A possibility of employing the shadow effect for studying the decay of quasistationary states

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It is sugessted that the shadow effect, which is observed in nuclear reactions in single crystals, be employed for studying the effect of nonuniform population of an isolated quasistationary state on its decay. It is shown that displacement of a compound nucleus from the crystal lattice site has a stronger effect on the shape of the shadow in the case of partial population of the state than in the case of uniform population.

In most nuclear-physics problems with which experimentalists have to deal, the decay of quasistationary states has an exponential nature. According to the Fock-Krylov theorem[1] the decay law L(t) of a state of a quantum-mechanical system is completely determined by the energy distribution function w(E) in this state:

$$L(t)=\left|\int w(E)e^{-iEt/\hbar}\,dE\right|^2. \tag{1}$$

For an isolated quasistationary state the energy distribution function can be written with sufficient accuracy in the form of a Lorentz distribution:

$$w(E)=\frac{1}{2\pi}\frac{\Gamma}{(E-E_r)^2+\Gamma^2/4}. \tag{2}$$

In this case the exponential nature of the decay follows directly from substitution of the distribution function (2) into Eq. (1):

$$L(t)=e^{-\Gamma t/\hbar}. \tag{3}$$

Here it is assumed that in excitation of the state its population occurs uniformly.

It is possible, however, to imagine a situation in which a state characterized by the distribution function (2) is populated nonuniformly. In this case the decay should already be nonexponential. There can be various means of producing the specific experimental conditions under which nonuniform population of states would occur. Some versions of these experiments have been discussed in the book by Baz', Zel'dovich, and Perelomov.[2] In the present article it is proposed to use for this purpose the blocking (shadow) effect observed in nuclear reactions in single crystals.[3]

In the case of a single-crystal target, initially all nuclei are at lattice sites. As the result of the incident-particle momentum, compound nuclei formed by fusion of these particles with target nuclei are displaced from the lattice sites. The distribution function of the decaying compound nuclei along the direction of displacement is determined by the decay law of the specific quasistationary state of the compound nucleus. Here the components of displacement normal to the crystallographic axis or plane to which the target nucleus belonged substantially affects the shape of the shadow (blocking pattern) from this axis or plane.[3,4] Thus, the greater the average value of the normal component of displacement, the higher the intensity of the product particles of the reaction in the center of the pattern. Various simplified models of the motion of charged particles in crystals are used at the present time to establish the corresponding functional relation.

Following Melikov et al.[4], we will write the expression for the intensity of particles at the center of the axial shadow, χ, which is related to the displacement of the compound nucleus from the lattice site as follows:

$$\chi=C\left\{\int_0^{r_0}\ln\frac{r_0^2}{r_0^2+r^2}L\left(\frac{\Gamma r}{\hbar v_\perp}\right)dr+\int_{r_0}^{3r_0}\ln\frac{r_0^2}{r_0^2-(2r_0-r)^2}L\left(\frac{\Gamma r}{\hbar v_\perp}\right)dr+\ldots\right\}\Big/\int_0^{\infty}L\left(\frac{\Gamma r}{\hbar v_\perp}\right)dr, \tag{4}$$

where πr_0^2 is the portion of the transverse plane in the crystal associated with one crystallographic axis, $v_\perp$ is the compound nucleus velocity component normal to the axis, and $C\approx 2.5$. It is evident that the value of χ depends substantially on the decay law $L(\Gamma r/hv_\perp)\equiv L(\Gamma t/\hbar)$ of the compound nucleus.

In discussing the practical achievement of a nonuniform population of a quasistationary state formed in a nuclear reaction, let us consider two types of experiments, with thick and thin targets. In the case of a thick target when the energy loss of the incident particle in the target is much greater than the width Γ of the state, the function w(E) in Eq. (1) must be written in the form

$$w(E)=\frac{\alpha\Gamma}{(E-E_r)^2+\Gamma^2/4}\theta(E_0-E),\qquad \theta(E)=\begin{cases}1, & E>0\\ 0, & E<0\end{cases} \tag{5}$$

(E_0 is the incident-particle energy, E_r is the resonance energy, and α is a normalization factor). By appropriate choice of the incident-particle energy it is possible to accomplish only partial population of the state and to control the degree of population. The energy spread of the incident particles ΔE_0 can still be neglected, i.e., we assume $\Delta E_0\ll\Gamma$. Substituting (5) into (1), we obtain the decay law of the quasistationary state.

In calculation of the intensity of particles in the shadow center, χ, we will take into account the energy spread of the beam of incident particles ΔE_0, assuming that in the interval from $E_0-\Delta E_0/2$ to $E_0+\Delta E_0/2$ all energies are equally probable. Substituting into (4) the corresponding decay laws and then performing an average of χ over the energy interval ΔE_0, we obtain the intensity of particles at the center of the axial shadow as a function of the various parameters describing the given quasistationary state and the incident-particle beam.

