ENERGY DISTRIBUTIONS OF LIGHT IONS SCATTERED BY SOLID SURFACES

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Abstract

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ENERGY DISTRIBUTIONS OF LIGHT IONS SCATTERED BY SOLID SURFACES

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1. The study of the energy distributions of fast ions scattered by solid surfaces is of considerable interest for elucidating the mechanism of ion slowing-down in matter and, in particular, for refining the expression for the potential describing the interaction of an incident ion with the atoms of the target.

At the present time, only the energy distributions of relatively heavy ions have been studied in sufficient detail ([1]). As a rule, in the case of heavy ions the energy distributions contain peaks superposed on more or less broad smooth distributions. The energy corresponding to the peaks is close to (but somewhat less than) the calculated energy of ions that have undergone elastic scattering by free target atoms. In addition to the peaks corresponding to singly charged ions, the distributions contain peaks of ions that have undergone stripping during scattering, as well as of ionized recoil atoms. A semiquantitative theoretical consideration of the regularities of the scattering of heavy ions by solid surfaces is contained in a series of works by Parilis and co-workers ([2]).

For the case of scattering of light ions with energies of several tens of keV, the experimental data are very scanty ([1]). It is known only that the character of the energy distributions in this case is substantially different from that in the scattering of heavy ions—the energy distributions are broad and have a dome-like shape.

Below are given the results of an experimental study of the energy distributions in the scattering of helium ions He^+ with an energy of 30 keV by various polycrystalline targets with strongly differing atomic and mass numbers. In addition, an attempt has been made to consider this problem mathematically, using the transport equation.

2. The experimental procedure was analogous to that described in ([3]). The glancing angle was 15°, and the scattering angles were varied from 20° to 45°. Since cleaning by ion bombardment is insufficient because of the small sputtering coefficient under irradiation with helium ions, during the measurements the targets (except graphite) were maintained at a temperature of approximately

Fig. 1

Figure 1: Fig. 1

9/10 of the melting temperature, which ensured the degree of target cleanliness necessary for obtaining reproducible results.

Figure 1 shows the distributions for a group of noble metals similar in properties –copper, silver, and gold. It is seen that these are rather broad dome-shaped distributions, in the high-energy part of which a narrow peak is observed. The energy of the ions in the peak is close to the energy of ions that have undergone single scattering by free target atoms. For convenience in comparing these data, the peak intensity has been taken as unity. For copper the intensities of the peak and the dome are approximately equal; for silver and gold the peak is much greater than the height of the dome.* The width of the spectrum

* Contrary to ([4]), where the appearance of the peak is associated with a small mass ratio of the interacting particles; however, no quantitative data are given in that work.

also decreases as the atomic number of the target increases. Measurements were also carried out for light targets (aluminum and graphite) (Fig. 2). In these cases the distributions are still broader than for scattering by heavy targets, and here the height of the dome is taken as unity.

Fig. 1

It is seen that for aluminum the peak is very small in comparison with the dome, while for graphite it is absent altogether.

3. The experimental data given above show that multiple collisions play an essential role in the formation of the spectrum. This makes it possible to use, for a theoretical consideration of the problem, the transport equation*. This equation, after some transformation, has the form

$$\mu\frac{\partial\Psi}{\partial x}+\frac{1}{l(v)}\Psi=\frac{1}{4\pi}\int d\varphi\int_{-1}^{1}d(\cos\theta)\,\frac{1}{l(v')}G(\cos\theta)\frac{{v'}^2}{v^2}\times$$

$$\times\Psi\left(x,\mu\mu'-(1-\mu^2)^{1/2}(1-\mu'^2)^{1/2}\cos\varphi,v'\right);$$

$$\frac{v^2}{{v'}^2}=1-\frac{2M}{(M+1)^2}(1-\cos\theta);\qquad \mu'=\frac{v'}{v}\frac{M}{M+1}\left(\cos\theta+\frac{1}{M}\right). \tag{1}$$

* In [5] an analogous kinetic equation was used to describe the passage of light ions through films of heavy metals.

All notation is standard [1]. Here $\Psi'(x,\mu,v)$ is the distribution function; $\frac{1}{4\pi}G(\cos\theta)\,d(\cos\theta)\,d\varphi$ is the probability of scattering into the solid angle $d(\cos\theta)\,d\varphi$; θ is the scattering angle in the c.m. system.

