remains, so that the 556-kev gamma ray is emitted by a nucleus which is already in motion. The 556-kev gamma energy is changed somewhat by the Doppler effect. Sufficiently great recoil velocities will result in the gamma energy required to produce resonance excitation of Cd^{114} nuclei. The mean free time of the recoiling atoms or molecules must considerably exceed the 556-kev level lifetime. Otherwise gamma rays may be emitted after collisions with neighboring molecules of the source material. The velocity of a molecule after a collision will generally be insufficient to supply the required energy to a 556-kev gamma ray. It is therefore necessary to use gaseous sources in which the mean free time of recoiling molecules is sufficiently long. The In^{114} source used in the

present experiment was contained in the compound $InCl_3$ volatilized at a relatively low temperature.

2. CALCULATION OF THE RESONANCE SCATTERING PROBABILITY

As a result of energy and momentum conservation the energy of a photon emitted or absorbed by a nucleus is less by the amount $E_0^2/2Mc^2$ than the transition energy E_0 (M is the mass of the recoiling molecule and c is the velocity of light). When the emitting and absorbing nuclei are included in molecules with masses M_1 and M_2, respectively, the total reduction of the photon energy is

$$\Delta E' = E_0^2(M_1 + M_2)/2M_1M_2c^2. \quad (1)$$

It is assumed here that no chemical bonds are disrupted during transitions. When a photon is emitted by a nucleus moving with the velocity v the photon energy is changed by the amount

$$\Delta E'' = E_0(v/c)\cos\vartheta, \quad (2)$$

where ϑ is the angle between the direction of emission and the direction in which the recoiling nucleus is moving. For resonance scattering some photons must satisfy the condition

$$\Delta E' = \Delta E''. \quad (3)$$

In the present experiment metallic cadmium served as the scatterer, i.e., the mass M_2 was that of the cadmium atom. Equation (3) imposes a certain limitation on the mass M_1 which includes the emitting nucleus. If M_1 is too large the recoiling molecule may have insufficient velocity to satisfy (3). It is easily shown that the molecular weight of the source in the present instance must not exceed 300. This condition is satisfied by $InCl_3$. The energy transferred to the recoiling molecule in the emission of a neutrino and a 722-kev photon is 0.27 and 1.27 ev, respectively, which is insufficient to affect the molecular bonds.

The probability of resonance scattering was calculated using Eq. (5) of reference 4; the probability may be expressed as a function of the excited level width. This width can be determined by comparing the experimental with the calculated probability. Constants in the formula are determined from the characteristics of the In^{114} decay scheme and from the parameters of the scatterer. The total resonance scattering probability for the given experimental geometry is calculated by numerical integration over the volume of the scatterer. For a sufficiently thin scatterer Eq. (5) of reference 4 is equivalent to the formula used in reference 5 to calculate the resonance scattering cross section.

It follows from (2) that photons impinging on the scatterer are not strictly monoenergetic. Their energy depends on v and ϑ, not all values of which are consistent with the resonance energy E_r. To calculate the probability of resonance scattering we must determine $N(E_r)$, the density distribution of photon energies about E_r. It is easily shown in the present case of a neutrino $-\gamma-\gamma$ cascade that the energy distribution for 556-kev photons, without taking γ-γ angular correlation into account is represented by

$$N(E) = \begin{cases} M_1c^2/2E_0E_2, & 0 \leqslant |E| \leqslant E_0(E_2 - E_1)/M_1c^2, \\ (M_1c^2/4E_0E_1E_2)(E_2 + E_1 - EM_1c^2/E_0), & |E| \geqslant E_0(E_2 - E_1)/M_1c^2, \end{cases} \quad (4)$$

where $E_2 = 722$, $E_1 = 334$, $E_0 = 556$ kev. The energy scale used in (4) is such that $E = 0$ represents a photon with the transition energy E_0. When the recoil energy loss (1) is taken into account the resonance energy E_r corresponds to the value $\Delta E'$ for E. For a source in $InCl_3$ and a metallic cadmium scatterer we have $N(E_r) = 0.092$ ev^{-1}. When the angular correlation of the 722- and 556-kev photons is taken into account we have $N(E_r) = 0.099$ ev^{-1}. The angular distribution of scattered photons was also taken into account in calculating the resonance scattering probability.[6]

