Measurement of the lifetime of a nucleus excited near a resonance

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The dependence of the lifetime of an unstable state of a nucleus on the energy of the particles exciting it is investigated, and the causes of this dependence are found. The lifetime of the nucleus in the excited state was determined directly by measurement of the delay times in two individual scattering experiments: In the first experiment we determined the lifetime of the intermediate excited state of a nucleus which had been subjected to exciting γ radiation, and in the second experiment we determined this same property under conditions of spontaneous decay of the excited nucleus. The experiment showed that the lifetime of a nucleus subjected to excitation will depend substantially on the energy of the bombarding particle, whereas the lifetime in spontaneous decay does not depend on the conditions of excitation. Comparison of the experimental data with theory gives satisfactory results.

1. INTRODUCTION

Nuclear spectra in the low-energy region are characterized by a low density of energy states: the energy levels are spaced far apart. Nuclear states in this region of the spectrum are almost stationary. A nucleus which finds itself in one of these states (for example, as the result of capture of an incident particle or after emission of a particle in a nuclear transformation) will live in it for a finite time which is long in comparison with the characteristic time of motion of the nucleons in the nucleus.

Direct determination of the lifetime of a nucleus in a quasistationary excited state is carried out most frequently by measurement of the time dependences of the decay of this state. If it is known that at some time $t = 0$ the nucleus is in the excited state being investigated, the characteristic delay in emission of a particle (the decay product) with respect to this time will serve as a measure of the lifetime of the state being studied.

The time behavior of decay of an excited quasistationary state was studied theoretically for the first time by Weisskopf and Wigner.[1] They showed in particular that a decay which occurs under the action of a weak perturbation obeys an exponential law with a constant equal to the lifetime τ_0: $\exp(-t/\tau_0)$. An unstable state decaying by this law corresponds to a smeared energy level with a Lorentz shape of the energy dependence having a width $\Gamma_0 = \hbar/\tau_0$.

The time $t = 0$ can be determined by various means, for example, from the instant of emission of a particle in a transition from a high-lying excited state to the state under investigation. However, when the excited state is produced not as a result of particle emission but as a result of capture of a particle (for example, in a scattering experiment in which the investigated state is intermediate), it is not always possible to determine the instant of time $t = 0$ beginning with which the nucleus is in the excited state. Here the method described above for determining the lifetime turns out already to be be inapplicable.

The definition of lifetime or, as it is often called, collision time in a scattering experiment was introduced by Wigner and Eisenbud[2,3] and subsequently generalized by Smith[4] (see also Refs. 5–7). According to this definition the lifetime of a virtual state produced in a reaction is equal to the time of retention of the incident particle in the region of collision with the nucleus. The theory predicted the existence in the general case of a dependence of the collision time on the bombarding-particle energy.

For the situation considered—the case of an isolated resonance of Lorentz shape—the collision time is given by the expression

$$Q=2\tau_0\frac{(\Gamma_0/2)^2}{(E-E_0)^2+(\Gamma_0/2)^2}. \tag{1.1}$$

Here E_0 is the resonance energy of the transition between the ground state and the metastable state and E is the energy of the incident particle. It is assumed that the energy of the incident particle is determined with accuracy $\delta E \ll \Gamma_0$. Equation (1.1) establishes a relation between the lifetime of the virtual bound state in the scattering experiment Q and the lifetime τ_0 of a prepared unstable state in its spontaneous decay. As can be seen from Eq. (1.1), the lifetime in a collision turns out to be greatest in a resonance, reaching values $2\tau_0$, and falls off to zero on going off resonance. The requirement of high monochromaticity of the incident radiation ($\delta E \ll \Gamma_0$) means that the lifetime of a virtual state (1.1) is determined under conditions of an excitation which acts essentially in a stationary manner (the duration of the wave packet which describes the incident particle is much longer than the characteristic lifetime of the virtual state).

It can be seen from this that a given unstable state of a nucleus can be characterized by different lifetimes, depending on whether the measurements are made in spontaneous decay or in the presence of an exciting factor. A difference of the lifetimes mentioned can be observed, according to Eq. (1.1), only in the presence of monochromatic nuclear radiation, in any case such that the relation $\delta E \approx \Gamma_0$ is satisfied.

In principle, experiments of this type became possible only after discovery of the Mössbauer effect. The first study of this subject was undertaken in Refs. 8 and 9. From the results of measurements of perturbed angular correlations of resonance-scattered γ rays in the ^{191}Ir nucleus the lifetime of the first excited state was calculated. It was shown that the lifetime of the intermediate excited state of the nucleus can depend on the width of the spectrum of the exciting radiation. The authors correctly noted that the method used by

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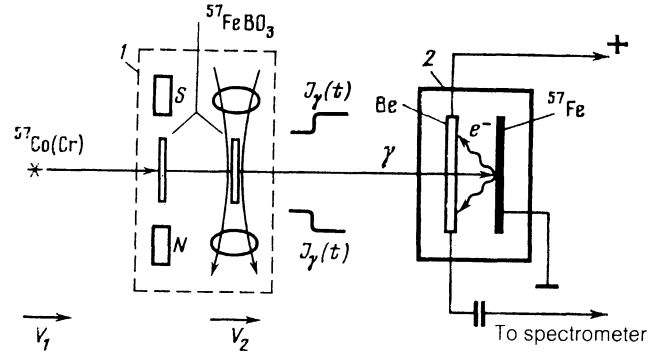

FIG. 1. Diagram of the experiment: 1—magnetic resonance gate assembly, 2—avalanche gas-discharge electron counter, V_1 and V_2—vibrators putting into motion with constant velocities the ^{57}Co source and the gate.

them (which actually makes possible the turning on of a unique nuclear clock) affords the rare possibility of determining the collision time in a stationary experiment.

