LIFETIME OF THE 0.845 MeV LEVEL OF THE Fe^{56} NUCLEUS

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The resonance scattering of 0.845 MeV γ-quanta on Fe^{56} nuclei was investigated using a gaseous Mn^{56} source in the form of the compound $MnCl_2$ under the conditions of ring and "plane" geometry. The lifetime τ_γ of the first excited level of Fe^{56}, determined by the self-absorption method, was $(9.6 \pm 1.8) \times 10^{-12}$ sec, which corresponds to an acceleration of the E2-transition by a factor of 15 compared with the single-particle model of Weisskopf.

1. INTRODUCTION

THE lifetime of the first excited state of the nucleus Fe^{56} at the energy 0.845 MeV has been investigated by several workers using the method of Coulomb excitation,[1-4] as well as the method of resonance scattering.[5,6] Ilakovac[5] made the first attempt at detecting resonance scattering using a liquid source. From the absence of the resonance effect an estimate of $> 8 \pm 10^{-12}$ sec was obtained for the mean lifetime of the 0.845 MeV level. The resonance effect was successfully observed by Kelly and Beard[2] and Metzger [6], who used gaseous sources of Mn^{56}[2] and Co^{56}.[6]

The present paper reports a study of the resonance scattering of γ-quanta from the 0.845 MeV level of the Fe^{56} nucleus using ring and "plane" geometry, as well as self-absorption with a gaseous $MnCl_2$ source (for Mn^{56} $T_{1/2} = 2.56$ hours). Use of the "plane" geometry reduced the background considerably and this permitted determination of the lifetime τ_γ by the self-absorption method with higher precision than in the work of Kelly and Beard.[2] It is known that on emission and absorption of a γ-quantum part of its energy is lost by nuclear recoil. If M is the mass of the radiating nucleus and E_0 is the energy of the transition, then the total energy loss is $\Delta E_1 = E_0^2/Mc^2$, which amounts to 14 eV in the present case. Since the width of the excited level Γ_γ is much smaller than ΔE_1, to observe the resonance effect it is necessary to restore the energy of the quantum back to its resonance value. The $Mn^{56} \rightarrow Fe^{56}$ decay scheme (Fig. 1) shows that the emission of a 0.845 MeV γ-quantum is preceded by: a β-transition of 2.860 MeV energy, and cascades

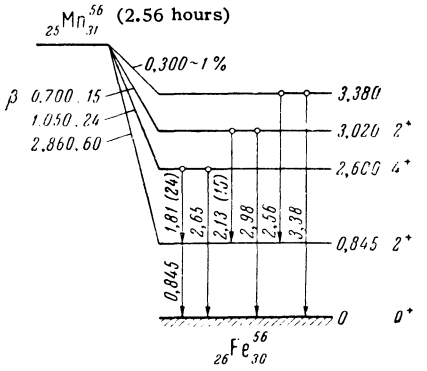

FIG. 1. $Mn^{56} \rightarrow Fe^{56}$ decay scheme including cascades leading to the 0.845 MeV level (energies are given in MeV).

$\beta(1.050)-\gamma(1.810)$ and $\beta(0.700)-\gamma(2.130)$; the energies are given in MeV.

Owing to the Doppler effect the energy of the 0.845 MeV quantum is altered by a quantity $\Delta E_2 = E_0(v/c) \cos \nu$, where $E_0 = 0.845$ MeV, v is the velocity of the recoil nucleus, and ν is the angle between the directions of the γ-quantum escape and the recoil-nucleus motion. Restoration of the energy to its resonance value will obviously occur if $\Delta E_1 = \Delta E_2$ in a gaseous source.

In the present work the source was the compound $MnCl_2$ having a boiling point of 1190°C.

To determine the lifetime τ_γ it is necessary to measure the mean resonance-scattering cross section $\bar{\sigma}$ and calculate theoretically the energy distribution of the emitted γ-quanta.

2. EXPERIMENTAL SETUP AND MEASUREMENTS

As mentioned earlier, we used both the ring geometry, similar to that employed earlier,[7] as well as the "plane" geometry which is shown

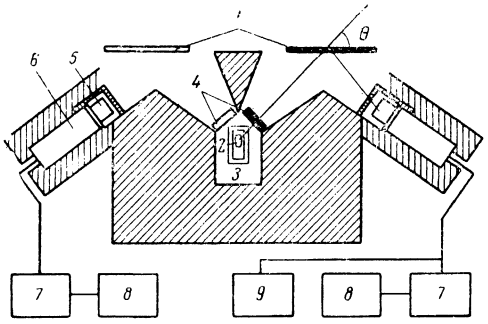

FIG. 2. Experimental setup under the "plane" geometry conditions: 1) scatterers; 2) source; 3) electrical furnace; 4) Fe and Cd absorbers (in the self-absorption experiment); 5) NaI: Tl crystal; 6) FÉU-12B; 7) single-channel pulse analyzer; 8) PS-10 000 scaler; 9) 100-channel pulse analyzer AN-100.

