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Reflection of Thallium, Lead, and Antimony Atoms from Sodium Chloride Crystals

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The reflection of atomic beams of thallium, lead, and antimony from a freshly cleaved surface of a crystal of sodium chloride has been studied by means of a deposit method. The beams of thallium and lead are in part scattered at random and in part reflected so that the angle of reflection is equal to the angle of incidence. Antimony incident at a large grazing angle is reflected so that the reflected beam makes a larger angle with the normal than the incident beam. It is suggested that the direction of this deviation may be qualitatively accounted for on the basis of the ideas of Duane and of Williams on the interchange of momentum between the incident particle and the crystal.

INTRODUCTION

ALTHOUGH the experiments of Stern and his collaborators[1,2,3] on the reflection of hydrogen and helium from sodium and potassium chloride crystals, and of Johnson[4] on the reflection of atomic hydrogen from lithium fluoride show the existence of surface diffraction phenomena, the experiments on the reflection of atomic beams of the metallic elements are so far not susceptible of such explanation. The specular reflection of beams of cadmium, zinc, and tetra-atomic arsenic from sodium chloride has been reported,[5,6] and the existence of a directed beam of atomic mercury after reflection from certain of the alkali halide crystals has been verified in considerable detail.[7] However, mercury is scattered at random from a crystal of potassium iodide[7] and no evidence of a specular beam can be found for cadmium reflected from orthoclase or fluorite.[5] Furthermore, Ellett and Olson,[8] and Taylor[9] have reported random scattering of certain of the alkali metals from sodium chloride.

There is no obvious explanation of this difference in behavior of different metallic atoms scattered from the same crystals, or of the same atoms scattered from different crystals, and it therefore seemed desirable to extend the work to other metals. In particular it was desired to obtain data on the reflection of thallium, for it was thought possible that the difference in be-

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[1] Knauer and Stern, Zeits. f. Physik **53**, 779 (1929).
[2] Estermann and Stern, Zeits. f. Physik **61**, 95 (1930).
[3] Estermann, Frisch, and Stern, Phys. Zeits. **32**, 670 (1931).
[4] Johnson, Phys. Rev. **37**, 847 (1931).
[5] Ellett, Olson and Zahl, Phys. Rev. **34**, 493 (1929).
[6] Zahl, Phys. Rev. **36**, 893 (1930).
[7] Zahl and Ellett, Phys. Rev. **38**, 977 (1931).
[8] Ellett and Olson, Phys. Rev. **31**, 643 (1928).
[9] Taylor, Phys. Rev. **35**, 375 (1930).

havior of the alkali metals and of zinc, cadmium, and mercury might be attributed to the difference in their magnetic moments. Thallium has the same magnetic moment as the alkali metals.

APPARATUS

A condensation method of detection of the beam was used throughout. The atomic vapor emitted from an orifice in a small steel boiler was defined by a circular slit, and, after reflection from the crystal, collected on a liquid air cooled glass surface. In the earlier runs the boiler, or *gun*, was heated by currents induced in it by means of high-frequency current circulated in a surrounding water cooled coil. This coil was made as small as possible and introduced into the experimental tube itself in order to minimize the heating effect on the metal of the beam defining slit S_2 and on the metal deposit formed above the gun during a run. However, this method proved to be rather unsatisfactory, for when the vapor pressure of the metal issuing from the boiler reached a value sufficiently large to permit detection of the beam, a discharge would start above the gun. This discharge rapidly worked down the coil and across the lead in wires. The pressure in the experimental tube during this time increased greatly.

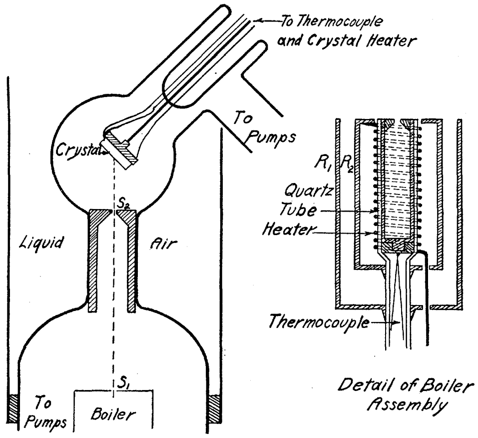

Fig. 1. Experimental arrangements.