The high energy resolution of Mössbauer spectroscopy in combination with the accessibility of a time analysis in the case of long-lived Mössbauer isomers permits simultaneous study of the time and frequency characteristics of resonance nuclear scattering of γ radiation. In Refs. 10–12 a delayed-coincidence technique was used to study the scattering of γ rays by resonance targets. However, the question of dependence of the lifetime of the nucleus on the energy of the exciting γ radiation was not raised in these studies.

The purpose of the present work was to investigate in a direct experiment the dependence of the lifetime of a quasistationary state of a nucleus on the energy of exciting radiation tuned to the vicinity of a resonance. Another problem of the experiment was comparison of the lifetime of a given unstable state under conditions of an acting excitation and under conditions of spontaneous decay. Excitation of the nuclear state was carried out by quasimonochromatic Mössbauer radiation. Two different experiments were set up. In the first experiment the decay of the excited state of the nucleus was investigated after turning on the flux of resonance γ rays, and in this way the initial instant of excitation of the nuclei was specified. In the second experiment the decay of the nuclear excited state was studied after turning off a flux of resonance γ rays, i.e., the time of removal of the excitation was determined.

Time dependences of the emission of the decay products were measured with various portions of the energy spectrum of the nuclei raised to excited states. The object of study was chosen to be the isomeric 14.4-keV ^{57}Fe-nucleus state well known in Mössbauer spectroscopy. Turning on and turning off the flux of resonance γ rays was accomplished by means of a magnetic resonance gate.[13–15] The duration of operation of the gate was much shorter than $\hbar/\Gamma_0$, where in this case Γ_0 is the natural width of the excited level of the ^{57}Fe nucleus. In the first part of the work we describe the experimental method and give the experimental results, and in the second part we analyze the results on the basis of the nonstationary theory of resonance scattering of particles.

2. METHOD OF MEASUREMENT

Let us consider the basic scheme of the experiment and the operation of the individual elements of the apparatus (Fig. 1). A continuous flux of 14.4-keV γ rays from a ^{57}Co(Cr) radioactive source passed through a magnetic-resonance gate[13,14] and was converted into periodically repeated positive or negative steps of almost rectangular shape with a frequency of 0.5 MHz. The characteristics of the γ-ray steps were measured with a spectrometer described in Refs. 13 and 14. The results of the measurements are shown in Figs. 2a and b. The fall time of the intensity in each step did not exceed 15 nsec, which is significantly less than the lifetime of the ^{57}Fe nucleus in the 14.4-keV excited state under study: $\tau_0 = 141.1$ nsec.[16] The depth of modulation on opening the beam was 15% (Fig. 2a) and on turning it off it was slightly less than 9% (Fig. 2b). The main contribution to the constant component was made by nonresonance 14.4-keV γ rays.

The γ beam modulated in the form of steps bombarded a target consisting of an iron foil enriched in the resonance nuclei ^{57}Fe to $\eta = 85\%$. The (γ,e^-) process was studied in excitation of nuclei near resonance. Detection of a conversion electron announced the decay of an individual excited nucleus. The conversion electrons could leave the target from a depth of no more than 3000 Å, which reduced to a minimum the distorting action of the thickness of the resonance scatterer on the shape of the step of the exciting γ beam.

In accordance with the problem posed, the main attention was concentrated on study of the time characteristics of emission from the target of conversion electrons after arrival of a positive or negative γ-ray step, in other words, after turning on or turning off the excitation of the nuclei. In order that the measured dependences adequately reflect the nuclear transition processes, it was necessary first of all to use

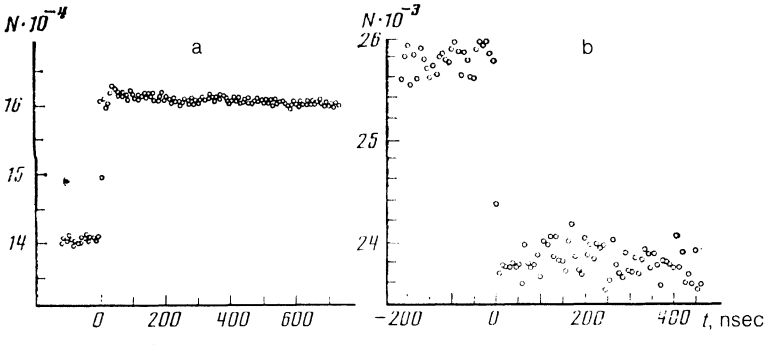

FIG. 2. Time behavior of the intensity of the 14.4-keV resonance γ radiation of ^{57}Fe nuclei which hit the nuclear target: (a)—$t = 0$ is the moment of opening of the magnetic resonance gate, channel width 7.0 nsec; (b)—$t = 0$ is the moment of closing of the magnetic resonance gate, channel width 7.1 nsec.

