Scattering of 200–500 keV protons in a thin gold film

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(Submitted September 10, 1975)

Zh. Eksp. Teor. Fiz. **70**, 427–429 (February 1976)

Measurements were made of the angular distributions of 200–500 keV protons scattered by a gold target 50 Å thick within the angular range 0–2°. The results obtained could not be explained by the existing theories of multiple scattering.

PACS numbers: 61.80.Ki

Details of the interaction between fast ions and atoms in "distant" collisions, when the impact parameter exceeds 0.1 Å, are of considerable interest in the physics of passage of charged particles through solids. Information on the nature of the atomic field at these relative large distances can be obtained by investigating the scattering of particles in very thin films through small angles. A convenient projectile for this purpose is the proton, because the probability of it capturing an electron is negligible even for energies ~200 keV.

The scattering of protons by thin films has been investigated on several occasions (see, for example, [1,2]) but no special attention has been paid to the range of very small scattering angles θ and the minimum target thickness has been ~360 atomic layers, [2] which corresponds to an "effective number of collisions" (or an "effective thickness of the target"[3–4]) amounting to $\tau \approx 2.7$. The present paper describes an investigation of the scattering of 200–500 keV protons by a gold target whose thickness was ~15 atomic layers ($\tau = 0.11$) in the angular range $0 \leqslant \theta \leqslant 2°$.

The measurements were carried out using an accelerator with a cascade high-voltage generator at three values of the proton energy $E = 200$, 350, and 500 keV. A collimating system ensured that the diameter of the beam reaching the target was 0.1 mm and that its angular divergence did not exceed ±0.03°. The scattered particles were recorded with a semiconductor counter whose angular resolution was $\Delta\theta = \pm 0.02°$. A second semiconductor counter, oriented at an angle of ~7° relative to the scattered beam axis, was used as a monitor.

Gold film targets were prepared by vacuum evaporation[5] on nickel grids with openings 30×30 μ (transparency ~80%); their quality was checked by electron microscopy. The selected sample was highly homogeneous in respect of its thickness, contained no micropores or foreign inclusions, and was free of any preferential crystallographic orientation. The target thickness was determined by comparing the yield of protons scattered through an angle of $\theta = 25°$ in the target and in thicker gold films (of known thickness): the target thickness was found to be 50 ± 10 Å. The working area of the target was ~3 mm^2.

The intensity of the scattered protons $I(\theta)$ was determined in the range of angles θ from −2° to +2°. A check showed that throughout this range the intensity of the particles scattered by the edges of the collimator diaphragms and by the open parts of the grid was negligible: (<0.001 of $I(\theta)$). The results of our measurements are plotted in Fig. 1.

There are at present two variants of the theory of multiple scattering of charged particles[4,6] which are convenient for analysis of the angular distributions of the scattered particles $f(\theta)$ in specific cases. Both variants are based on the statistical model of the atom and require a numerical solution of the basic equation in the Moliere theory of multiple scattering[3] without restriction by the condition $\tau \gtrsim 20$. The cross section for the interaction of a particle with a target atom was found by Meyer[4] using the Lindhard "universal function,"[7] whereas Keil *et al.*[6] employed an approximate analytic expression proposed by Moliere[3] for obtaining such estimates. This expression underestimates seriously the scattering cross section in the case of large impact parameters so that the results of[6] are not very suitable for the analysis of the present case.[1)]

We carried out a comparison with the predictions of the Meyer theory by calculating the necessary parameters and finding, with the aid of tables in[4,8], the theoretical angular distributions $f(\theta)$ and their half-

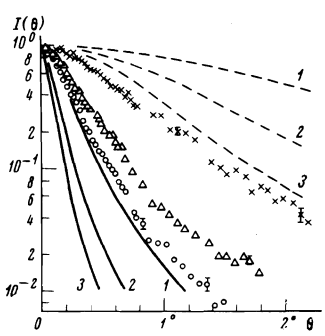

FIG. 1. Angular distributions of scattered protons (the intensity I is given in relative units): ×), △), ○) results of measurements on protons of initial energies $E = 200$, 350, and 500 keV; here, 1–3 are curves calculated on the basis of the theory in[4] (continuous curves) and in[6] (dashed curves).

TABLE 1.

	$(\theta_{1/2})_1$	$(\theta_{1/2})_2$	$(\theta_{1/2})_3$	$\frac{(\theta_{1/2})_3}{(\theta_{1/2})_2}$	$\frac{(\theta_{1/2})_3}{(\theta_{1/2})_1}$
	$E=200$	350	500		
Experiment	0.56	0.28	0.20	0.71	0.36
Theory[4]	0.19	0.11	0.075	0.68	0.40

Note. The angles are given in degrees and E in kiloelectron-volts.

widths $\theta_{1/2}$; they are given in Fig. 1 and Table 1. We can see that in general the Meyer theory predicts correctly the dependences of the half-widths of the angular distributions of the scattered particles on their energy, but the absolute values of $\theta_{1/2}$ are much smaller than the measured values. One of the reasons for this discrepancy is the scattering of the incident particles by individual electrons in atomic shells, whose contribution rises with decreasing scattering angle θ. Estimates obtained in accordance with the adopted method for including this contribution on the basis of the energy losses[9] show that in our case this contribution cannot represent more than half the calculated value of $\theta_{1/2}$ and allowance for it does not improve greatly the agreement with the experimental results. If an attempt is made to reach agreement by altering the screening parameter occurring in the theory,[8] it is found that this parameter should be more than twice as large as the value given by the statistical theory (Thomas–Fermi atomic "radius"). The angular distributions, calculated on the basis of the theory of Keil *et al.*[6] are found, as expected, much wider than the measured values (Fig. 1).

Thus, the existing theories are unsuitable for the description of proton scattering through very small angles. Clearly, the model of the interaction of a charged particle with an atom, utilizing a screened Coulomb potential obtained from the statistical model of the atom, has to be altered or modified considerably.

The authors are grateful to V. S. Kulikauskas and the accelerator team for their help in this investigation, and to A. F. Tulinov and B. Ya. Yurkov for valuable discussions of the results.

1)In the case of much thicker targets the influence of collisions characterized by large impact parameters on the total scattering angle decreases and the theory of Keil *et al.*[6] describes satisfactorily[2] the results of measurements corresponding to $\tau \approx 2.7$.

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Translated by A. Tybulewicz