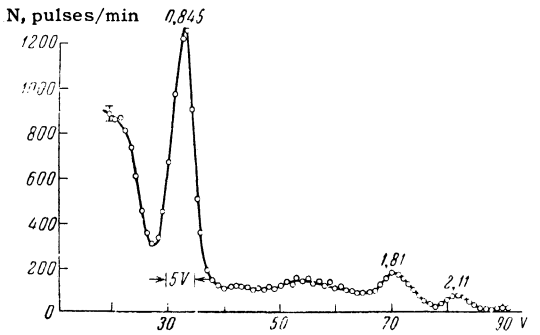

FIG. 3. γ spectrum of the Mn^{56} nucleus in the energy range 0.530-2.400 MeV.

schematically in Fig. 2.

In the ring-geometry case the length of the lead cone was 40 cm and its diameter 12 cm. The cylindrical scatterer of Fe was of 37.5 cm diameter, 13.5 cm width, and 0.9 cm thickness. The mean scattering angle was 107°. The scattered quanta were detected by an NaI: Tl crystal coupled to a photomultiplier FÉU-12B, a single-channel pulse analyzer and a scaler.

In the "plane" geometry case the scatterer dimensions were 30 × 30 × 1 cm and the mean scattering angle was 104°. In both cases a copper scatterer was used for comparison; under non-resonant conditions it scattered in the same way as Fe to within 3%.

The main non-resonant scattering processes are Rayleigh scattering (scattering of γ-quanta by bound electrons) and Compton scattering by the scatterer and the surrounding objects. Considering the Rayleigh scattering we must take into account the possibility of elastic scattering of γ-quanta of energies $E_\gamma > 0.845$ MeV (see Fig. 1). The Compton scattering of γ-quanta of energies 0.845—3.200 MeV in the angular range 100—110° yields γ-quanta with energies from 0.26 to 0.380 MeV. The processes occurring in the crystal generate strong pulses, including those corresponding to energies in the range 0.785—0.915 MeV (the energy width of the analyzer "window"). The latter circumstance is important in the case of the cascade transitions: 1.810—0.845 MeV and 2.130—0.845 MeV in our case.

The investigation showed that the "plane" geometry ensured better screening of the source than the ring geometry, and this reduced considerably non-resonant scattering in the energy range 0.785—0.955 MeV. To reduce the loading of the apparatus by the Compton quanta the crystals were surrounded by a filter of 3.5 mm Pb + 1 mm Cd (selected experimentally). The $Mn^{56}Cl_2$ source was prepared by irradiation of a quartz ampoule of ≈ 3 cm^3 volume containing 2 mg of carefully dried (by vacuum heating) $Mn^{55}Cl_2$ in the reactor of the Nuclear Physics Institute of the Uzbek S.S.R. Academy of Sciences using a neutron flux of 1.8×10^{13} cm^{-2} sec^{-1}. The irradiation period was 3—5 hours, and was followed by several hours storage.

The γ-spectrum of Mn^{56} is given in Fig. 3. The specific activity of the source was 40 millicuries/mg at the end of the activation. The experimental technique was similar to that described earlier.[7] The initial activity of the source was 15—20 millicuries.

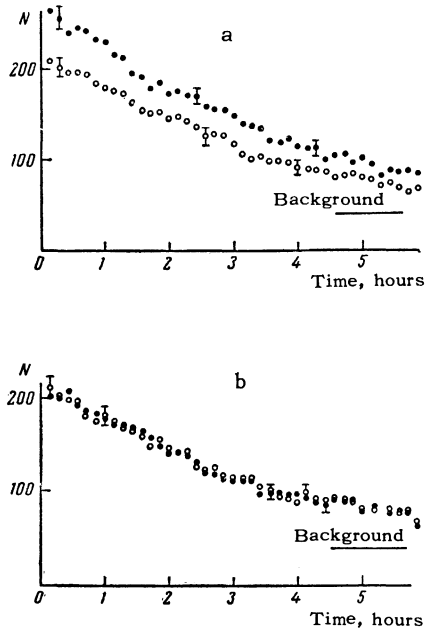

FIG. 4. Intensities of resonant scattering of γ-quanta on Fe^{56} nuclei ("plane" geometry): a) gaseous source; b) solid source; ● – Fe scatterer; o – Cu scatterer. The ordinate axis gives the number of counts per 2 min.

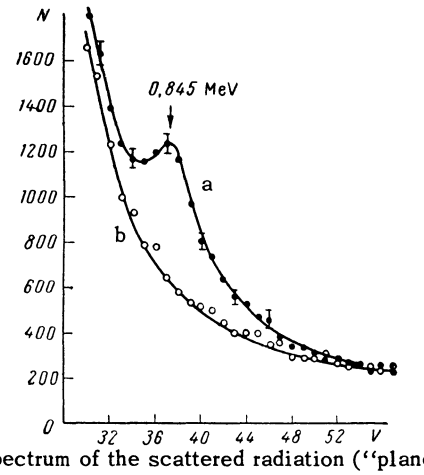

FIG. 5. Spectrum of the scattered radiation ("plane" geometry): a) gaseous source; b) solid source. The ordinate axis gives the number of counts in 2 hours.

