The Scattering of Lithium Ions by a Polycrystalline Nickel Surface

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Positive ions scattered by a nickel target were measured both as to energy and quantity in various directions. The ions are scattered in a forwardly directed beam whose width at one-half the maximum intensity is about 45°. The direction of the maximum is independent of the incident energy and nearly so of the angle of incidence. The ratio of the most probable energy of the scattered ions to that of the incident ions is found to decrease as the total angle of scattering increases and to be independent of the energy or the angle of incidence. To a first approximation the energy distribution is found to be the same as that for projectiles of macroscopic size undergoing elastic impacts at a rough surface with a small coefficient of restitution.

THE investigation of the scattering of positive ions by a metal surface was undertaken at the same time by both Read[1] and Gurney[2] and has also been studied by Sawyer[3] and Woodcock.[4] The essential results found were that the ions were scattered in a forward direction and concentrated into a more or less well-defined beam. The position of the maximum concentration was associated by three investigators[1, 3, 4] with the specular direction while it was considered by the other[2] to be independent of that direction. It was also found that the mean energy of the scattered ions varies with the angle through which they are scattered.

The present work was undertaken to attempt to settle the question of association with specular reflection and to discover, if possible, any functional relation between the mean energy of the scattered ions and their direction.

THE APPARATUS

The apparatus was modeled somewhat after that used by Davisson and Germer[5] in their first electron diffraction experiments. The essential parts are shown in Fig. 1. The ion gun G and the target T rotated about the axis O that passed along the surface on the target perpendicular to the plane defined by the incident and collected beams. The outer walls of the gun, the target, the outer box of the collector C, D, and the frame supporting these were all of brass and interconnected, thus forming a field-free enclosure around the target.

The target T was a disk about 3.8 mm in diameter and 0.9 mm thick which had been cut from a piece of ordinary nickel rod. Although the polycrystalline surface had been highly polished by grinding with alundum and rouge, it lost this polish in the course of experimentation. Thus the results described are for a fine matte surface on three similar targets, numbered 1, 2 and 3. Precautions were always taken to keep the target clean. Also it was later heated to a bright red (1500°C) by radiation from the flat spiral tungsten filament H and thus thoroughly outgassed. To keep vapors from collecting on it during measurements it was kept at a dull red (500°C).

The inner box C of the collector was supported through its lead, so that the entire system of metallic connections between it and the electrometer was shielded from induction by an insulator supporting a difference of potential. The positive lithium ions were emitted thermionically from powdered spodumene[6] deposited on the small helical tungsten filament F.

The vacuum tube was in two sections which were connected by a large picein seal so that the apparatus might be easily removed for cleaning and reloading the source. Six long tubes extended from the under side of the larger section and enclosed the soft iron plungers which effected the changes in the positions of the gun and target. This section also had a Dewar seal holding a glass thimble near the metal parts. By keeping this filled with liquid air it served as a trap for vapors auxiliary to those traps in the vacuum system proper.

[1] G. E. Read, Phys. Rev. **31**, 629 (1928).
[2] R. W. Gurney, Phys. Rev. **32**, 467 (1928).
[3] R. B. Sawyer, Phys. Rev. **35**, 1090 (1930).
[4] K. S. Woodcock, Phys. Rev. **38**, 1696 (1931).
[5] C. Davisson and L. H. Germer, Phys. Rev. **30**, 750 (1927).
[6] K. T. Bainbridge, J. Frank. Inst. **212**, 317 (1931).

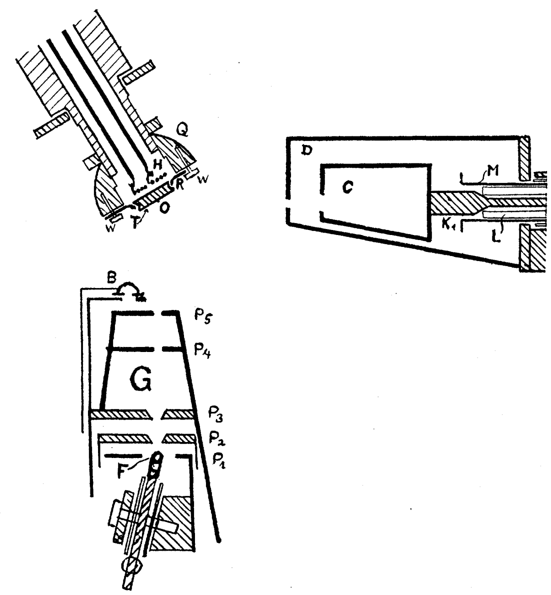

FIG. 1. 1.4 actual size.

The vacuum system consisted of a two-stage Pyrex mercury vapor pump backed by a Hy-Vac, a McLeod gauge, two liquid air traps and a Pirani gauge. The latter was as close to the tube as possible in order to detect fluctuations in pressure that might arise since the tube could not be baked out. The pumps were kept running continuously as long as the tube was assembled. The filament H (Fig. 1) was made to heat the entire tube until the walls in the immediate vicinity of the apparatus were about 50°C and no data were taken until the pressure remained below 10^{-5} mm of mercury. The mean free path of a positive ion with 100 or more volts kinetic energy is then greater than the 30 mm from the source to the collector.

