A. F. TULINOV

1965

SovietRxiv

Fig. 1

Figure 1: Fig. 1

Abstract

Full Text

A. F. TULINOV

ON AN EFFECT ACCOMPANYING NUCLEAR REACTIONS IN SINGLE CRYSTALS, AND ON ITS USE IN VARIOUS PHYSICAL INVESTIGATIONS

(Presented by Academician D. V. Skobel' tsyn, March 10, 1965)

In the author' s report at the XV Annual Conference on Nuclear Spectroscopy and the Structure of the Atomic Nucleus (^{1}), it was reported that, when a tungsten single crystal was irradiated with a beam of accelerated particles, a new effect was observed, associated with the ordered arrangement of nuclei in the target. It was shown that this effect can be used to determine the lifetimes of nuclear states in the range of ultrashort values (10^{-16}—10^{-19} sec), and also for investigations in the physics of the solid state. In the present work certain questions related to this are discussed.

1. The angular distributions of charged products of reactions or scattering when a single-crystal target is used will, generally speaking, differ from the corresponding distributions characteristic of an amorphous or polycrystalline target. These differences should be observed near directions in which the nuclei are "lined up." The reason for the appearance of such differences is easy to understand from Fig. 1. Particles emitted by any nuclei initially in directions close to the corresponding crystal axis (for example OA) will be deflected by nuclei belonging to the corresponding chains. Thus, in the directions of the crystal axes there will arise local distortions of the angular distributions of reaction products, having a peculiar form of "lunules" with small angular dimensions. The collection of such lunules forms a certain analogue of a Laue pattern. It is easy to see that subsequent multiple scattering of particles in the thickness of the single crystal will not lead to the disappearance of the effect; it can be observed when using not only a thin but also a thick target.

Fig. 1

2. The question of the practical possibility of observing and using, for various purposes, the effect described above is connected with the angular dimensions of the lunules. Below is given a theoretical estimate of their magnitude. We shall assume that the interaction of a particle—the reaction product (Z_1e)—with the nuclei of the corresponding chain (Z_2e)

Fig. 2

Figure 2: Fig. 2

is described by the potential $V = \dfrac{Z_1 Z_2 e^2}{r} e^{-r/a}$, where a is the known screening parameter.

The upper limit of the angular dimensions of the lunules Ψ (see Fig. 1) can be obtained under the assumption that all nuclei are rigidly fixed at the lattice sites. It can be shown that, for particle energies of several megaelectronvolts, which is typical for products of nuclear reactions,

$$\Psi^2 = 2\frac{b}{l}\left[K_0\left(\frac{\sqrt{bl}}{a}\right) + 2\right], \tag{1}$$

where $b = Z_1 Z_2 e^2/E$; l is the distance between neighboring nuclei in the chain; E is the energy of the reaction product; K_0 is a cylindrical function of the third kind.

To estimate the mean angular dimensions of the lunules we shall use another, extreme, although more plausible model, describing the nuclei of the chain as an ensemble of three-dimensional classical oscillators which oscillate completely independently of one another. Let the amplitude of oscillation be denoted by g. Then the particle—the reaction product—emitted initially along the axis of the chain will cross the localization regions of the nuclei of the chain many times before it is deflected from the axis by a distance g (Fig. 2).

Fig. 2

In this case, for the mean square of the angle θ_g, using the theory of multiple scattering of charged particles, we obtain

$$\overline{\theta_g^2} = \left[\frac{3}{2}\frac{b^2}{gl}\ln\frac{a}{b}\right]^{2/3}. \tag{2}$$

After the particle leaves the tube of radius g, it undergoes an additional series of scattering events. The magnitude of the additional angle can be calculated from the formula

$$\overline{(\Delta\theta)^2} = 2\,\frac{l}{e}\,K_0\left(\frac{g}{a}\right). \tag{3}$$

It can be shown that the mean angle of the resulting deflection is equal to

$$\Phi = \left[\overline{\theta_g^2} + \overline{(\Delta\theta)^2}\right]^{1/2}. \tag{4}$$

Using the calculations carried out in work (2), we obtain an expression for the oscillation amplitude of atoms of mass M at temperature T:

$$g^2 = \frac{18\hbar^2}{Mk\Theta_0}\left[\frac{T^2}{\Theta_0^2}\int_0^{\Theta/T}\frac{x\,dx}{e^x-1}+\frac{1}{4}\right], \tag{5}$$

where Θ_0 is the Debye temperature of the crystal. Table 1 gives the values of 2Ψ and 2Φ, calculated from formulas (1) and (4) at room temperature for reaction-product energies of 1, 10, and 100 MeV, for light (Mg), medium (Mo), and heavy (W) nuclei. The table shows that, although the angular dimensions of the corresponding lunules are rather small, the effect can nevertheless be observed with good angular resolution of the experimental apparatus.