an electron detector of low inertia. In our experiment this was a gas-discharge avalanche detector similar to that described in Ref. 17. The inherent time of operation of a detector of this type is about 1 nsec. Our counter was filled with acetone vapor to a pressure of 5 Torr. The cathode was a metallic target of ^{57}Fe. The distance between the cathode and anode (a polished beryllium foil) was 4 mm. A voltage of 0.75 kV was applied to the anode. The signal taken from the anode through a capacitive divider was fed to a fast preamplifier. The rise time of the signal did not exceed 2.5 nsec. After amplification it was fed to a spectrometer circuit in which a standard measurement[13-15] was made of the time interval between the moment of appearance of the signal and the beginning of the counting time (the moment of operation of the gate).

The time resolution of the detector was estimated in measurements of the time dependence of the emission of photoelectrons from the target when the γ pulse hit it (Fig. 2a). The possibility of evaluating the speed of action of the apparatus in this way was based on the fact that the photoemission process occurs without time delay. To obtain the photoemission signal the γ-ray energy was set far from resonance. The measured time dependence of the yield of photoelectrons showed that the time resolution of the electron counter was no worse than the similar characteristic of the scintillation detector which was used to measure the dependences in Fig. 2 (the time resolution of the NaI(Tl) detector with an FÉU-85 photomultiplier was 5.2 nsec).

A system of two vibrators was used in the Mossbauer part of the spectrometer. The vibrators V_1 and V_2 (Fig. 1) worked synchronously in a constant-velocity mode with the velocities directed along the axis of propagation of the γ rays. By means of the first vibrator V_1 the line of the ^{57}Co source, which had a width at half-height $\Gamma_s = 0.25$ mm/sec (with an activity of $5\cdot 10^9$ Bq), could be set at any energy E_s near the energy E_0 of the $+\frac{1}{2}\rightarrow+\frac{1}{2}$ nuclear transition in the ^{57}Fe target nucleus. The second vibrator V_2 provided matching of the $+\frac{1}{2}\rightarrow+\frac{1}{2}$ nuclear resonance in the $^{57}FeBO_3$ crystals comprising in the gate[13] to the line of the radiation source. In this way the necessary conditions were created for conversion of the stationary flux into steps of γ radiation with a definite average energy.

3. RESULTS OF MEASUREMENTS

Two independent series of experiments were carried out. In one of them we measured the time dependences of the emission of electrons from a nuclear target on turning on (Fig. 2a) the exciting γ ray, and in the other we measured the same dependences after turning off the γ beam (Fig. 2b). The results of these measurements will be discussed below, and here we shall make a remark concerning the method of taking into account the contribution of photoemission to the measured dependences. Obviously the γ beam knocked out of the target, together with conversion electrons, also photoelectrons, and the fraction of conversion electrons in the total measured intensity varied with the displacement of the γ-ray energy from the resonance. Under stationary conditions the ratio Z of intensities of conversion electrons and photoelectrons should be determined by the ratio of the corresponding interaction cross sections averaged over the spectrum of incident γ radiation:

$$Z=\frac{\sigma_r}{\sigma_{ph}}\frac{wf_M\eta\Gamma_c(\Gamma_0+\Gamma_s)}{4[(E_s-E_0)^2+(\Gamma_0+\Gamma_s)^2/4]}, \qquad (3.1)$$

where σ_r is the total cross section for nuclear resonance absorption in ^{57}Fe, w is a factor taking into account absorption only in one of the resonances of the hyperfine structure of ^{57}Fe (for the transition $+\frac{1}{2}\rightarrow+\frac{1}{2}$ we have $w=1/6$), σ_{ph} is the cross section for the photoeffect, E_s is the γ-ray source energy corresponding to the maximum of the energy distribution of the γ rays emitted by the source (we assume that it has a Lorentz shape with a linewidth Γ_s), E_0 is the energy of the nuclear resonance (it is known that the distribution of energy in the excited state of ^{57}Fe is with high accuracy a Lorentzian of width Γ_0), Γ_c is the partial width of the conversion decay channel, and f_M is the absorption factor without recoil. The following values of the constants were used in the calculations: $\sigma_r = 2.55\cdot 10^{-18}$ cm^2, $\sigma_{ph} = 5.98\cdot 10^{-21}$ cm^2, $f_M = 0.87$, $\Gamma_0 = 0.097$ mm/sec, and $\Gamma_c = 0.89\Gamma_0$.

The fraction of photoelectrons is easily separated from the total dependence if one takes into account that the photoemission signal reproduces the shape of the step of exciting Γ radiation. The total signal of electron emission can be written in the form

$$J(t)=(Z+1)^{-1}[ZJ_c(t)+J_\gamma(t)]+B. \qquad (3.2)$$

The first term $J_c(t)$ is the desired time behavior of the yield of conversion electrons, and the second term $J_\gamma(t)$ is the time dependence of photoelectrons, which is identical to the incident step of γ radiation. The quantities $J_c(t)$ and $J_\gamma(t)$ are functions of time normalized to unity, and B is a constant component. The time dependence of the conversion electrons $J_c(t)$ obtained after subtraction of the photoemission signal will reflect the change with time of the probability of finding the nucleus in the excited state. We now turn our attention to the results of the measurements.

