ASYMMETRY OF SHADOWS ARISING IN THE INTERACTION OF FAST CHARGED PARTICLES WITH SINGLE CRYSTALS

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The shapes of shadows in the region of superposition of the axial [111] and linear (110) and (112) shadows produced in Coulomb scattering of 190, 350, and 500-keV protons by a tungsten single crystal are measured. When the linear shadow is perpendicular to the reaction plane it is found to have an asymmetric shape which changes with the distance from the center of the axial shadow. The asymmetry may be due to a displacement of the source of scattered particles from the crystal lattice site.

1. It has been shown[1,2] that shadows, i.e. regions with sharply lower particle densities, are observed in the angular distributions of the charged-particle products of nuclear reactions when use is made of a single-crystal target. When the reaction products are recorded, say by means of photographic emulsions, the system of shadows constitutes an aggregate of spots (traces of the crystal axes) and straight lines (traces of the corresponding planes). It is readily seen that in principle this phenomenon can be used to determine the time during which nuclear reactions occur. In fact, when the incident particle interacts with the target nucleus which is initially at a site of the crystal lattice, the produced compound nucleus receives an impulse in the direction of motion of the primary particle. The magnitude of the displacement of the compound nucleus up to the instant at which the secondary particle is emitted is related to its lifetime (τ). On the other hand, the displacement of the source of secondary particles from the lattice site leads to distortions of the pattern of shadows which can be determined experimentally.

A satisfactory theory of the phenomenon is required in order to analyze the nature of the distortions which appear and to relate these reliably with the magnitude of the displacement of the compound nucleus (S). No such theory is available at present; it would therefore first be desirable to elucidate, even if only qualitatively, which elements of the shadow pattern are sensitive to a displacement of the source of secondary particles. Obviously, when S is an appreciable fraction of the interatomic distances both the spots and the lines will undergo appreciable distortion. Estimates indicate that a realistic analysis of the shape of the spots and lines considered separately makes it possible in principle to measure the quantity τ in the range of 10^{-16}–10^{-18} sec. However, even shorter times, in particular $\tau \sim 10^{-19}$–10^{-20} sec, are extremely important for the physics of nuclear reactions. This gives rise to the problem of seeking in the pattern of shadows elements with an enhanced sensitivity to the displacement of the source.

2. It has been indicated in[3] that regions in which axial and linear shadows superimpose partially are of special interest for discovering elements in the pattern of shadows which are particularly sensitive to the displacement of the source. The fact that such regions exist is clearly seen on Fig. 1 depicting a section of a proton pattern in the neighborhood of the axial [111] shadow (single crystal of tungsten). Figure 2 shows on a somewhat magnified scale the corresponding topographic scheme obtained by photometry. The circle marked on the diagram by a dashed line has been drawn through the "shoulder" of the axial shadow. It is readily seen that the center of the circle will be the center of symmetry of the shadow pattern when the distribution of secondary particles is isotropic and their source is at the lattice site. It can be shown that when the source is displaced from the site a distance S in the direction of the primary beam for not too high energies of the secondary particles the axial shadow should shift with respect to the plane ones by an angle $\Delta\theta = Sl^{-1} \sin\theta$ where θ is the angle at which the axial

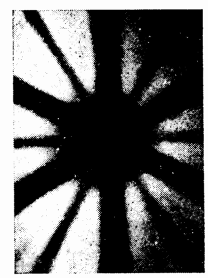

FIG. 1.

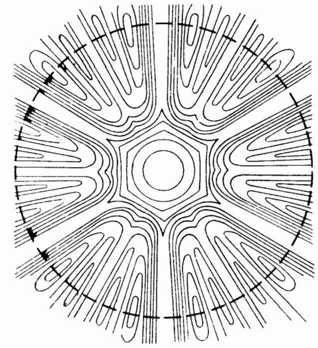

FIG. 2.

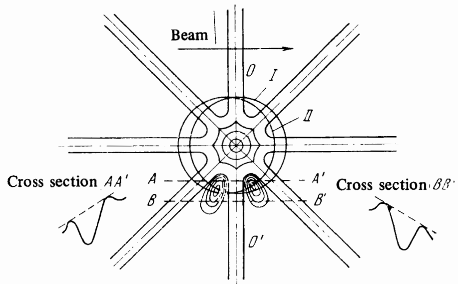

FIG. 3. Simplified diagram of the pattern of shadows in the vicinity of the [100] spot for a cubic lattice: I – shoulder of the axial shadow not displaced with respect to the shadows due to the planes; II – shoulder of the axial shadow when its center is displaced with respect to the center of the shadows due to the planes.

shadow is observed, and l is the distance between neighboring nuclei in the corresponding chain.

