

## Reflection of Metallic Atoms from Alkali Halide Crystals\*

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The scattering of molecular beams of mercury from crystals of lithium fluoride, lithium chloride, sodium fluoride, and potassium iodide has been studied as a function of crystal and beam temperatures. A similar study has been made of the scattering of a molecular beam of cadmium from sodium chloride crystals. In all cases a quasi-specular beam of the type reported by Zahl and Ellett (Phys. Rev. **38**, 977 (1931)) for other alkali halide crystals was observed, with the same characteristic temperature changes. Former failures to detect a directed beam in the case of mercury scattered from potassium iodide were shown to have been due to moisture on the crystal surface. The relative number of atoms in the directed beam has been found to decrease with time at low crystal temperatures.

### INTRODUCTION

**B**EAMS of heavy atoms and molecules whose de Broglie wave-lengths, at ordinary thermal velocities, are small compared to crystal spacings do nevertheless when incident upon certain crystals give rise to an apparently coherent scattering.<sup>1,2,3,4</sup> A beam of cadmium atoms incident upon a rock-salt crystal is not simply absorbed and more or less quickly reevaporated, for this would result in a random distribution of atoms leaving the crystal surface. Only in the case of mercury and certain alkali halide crystals has this scattering been studied in detail. The use of the ionization gauge to determine the spacial distribution of mercury atoms scattered from alkali halide crystals revealed a dependence of the relative probabilities of random and directed scattering and of the direction of maximum intensity in the directed beam upon crystal and beam temperatures. This had not been observed in earlier studies carried out by the condensation method.

The only obstacle to the application of the ionization gauge with other heavy atoms, such as cadmium, is their lower vapor pressure which makes condensation in the gauge more likely. However as it is never necessary to build up a pressure in the ionization gauge greater than say  $10^{-5}$  mm of mercury this obstacle is not a very serious one. The gauge has been used to study the scattering of cadmium from sodium chloride crystals. The phenomena observed in the scattering of mercury from these crystals are observed with cadmium also. The anomalous behavior of potassium iodide re-

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<sup>1</sup> A. Ellett and H. Olson, Phys. Rev. **31**, 645 (1928).

<sup>2</sup> A. Ellett, H. Olson and H. Zahl, Phys. Rev. **34**, 493 (1929).

<sup>3</sup> H. A. Zahl, Phys. Rev. **36**, 893 (1930).

<sup>4</sup> H. A. Zahl and A. Ellett, Phys. Rev. **38**, 977 (1931).

ported by Zahl and Ellett has been found to be due to the effect of moisture upon the crystal surface. Crystals of lithium fluoride, sodium fluoride, and lithium chloride, not previously available have been used with an incident beam of mercury atoms. Lithium fluoride is found to indicate especially clearly the existence of both directed and random scattering.

## APPARATUS

The apparatus, shown in Figs. 1 and 2, is essentially the same as that used by Zahl and Ellett,<sup>4</sup> the only major modification being that the gauge and crystal are mounted on the same rigid metal support. This change was made

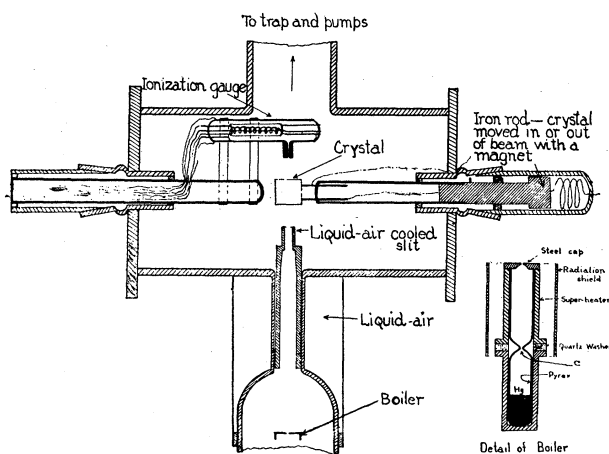


Fig. 1. Diagram of apparatus.