THE PROCEDURE

Because of the construction of the apparatus the target carriage had to be clamped either to the gun or to the collector at an arbitrary angle before assembling it in the vacuum tube. Thus either the angle of incidence Φ, or the angle of scattering Θ, was determined. With Φ fixed and the acceleration voltages (V_{FA} between the filament F and the plate P_2, and V_{FG} between the filament F and the plate P_3 plus the rest of the metal parts) constant, two procedures were followed. The first led to a determination of the intensity distribution and consisted in measuring the current i as a function of the angle of scattering Θ when the retarding potential was kept zero. The second procedure led to a determination of the energy distribution. It consisted in measuring the current i to the collector C as the retarding potential V_{GS} between the boxes C, D was varied. The most probable energy E' of the ions scattered through the angle Θ was then obtained from the curve. By changing Θ and repeating, E' was measured as a function of Θ.

RESULTS AND DISCUSSION

Properties of the incident beam

Preliminary tests, with the target carriage removed, showed the incident beam to be relatively homogeneous as to energy (± 2.5 volts) and of small angular divergence ($<2°$). These properties vary somewhat with the relative values of V_{FA} and V_{FG}. The best conditions were found for V_{FA} equal to 0.1 V_{FG}. Also the most probable energy was 3 volts less than the value of V_{FG}.

Properties of the scattered ions

Table I is a summary of the twenty-four sets of data which were collected for the intensity distribution. The larger values for the breadth of curves 9 to 13 may be explained by referring to Fig. 1. For these curves the axis O inadvertently passed through the body of the target so that for large values of Φ, such as 70°, the entire beam was not incident upon the face of the target and some of the ions were scattered by the edge nearest the gun.

For ions with energies greater than 100 volts the position of the maximum does not seem to depend upon the incident energy. This is in accord with previous results.[1, 2, 3]

In regard to the connection between the position of the maximum and the specular angle the several investigators disagree. The data of Table I show that the angle of maximum scattering tends to remain constant rather than to vary with changes in the angle of incidence and therefore any association of this with the specular angle is probably fortuitous.

Four curves were obtained for constant Θ and varying Φ, which is analogous to part of Gurney's[2]

TABLE I. *Summary of data on intensity distribution. Columns 2 and 3 give the two accelerating potentials for maximum scattering in curves 12 to 24; column 5, angle of incidence; column 6, angle at maximum scattering; column 7, angular width to half maximum of scattered beam; column 8, angular position of mid-point of scattered beam.*

1	2	3	4	5	6	7	8
Curve No.	V_{FG} (volts)	V_{FA} (volts)	Target No.	Φ	Θ_{max} $\pm 2°$	Breadth at $I/I_{max}=0.5$	Middle point of breadth
1	186	186	1	70°	63°	55°	69°
2	195	193	1	70°	67°	40°	64°
3	180	100	2	68°	64°	40°	63°
4	180	100	2	72°	72°	35°	68°
5	180	100	2	67°	72°	30°	70°
6	180	100	2	71°	70°	35°	67°
7	150	100	2	71°	71°	30°	70°
8	180	100	2	49°	57°	45°	58°
9	250	100	3	70°	50°	70°	39°
10	250	100	3	70°	55°	75°	38°
11	200	100	3	70°	58°	55°	44°
12	300	30	3	70°	63°	90°	?
13	200	20	3	70°	55°	60°	49°
14	400	40	3	69°	65°	45°	60°
15	200	20	3	69°	65°	45°	58°
16	492	49	3	69°	67°	40°	62°
17	400	39	3	69°	69°	50°	60°
18	300	29	3	69°	67°	45°	61°
19	200	20	3	69°	66°	50°	61°
20	100	18	3	69°	63°	60°	55°
21	200	20	3	49°	63°	60°	54°
22	400	40	3	49°	72°	55°	56°
23	200	25	3	32°	63°	65°	51°
24	400	30	3	32°	55°	90°	?

work. The intensities observed are independent of both the incident energy and the arbitrary angles of scattering so they were plotted on a single graph (Fig. 2). The values of the radius vector are thus a measure of the relative efficiency of the scattering of ions as a function of the angle of incidence.

Data on the energy distribution were obtained, as described under "Procedure," for ions with

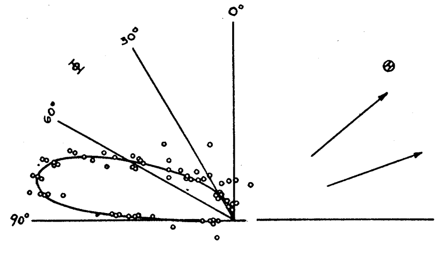

FIG. 2. $V_{FG}=200$ and 400 volts, $V_{FA}=20$ and 40 volts, respectively. $\Theta=70°$ and 50°, target No. 3.

