[4]V. N. Gribov, in: Elementarnye chastitsy, I shkola fiziki ITÉF (Elementary Particles, First Physics School Inst. Theor. and Exptl. Phys.), Atomizdat, 1973.
[5]H. Kendall, Cornell Internat. Conf. on Electron and Photon Interactions, Cornell Univ. Press, 1972.
[6]A.H. Mueller, Phys. Rev. D 2, 2963 (1970); O. V. Kancheli, ZhETF Pis. Red. 11, 397 (1970) [JETP Lett. 11, 267 (1970)].

One possibility of measuring the lifetimes of short-lived atomic nuclei

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The feasibility in principle is considered of measuring the lifetimes of short-lived nuclei by determining the change in the energy and radiation intensity of nuclei scattered through large angles.

Measurement of the lifetimes of short lived states of atomic nuclei is of fundamental significance for nuclear spectroscopy as well as for the observation of short-lived particle emitters. This problem becomes methodologically exceedingly complicated if the nuclear lifetimes are $\tau < 10^{-11}$ sec. Yet the "natural" times of γ radiation are $\tau = 10^{-11} - 10^{-15}$ sec, while the lifetimes of compound nuclei are even shorter. To measure such short τ it is necessary to compare the duration of the investigated nuclear process with another microscopic "standard" process of known lifetime. To measure the lifetime of a nucleus relative to γ radiation, use is made of the method based on the change of the Doppler shift of nuclei as they are stopped in matter (1948).[1] The "standard" process in this method is the nuclear range time t_R. The free path times lie in the interval $10^{-12} - 10^{-14}$ sec, and accordingly this interval contains values of τ that lend themselves to investigation.

Another important idea for measuring ultrashort times is based on the shadow method (1965, Tulinov).[2] The "standard" process in this method is the shift of the nuclei over distances that change the character of the "shadows" $(10^{-9} - 10^{-10})$ cm. The nuclear lifetime intervals that can be investigated by this method is $10^{-16} - 10^{-19}$ sec. We propose below that it is feasible in principle to perform measurements in the interval $10^{-16} - 10^{-14}$ sec.

Idea of Measurements of τ and Experimental Setup

Assume that the nucleus A in the target at the point (1) has been transformed as a result of a nuclear reaction into a compound or excited short-lived nucleus A^*, which moves in the direction $00'$ with velocity v_0. The moving nuclei A^* will be stopped in the target. We consider unstable nuclei for which the condition $\tau \ll t_R$ is satisfied. After a time τ, such nuclei do not experience an appreciable deceleration. The initial velocity v_0 becomes close to the velocity of the nucleus after a time $t = \tau$ are close, i.e., $(v_0 - v_\tau)/v_0 \ll 1$.

1. We examine the idea of the measurement method using as the example the nuclei A^*, which decay after a time τ emitting a γ quantum of energy $\hbar\nu$. The γ-quantum detector lies on the $O'D$ perpendicular to the direction of motion of the nuclei A^*. The quanta emitted by the nuclei in the $O'D$ direction and registered by the detector will experience no Doppler shift in energy. More accurately, this shift will be of the order of $(v_0/c)^2$ and can be neglected. The energy of the quanta emitted by such nuclei, as registered by the detector, is equal to the energy $\hbar\nu$ of the nuclei at rest.

We consider now the nuclei which were scattered through a large angle θ by the atoms of the target *prior to the emission of the γ quantum*. After the scattering, such nuclei have a velocity $v_p(\theta)$ and move in the direction of the detector at an angle $\pi/2 \pm \theta$.[1)]

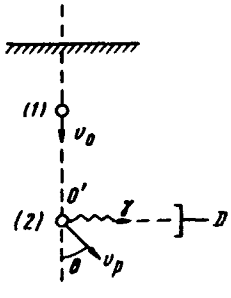
The γ quanta obtained by such nuclei will have a maximum Doppler shift $\Delta\nu_{max} = \nu(v_p(\theta)/c)\sin\theta$.

We shall show that the intensity of the scattered nuclei, and consequently also the intensity of the Doppler-shifted component of the γ radiation, is proportional to the nuclear lifetime τ.

