Concerning One Method of Measuring the Lifetimes of Excited States of Atomic Nuclei

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IN THE PRESENT LETTER the possibility is considered of using a new method for the measurement of the lifetimes τ of excited states of light nuclei, ranging from 10^{-12} to 10^{-14} sec.

We will consider the nuclear reaction occuring in a thin target acted upon by a beam of monoenergetic particles. Let the counters, connected in the circuit, detect both component products of reaction (the light component and the recoil nucleus). If we fix the direction of emergence of the light component, angular distribution of the recoil nuclei corresponding to this light component will be represented by a system of peaks, each of which will relate to a definite energy level of the final nucleus.[1] The peaks corresponding to the excited states, in general, will be broad, since the recoil nuclei, besides the momenta acquired in the reaction, will receive additional momenta from the γ-quanta at the instant of radiation. The width of each peak will be determined by the ratio of the γ-quantum momentum to the initial momentum of the recoil nucleus. If along the path of motion of the nuclei directly behind the target we place a layer of substance, so that the recoil nuclei will be partially retarded in it, then the width of the peak will depend on how much the recoil nucleus has been retarded at the instant of radiation, in other words, on the rate of retardation and on the time interval between the formation of the recoil nucleus and its γ-radiation. Thus a comparison of the shapes of the peaks obtained with and without a retarding layer can provide information regarding the value τ.

In order to establish quantitative relationships we will consider the case in which the recoil nucleus, having been produced in an excited state, goes over into the ground state with emission of a single γ-quantum of energy E_γ. Since the degree of anisotropy of the emission of γ-quanta does not exceed a few percent, we will consider the emission as isotropic. In addition, we will assume that the relationship $p_\gamma/p_n \ll 1$, where p_γ and p_n are the momenta of the γ-quantum and of the recoil nucleus, will hold. This condition is practically always fulfilled. Finally, let the diaphragm in front of the counter of the recoil nuclei be adequately narrow and high. From geometric considerations it can be easily shown that, under the conditions formulated above, for a thin target without a retarding layer the angular distribution of the recoil nuclei, pertaining to the excited state under consideration, will have a rectangular form with a total width $\Gamma_1 = 2p_\gamma/p_n$ (see Fig. 1a). If we place directly behind the target a retarding layer of matter of thickness d (the lining can serve as such a layer), then the total angular distribution will consist of two parts, I and II (Fig. 1b). Part I will be dependent on the nuclei whose

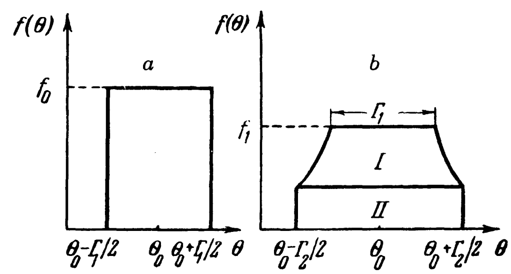

FIG. 1

radiation takes place inside the retarding layer, and part II – after the passage through the layer. Let the range R of the recoil nuclei in the retarding substance be related to the velocity v by $R = \alpha v^2$, where α is a coefficient dependent on the nature of the recoil nuclei and of the retarding substance. Then the velocity with which the nuclei leave the retarding layer, will be $v_d = v_0(1 - d/R)$, where v_0 is the initial velocity of the recoil nucleus, and, therefore, the width of part II of the distribution will be given by $\Gamma_2 = \Gamma_1/(1 - d/R)$. Taking into account the exponential character of radiation, it can be shown that the angular distribution of the fissioning nuclei in this case will be given by

$$f(\theta-\theta_0)=\frac{1}{(1+\lambda\alpha)\Gamma_1}\left\{\lambda\alpha\left(\frac{\Gamma_{1/2}}{|\theta-\theta_0|}\right)^{\lambda\alpha-1}+\left(1-\frac{d}{R}\right)^{\lambda\alpha+1}\right\}\ \text{for}\ \frac{\Gamma_1}{2}\leqslant|\theta-\theta_0|\leqslant\frac{\Gamma_2}{2}, \quad (1)$$

$$f(\theta-\theta_0)=\frac{1}{(1+\lambda\alpha)\Gamma_1}\left\{\lambda\alpha+\left(1-\frac{d}{R}\right)^{\lambda\alpha+1}\right\}\ \text{for}\ |\theta-\theta_0|\leqslant\frac{\Gamma_1}{2}, \qquad (1)$$

where $\lambda = \ln 2/\tau$. The function f is normalized so that the area under the curve (Fig. 1b) is unity. At $\lambda\alpha \gg 1$ we have $f = 1/\Gamma_1$ for $|\theta - \theta_0| \leq \Gamma_1/2$ and $f = 0$ for $|\theta - \theta_0| > \Gamma_2/2$, *i.e.*, rectangular distribution of nuclei is obtained, corresponding to the case when they radiate before passing through the retarding layer.