Table 1

	1 MeV	1 MeV	10 MeV	10 MeV	100 MeV	100 MeV
	2Ψ, deg	2Φ, deg	2Ψ, deg	2Φ, deg	2Ψ, deg	2Φ, deg
Mg	1.8	1.1	1.0	0.3	0.3	0.09
Mo	4.2	2.7	1.5	0.7	0.5	0.2
W	4.6	3.9	1.7	1.0	0.6	0.3

3. An experiment was set up in order to detect the effect described above in the case of elastic scattering of protons by a thick sample of a tungsten single crystal. A preliminary determination of the directions of the crystallographic axes was made by means of x-ray techniques. The investigations were carried out on the cyclotron of the Scientific Research Institute of Nuclear Physics of Moscow University at an incident-proton energy of 3 MeV. The crystal was mounted so that its [111] axis lay in the horizontal plane at an angle of 105° to the incident beam. The scattered protons were recorded by a semiconductor counter,

in which the high-energy part of the continuous spectrum was recorded. The result of measurements of the angular distribution of protons near the angle $\varphi = 105^\circ$ is shown in Fig. 3. The crosses refer to the results of measurements with a polycrystalline target. It is seen from the figure that the mean width of the dip has a size of $\sim 2^\circ$. The quantity 2Φ, calculated from formula (4) ($l = 2.7$ Å), proves to be equal to 2.1°. A detailed theoretical analysis of the form of the dip shows that the distance between the maxima on the curve should be close to the value 2Ψ. The theoretical calculation gives $2\Psi = 3.3^\circ$; from Fig. 3 we obtain $\sim 4^\circ$. A more detailed account of the results of measurements obtained at various energies and temperatures is given in work (^{4}).

Fig. 3

4. The idea of determining the lifetime τ of nuclear systems (the compound nucleus, the reaction product with high excitation) can be understood

Fig. 3

Figure 3: Fig. 3

from the following considerations. If, say, the compound nucleus in the reaction has a sufficiently short lifetime τ and by the moment of decay has not yet gone beyond the tube of radius g (Fig. 2), the effect is preserved. If, however, during the time τ the compound system, under the action of the momentum transferred by the incident particle, is displaced by a distance exceeding the magnitude g, the effect will be disturbed and the corresponding dip will disappear; in this case there may even appear a local maximum associated with the well-known effect of capture of particles into channels (^{3}). Since g is of the order of 10^{-9}-10^{-10} cm, and the velocity of the compound system is 10^7-10^9 cm/sec, the method may be sensitive to values of τ in the range 10^{-16}-10^{-19} sec. The method described may prove useful in investigating questions connected with the rate at which nuclear reactions proceed.

5. The rigid-lattice model and the model of independent oscillators, i.e., of the complete absence of correlations in the motion of atoms, correspond to an extreme simplification of the real situation. In fact, the motions of atoms are correlated to a considerable degree, and the degree and character of the correlation are connected with details of the phonon spectra in crystals. It is known that investigations of these questions are at present associated with great experimental difficulties. Apparently, studies of nuclear reactions on single crystals open up, in this respect, additional possibilities. It is easy to see that details of the effect considered (the form of the dip) depend in an essential way on the character of the correlations in the motion of the nuclei of the chain. This connection will be manifested most clearly in the region of low energies of the reaction products, where only the nearest nuclei participate in the game.

V. S. Kulikauskas, G. A. Iferov, and M. M. Malov took part in the measurements, for which I express my gratitude to them.

I also express my appreciation to S. N. Vernov and S. S. Vasil’ ev for their interest in the work and assistance in carrying it out, and to L. V. Groshev and V. V. Balashov for interesting discussions.

Moscow State University
named after M. V. Lomonosov

Received
9 III 1965

CITED LITERATURE

1. A. F. Tulinov, *Dokl. at the XV Annual Conference on Nuclear Spectroscopy and the Structure of the Atomic Nucleus*, Abstracts, "Nauka," 1965.

2. R. S. Nelson, M. W. Thompson, H. Montgomery, *Phil. Mag.*, **7**, No. 80, 1385 (1962).

3. I. Lindhard, *Phys. Lett.*, **12**, 126 (1964); E. Bøgh, I. A. Davis, K. O. Nielsen, *Phys. Lett.*, **12**, 129 (1964); M. W. Thompson, *Phys. Rev. Lett.*, **13**, No. 25, 756 (1964).

4. A. F. Tulinov, V. S. Kulikauskas, M. M. Malov, *Phys. Lett.* (in press).

Note: Figure translations are in progress. See original paper for figures.