Purely as an illustration, Fig. 3 shows a simplified diagram of the pattern of shadows in the region of the [100] spot for a cubic lattice. It is seen from it that a displacement of the axial shadow (the circle II) leads to a characteristic redistribution of the particle intensity in the region of the shoulder. The shape of the linear shadow which is not in the scattering plane (as an example we consider in Fig. 3 the shadow OO′) will be asymmetric on both sides of the shoulder; the sign of the asymmetry changes on passing through the shoulder. Preliminary results of an investigation of the $F^{19}(p, \alpha)O^{16}$ reaction on a single crystal of fluorite[3] indicate that for $\tau \sim 10^{-19}$ sec the above asymmetry can be observed experimentally. It was proved in this experiment that sufficiently far away from the axial shadow the shape of the same linear shadow is symmetric within the limits of the experimental error.

3. The displacement of the compound nucleus from site of the crystal lattice is not the only phenomenon which leads to a displacement of the source of particles from the lattice site. Another such possibility occurs in Coulomb scattering of charged particles with an appreciable scattering parameter, as takes place, for example, in the scattering of relatively low-energy particles by heavy nuclei. Obviously the directions of the displacement of the source of particles with respect to the incident beam in the case of a reaction and in Coulomb scattering are opposed. The nature of the asymmetry for both these cases should also be correspondingly opposed. It should be noted that Coulomb scattering is a very convenient means of modeling the problem of determining τ. In fact, its cross section is appreciably larger than in the case of a reaction, permitting one to cut down sharply the duration of the experiment; in addition, by changing the scattering angle one can change in controllable fashion the value of the scattering parameter. True, there does appear an additional difficulty connected with the presence of asymmetry due to the Rutherford anisotropy in the angular distribution of the scattered particles. The first results of the investigation of the asymmetry of shadows appearing in the Coulomb scattering of 50–200 keV protons by a tungsten single crystal have been reported in[4]. Below we present the results of

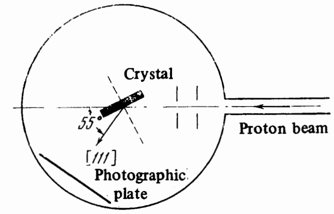

FIG. 4.

an investigation of certain details of the shape of the shadows appearing in Coulomb scattering of 190–500 keV protons by a tungsten single crystal.

4. The experiment was carried out on the cascade accelerator of the NIIYaF MGU [Scientific Research Institute of Nuclear Physics at Moscow State University] which allows one to obtain protons with energies between 150 and 500 keV. The proton beam 0.7 mm in diameter was incident on a single-crystal sample of tungsten located at the center of a vacuum chamber (Fig. 4). The surface of the crystal was treated directly before the experiment on an electropolishing device. The crystal was oriented in the chamber in such a way that its [111] crystallographic axis was located in the plane of reaction at an angle of 55° to the direction of the incident beam, and the (110) plane was perpendicular to the plane of the reaction. The scattered protons were recorded on nuclear emulsions placed perpendicular to the [111] axis at a distance of 107 mm from the crystal.

Samples of proton patterns obtained with 500, 350, and 190-keV incident protons are shown in Fig. 5. The information about the structure of the shadows was extracted by photometry of the proton patterns on a microphotometer along directions perpendicular to the trace of the (110) plane (in Fig. 5 the trace is vertical) at various distances from the center of the axial [111] shadow. The conversion of blackening density measured photometrically to intensities I of the recorded particles was carried out by means of the densitometer characteristic (see, for instance,[5]). Work within the limits of the linear portion of this characteristic was insured by a suitable choice of the length of exposure.

Some of the obtained results are presented in Fig. 6. The curves were obtained at distances from the center of the [111] spot marked in Fig. 5. The densitometer readings were taken every 0.05–0.10° and for this reason the individual points on the graphs have coalesced into continuous lines. Our attention is drawn to a number of features of the curves shown in Fig. 6. As was to be expected, the width of the axial shadow (curve 1) and of the plane shadows increases on decreasing the energy of the incident protons. Shadows due to the planes begin to appear at some distance from the center of the axial shadow. As one goes further away from the center their depth increases initially and then becomes constant. The aggregate of shadows is observed on a background of a monotonic decrease in the particle intensity with increasing scattering angle. The latter is due to the Rutherford scattering anisotropy mentioned above.

