Directed atomic collisions in single crystals as a method of measuring the lifetimes of short-lived nuclei and of crystal-lattice investigation

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A method is proposed for measuring the lifetimes of short-lived nuclei ($\tau \sim 10^{-16}$–10^{-14} sec) and for the use of such nuclei as indicators. The method is based on controlled collisions of unstable nuclei (atoms) with the nearest neighbors in a single-crystal lattice.

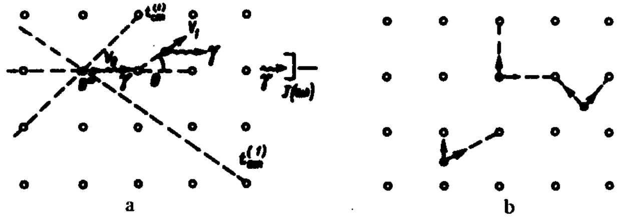
At the present time, the region least accessible to measurements is that of existence of ultrashort-lived nuclei with lifetimes from 10^{-16} to 10^{-4} sec. This region can include "long-lived" compound nuclei and "ultrashort-lived" γ-excited nuclear states. The "shadow" method is used principally in the interval from 10^{-19} to 10^{-16} sec (Tulinov[1]), and the method based on the decrease of the Doppler shift of γ photons as the nuclei are slowed-down in matter[2] is ineffective at $\tau \leqslant 10^{-14}$ sec. Within a time 10^{-14} sec, the usual slowing-down mechanisms do not manage, in practice, to change the velocity and direction of nuclei of energy $E_0 \sim 10^4$ eV. The slowing-down method can therefore not serve as a "clock" for measuring nuclear lifetimes. An appreciable change in the energy and momentum of the nucleus can cause collisions with large-angle scattering. Such a process can be used in principle for measurements,[3] but under ordinary conditions these collisions are random and have a rather low probability, 10^{-3} to 10^{-5}. In the method proposed, the "microclock" constitutes controlled atomic collisions in single crystals.

DIRECTED ATOMIC COLLISIONS

Assume that monokinetic beam of particles a with small angle divergence ~ 1 to 3° is incident on a single crystal consisting of atoms A. We consider the compound or γ-excited nucleus B'' produced at the site (0) as a result of capture of the incident particle a. The nucleus B^* has the momentum of the incident particle, so that a beam of excited nuclei B^* is produced in these reactions. For the sake of argument, we consider the reaction (a, γ) with a γ-excited nucleus B^*, but the method can be used also for "long-lived" compound nuclei. Orienting the crystal relative to the beam of atoms B^*, we direct the latter along a line of atomic sites of the crystal. It is thus possible to produce directed atomic collisions of the atoms B^* with neighboring atoms in the lattice. The probability of the scattering of atoms moving with velocity v_0 along the chain A, through an angle θ, is

$$\mathcal{P}(\theta) = 2\pi p(\theta) \left| \frac{dp}{d\theta} \right| W(p) \exp - \frac{d^{(s)}}{v_0 \tau} \; ; \; W(p) = \frac{1}{2\pi\beta} \exp - \frac{p^2}{2\beta}$$

where $p(\theta)$ is the impact parameter, β is the mean-squared relative displacement of the nucleus B^* and of the atomic nucleus A, and $d^{(s)}$ is the distance from the site (0) to the atom A in a chain with arbitrary index s. If $a_0 \geqslant \beta^{1/2}$ (πa_0^2 is the effective scattering cross section), then the total probability of the collisions is $\mathcal{P} \approx 1$, and if $a_0 \leqslant \beta^{1/2}$ (high energy of the indicator atoms and low temperatures) then $\mathcal{P} \approx a_0^2/2\beta$. At $\beta \approx 10^{-18}$ cm^2 and $a_0^2 \approx 2 \times 10^{-19}$ cm^2 we have $\mathcal{P} \approx 0.1$. Under these conditions the probability of random collisions is $\mathcal{P}^{(r)} = v_0 \tau N \pi a_0^2 \approx 10^{-3} - 10^{-4}$ (N is the concentration of the atoms A). Let us note the following peculiarities of directed



Controlled atomic collisions ($\beta^{1/2} \ll a_0$): a—method for determining the nuclear lifetime, b—different positions of the indicator atom in the lattice correspond to different "beam-crystal" orientations and to different collision times.