In the excitation mode we measured three time dependences of electron emission at γ-ray energies $E_s = E_0$, $E_s = E_0 + \Gamma_0$, and $E_s = E_0 + 2.5\Gamma_0$. The dependences obtained in the measurements are shown in Fig. 3. We have shown the combined emission signal including conversion electrons and photoelectrons. All spectra have been normalized to the maximum intensity differential.

A characteristic feature of the emission time dependences is the delay in emission of electrons after turning on the exciting γ beam. Just this delay contains information on the duration of existence of the virtual state in the reaction of scattering of a γ ray by the nucleus. For a quantitative evaluation of the characteristic delay time we separated the photoelectron contribution to the total intensity on the basis of Eqs. (3.1) and (3.2). The left-hand outer vertical scale in Fig. 3 refers to the combined intensity of the photoelectrons and conversion electrons knocked out of the target. The zero of the counting rate on the inner scale has been shifted upward by an amount $(Z+1)^{-1}$ equal to the contribution of photoelectrons to the total signal. In this way the inner scale shows the relative content of conversion electrons to the combined signal. As can be seen, the contribution of nuclear decay products is dominant. At resonance it amounts to 93%, and far from the resonance at $E_s - E_0 = 2.5\Gamma_0$ it is 77%.

Comparison of the spectra in Figs. 3a–c shows directly that the delay in the emission of the nuclear-reaction prod-

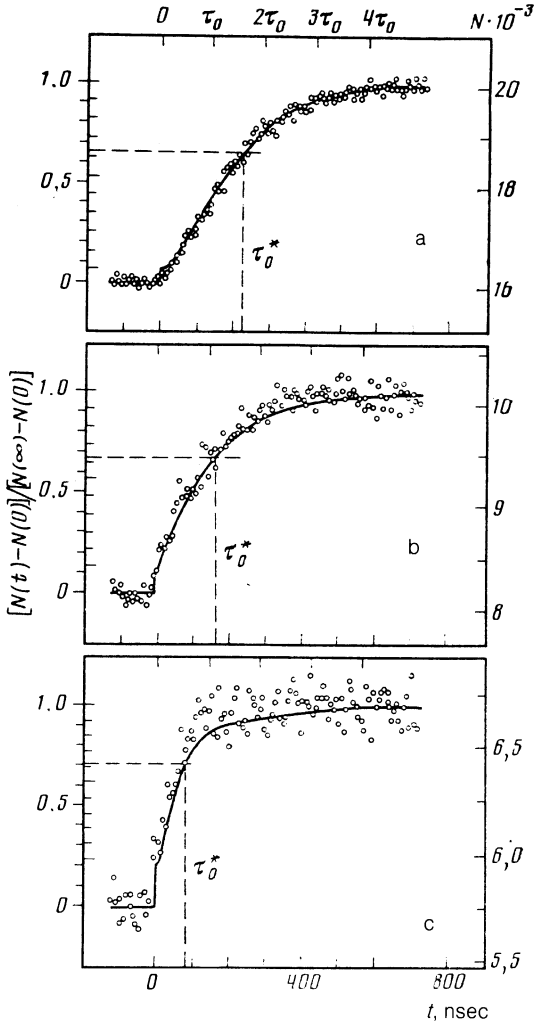

FIG. 3. Time dependences of the emission of electrons from the target after turning on exciting radiation with energy E_s near the resonance E_0: $E_s = E_0 + \Delta E$; (a)—$\Delta E = 0$, (b)—$\Delta E = \Gamma_0$, (c)—$\Delta E = 2.5\Gamma_0$; $N(t)$ is the intensity of emission of photoelectrons and conversion electrons at time t. The inner left scale refers only to conversion electrons; τ_0^* is the characteristic response time of the nuclei to step excitation; (a)—$\tau_0^* = 230 \pm 10$ nsec, (b)—160 ± 15 nsec, (c)—78 ± 15 nsec. The solid lines are calculations according to the theory. The channel width is 7.0 nsec.

ucts depends on the location of the average energy of the exciting particles with respect to the resonance. The farther from the resonance, the faster the secondary particle is emitted, and consequently the shorter the lifetime of the virtual excitation of the nuclear state. If the duration of the delay is characterized by the time interval τ_0^* during which an identical relative level of the conversion-electrons emission intensity is reached: $1 - e^{-1} = 0.63$, then at exact resonance ($E_s = E_0$) the time is $\tau_0^* = 230 \pm 10$ nsec; at $E_s = E_0 + \Gamma_0$ we have $\tau_0^* = 160 \pm 15$ nsec and at $E_s = E_0 + 2.5\Gamma_0$ we have $\tau_0^* = 78 \pm 15$ nsec. Thus, in the experiment described a change by more than a factor of three of the collision time in the scattering reaction is observed.