5. Even a qualitative analysis of the graphs shown in Fig. 6 reveals that the shape of the linear (110)

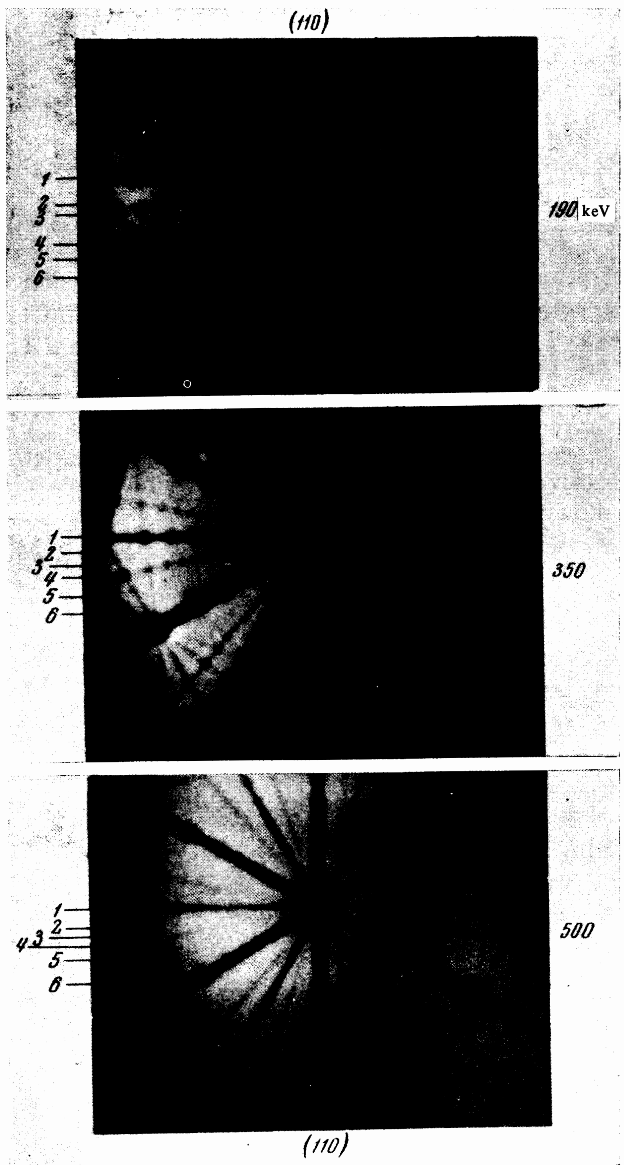

FIG. 5.

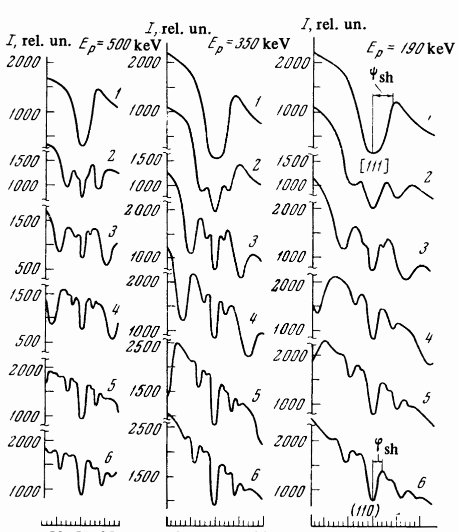

FIG. 6.

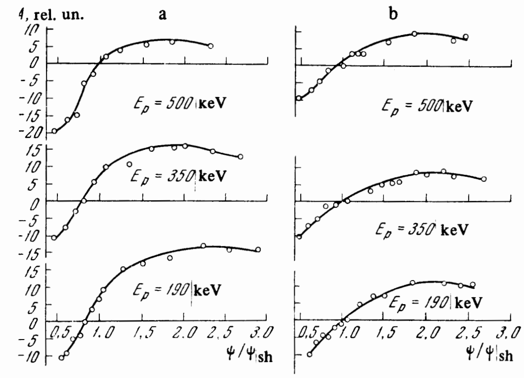

FIG. 7.