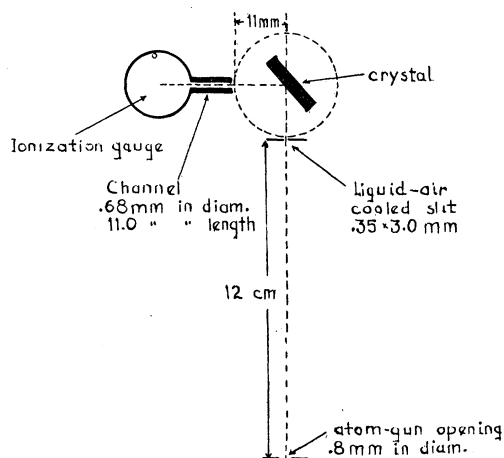


Fig. 2. Essential details of beam system.

to avert the possibility of the gauge and crystal changing their positions after being lined up. The dimensions of the slit defining the incident beam, and the gauge opening were also changed somewhat in order to obtain greater resolving power.

In the use of the apparatus it is necessary that the area on the face of the crystal which is illuminated by the incident beam shall remain stationary as the crystal is rotated, and that the gauge opening shall point directly at this illuminated spot for all positions of the gauge. In order for these conditions to obtain, the axes of rotation of the gauge holder and the crystal holder must be co-linear, and the illuminated area on the crystal face must lie on this common axis of rotation. The proper relative positions of the gauge and crystal were found by placing a closely fitting needle, equal in length to the radius of the circle about which the gauge rotates, into the cylindrical gauge opening and adjusting the relative positions of the gauge and crystal until the point of the needle remained stationary on the crystal face for all positions of the gauge and crystal. Once fixed, this adjustment was permanent since both gauge and crystal were mounted on the same support. The proper positions of the boiler opening and the slit relative to the crystal were found by placing a source of light 1 mm in diameter directly below the slit, the support on which the gauge and crystal were mounted was moved until a beam of light from this source reflected from the crystal face passed into the gauge for all positions of the crystal and the proper relative position of the gauge. Marks were then made on the walls of the glass tube by means of which the boiler opening was mounted at exactly the position of the light source.

In order that the readings of the ionization gauge may represent the actual distribution of atoms scattered by the crystal it is necessary that atoms from all portions of the illuminated area on the crystal face should be able to pass through the gauge opening without collision with the walls. With the incident beam making an angle of  $18^\circ$  with the crystal face the dimensions of the beam system shown in Fig. 2 allow a width of 1.52 mm on the crystal face to be struck by the incident beam. The gauge will admit atoms from a width on the crystal face of 2.04 mm. It is believed that this allows for more error in alignment than was present at any time.

The gauge was of the same type used by Zahl and Ellett,<sup>4</sup> and was of approximately the same dimensions except for the capillary tube forming the opening into the gauge which was 11 mm long and 0.68 mm in diameter. With a galvanometer of sensitivity  $4.5 \times 10^{-9}$  A/mm (ampere per millimeter) and a filament to grid current of 16 m.A. (milliamperes) in the gauge it is estimated that a galvanometer deflection of 1 mm corresponds to a pressure change in the gauge of  $2.1 \times 10^{-8}$  mm of mercury.

For the experiments with an incident beam of cadmium and with mercury at very low boiler pressures, a galvanometer of sensitivity  $4.2 \times 10^{-10}$  A/mm was used. This, coupled with a filament to grid current of 36 m.A. increased the sensitivity of the gauge by a factor of 21.

The calculation of the gauge sensitivity is based upon the fact that at the equilibrium condition as many atoms leave the gauge per second as enter it. The gauge opening offers no impedance to the incident beam provided the divergence of the beam is negligible. However, to atoms leaving the gauge the impedance is that characteristic of a tube of the dimensions of the gauge opening. This means that a pressure will be built up in the gauge by the

incident beam. If we know the number of atoms entering the gauge per second we can calculate the pressure which they produce and by observing the galvanometer deflection can calculate the sensitivity of the gauge.