3. EXPERIMENTAL TECHNIQUE

The $In^{114}Cl_3$ source was prepared from metallic indium, which was irradiated with thermal neutrons in a reactor and was then slightly heated while exposed to a stream of chlorine. The indium chloride was purified through distillation into a glass ampoule, which was then evacuated and sealed. The activity of the source was 15 microcuries, although only 3.5% of the In^{114} decays were accompanied by the emission of 556-kev photons. The $InCl_3$ source was volatilized in an electric oven at about 500° C. Complete volatilization resulted in a pressure of 0.2 atmos, thus excluding the possible influence of collisions of recoiling molecules. The technique used to produce $InCl_3$ permitted a possible admixture of $InCl_2$, the presence or absence of which could not be determined precisely. However $N(E_r)$, which determines the probability of resonance scattering, in the case of $InCl_2$ was very close to the result obtained above for $InCl_3$. The calculation of the overall error of the final results took into account the possible contribution from $InCl_2$. It was determined through control measurements that under the working conditions the entire active source was gaseous.

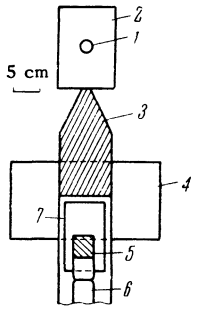

FIG. 1. Diagram of experimental setup. 1 – source, 2 – electric oven, 3 – lead cone, 4 – scatterer, 5 – NaI(Tl) crystal, 6 – photomultiplier tube, 7 – lead absorber.

Resonance scattering was measured using the circular geometry which is customary in such experiments[3,5] to permit the maximum solid angles and for convenience in calculating. The experimental setup is represented in Fig. 1. Scattered radiation was registered by a NaI(Tl) crystal measuring 4 cm in both height and diameter, and by a FEU-29 photomultiplier tube. A lead cone 22 cm high was used to shield the counter from direct radiation out of the source. The electric oven enclosing the source was located at the apex of the cone. The crystal was surrounded by a lead absorber 1 mm thick in order to reduce the pulse count produced by Compton-scattered photons. The scatterer was a hollow cadmium cylinder 30 cm in diameter, 15 cm long and 0.45 cm thick. Scatterers of the same dimensions, consisting of tin and lead instead of cadmium, were used for comparison. The scatterers were interchanged every two minutes in order to exclude any effect which drift of the electronic circuit would have on the results. The differential discriminator channel was set for a photopeak of 556 kev in the interval 530 — 590 kev. Measurements were obtained with the source in both the solid and vapor states. With the volatilized source the counting rate produced by the cadmium scatterer increased due to resonance scattering, whereas with a non-cadmium scatterer or with no scatterer the rate was independent of the state of aggregation of the source. The method described in reference 5 was used to determine the resonance scattering probability.

4. RESULTS AND DISCUSSION

The average counting rate produced by resonance scattering was 0.3 pulse/sec, which comprised 23% of the total rate, most of which was produced by the laboratory background. The effect was large enough to permit measurements of the resonance scattering spectrum shown in Fig. 2. The spectrum for the vaporized source exhibits a photopeak at 556 kev, which is the energy of resonance-scattered gamma rays. The lifetime of the first excited state

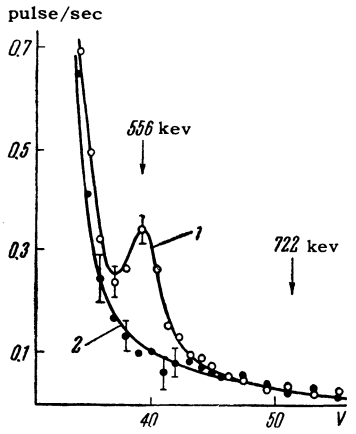

FIG. 2. Spectrum of resonance radiation from cadmium scatterer. 1 – gaseous source, 2 – solid source.