3. RESULTS OF EXPERIMENTS AND DISCUSSION

Figure 4 shows the results of one of the series of measurements with the spectrometer under "plane" geometry conditions. This figure indicates that replacement of a solid by a gaseous source increases the count for the Fe scatterer by 18—20% with respect to the Cu scatterer.

Figure 5 shows the spectrum of scattered radiation recorded with a 100-channel pulse analyzer AI-100. The mean resonant-scattering cross section, averaged for the two cases, was found to be $(1.36 \pm 0.12) \times 10^{-26}$ cm^2. Partial values of the microspectrum were calculated in the approximation of a monatomic source for all the cascades leading to the 0.845 MeV level; they are listed in Table I. From the mean cross section $\bar{\sigma}$ and the total value of $N(E_p) = 0.0143$ eV^{-1} we find $\tau_\gamma = 1.84 \times 10^{-11}$ sec. Allowance for the chemical bonding reduces the value of $N(E_p)$ and consequently τ_γ. The value of τ_γ quoted above is the upper limit.

To determine the true value of τ_γ we used the method of self-absorption of the resonantly scattered radiation.[8] The positions of the Fe and Cd absorbers are shown in Fig. 2. The initial activities of the sources in all ten series of tests were 60—80 millicuries. The attenuation of the resonance effect by the Fe absorber was found to be 0.837 ± 0.034. Allowing for the Debye temperature of Fe (420°K) and the actual temperatures of the absorber (325°K) and scatterer (291°K), we find that the effective temperatures were 354 and 320°K and the corresponding Doppler widths 0.91 eV for the absorber and 0.86 eV for the scatterer. Using the values $\lambda^2 = 2.15 \times 10^{-20}$ cm^2, $n = 7.8 \times 10^{22}$ cm^{-3}, d = 2.5 cm, we find $\Gamma = (6.9 \pm 1.3) \times 10^{-5}$ eV which corresponds to $\tau_\gamma = (9.6 \pm 1.8) \times 10^{-12}$ sec, found from the indeterminacy relationship ($\tau_\gamma\ \Gamma = 6.6 \times 10^{-16}$ eV). Calculations carried out by means of the Weisskopf formula, based on the one-particle model, gave $\tau_{\gamma\ op} = 1.43 \times 10^{-10}$ sec. Thus the E2-transition with $E_\gamma = 0.845$ MeV is accelerated with an acceleration factor $F = \tau_{\gamma\ op}/\tau_{\gamma\ exp} = 15$, which allows us to consider the excited 0.845 MeV state of the Fe^{56} nucleus as a result of quadrupole oscillations of the nucleus surface about its equilibrium spherical shape.

Table I

End-point energy of β-transition, MeV	2.860	1.050	0.700
Relative intensity of β-transition, %	60	24	15
Cascade leading to 0.845 MeV level	β (2.860)	β(γ—1.811)	β(γ—2.11)
Partial value of $N(E_p)$, %	0.83	0.38	0.22
Total value of $N(E_p)$, %		1.43	

Table II. Experimentally determined lifetimes of the 0.845 MeV level of the Fe^{56} nucleus

Method used	τ_γ, 10^{-12} sec
Coulomb excitation:	
α-particles, 4.0 and 6.5 MeV[1]	8.6 ± 1.3
O^{16} nuclei, 30.5 MeV (Adams et al., see [2])	9.3 ± 2.3
O^{16} nuclei, 27 MeV (Hove and Broude, see [2])	9.3
N^{14} nuclei, 15.9 and 36 MeV[3]	12.4
N^{14} nuclei, 16.3 and 36 MeV[4]	14.3
Resonance scattering:	
$Mn^{56} \rightarrow Fe^{56}$ (liquid)[5]	>7.8
$Mn^{56} \rightarrow Fe^{56}$ (gas)[2]	8.6 ± 2.9
$Co^{56} \rightarrow Fe^{56}$ (gas)[6]	10.6 ± 1.7
$Mn^{56} \rightarrow Fe^{56}$ (gas), present work	9.6 ± 1.8

Table II lists all the experimental data for τ_γ. The results obtained by the method of resonance scattering agree satisfactorily. The mean value for the earlier[2,6] and present work is 9.5×10^{-12} sec. It is interesting to compare the experimental values of τ_γ with the calculated ones. Kaipov and Pertsev[9] analyzed the experimental data on the probabilities of transitions in even-even nuclei and deduced a relationship between the lifetime of the first excited level τ_γ and the transition energy E_γ; they found: $\log \tau_\gamma = (a + bA) \log E_\gamma$, where A is the atomic weight, and a and b are constants. For the atomic weights A = 50—82, a = 3.753 and b = 0.0012. This empirical relation gives $\tau_\gamma = 6.7 \times 10^{-12}$ sec, which is in agreement with the experimental results.

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26