By using the galvanometer of sensitivity of  $4.4 \times 10^{-9}$  A/mm it is found that a pressure of 0.708 mm in the boiler and a filament to grid current of 1 m.A. give a galvanometer deflection of 10 cm when placed in the main beam. With kinetic theory formula<sup>5</sup> for the mass of a gas striking the walls of a container per unit area per second, and for the number of molecules striking unit area per second,

$$n = 3.53 \times 10^{22} \times P/MT^{1/2}$$

and the dimensions of the beam system given in Fig. 2 we find that the number of atoms entering the gauge per second is  $11.8 \times 10^{11}$ . Since this is also the number of atoms leaving the gauge per second we can now make use of Knudsen's<sup>6</sup> formula for the pressure difference necessary to produce the flow of a quantity of gas,  $Q$  measured in  $\text{cm}^3$  at 1 bar through a cylindrical tube of length  $L$  and radius  $r$ , per second.

$$Q = \frac{1}{\rho_1} \frac{P_1 - P_2}{W_1 - W_2}$$

where  $\rho_1$  is the density of the gas at 1 bar pressure and the temperature of the apparatus, and  $W_1$  and  $W_2$  the partial impedance of the tube are given by,

$$W_1 = (2\pi)^{1/2}/S$$

$$W_2 = 3L/4(2\pi)^{1/2}r^3.$$

A thermocouple placed in contact with the glass walls of the gauge read  $220^\circ\text{C}$ . Since the temperature of the gauge varies somewhat over different parts of the gauge and the point at which the thermocouple junction was placed was in a cooler part of the gauge.  $250^\circ\text{C}$  will be used as the mean temperature of the gauge.

Using the ordinary gas laws we find that the density of mercury vapor at 1 bar pressure and  $250^\circ\text{C}$  is  $4.26 \times 10^{-10}$  g/cm<sup>3</sup>. Substituting these in Knudsen's equation we find for the pressure difference,

$$P_1 - P_2 = 4.53 \times 10^{-2} \text{ dynes/cm}^2$$

$$= 3.4 \times 10^{-5} \text{ mm of mercury.}$$

This is the pressure produced in the gauge by the incident beam of mercury atoms. Since this pressure produced a galvanometer deflection of 10 cm with a filament to grid current of 1 m.A. it is easily calculated that with a current of 16 m.A. the sensitivity is  $2.1 \times 10^{-8}$  mm pressure change per mm galvanometer deflection.

If care was taken to maintain the liquid air about the slit at the same level, the drift of the low sensitivity galvanometer could be kept less than 2

<sup>5</sup> Saul Dushman, *High Vacuum*, pp. 234.

<sup>6</sup> M. Knudsen, *Ann. d. Physik* **28**, 75 and **28**, 999 (1909).

mm per half hour. However, when taking readings of the scattered beam, no attempt was made to keep this level constant. A period of about ten minutes was required to sweep the gauge across the crystal face and during this interval the liquid air level lowered sufficiently to allow a drift of 2 to 4 mm. This is probably due to the liberation of gas from the walls of the apparatus and since it appeared quite uniform could be corrected for.

With the crystal heater at 350°C the residual pressure in the gauge gave a galvanometer deflection of 20 to 30 cm corresponding to a pressure, in mercury vapor, of approximately  $5.75 \times 10^{-6}$  mm. The actual pressure in the gauge was probably greater than this since the gases present would give a lower ionization current than mercury vapor. On the other hand, the pressure in the gauge was probably greater than the pressure in the experimental chamber, due to the continuous liberation of gas from the walls of the gauge. With the crystal heater at 50°C the residual pressure was approximately half the above figure. The residual deflection was balanced out by an opposing potential across the galvanometer.

The system was ordinarily kept evacuated and dry nitrogen admitted for a few minutes while the crystal was being placed in the apparatus. Under these conditions it was only necessary to run the pumps for the period required to outgas the gauge before readings could be taken. The gauge was superheated at a filament current sufficient to give a grid current of 50 m.A. for a period of 4 to 6 hours before readings were taken.

When the high-sensitivity galvanometer was used and the grid current run at 36 m.A., longer outgassing periods were required and an unsteadiness in the residual deflection of the order of a millimeter was usually present. This unsteadiness was approximately one percent of the maximum reading in the scattered beam.