In the case considered the scattering reaction was studied in a typical nonstationary experiment: the time of beginning of excitation of the nucleus was identified. Just for this reason the possibility existed of tracing in time the response of the nucleus to the excitation which arises. In contrast to stationary conditions, in this case the spectrum of exciting nuclear particles undergoes an evolution: it becomes narrower with increase of the distance from the leading edge, approaching in the limit the shape of the source line. Therefore Eq. (1.1), which applies to a stationary mode of scattering, is inapplicable directly for a quantitative description of the experimental results. However, even in the case of excitation of nuclei by a wave packet in the form of a step, the dependence of τ_0^* on the energy of the incident particles is preserved, as is in fact observed in the experiment. The solid lines in Fig. 3 are the theoretical curves, the calculation of which we will discuss in the next section.

Let us turn to the results of measurement of the time dependences of electron emission after turning off the beam of exciting γ radiation. We obtained two dependences at γ-ray energies $E_s = E_0$ and $E_s = E_0 + \Gamma_0$. The net conversion-electron emission signals were separated by means of Eqs. (3.1) and (3.2) and are shown in Figs. 4a and b. The zero on the time scale corresponds to the instant of shutting off of the exciting γ beam. Beginning with this time there is spontaneous decay of the excited state of the nucleus prepared in the reaction with the quasimonochromatic beam. Even at first glance it can be seen that there is no appreciable difference in the time behavior of the decay for the two cases studied (at least on the scale of the effect observed for the excitation curves). The solid curves in Figs. 4a and b are the result of a fit by the exponential function $\exp(-t/\tau_x)$ to the experimental spectra. The best agreement was achieved in both cases with the same value of the adjustable parameter $t_x = 137$ nsec, which was determined with errors ± 14 nsec (Fig. 4a) and ± 21 nsec (Fig. 4b); within experimental error τ_x is equal to the lifetime $\tau_0 = 141.1$ nsec of this same nuclear state produced by in a γ transition from a higher level. Thus, whether the excited state is populated, by a quasimonochromatic beam as in our experiment or at an uncertain energy as in decay from the second excited state of the ^{57}Fe nucleus, the time behavior of spontaneous decay and consequently also the lifetime of the unstable state of the nucleus turn out to be the same.

4. RESONANCE SCATTERING WITH STEP MODULATION OF THE GAMMA BEAM INTENSITY. THEORY

For analysis of the time behavior of nuclear resonance scattering of γ rays we shall use the formalism of response functions. In Ref. 18 this method was used to calculate resonance scattering of pulses of radiation having a white spectrum. In the present section the method of response functions is extended to the case of incident quasimonochromatic radiation. The conditions in our experiment were just of this type.

Let the resonance scatterer be bombarded in the direction of the z axis by an amplitude-modulated plane wave of radiation

$$A_E'(t) = \mathscr{E}_E \exp[i(\varkappa z - Et/\hbar)]\psi(t), \qquad (4.1)$$

where $\mathscr{E}_E$ is the amplitude of the wave, the function $\psi(t)$ gives the shape of the modulating signal, $E/\hbar$ is the fundamental frequency of the radiation, $\varkappa = 2\pi/\lambda$, and λ is the wavelength. At a distance r from the scattering center the diverging spherical wave is described by the following time dependence[18]:

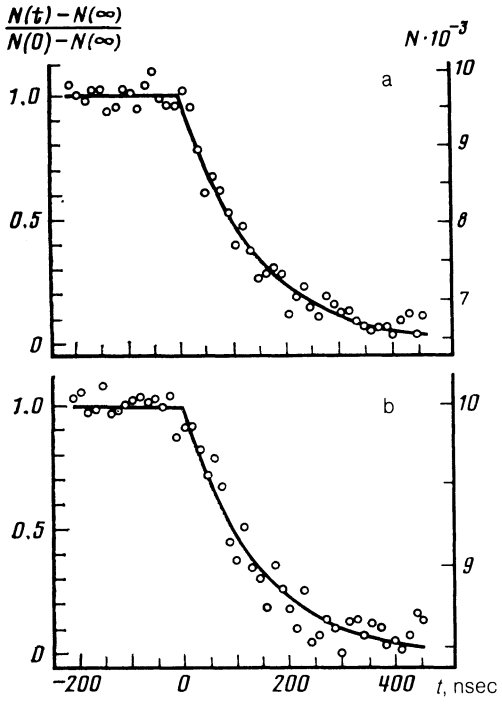

FIG. 4. Time dependences of the emission of conversion electrons from the target after cutoff of the exciting radiation with energy E_γ near the resonance E_0: $E_\gamma = E_0 + \Delta E$; (a)—$\Delta E = 0$, (b)—$\Delta E = \Gamma_0$; $N(t)$ is the intensity of the emission of conversion electrons. The solid lines beginning at $t = 0$ represent the function $\exp(-t/\tau_\gamma)$; (a)—$\tau_\gamma = 137 \pm 14$ nsec, (b)—137 ± 21 nsec. The channel width is 14.2 nsec.

$$A_E(t) = \mathscr{E}_E(e^{i\varkappa r}/r) \int_{-\infty}^{\infty} dt'\, G(t-t') e^{-iEt'/\hbar}\psi(t'), \qquad (4.2)$$

$$G(t) = \int_{-\infty}^{\infty} \frac{dE}{2\pi\hbar} R(E) e^{-iEt/\hbar}. \qquad (4.3)$$

In Eqs. (4.2) and (4.3) the quantity $G(t)$ is the response function, which is directly related by a Fourier transformation to the scattering amplitude $R(E)$ in the investigated system. In a physical sense $|G(t)|^2$ is proportional to the time behavior of emission in decay of a state excited by a very short radiation pulse [when $\psi(t) = \delta(t)$].