Fig. 1 shows the final arrangement of the apparatus. The boiler, a steel cylinder 6 mm in diameter and 33 mm long, fitted into a quartz tube about which a heater of 20 mil tungsten wire was wound. The metal under investigation was inserted into the boiler from the top and a plug containing the boiler orifice forced in. When empty the boiler may be thrown away and a new one inserted. With two radiation shields, R_1 and R_2, Fig. 1, a boiler temperature of 1100°C could be reached with a heater input of 45 watts. Thermocouples attached to the top and bottom of a *dummy* boiler showed the top to be at a temperature only slightly lower than the bottom. This difference, about 3°C, was not sufficient to cause any condensation in the boiler orifice, or to change the vapor pressure by more than a small amount.

In all the runs the crystal was kept at 350°C. As usual, the upper limit for crystal temperature was set by the temperature at which distortion and disintegration of the crystal set in. The lower limit was set in this work by the tendency of the metals to condense on the crystal surface itself.

The dimensions of the apparatus used in the runs on thallium and antimony were as follows: boiler orifice S_1 to beam defining slit S_2, 10 cm; slit to crystal, 2 cm; crystal to collector, 2 cm. The aperture defining the beam was circular and 2 mm in diameter; the boiler orifice was also circular, and 1 mm in diameter. For lead, the beam-defining slit and the gun aperture were 1 mm, and 0.7 mm in diameter, respectively.

Although the angles of incidence and reflection of the beam were not determined with a precision greater than $\pm 2°$, the position of a specular spot could be ascertained quite accurately by sighting through the collecting surface at the image of the gun opening in the crystal. This position was then marked on the collector, and, after a run, compared with the position of the center of the deposit obtained.

RESULTS

1. Reflection of thallium from sodium chloride

Table I shows the results obtained, α_0 being the grazing angle of the incident beam and α the grazing angle of the reflected beam as measured to the center of the deposit formed by the condensed reflected atoms. T is the gun temperature in degrees C, P the vapor pressure of the metal in mm of Hg, L the length of the run in minutes, and D the diameter of the spot in cm.

TABLE I. *Thallium reflected from sodium chloride.*

T	P	L	α_0	α	D
800	1.7	25	50	50	1.5
800	1.7	30	44	44	1.7
750–800	0.9–1.7	60	46	46	3
860	4	10	25	25	1
890	5	20	23	23	1.5

Due to the rather large diameter of the spots it is not possible to conclude that the reflected beam was accurately specular, but there can be no doubt of the existence of a beam at or quite near the specular position. The size of the deposit could be reduced by shortening the length of run, but only at the expense of density of the deposit. In the second and fourth runs the spot had well-defined borders, but in the other runs the confines were marked only by a rapid shading. A background apparently formed by a cosine distribution was evident in all cases. Thallium oxidizes readily, and the deposit disappeared rapidly on exposure to air.[10]

2. Reflection of lead from sodium chloride

Lead is also scattered from sodium chloride with the angle of reflection equal to the angle of incidence. Table II gives the results of five runs. In all

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[10] Gerlach, Ann. d. Physik **76**, 179 (1925).

runs but the first the deposit required development. This was done by the method of Estermann and Stern.[11] After the run the liquid air is removed from a trap, and the mercury vapor which enters the crystal chamber condenses preferentially on the slight deposit of lead already present on the glass, thus rendering the deposit more easily visible.

TABLE II. *Lead reflected from sodium chloride.*

T	P	L	α_0	α	D
1010	1.5	45	32	32	1.4
1000	1.2	20	45	45	
870	0.2	30	44	44	
800	0.05	30	45	45	1.5
750	0.002	180	45	45	1.8

Considerable difficulty was experienced in keeping the lead from condensing on the crystal face. In the first two runs this deposit was quite noticeable, while in the next, with the vapor pressure cut down to 1/6 its former value, the deposit on the crystal was barely visible. No explanation of the formation of a specular beam by reflection from a crystal coated with a metallic film can be offered here, unless it be that the formation of the specular deposit had started before the crystal became coated.