All the crystals used in this work, with the exception of those noted in the table, were grown in this laboratory by R. M. Zabel and the writer. The method used was similar to that used by Strong.<sup>7</sup>

#### EXPERIMENTAL RESULTS

Data obtained by Zahl and Ellett<sup>4</sup> on the scattering of mercury from several alkali halide crystals indicated the following points: (1) The existence of a directed beam; (2) the deviation of the direction of maximum intensity in this beam from the direction of specular reflection; (3) the decrease of this deviation with higher beam and lower crystal temperatures and with lighter atoms; (4) better definition of the directed beam (narrowing of the beam) at low crystal temperatures, accompanied by an increase in the relative amount of random scattering.

The results of the present investigation agree with all except the third of these points. The shift in the position of the directed beam with a decrease in crystal temperature or an increase in beam temperature is found to be toward lower grazing angles. At sufficiently large angles of incidence the directed beam lies below the specular position and the shift in its position

<sup>7</sup> John Strong, *Phys. Rev.* **35**, 1663 (1930).

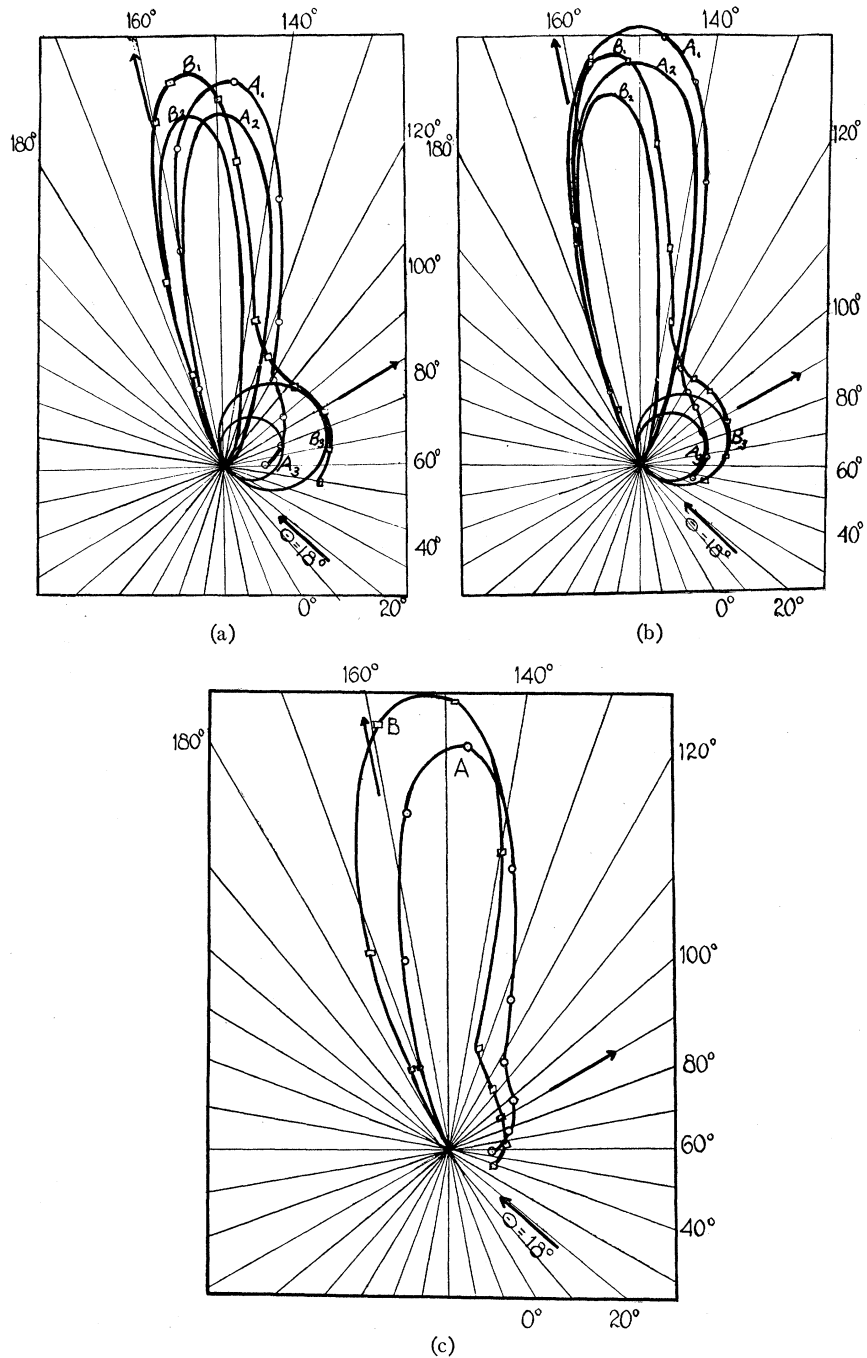


Fig. 3. Distribution of mercury atoms from lithium fluoride as a function of the crystal temperature and the temperature of the incident beam, Table I.<sup>8</sup>

<sup>8</sup> The detailed analysis of all curves is given in the appropriate table.

which accompanies a decrease in crystal temperature is away from the specular. Data were not taken by Zahl and Ellett at sufficiently large angles of incidence to bring out this fact.

The observations made by Zahl and Ellett<sup>4</sup> led them to conclude that the increase in random scattering which accompanied a decrease in crystal temperature was not due to the formation of a gas layer on the crystal surface. The data obtained in this work indicate that the formation of a gas layer on the crystal surface is an important factor when the temperature of the crystal is below that at which occluded gas atoms are driven off the crystal.