Let us consider the scattering processes of interest, which occur after turning on and turning off the excitation of the nucleus. We shall begin with the case of a step interruption of the exciting radiation. In the calculations we shall assume that in this case $\psi(t) = \Theta(-t)$, where $\Theta(t) = 0$ at $t < 0$ and $\Theta(t) = 1$ at $t \geqslant 0$. This approximation is permissible since in a real situation the duration of the interruption is substantially shorter than the characteristic lifetime of the nucleus in the excited state. We shall not calculate the time behavior of the scattering for a specific case, but shall prove a theorem which will permit us to answer a larger set of questions.

Theorem. The time behavior of the radiation in spontaneous decay of an intermediate excited state produced in a scattering reaction will not depend on the energy of the radiation which excited it when and only when the scattering amplitude $R(E)$ has a standard resonance energy dependence which leads to an Lorentz shape of the cross section.

The response function $G(t)$ can in the general case be represented (by modification of the stationary solution) in the following form:

$$G(t) = \exp(-iE_0 t/\hbar) g(t) \Theta(t). \qquad (4.4)$$

Here E_0 is the energy of the decaying excited state. The function $\Theta(t)$ in Eq. (4.4) reflects the retarded nature of the response function, and $g(t)$ is an arbitrary function of time which vanishes at infinity. When (4.2) and (4.4) are taken into account, the expression for the scattered wave at $t > 0$ can be reduced to the following form:

$$A_E(t) = \mathscr{E}_E \frac{\exp\{i(\varkappa r - E_0 t/\hbar)\}}{r}\left[-\frac{g(t)}{u(E)} + \frac{dg(t)/dt}{u^2(E)} - \frac{d^2 g(t)/dt^2}{u^3(E)} + \ldots\right],$$

$$u(E) = i(E - E_0 + i\alpha)/\hbar, \quad \alpha \to +0. \qquad (4.5)$$

The time dependence of the emission of the radiation is proportional to $|A_E(t)|^2$. It will not be a function of the energy of the exciting radiation E only if in the expression (4.5) there is factorization of the parts which depend on E and t. For this it is necessary and sufficient that the following equality be satisfied:

$$dg(t)/dt = -g(t)/\beta, \qquad (4.6)$$

where β is an arbitrary positive constant having the dimensions of time. As will be clear from what follows, it is equal to twice the lifetime: $\beta = 2\tau_0$. The minus sign in (4.6) was chosen to cause the function $g(t)$ to vanish at infinity.

It follows directly from (4.4) and (4.6) that $g(t)$ must be an exponential function of time, and consequently we have for $G(t)$

$$G_0(t) = i\xi \exp[-i(E_0/\hbar - i/2\tau_0)t]\Theta(t). \qquad (4.7)$$

Here ξ is an arbitrary constant.

Proceeding from Eqs. (4.5) and (4.7), we obtain the following expression for the scattered wave:

$$A_E(t) = -\mathscr{E}_E \xi\hbar \frac{\exp[i(\varkappa r - E_0 t/\hbar + it/2\tau_0)]/r}{E - E_0 + i\Gamma_0/2}. \qquad (4.8)$$

In (4.8) we have used the notation $\hbar/\tau_0 = \Gamma_0$.

Thus, in reality when the condition (4.6) is satisfied the expression in square brackets in (4.5) can be represented as the product of two functions each of which individually depends on E and t. The scattering amplitude $R_0(E)$ corresponding to the response function (4.7) must, according to (4.3), have a standard resonance dependence on the energy:

$$R_0(E) = -\frac{\xi\hbar}{E - E_0 + i\Gamma_0/2}. \qquad (4.9)$$

Therefore the theorem is proved.

Since we know that the cross section for scattering with excitation of the 14.4-keV isomeric state in ^{57}Fe has a Lorentz shape (like all other known isolated excited nuclear states), on the basis of the theorem proved above we can now state that the time behavior of the decay after cutoff of the excitation will follow the exponential form (4.8) and need

not depend on what incident-particle energy produced the excited state. As can be seen from (4.8), only the absolute level of intensity of the scattered radiation will depend on the magnitude of the detuning $E - E_0$. These statements are in complete agreement with the results of an experiment (Figs. 4a and b). It is interesting also to note that the fundamental frequency of the radiation, according to Eq. (4.8), is equal not to the frequency of the incident particle $E/\hbar$, but to the eigenfrequency of the transition $E_0/\hbar$.