shadow in the vicinity of the [111] spot is different at various distances from the center of the axial shadow. Thus, whereas far from the spot the left-hand shoulder of the linear shadow is higher than the right-hand one (which is due to the Rutherford-scattering anisotropy), on approaching the center of the axial shadow the asymmetry of the linear shadow decreases, then the intensities of the particles producing the shoulders equal out, and finally near the center of the spot the right-hand shoulder becomes higher than the left-hand one. As a quantitative characteristic of the asymmetry one can make use of the quantity

$$A = \left(\frac{\Delta I}{I_{av}}\right)\left(\frac{\varphi_{sh}}{\varphi_{sh}^{max}}\right)^{-1},$$

where

$$\Delta I = I(\theta_{min} - \varphi_{sh}) - I(\theta_{min} + \varphi_{sh}),$$

$$I_{av} = {}^1/_2[I(\theta_{min} - \varphi_{sh}) + I(\theta_{min} + \varphi_{sh})].$$

Here θ_{min} corresponds to the position of the intensity minimum of the axial shadow, and φ_{sh} corresponds to the angular half-width of the linear shadow measured between its shoulders. The results of a calculation of the magnitude of the asymmetry A of the linear (110) shadow at various distances from the center of the [111] spot are shown on Fig. 7a in which the distance from the center of the [111] spot referred to its half-width is plotted along the abscissa.

Figure 7b shows the results of analogous measurements of the asymmetry of the linear shadow for another ratio of the width of the axial and linear shadows. In this case the tungsten crystal was oriented in such a way that the crystallographic (112) plane was perpendicular to the plane of reaction. Otherwise the geometry of the experiment remained the same as before. It is seen that the general character of the dependence of the asymmetry on the distance from the center of the axial shadow is repeated for all proton energies employed in the experiment and for different ratios of the widths of the linear and axial shadows. This circumstance indicates that in the region of the axial shadow some other factor, in addition to the Rutherford scattering anisotropy, is active which also leads to asymmetry of the linear shadow. Such a factor can be the displacement of the source of scattered particles from the crystal lattice site.

6. In order to check that the observed asymmetry is really connected with a displacement of the source,

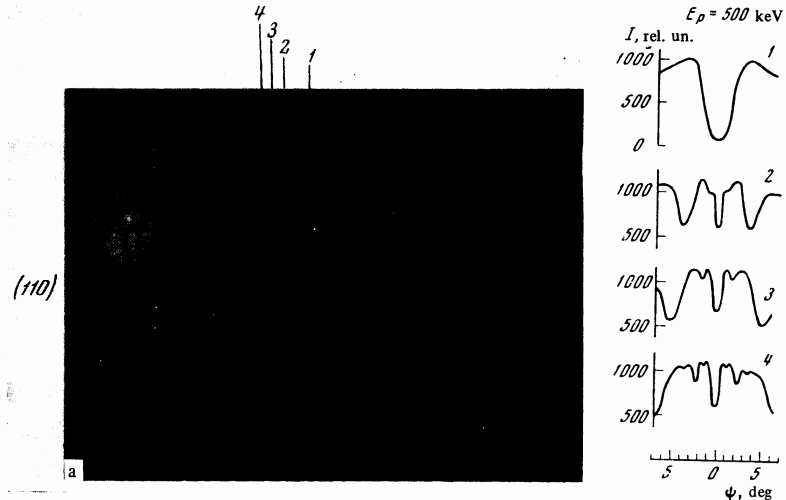

FIG. 8.

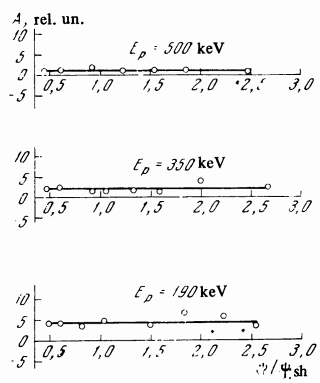

FIG. 9.

control experiments were carried out at the same proton energies in which the (110) and (112) planes were located in the plane of reaction. In this case the displacement of the source occurred within the indicated crystallographic planes and therefore it should not have given rise to the asymmetry of the corresponding linear shadows. Figure 8a shows the proton pattern obtained under such conditions at a proton energy of 500 keV, and Fig. 8b shows the results of photometering it along directions perpendicular to the trace of the (110) plane at various distances from the center of the axial [111] shadow. From a comparison of Figs. 6 and 8 it follows that the general structure of the pattern of shadows about the [111] spot does not depend on the orientation of the (110) plane with respect to the plane of reaction, whereas no asymmetry of the shape of the linear shadow is observed in the latter case.

The results of a quantitative processing of the control measurements for the linear (110) shadow are shown in Fig. 9. It is seen that there is no asymmetry which varies with the distance from the axial shadow; a certain constant asymmetry may be connected with an insufficiently accurate coincidence of the crystallographic (110) plane with the plane of reaction. Analogous results were also obtained in the case when the (112) plane coincided with the plane of reaction.

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