### I. Reflection of mercury from lithium fluoride

Fig. 3 shows typical sets of curves obtained for mercury beams scattered from a lithium fluoride crystal. Fig. 3a shows the distribution in the scattered beam with a beam temperature of 375°C and an angle of incidence of 18°. Curves  $A_1$  and  $B_1$  are obtained experimentally,  $A_1$  being taken with a crystal temperature of 470°C, and  $B_1$  with the crystal at 50°C. These curves, as Zahl and Ellett pointed out, appear to be the result of superimposing two curves of very simple type, one a circle and the other a symmetrical curve represented approximately by an equation of the form  $r = C \cos M\theta$ . It appears reasonable to suppose that these curves represent distinct processes one resulting in random scattering, the other giving rise to a directed or coherently scattered beam.

The analysis in this manner of the experimental curves  $A_1$  and  $B_1$  is given in the figure,  $A_1$  being broken up into the circle  $A_3$  and the symmetrical curve  $A_2$ ,  $B_1$  into  $B_2$  and  $B_3$ . A similar notation is used throughout. The directed beams,  $A_2$  and  $B_2$ , lie between the specular position and the normal. Comparison of the directed beams shows that the beam from the cold crystal has been shifted away from the normal by 6.3°. The beam from the crystal at 50°C has also been narrowed, and the relative number of atoms scattered at random has been increased as evinced by the larger circle necessary to represent these atoms.

Fig. 3b shows curves taken with a beam temperature of 525°C. Fig. 3c shows the distribution for different beam temperatures, the crystal being at 470°C in both cases. Curve  $A$  is taken with the incident beam at 375°C and  $B$  with the beam at 525°C. An increase in beam temperature causes the quasi-specular beam to shift in the same direction as a decrease in crystal temperature.

Fig. 4a shows the distribution with an angle of incidence of 57°. The beam in this case has crossed over the specular position and lies closer to the crystal face than a regularly reflected beam. This change in the position of the beam relative to the specular position for varying angles of incidence was consistently observed as an inspection of the table will show. The cosine correction is somewhat uncertain in this case since the larger angle of incidence does not allow the gauge to be rotated over as large an angle. However, the beam is below the specular position whether a cosine correction is made or

not. Also the shift of the quasi-specular beam for a decrease in crystal temperature is definitely away from the specular position. Fig. 9 of the paper by Zahl and Ellett<sup>4</sup> shows evidence of a similar shift.