In the case of a thin target the energy loss of the incident particles in the target can be neglected and the populated region of the quasistationary state is determined only by the energy spread of the beam ΔE_0 and the location of the average beam energy E_0 relative to the resonance energy E_r. For definiteness we will assume $E_0=E_r$ and we will assume equally probable all energy values of the incident particle inside the interval ΔE_0. Then

$$w(E)=\frac{\alpha'\Gamma}{(E-E_r)^2+\Gamma^2/4}\theta\left[E-\left(E_r-\frac{\Delta E_0}{2}\right)\right]\theta\left[\left(E_r+\frac{\Delta E_0}{2}\right)-E\right] \tag{6}$$

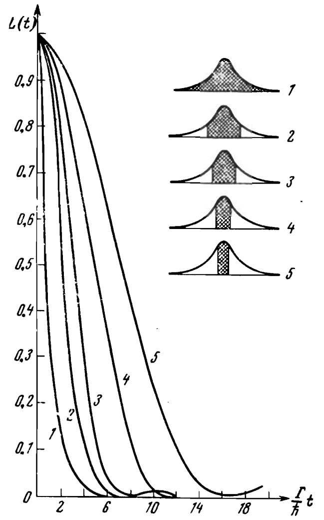

FIG. 1. Plots of decay laws of a quasistationary state, corresponding to various degrees of population, for the case of a thin target: 1—uniform population; 2, 3, 4, 5—partial population for $E_r = E_0$, $\Delta E_0 = 1.4\Gamma$ (2); for $E_r = E_0$, $\Delta E_0 = \Gamma$ (3); for $E_r = E_0$, $\Delta E_0 = 0.6\Gamma$ (4), and for $E_r = E_0$, $\Delta E_0 = 0.4\Gamma$ (5).

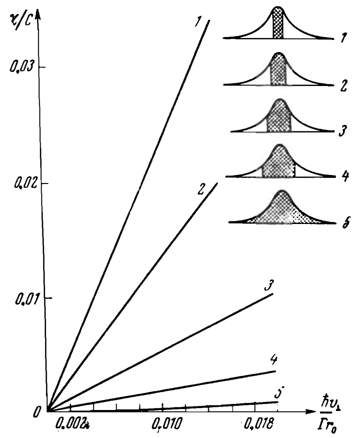

FIG. 2. Intensity at the center of the axial shadow for various cases of partial population of a quasistationary state, with use of a thin target: 1—$E_r = E_0$, $\Delta E_0 = 0.4\,\Gamma$; 2—$E_r = E_0$, $\Delta E_0 = 0.6\,\Gamma$; 3—$E_r = E_0$, $\Delta E_0 = \Gamma$; 4—$E_r = E_0$, $\Delta E_0 = 1.4\,\Gamma$. For comparison the case of uniform population is shown (5).

In Fig. 1 we have shown plots of the decay laws which are obtained by substitution of (6) into (1) for various ratios between the energy spread of the incident particle beam ΔE_0 and the resonance width Γ. The particle intensity at the center of the axial shadow in the case of a thin target, calculated on the basis of Eq. (4) for various values of ΔE_0 and Γ, is shown in Fig. 2.

From the functions shown in Figs. 1 and 2 it is evident that, the smaller the degree of population of the quasistationary state, the more extended in time is its decay (for a given width Γ) and the more significantly is the displacement of the compound nucleus from the lattice site reflected in the shape of the shadow. We note that for $\Delta E_0 < \Gamma$ this effect appears more strongly in the case of a thin target, and for $\Delta E_0 \gtrsim \Gamma$ it appears more strongly in the case of a thick target. Since we can actually measure only values of χ which exceed some lower limit, say, $\chi \gtrsim 0.01$, partial population of the excited quasistationary states provides the possibility of observing the effect of compound-nucleus displacement even for rather broad resonances with $\Gamma \sim 1$ keV, while for a uniform population of these states the changes in the shadow shape are much smaller than the limit mentioned.

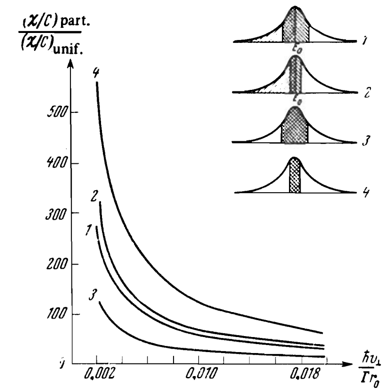

FIG. 3. Ratio of intensities at the center of the axial shadow in the cases of partial and uniform population of a quasistationary state, with use of a thick target (1, 2) and a thin target (3, 4): 1—$E_r = E_0$, $\Delta E_0 = \Gamma$; 2—$E_r = E_0$, $\Delta E_0 = 0.4\,\Gamma$; 3—$E_r = E_0$, $\Delta E_0 = \Gamma$; 4—$E_r = E_0$, $\Delta E_0 = 0.4\,\Gamma$.

For illustration of this effect we have shown in Fig. 3 the ratios of the χ values corresponding to partial and uniform population of states with various widths Γ in the case of thick and thin targets. It follows from this also that partial population of a quasistationary state can be considered as a means of increasing the sensitivity of the method of measuring the time characteristics of nuclear processes based on the blocking effect.

[1] N. S. Krylov and V. A. Fock, Zh. Eksp. Teor. Fiz. 17, 93 (1947).
[2] A. I. Baz', Ya. B. Zel'dovich, and A. M. Perelomov, Rasseyanie, reaktsii i raspady v nerelyativistskoĭ kvantovoĭ mekhanike (Scattering, Reactions, and Decays in Nonrelativistic Quantum Mechanics), Nauka, 1971.
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[4] Yu. V. Melikov, Yu. D. Otstavnov, A. F. Tulinov, and N. G. Chetchenin, Nucl. Phys. A180, 241 (1972).

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