Equation (1) takes into account only elastic collisions*.

The function $G(\cos\theta)$ is determined by the interaction potential. As the interaction potential, it is assumed to be a screened Coulomb potential

$$U(r) = \frac{Z_1 Z_2 e^2}{r}\,\varphi\Big(\frac{r}{b}\Big),$$

where e is the electron charge; Z_1 and Z_2 are the atomic numbers of the incident particle and the target atom, respectively; b is the screening radius. For potentials of this type, the most essential scattering is at small angles of order $\frac{\alpha}{E_r b}$, where $\alpha = Z_1 Z_2 e^2$, $E_r = \frac{M}{M+1}E$ is the energy of the incident particle in the c.m. system.

For small angles, according to [^7],

$$G(\cos\theta) = \frac{1}{h}\,G\Big(\frac{1-\cos\theta}{h}\Big),$$

where $h \sim \alpha^2/E_0^2 b^2$ is a small parameter, and E_0 is the energy of the primary ion.

From equation (1) one easily calculates the number of emitted particles that have undergone only one collision with target atoms:

$$\frac{(M+1)^2}{M}\frac{1}{v_0}\frac{1}{(|\mu| + \mu_0 l(v_0)/l(v))}\frac{G(\cos\theta)}{2\pi\sqrt{1-(f(v)-\mu\mu_0)^2/(1-\mu^2)(1-\mu_0^2)}}\times$$

$$\times\,\eta\Big(1 - \frac{(f(v)-\mu\mu_0)^2}{(1-\mu^2)(1-\mu_0^2)}\Big);$$

$$f(v) = \frac{(M+1)^2 v^2 - (M-1)^2 v_0^2}{2vv_0}; \qquad \eta(z) = 1, \quad z>0, \quad \eta(z) = 0, \quad z<0.$$

[1] Generally speaking, since the velocity of the incident helium ions in the case under consideration is of the order of the electron velocity in the first Bohr orbit of the hydrogen atom, the probabilities of elastic and inelastic collisions are comparable. However, consideration of the problem with inelastic collisions taken into account is still very difficult. One may nevertheless expect that, in view of the fact that in the case under consideration elastic and inelastic losses are of approximately the same order, the estimates of the relative widths of the spectra made in this work will be valid.

It follows from this that, for scattering angles greater than $\alpha/E_0 b \sim 10^{-1}$, the "single-scattering" peak should be the more noticeable, the larger the atomic number of the target, which is in complete agreement with the experimental results given above.

In the present problem there is one more small parameter, $1/M$—the ratio of the mass of the light helium ion to the mass of the target atoms ($\sim 1/16$ for Cu, $\sim 1/30$ for Ag, $\sim 1/50$ for Au).

From the theory of equations with a small parameter [^8] it follows that, to first approximation, the width of the energy spectrum of the scattered particles is a quantity of order

$$\frac{\alpha^2}{ME_0^2 b^2} \ln \frac{ME_0^2 b^2}{\alpha^2}.$$

This estimate is not absolute in the sense that it merely makes it possible to estimate the ratio of the widths of the spectra for different elements at a fixed scattering angle. The corresponding estimates were carried out with various specific forms of the screened poten-

potential: with the potential of O. B. Firsov ([9]), with a Coulomb potential cut off at half the interatomic distance, and with the "corrected"Bohr potential (with the parameters from ([10])). The corresponding experimental and calculated data are given in Table 1.

Table 1

Ratio of spectrum widths	Experimental data	Experimental data	Experimental data	Calculated data	Calculated data	Calculated data
Ratio of spectrum widths	$\theta = 20^\circ$	30°	45°	Bohr	Firsov	cut-off Coulomb
Ag/Cu	0.65	0.604	0.518	0.74	1.71	1.353
Au/Cu	0.75	0.652	0.625	1.05	2.99	2.17
Au/Ag	1.15	1.08	1.20	1.42	1.75	1.602

It is seen that the best agreement with the experimental data is observed when using the "corrected" Bohr potential with a screening radius obtained from scattering experiments ([10]).

The above consideration shows that the transport equation describes the passage of fast ions through solids quite well. Even very approximate estimates make it possible to describe the general picture of the energy distributions and the ratio of the widths of the spectra. In addition, the calculations performed make it possible, by comparing the calculated data, to choose between interaction potentials.

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