Let us turn to a description of the time behavior of the response of the nucleus to step excitation. In this case in (4.2) $\psi(t) = \Theta(t)$. In a real situation the radiation of the source is nonmonochromatic. We shall assume that the source energy spectrum described by the function $|\mathscr{E}_E|^2$ has a Lorentz distribution with a width Γ_s and a maximum at energy E_s. Averaging the quantity $|A_E(t)|^2$ over E, we obtain an expression for the intensity of the time behavior of scattering with step excitation:

$$J(t) \propto 2\,\mathrm{Re}\left\{\int_0^t d\tau\, G(\tau) H^*(\tau)\right\}, \tag{4.10}$$

$$H(t) = i\int \frac{dE}{2\pi} R(E)\,\frac{e^{-iEt/\hbar}}{E - E_s + i\Gamma_s/2}. \tag{4.11}$$

For $R(E)$ given by expression (4.9), the function $H(t)$ in (4.11) and the dependence (4.10) are calculated analytically. As a result we eventually obtain

$$J(t)/J(\infty) = 1 - \frac{(\Delta E^2 + \Gamma_+^2/4)\Gamma_-}{(\Delta E^2 + \Gamma_-^2/4)\Gamma_+} e^{-t/\tau_0} - 2\frac{(\Delta E^2 - \Gamma_+\Gamma_-/4)\Gamma_0}{(\Delta E^2 + \Gamma_-^2/4)\Gamma_+} \times e^{-t/2\tau_+}\cos(\Delta E t/\hbar). \tag{4.12}$$

Here $\Gamma_\pm = \Gamma_s \pm \Gamma_0$ and $\tau_+ = \hbar/\Gamma_+$. As can be seen from (4.12), the response of the nucleus to step excitation, in contrast to the time behavior of spontaneous decay, is determined not only by the intrinsic characteristics of the excited nuclear state (the width of the energy level Γ_0) but will depend also on the displacement of the energy of the incident particle from the resonance, $\Delta E = E_s - E_0$, and on the spectral width Γ_s of the exciting radiation; i.e., in contrast to spontaneous decay the lifetime of an actively excited state will depend on the energy parameters of the bombarding particles.

In Figs. 3a–c the solid lines are calculations using Eq. (4.12) with corresponding values of Γ_s and ΔE. We have taken into account also the instantaneous response of photoelectrons to step excitation on the basis of Eqs. (3.1) and (3.2). The experimental points lie satisfactorily on the calculated plots.

5. DISCUSSION AND CONCLUSIONS

We have investigated the time dependences of the emission of the decay products of the intermediate excited nucleus in two different scattering experiments. In one of them the decay was studied after the beginning of bombardment of the nucleus by the exciting particles, and in the other it was studied on termination of the bombardment. As the result of the use of quasimonochromatic beams of bombarding particles, the conditions for selective excitation of the spectrum of a nuclear level were satisfied; here the energy of the incident radiation could be tuned in the vicinity of the resonance. The gist of the difference between the experiments is the following.

For an active flux of bombarding particles, the absorption and emission by the nuclei are not separated in time, although undoubtedly there is a causal connection between them (the decay-product particle cannot be emitted before the exciting radiation reaches the vicinity of the nucleus). However, when the flux of particles is interrupted and the excitation of the nuclei is cut off, then spontaneous decay occurs of all nuclei which at this moment turn out to be in an excited state. Thus, the bombardment cutoff breaks up the process of resonance nuclear scattering into two stages: excitation before cutoff and decay after cutoff. However, at the instant of cutoff the nucleus is in an intermediate excited state.

From the results of the experiments which have been carried out we can draw the following conclusions:

1) the lifetime of the virtual intermediate state of the nucleus under conditions of acting excitation differs from the lifetime of the nucleus in the excited state in spontaneous decay;

2) the lifetime under conditions of excitation undergoes changes with retuning of the energy of the exciting radiation in the vicinity of the nuclear resonance, whereas a similar retuning of the energy is in no way reflected in the lifetime of the nucleus after cutoff of the action of the excitation.

Let us dwell briefly on the physical reasons for our results. As is well known, a transition from one quantum state to another is brought about by a perturbation acting on the system. In the situation under discussion the role of the perturbation is played by the interaction of the nucleus with the radiation field and with the electron shell of the atom.

In an experiment in which the flux of bombarding γ rays is cut off but one of the nuclei remains in an excited state as the result of the previous bombardment, one observes only a transition from the excited state to the ground state with emission of a conversion electron. Under these conditions the interaction between the protons of the nucleus and the atomic electrons which leads to decay of the excited state is determined by the intrinsic structural and dynamic characteristics of the nucleus and of the electron shell, i.e., only by the intra-atomic parameters.[1)] Accordingly the dependence of the amplitude of the excited state on the time, and therefore also the time behavior of the decay of the nucleus, are determined by the internal parameters of the atom. In this case the observed delay in the emission of electrons is an intrinsic characteristic of the nuclear excited state.