It is to be expected from the results of Chariton and Semenoff[12] that for a given crystal temperature there should exist a critical beam density below which reflection may be obtained without condensation on the crystal. This expectation was borne out by the results of the last two runs, for with the low vapor pressures used, a specular deposit was obtained, while no evidences of a deposit on the crystal appeared.

3. Reflection of antimony from sodium chloride

The results for antimony definitely show the existence of a directed rather than a specular beam. The details are given in Table III. In a consideration of the third and fourth runs it should be remembered that although the actual values of the angles α_0 and α were not known to within 2 or 3 degrees, any displacement of the center of the deposit from the position which would be occupied by a strictly specular beam could be determined. On the other hand, the center of a deposit is not necessarily the region of maximum density of the deposit. Consequently no great weight can be attached to the slight

TABLE III. *Antimony reflected from sodium chloride.*

T	P	L	α_0	α	D
825–850	1–1.8	10	49	41	1
880	4	15	50	40	0.5
780	0.6	25	22	24	1
860	2.3	20	26	25	1.5

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[11] Estermann and Stern, Zeits. f. physik. Chem. **106**, 399 (1923).

[12] Chariton and Semenoff, Zeits. f. Physik **25**, 287 (1924).

deviation of the beam from the specular in these runs. Any attempt to do so would be further complicated by the existence of the ever present background of randomly scattered atoms. If this background is intense enough to produce any shift in the apparent position of the deposit, it will be in a direction towards the normal. This is just the shift found to occur here.

However the shifts in the first two runs made at grazing angles of 49° and 50° are real. These deviations are of the order of 8 or 10 degrees and in a direction away from the normal.

Discussion

Zahl and Ellett[7] pointed out in their paper on the scattering of mercury by the alkali halides, that a deviation of the reflected beam from the specular path may be accounted for on the basis of the ideas advanced by Duane,[13] Compton,[14] and Williams.[15] It is assumed that momentum is transferred from an incident particle to the crystal in quanta and only in directions parallel to the principal axes of the crystal, and that an energy interchange takes place between the particle and the crystal. The mass of the crystal to be considered in applying the laws of conservation of momentum and energy is not the mass of the entire crystal, but only of that portion of it which scatters coherently, i.e., as a rigid body. Thus the larger the portion of the crystal scattering coherently, the less will the reflected beam deviate from the specular path. This is in accord with the experimental evidence of Zahl and Ellett. For as they point out, it is to be supposed that at higher crystal temperatures the increased thermal agitation would decrease the size of the part of the crystal which scatters coherently, and consequently increase the deviation of the path of the reflected beam from the specular, which was precisely the result obtained.

Furthermore, their results show that in every case in which a directed beam was observed, the direction of the reflected beam makes an angle with the normal smaller than would be made by a strictly specular beam. The present results for antimony show a directed beam making an angle with the normal larger than the specular. However, the corrected data on the reflected beams of mercury atoms were taken at rather small grazing angles of incidence (less than 22°), while the grazing angle of incidence for the antimony beam was 50°. This difference in the direction of deviation of the two atomic beams may be accounted for if it is further assumed that, given the same impulse, the portion of the crystal which scatters coherently is equally likely to absorb momentum in each of the three preferred directions. For these considerations require that a particle incident on the crystal almost normally should lose more momentum in the normal than in the tangential direction, and consequently experience a greater decrease in velocity in the normal than in the tangential direction. As a result the particle will be deflected from the specular position in a direction away from the normal. This is in agreement

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[13] Duane, Proc. Nat. Acad. Sci. **9,** 158 (1923).

[14] Compton, Proc. Nat. Acad. Sci. **9,** 359 (1923).

[15] Williams, Proc. Camb. Phil. Soc. **24,** 343 (1928).

with the results obtained for antimony. On the other hand a particle incident at a small grazing angle should lose more momentum in the tangential than in the normal direction. Reasoning exactly similar to that above then leads to the conclusion that in this case the particle will be deflected toward the normal, which is in accord with the experiments on mercury.

In conclusion the writer wishes to acknowledge his indebtedness to Professor A. Ellett who proposed the problem, and to express his appreciation for the advice and many helpful suggestions advanced throughout the course of the work.