The above curves were taken with the crystal oriented so that alternate positive and negative ions were parallel and perpendicular to the plane of the

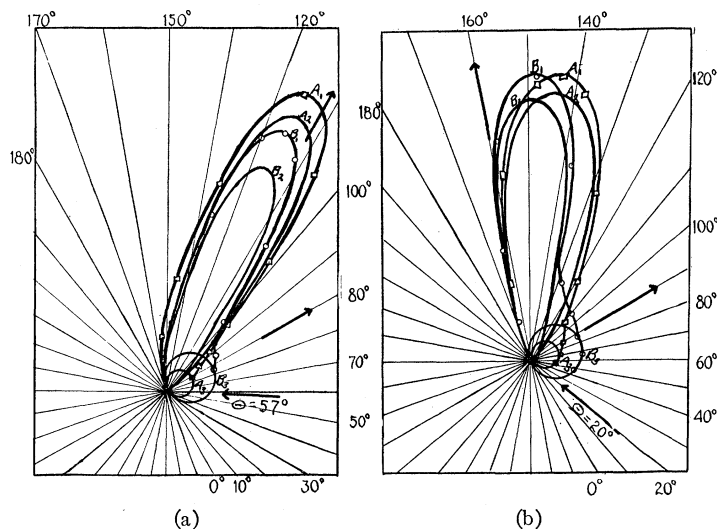


Fig. 4. Distribution of mercury atoms from lithium fluoride as a function of the crystal temperature and the temperature of the incident beam. Table I.

incident beam. Fig. 4b shows a set of curves taken with the crystal rotated  $45^\circ$  about an axis perpendicular to the plane of the incident beam. No change in the scattered beam is observed.

## II. Reflection of mercury from sodium fluoride

Fig. 5 (a, b, c) shows the distribution obtained for mercury reflected from sodium fluoride. 5a was taken with a beam temperature of  $280^\circ\text{C}$  and crystal temperatures of  $550^\circ\text{C}$  and  $50^\circ\text{C}$ . 5b was taken with a beam temperature of  $475^\circ\text{C}$  and the same crystal temperature as 5a. 5c shows two curves taken at same crystal temperatures but different beam temperatures,  $A_1$  being taken at a beam temperature of  $280^\circ\text{C}$  and  $B_1$  at a temperature of  $475^\circ\text{C}$ . The curves are somewhat broader than for lithium fluoride but show the same behavior for changes in relative temperature of beam and crystal, and for changes in angle of incidence. The unusually large amount of cosine scattering in 5b is believed to be due to the fact that the crystal had been cold for approximately an hour.

## III. Reflection of mercury from lithium chloride

Fig. 6 (a, b) shows curves obtained from lithium chloride. 6a was taken at a beam temperature of  $260^\circ\text{C}$  and crystal temperatures of  $500^\circ\text{C}$  and  $50^\circ\text{C}$ . 6b shows curves taken at a crystal temperature of  $500^\circ\text{C}$ , but different beam temperatures,  $A_1$  being taken at a beam temperature of  $260^\circ\text{C}$  and  $B_1$  at a



temperature of 500°C. They show the same behavior as the cases discussed above. Crystals of lithium chloride are very deliquescent and it was necessary to adopt some means of getting the crystal in the apparatus without exposure