A different picture arises under conditions of bombardment of nuclei by γ rays. Here the process of production of an electron includes already two nuclear transitions: from the ground state to an intermediate state and from the intermediate state to the ground state. The transition between the initial and final states is due to the interaction of the unexcited nucleus with the incident γ ray and to the interaction of the excited nucleus with the electron shell (and also with the radiation field itself). Consequently the transition from the initial state to the final state and the production of a particle are accomplished by the action of both internal and external causes. With respect to the time dependence of the amplitude of the excited state, in this case a completely different dynamical situation is created. The time dependence of the

amplitude of the excited state, including its phase, is determined now simultaneously by the excitation and decay processes. This cause is also responsible for the result that the characteristic delay time in emission of conversion electrons will depend on the average energy of the γ rays in the bombarding beam. The observed times τ_0^* (230, 160, and 78 nsec) turned out to be both greater and less than the known lifetime $\tau_0 = 141.1$ nsec of the state under study. The delay time τ_0^* would be exactly equal to the lifetime τ_0 if, with the same time dependence of the intensity of the bombarding beam, radiation with a white spectrum was used.

The dynamic balance between the excitation and decay processes predetermines the sensitivity to the energy of the incident particles not only of the time dependence of the amplitude of the excited state during the transition period, but also of the amplitude of the excitation and of its phase in the stationary scattering regime. The duration Q of a collision in this regime, as is well known, is proportional to the derivative with respect to energy of the difference of the phases of the incident and scattered wave packets.[2-7]

Let us now turn to the case of nuclear decay after termination of the excitation. The observed absence of a dependence of the characteristic decay time on the energy of the bombarding particles is in correspondence with the theorem proved in the preceding section, according to which only for resonances of Lorentz shape which are characteristic of scattering by a nucleus, does the time behavior of the emission in spontaneous decay not depend on the energy of the captured particles. For resonances with a different shape of the scattering cross section the time behavior of the radiation after cutoff of the excitation must depend on the energy of the bombarding particles. As an example we can cite a collective nuclear resonance, which is characteristic of the elastic scattering of γ rays in a regular system of nuclei.[19,20]

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[1)]Decay of the excited state is also produced by interaction of the nucleus with the radiation field. In this channel the decay is accompanied by emission of a γ ray. The two channels, conversion and radiation, act simultaneously.

[1]V. F. Weisskopf and E. P. Wigner, Z. Phys. **63**, 54 (1930); **65**, 18 (1930).
[2]E. P. Wigner, Phys. Rev. **98**, 145 (1955).
[3]E. P. Wigner and L. Eisenbud, Phys. Rev. **72**, 29 (1947).
[4]F. T. Smith, Phys. Rev. **118**, 349 (1960).
[5]M. Froissart, M. L. Goldberger, and K. M. Watson, Phys. Rev. **131**, 2820 (1963).
[6]M. L. Goldberger and K. M. Watson, *Collision Theory*, N.Y., John Wiley and Sons Inc., 1964, Ch. 8.
[7]A. I. Baz', Zh. Eksp. Teor. Fiz. **47**, 1874 (1964) [Sov. Phys. JETP **20**, 1261 (1965). A. I. Baz', Ya. B. Zel'dovich, and A. M. Perelomov, *Scattering, Reactions, and Decays in Nonrelativistic Quantum Mechanics* (in Russian), Nauka, Moscow, 1966.
[8]A. V. Davydov. M. M. Korotkov, and P. I. Romasheva, Izv. AN SSSR, Ser. Fiz. **44**, 1778 (1980) [Bull. USSR Acad. Sci., Phys. Ser.].
[9]A. V. Davydov, M. M. Korotkov, and P. I. Romasheva, Izv. AN SSSR, Ser. Fiz. **45**, 1874 (1980) [Bull. USSR Acad. Sci., Phys. Ser.].
[10]W. Neuwirth, Z. Phys. **197**, 425 (1966).
[11]P. Thieberger, J. A. Moragues, and A. W. Sunyar, Phys. Rev. **171**, 425 (1968).
[12]H. Drost, H. Lojevski, K. Palow, *et al.*, Proc. Fifth Int. Conf. on Mossbauer Spectroscopy, Bratislava, 1973, p. 713.
[13]G. V. Smirnov, Yu. V. Shvyd'ko, O. S. Kolotov, *et al.*, Zh. Eksp. Teor. Fiz. **86**, 1495 (1984) [Sov. Phys. JETP **59**, 875 (1984)].
[14]G. V. Smirnov. Yu. V. Shvyd'ko, and E. Realo, Pis'ma Zh. Eksp. Teor. Fiz. **39**, 33 (1984) [JETP Lett. **39**, 41 (1984)].
[15]G. V. Smirnov and Yu. V. Shvyd'ko, Pis'ma Zh. Eksp. Teor. Fiz. **44**, 431 (1986) [JETP Lett. **44**, 556 (1986)].
[16]R. L. Auble, Nucl. Data Sheets **20**, 327 (1977).
[17]Yu. V. Petrinkin, V. N. Alekseev. V. A. Bychkov, *et al.*, Zavod. lab., No. 11, 46 (1983).
[18]Yu. Kagan, A. M. Afanas'ev, and V. G. Kohn, J. Phys. C **12**, 615 (1979).
[19]A. M. Afanas'ev and Yu. Kagan, Zh. Eksp. Teor. Fiz. **48**, 327 (1965) [Sov. Phys. JETP **21**, 215 (1965)].
[20]Yu. Kagan, A. M. Afanas'ev, and I. P. Perstnev, Zh. Eksp. Teor. Fiz. **54**, 1530 (1968) [Sov. Phys. JETP **27**, 819 (1968)].

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