The probability that the excited nucleus does not decay on its motion path, but is scattered through an angle θ, is equal to

$$w(x,\theta) = \exp\left(-\frac{t}{\tau}\right) N\sigma(\theta)\Delta x$$

t is the time required for the nucleus to transverse the distance x, N is the number of atoms per cm^3 of the target, and $\sigma(\theta)$ is the probability of scattering through an angle θ. The probability $w(x,\theta)$ is indeed the prob-



Scheme of τ measurement

ability of the appearance of a Doppler-shifted γ quantum, since the probability of emission of a γ quantum excited by nuclei scattering through an angle θ is

$$w(\theta) = \int_x w(x, \theta)dx = N\sigma(\theta)\int_0^\infty \exp\left(-\frac{t}{\tau}\right)dx.$$

Since $t = x/v_0$ if the condition $(v_0 - v_\tau)/v_0 \ll 1$ is satisfied, we get

$$w(\theta) = N\sigma(\theta)v_0\tau.$$

To study nuclei that experience scattering in a solid angle Ω containing the angle interval from θ to $\theta + \Delta\theta$, the corresponding probability is

$$w(\Omega) = N\sigma(\Omega)v_0\tau.$$

Let the total number of the nuclei A^* produced in one second be n^*, and let Δn^* be the number of nuclei scattered in the angle Ω; then

$$\Delta n^* = n^*\sigma(\Omega)v_0\tau.$$

The main intensity I_γ will be produced by γ quanta emitted from nuclei that have experienced no scattering, with energy $\hbar\nu$. The low-intensity "wings" of the γ line ($\Delta I_{\nu+\Delta\nu}$) will belong to nuclei A^* that have experienced scattering and have emitted Doppler-shifted quanta with energy $\hbar(\nu + \Delta\nu)$.

Thus, by measuring the intensity of the Doppler-shifted "wings" of the γ line we can determine the value of $N\sigma(\Omega)v_0\tau$. The velocity v_0 is known, we can determine τ and if $\sigma(\Omega)$ are calculated or measured. We note that $v_0\tau = x_\tau$ is the mean path covered by the nuclei in the excited state. The quantity x_τ should be larger than the interatomic distance, or otherwise there will be no scattering, and should be less than the range R of the nucleus. Assuming that $5\times10^{-8} \leqslant x_\tau \leqslant 10^{-5}$ cm and $v_0 = 5\times10^8$ cm/sec, we obtain the lifetime interval $10^{-16} \leqslant \tau \leqslant 10^{-14}$ sec. Since

$N = 10^{22}$ cm^{-3} and $x_\tau = (10^{-7}$ to $10^{-5})$cm, it follows that

$$\frac{\Delta I_{\nu+\Delta\nu}}{I_\nu} = 10^{-5} \text{ to } 10^{-3} \text{ at } \sigma(\Omega) \sim 10^{-20} \text{ cm}^2.$$

2. If the excited nucleus emits not a quantum but a secondary particle, then the principal scheme for the measuring the lifetime of the compound nucleus produced in inelastic scattering or upon capture of a primary particle remains the same. To determine the compound nucleus it is necessary to measure the intensity and the "Doppler" change of the energy of the secondary particles emitted by nuclei scattered through large angles. The maximum "Doppler" change of the secondary-particle energy, due to the motion of the compound nucleus, is equal in first-order approximation to $\Delta\epsilon^{(2)}_{\max} \approx (2/M)[\epsilon^{(1)}\epsilon^{(2)}m_1m_2]^{1/2}$ ($\epsilon^{(1)}$ and $\epsilon^{(2)}$ are the energies of the primary and secondary particles, m_1 and m_2 are their masses, and M is the mass of the nucleus). The relative change of the energy is

$$\left.\frac{\Delta\epsilon^{(2)}}{\epsilon}\right|_{\max} = \frac{2}{M}\sqrt{\frac{\epsilon^{(1)}}{\epsilon^{(2)}}m_1m_2}.$$

The relative change of the energy of the secondary particle can be much larger than the Doppler shift of the γ quanta.

3. The greatest difficulties in the realization of this measurement method will obviously be due to the low intensity of the radiation produced by the nuclei scattered through large angles. One can hope, however, to overcome these difficulties. To increase the scattering probability we can use the existence in the crystals of directions that are practically "closed" for the motions. When nuclei move in directions close to the "shadow" directions, the large-angle scattering probability will be greatly increased.

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1) The scattering angles and the velocities are given in the laboratory frame; they are connected with the corresponding c.m.s. values by the known relations.[3]

[1] Elliott and Bell, Phys. Rev. 12, 1869 (1948).
[2] N.F. Tulinov, Dokl. Akad. Nauk SSSR 165, 545 (1965) [Sov. Phys.-Dokl. 10, 1113 (1966)].
[3] L.D. Landau and E.M. Lifshitz, Kvantovaya mekhanika (Quantum Mechanics), Fizmatgiz, 1963 [Addition-Wesley, 1965].