of Cd^{114} (556 kev) is found to be $\tau = (1.42 \pm 0.21) \times 10^{-11}$ sec. The reduced probability B(E2) of the 556-kev E2 gamma transition is calculated from the measured lifetime to be $0.108e^2 \times 10^{-48}$ cm^4. This is in excellent agreement with the results given in references 7 and 8 in connection with the Coulomb excitation of Cd^{114}, the numerical coefficients of B(E2) being 0.110 and 0.104, respectively. There is also agreement within experimental error with the value 0.117 given in reference 9. The hypothesis of reference 10 that the lifetime determined by resonance scattering will always be shorter than that obtained by Coulomb excitation is thus not confirmed. The results obtained in reference 11 for the Coulomb scattering of Cd^{114} disagree sharply with the results obtained in references 7 — 9 and in the present work and are probably incorrect.

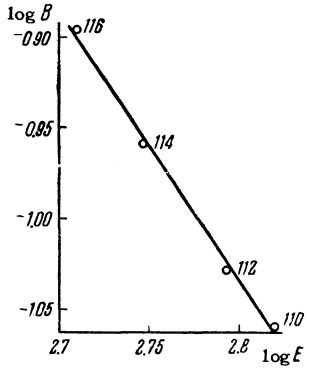

FIG. 3. Log B(E2) as a function of log E. The mass numbers of the cadmium isotopes are indicated.

In references 7 — 9 the reduced probabilities for E2 transitions were determined for even-even cadmium isotopes with mass numbers A = 110, 112, 114, and 116. These results are consistent among themselves, so that we may assume that reliable values of B(E2) have been established for these four cadmium isotopes. The data reveal the dependence of B(E2) on the excitation energy E of the corresponding levels. Figure 3 shows log

B(E2) as a function of log E for the four cadmium isotopes. The results of references 7 — 9 and of the present experiment were averaged for the purpose of the plot, which is a straight line represented by

$$\log B(E2) = a \log E + b, \qquad (5)$$

where a and b are constants. The constant a, which determines the power-law dependence of B(E2) on excitation energy, was calculated at −1.5 by least squares. Equation (5) agrees with experiment to within 1%. Stelson and McGowan[9] have previously noted that the relation between B(E2) and E for even-even nuclei with masses A = 90 — 130 can be represented satisfactorily by $B(E2) = bE^{-1}$. Van Patter[12] has suggested that the formula $B(E2)/Z^2 = bE^{-1.4}$ is accurate to within 25% over a broad range of mass numbers. The relation between B(E2) and E for the cadmium isotopes gives a different power in the functional dependence. It is also found that (5) is valid for isotopes of other elements but that the constant a, which is the power of E in the formula for B(E2), generally varies as a function of Z. For example, in the case of even-even gadolinium isotopes, for which the reduced probabilities for E2 transitions are given in reference 13, the experimental results agree to within 1% with (5) when a = −1.1. For Se and Dy isotopes the absolute value of a is greater than 3. For a large group of elements (Ru, Pd, Cd, Te, Sm, Gd, W, Pt) the values of a lie within a small range, from −1.1 to −1.5. It cannot be determined at the present time whether this spread of the values of a is significant or results from inaccurate experimental data. It is significant, however, that the given group of elements includes nuclei with a rotational spectrum of low-lying excited levels and nuclei which are excited by quadrupole-type vibrations according to the unified model.[14] It is difficult to interpret the observed relations theoretically, but it may be noted that (5) can be predicted for nuclei whose first excited levels are of rotational character. For such nuclei B(E2) is proportional to the square of the deformation parameter while the first excited-level energy is proportional to the nuclear moment of inertia. Assuming a power-law relation between the moment of inertia and the deformation parameter, (5) is easily derived with a and b constant for isotopes of a single element. The determination of the relation between B(E2) and E may thus furnish information concerning the relation between the nuclear moment of inertia and the deformation parameter.

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