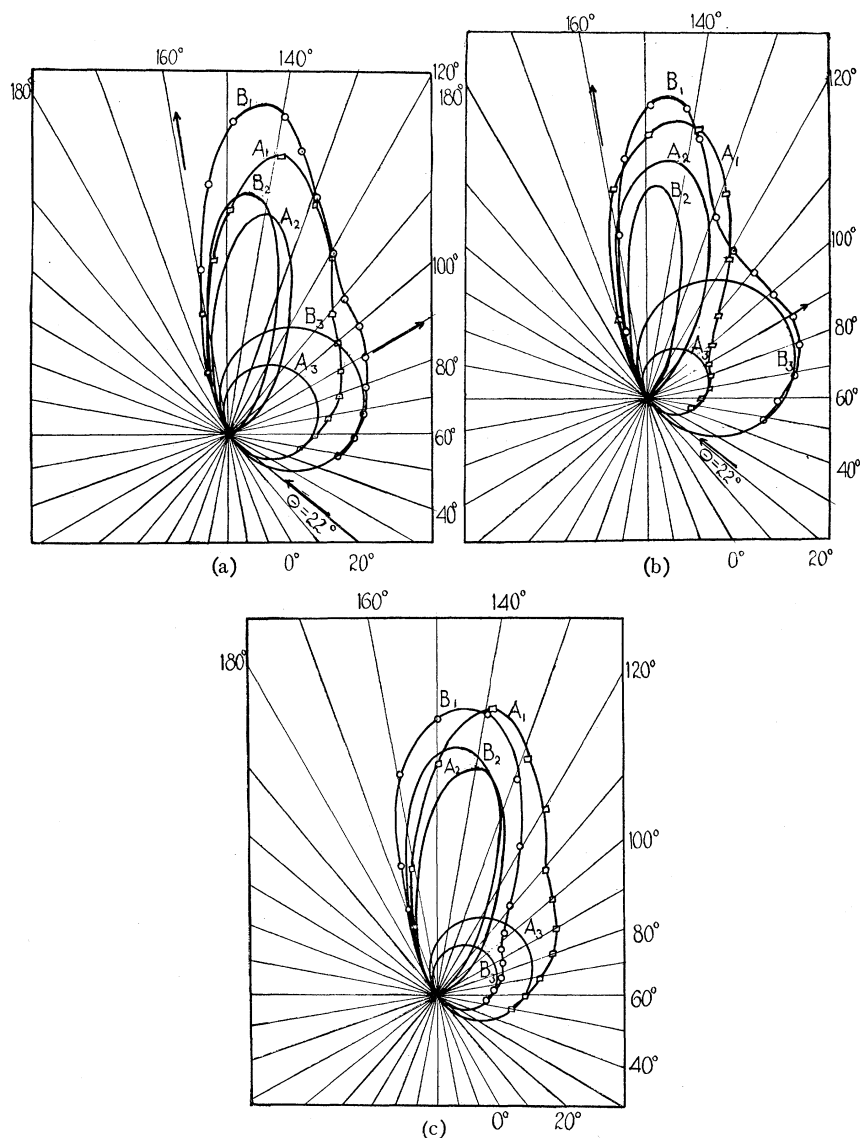


Fig. 5. Distribution of mercury atoms from sodium fluoride crystals as a function of the crystal temperature and the temperature of the incident beam. Table I.

to air. This was done by mounting a tin box with glass windows above the experimental chamber and filling both the box and the entire vacuum system with dry nitrogen at a pressure somewhat above atmospheric, all work on the crystal being done inside this tin box. The connection between the box

and the experimental chamber was made by a short length of tubing made of rubber dam. Long sleeved rubber gloves were attached to the openings in the box through which one worked, so that the crystal could be handled without exposing it to moisture from the hands. The box was thoroughly dried by leaving a dish of phosphorus pentoxide in it for about twelve hours before it was used. The crystal of lithium chloride from which a surface was to be

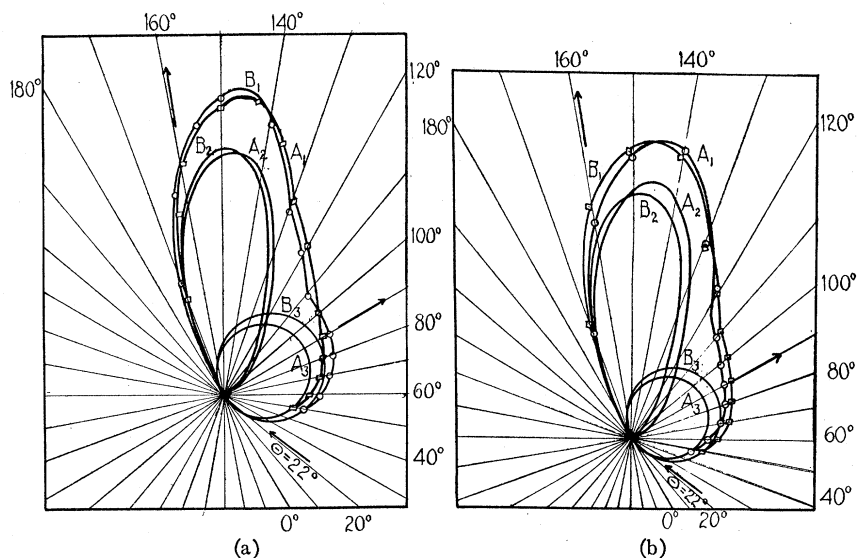


Fig. 6. Distribution of mercury atoms from lithium chloride crystals as a function of the crystal temperature and the temperature of the incident beam. Table I.