For the case $\lambda\alpha \ll 1$ we obtain $f = (1/\Gamma_1)(1 - d/R)$ for $|\theta - \theta_0| \leq \Gamma_2/2$ and $f = 0$ for $|\theta - \theta_0| > \Gamma_2/2$, *i.e.*, we again have a rectangular distribution of the nuclei whose radiation takes place after they have passed the retarding layer. Thus, all the information regarding τ is contained in the form of the curve at $\Gamma_1/2 < |\theta - \theta_0| < \Gamma_2/2$ and in the value of the function $f(\theta)$ at $|\theta - \theta_0| < \Gamma_1/2$. To obtain precise values for τ from an analysis of the form of the curve at $\Gamma_1/2 < |\theta - \theta_0| < \Gamma_2/2$ is apparently impossible, for owing to the effect of multiple scattering and to other causes (final target thickness, inhomogeneity of the beam with respect to energy, *etc.*) the form of the curve will be distorted. However, it is possible to make use of the value of the ordinate at the peak for the determination of τ, since under definite conditions this value will not be affected significantly by the above-mentioned causes. To determine the conditions under which the latter statement will hold, it is sufficient to take into account only the multiple scattering, since the effect of the other factors can be made insignificant. If we assume the multiple scattering to have a Gaussian distribution with a mean square deviation angle of $\overline{\Phi^2}$ and the distribution shown in Fig. 1b to be rectangular with a width Γ_1, the value of the ordinate at the peak will be determined by the expression $f(\theta_0)P(\Gamma_2/2\sqrt{2\overline{\Phi^2}})$, where P is the probability integral. The multiple scattering can be neglected when the value P is close to unity. We shall assume that $P > 0.95$, corresponding to the inequality $\sqrt{\overline{\Phi^2}} < \Gamma_1/4$. From the theory of multiple scattering,[3] it can be shown that this inequality will hold for γ-radiation levels with sufficiently high excitation energy. For the actual evaluations it is necessary to know the magnitude of α. Unfortunately, the literature contains practically no data on this quantity for the passage of multi-charged particles through solid substances. Ia. A. Teplova (Moscow State University) has carried out recently tentative measurements of α for the passage of light nuclei (Be^9, C^{12}, N^{14}) through organic films. These values were found to differ little for the various nuclei and at the energy of $\sim$ 1 Mev are approximately equal to 6×10^{-13} sec^{-1}. If we assume that the recoil nuclei lose half their velocity in the organic lining, which acts like a retarding layer, the calculation carried out for light recoil nuclei ($A \approx 15$) yields $E_\gamma > 1.8\, Z^{1/3}$, where Z is the charge of the recoil nucleus and E_γ is expressed in Mev. If this relationship is not satisfied, it is necessary to introduce a corresponding correction for the effect of multiple scattering.

It is convenient to determine $\delta = f_1/f_0$ directly from experiment (see Fig. 1), using alternate rotation of the target with the corresponding lining through 180°. It can be easily shown that the following relationship will hold:

$$\delta = \frac{1}{1+\lambda\alpha}\left\{\lambda\alpha + \left(1 - \frac{d}{R}\right)^{\lambda\alpha+1}\right\}, \tag{2}$$

from which we can obtain $\lambda\alpha$. Fig. 2 shows the dependence of δ on $\lambda\alpha$ for various values of d/R. It is evident that δ is more sensitive to changes in $\lambda\alpha$ at $\lambda\alpha < 5$. Hence, for each substance of the lining exists a range of λ which is more favorable for measurements. Since the values of α for various substances range from 10^{-12} to 10^{-14} sec^{-1}, these limits also determine the range of values of τ which can be measured.