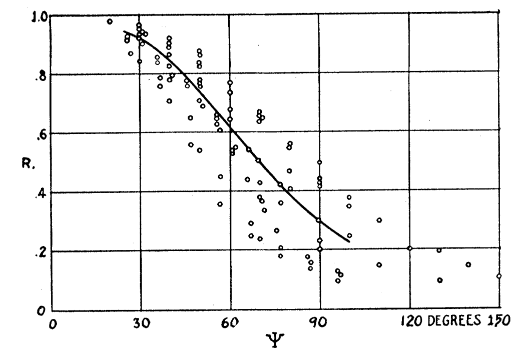

FIG. 3.

kinetic energies between 125 and 450 volts at angles of incidence near to 70° and 50°. The values of the ratio R of the most probable energy E' to the incident energy $E(V_{FG}^{-3})$ are plotted in Fig. 3 as a function of the total angle of scattering Ψ, where $\Psi=2\pi-(\Phi+\Theta)$. The heavy curve drawn through these points is a best curve obtained from averages. The spread of the points is so large that this curve would have little significance were it not for the fact that the points exist in sets in each of which R decreases as Ψ increases. Fig. 4 shows the family of curves corresponding to the data. It is to be observed that no distinction can be made between these on a basis of either the incident energy or the angle of incidence.

One set of retarding potential curves was taken for a constant angle of scattering, $\Theta=50°$, and the results are in all respects similar to those obtained with a constant angle of incidence. This is analogous to Gurney's[7] investigation with a mass-spectograph. His results are similar and his values of R would fall in the midst of the points below the curve in Fig. 2.

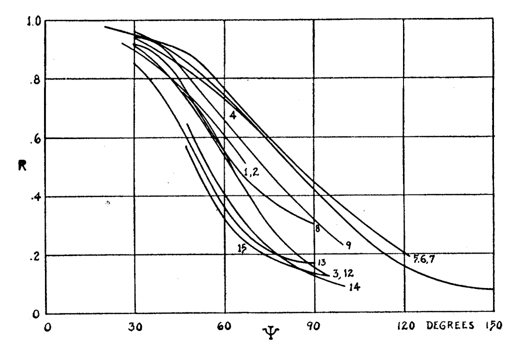

FIG. 4.

Theoretical Considerations

It was found easier to obtain a functional relation between the energy of a scattered ion and its direction than to obtain one for the intensity distribution. Consider the problem of particles undergoing elastic impacts with a rough surface. These impacts take place as though the tangential plane at the point of impact is all that is involved. Applying a coefficient of restitution b to the normal components of velocity one obtains:

$$R=(1-b)R^{\frac{1}{2}}\cos\Psi+b. \qquad (1)$$

The curves of Fig. 5 where $k=0$ are computed from this equation. However, with one or two

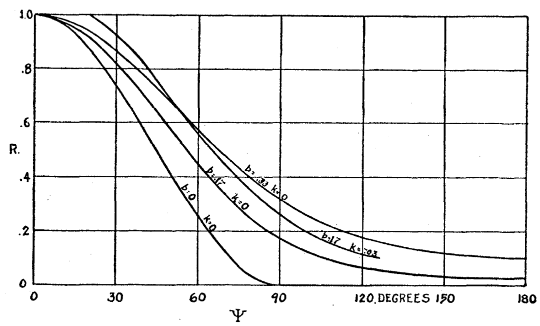

FIG. 5.

exceptions, no choice of b will make the curve of Eq. (1) fit the observed points perfectly. The introduction of a second parameter k, which may be thought of as expressing the effect of a charged layer on the surface of the target, gives a more complicated equation but makes it possible to obtain a better agreement with the experimental results. However, to represent all the experimental curves of Fig. 4 by theoretical curves it is necessary to use values of b ranging from 0 to 0.40 with most of them about 0.30 and to use values of k between -0.10 and $+0.01$. This variation probably results from variations in the target surface in different runs but makes the significance of b and k doubtful. It is to be emphasized that every effort was made to keep the surface clean, some data even being taken while the temperature of the target was greater than 850°C. It was further found possible to make an estimate of b and k for three curves published by Gurney.[7] These estimates fall within the limits given above.

Any attempt to extend this mechanism of scattering to the intensity distribution necessitates some assumptions concerning the roughness of the surface. However, this mechanism does provide that the incident energy will not effect this distribution.

For scattering outside of the plane of incidence one would expect a cosine law for the intensity when it is projected onto the plane through the normal and perpendicular to the incident beam. Gurney's two curves[8] become superimposed when so treated and therefore no further study was made of this.

Thus the scattering of positive ions by a metallic surface, to a first approximation, is the same as would be expected from a consideration of projectiles undergoing elastic impacts at a rough surface with a small coefficient of restitution.

In conclusion I wish to express my sincere thanks to Dr. K. T. Compton and to Professor H. D. Smyth for suggesting this problem and to Professors Smyth and Ladenburg for their continued interest throughout the work. Also I wish to express my appreciation for the assistance of R. T. Roberts in the taking of data, and to thank Mr. C. Stryker and Mr. L. Harris for their valuable assistance with the construction of the apparatus.

[7] Reference 2, p. 471, Figs. 3 and 4.
[8] Reference 2, p. 474, Fig. 8.