atomic collisions: 1) by producing almost "frontal" collisions we can effect, with high probability, scattering of the atoms B^* through large angles $\theta \sim 1$; 2) for indicator atoms with energies exceeding 10^4 eV, the cross section for collisions with the lattice atoms is $\pi a_0^2 \ll d^2$ (d is the lattice parameter) and directed collisions can occur only in a narrow angle interval a_0/d; 3) by rotating the crystal, collisions with different neighbors can be produced. The time of the collisions of the atom B^* with the nearest neighbor is $t_{col} = d^{(s)}/v_0$. The nucleus B^* can be directed along a line of sites with different crystallographic indices, by varying the distance $d^{(s)}$ (from d to $10d$). Thus, directed collisions make it possible to produce, with high probability, scattering through large angles and to measure discretely the collision time.

METHOD OF DETERMINING THE LIFETIMES OF NUCLEI

We measure the energy of γ photons emitted in the direction of v_0. The Doppler shift (DS) of the quantum frequency depends on the velocity and direction of the nucleus B^* and consequently on the intant of time before or after the collision when the photon was emitted. The photons emitted prior to the collisions produce in the photon spectrum $J(\omega)$ a narrow "collisionless" line $J(\omega_0)$ with an apparatus width Γ shifted by an amount equal to the total shift $\omega_D = \omega_0 v_0/c$ relative to the frequency ω_0 of the photon emitted by the immobile nucleus. A fraction of the photons will be emitted after the collisions. Since $v_0\tau \ll R$ (R is the total range of the nuclei B^*), we can neglect the deceleration, in first-order approximation assuming that the latter does not change the DS of the γ photons emitted after the collision. The distribution of these photons produces relatively wide "wings" in the spectrum. The Doppler shift of these photons is equal to

$$\Delta\omega_D = \omega_D (E_1/E_0)^{1/2} \cos\theta = \omega_D (M_2/2M_1)\{[1 + (M_1/M_2)](E_1/E_0) - [1 - (M_1/M_2)]\}$$

E_1 is the energy of the atom B^* after scattering through the angle θ; M_1 and M_2 are the masses of the atoms B^* and A. The complete distribution of the emitted atoms with respect to frequency is of the form

$$J(\omega) = J_0(\omega)[1 - \exp(-d^{(s)}/v_0\tau)] + J_1(\omega)\exp(-d^{(s)}/v_0\tau),$$

$$J_1(\omega) = 2\pi p(\theta) \left|\frac{d\omega}{dp}\right|^{-1}.$$

The width of the "collisionless" peak can be much smaller than the width of the "wings" ($\Gamma \ll \omega_D$). The ratio of the integrated intensities of the "peak" and of the "wings" enables us to determine τ. Usually the B^* nuclei have a velocity $v_0 = 10^8$ to 3×10^8 cm/sec and $d^{(s)} = 2\times10^{-8}$ to 10^{-7} cm, so that the nuclear lifetimes that lend themselves to measurement by this method range from 10^{-16} to 10^{-14} sec.

COMPOUND NUCLEI CAN BE INVESTIGATED IN PRINCIPLE IN THE SAME MANNER

Ultrashort-lived indicators. The directivity of the atomic collisions is manifest in a narrow angle interval and has a sharply pronounced dependence on the orientation of the crystal relative to the primary beam. Depending on whether the indicator atoms are in sites or interstices, or else in normal and shifted positions, the crystal orientations corresponded to the directed collisions are perfectly well defined and essentially different. A deflection through an angle $\sim a_0/d$ from a definite orientation leads to a vanishing of the DS connected with the collisions, and to transformation of the spectrum into a practically collisionless line. Thus, by using ultrashort-lived nuclei with known τ as indicators, we can determine the structural features of crystals such as (a) the positions of the indicator atoms in the lattice, (b) the distance to the nearest neighbors, (c) to assess to some degree the mass of the neighbors, (d) to determine in principle at $a_0 \geqslant \beta^{1/2}$ the differential cross sections of the atomic collisions, and (e) to use nuclei with $\tau \sim 10^{-13}$ as indicators, taking account of the deceleration of the nuclei after the collision.

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