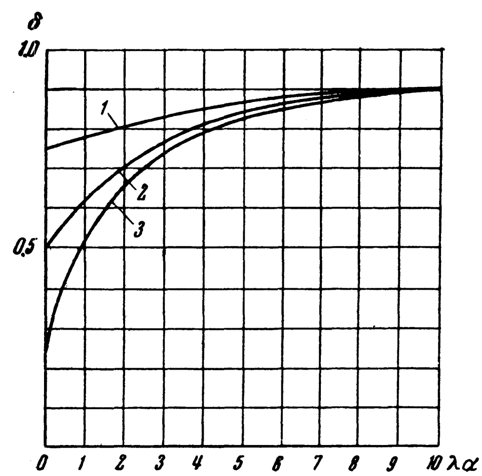

FIG. 2. Curve $1 - d/R = 1/4$; $2 - d/R = 1/2$; $3 - d/R = 3/4$.

In conclusion, I wish to express my gratitude to S. S. Vasil'ev for valuable discussion of this work.

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Scattering of Photons by Protons

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IN CONNECTION with the beginning of experimental investigation of the scattering of photons by protons,[1] we feel it would be of interest to examine this process, starting from the general properties of the S-matrix and elementary physical considerations. The purpose of the present note is to obtain information on the structure of the S-matrix and the minimum number of parameters necessary for describing the process in question.

We shall use the following approach to the problem. We write out the S-matrix in the representation in which its properties are most simply expressed, *i.e.*, in the representation of the total momentum I and its projection M, the total isotopic spin T and its projection T_z, and the parity Π. All the quantities are defined in the center-of-mass system

$$S_{\mu\nu} = (m'\alpha' \mid S^{I\Pi} \mid m\alpha)\ \delta_{(J'J)}\,\delta(M'M)\,\delta(\Pi'\Pi)\,\delta(T'_zT_z), \tag{1}$$

where the m's are the other variables characterizing the channel α. The S-matrix is examined on an energy surface. Next we enumerate all the open channels with the given energy (we restrict our examination to the region of energies under 300 Mev) and all quantum numbers characterizing these channels. In our analysis we shall examine only the following α channels: γ-quantum and proton (γ) and π-meson and nucleon (π). Taking account of the other channels would not substantially affect our results. It must be noted, however, that the channel with the formation of an electron-positron pair is an exception; the matrix element of the S-matrix describing the transition in this channel is not small.

Actually the process of pair formation leads to so-called scattering in the Coulomb field. However, this process, as has been shown by Bethe and Rohrlich,[2] is characterized by a sharply limited forward angular distribution. It can be shown that if we do not consider scattering angles of the order of $m_e c^2/E_\gamma$ this effect can be neglected.

Let us impose the requirements of unitarity and symmetry on the S-matrix.

$$SS^+ = 1,\ S_{\mu\nu} = S_{\nu\mu};\ S_{\mu\nu} = r_{\mu\nu}e^{i\varphi_{\mu\nu}}. \tag{2}$$

Each of the indices μ and ν goes through eight values. The first condition in (2) is of course approximated with an accuracy equal to the value of the matrix elements describing the transitions in the rejected channels. The second condition in (2) is a consequence of the reciprocity theorem[3] and of the fact that the selected representation does not comprise projections of spins and directions of velocities. These conditions represent the system of transcendental equations which $\alpha_{\mu\nu}$ and $r_{\mu\nu}$ must satisfy. Before attempting to solve the system, we make two simple assumptions which actually follow from experiment: (1) we use the long-wave approximation, whereby we consider the interaction of only dipole quanta (electric and magnetic) with the proton and (2) we assume that the moduli of the matrix elements linking channels γ and γ', γ and π and π with π' are related, respectively, as

$$e^2/\hbar c : \sqrt{e^2/\hbar c} : 1. \tag{3}$$

Part of the S-matrix describing the meson scattering contains isotopic invariant terms regarding which we also assume that they are of the order of $e^2/\hbar c$. The first assumption follows, for example, from experiments on electron-nucleon scattering which show that the dimensions of a nucleon are less than $\hbar/\mu c$ (*i.e.*, smaller than the photon wavelength at the energies under consideration) and also from experiments on scattering and photoproduction of mesons.

The last approximation makes it possible to solve the system of equations by the method of successive approximations, expressing $\alpha_{\mu\nu}$ and $r_{\mu\mu}$ in terms $\alpha_{\mu\mu}$ and $r_{\mu\nu}$, where $\mu \neq \nu$. The ratios between the scattering and photoproduction matrix element obtained in the calculations agree within the limit of small corrections with analogous ratios obtained by Watson.[4] In order to obtain the angular distribution of the scattered photons one must bring the S-matrix to the angular representation, square its modulus, average over the initial and sum over the