split was heated in a vacuum to a temperature of  $400^{\circ}\text{C}$  for four or five hours and then a small glass bomb containing the crystal was sealed off. The glass bomb was broken in the atmosphere of dry nitrogen inside the tin box, the crystal split, mounted on the crystal holder, placed in position and the pumps started immediately. About one minute elapsed from the time the crystal was split until the pumps were started. After taking these precautions in mounting, lithium chloride crystals were found to reflect as well as other non-deliquescent crystals used.

#### IV. Reflection of mercury from potassium iodide

Other experiments carried out in this laboratory had indicated that in certain cases, exposure to air had an action on the crystal surface which was not reversed by heating in a vacuum. In view of the success attained with lithium chloride it was decided to try the same method of mounting with potassium iodide. It was found that under these conditions a crystal of potassium iodide did give a directed beam. Fig. 7a shows the type of curves obtained. They were taken at a beam temperature of  $170^{\circ}\text{C}$  and crystal temperatures of  $400^{\circ}\text{C}$  and  $50^{\circ}\text{C}$ . In order to determine the effect of air on the reflecting power of the crystal, air was admitted to the system for a period of twenty minutes. This air flowed through a liquid air trap before reaching

the experimental chamber and although the trap was at room temperature within a few minutes after the air was admitted it is doubtful whether much water vapor had diffused into the experimental chamber by the end of the twenty minutes. After outgassing the system and heating the crystal at  $400^{\circ}\text{C}$  for several hours it was found to reflect as well as before. The curves obtained were practically identical with these shown in 7a. The system was then opened again and moist air from the room was driven past the crystal for several minutes by running oil pumps. The pumps were then shut off and the system left open for a period of eighty minutes. Fig. 7b shows the

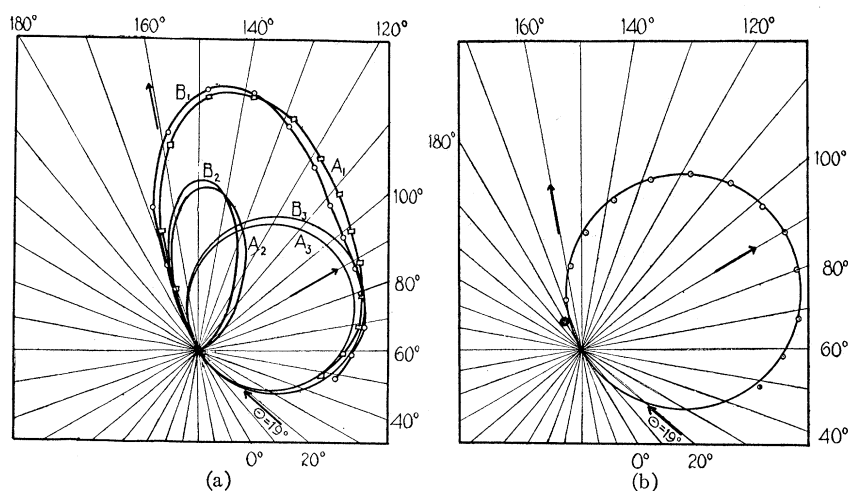


Fig. 7. Distribution of mercury atoms from potassium iodide as a function of the crystal temperature. Table I.

distribution obtained after this exposure. After prolonged heating at a temperature of  $450^{\circ}\text{C}$  the crystal still failed to show any indication of a directed beam. The crystal surface had apparently been completely and permanently ruined as far as its reflecting power was concerned.

#### V. Reflection of cadmium from NaCl

Since cadmium has a much lower vapor pressure than mercury it appeared that in order to prevent condensation in the gauge, two things were necessary, (1) the sensitivity of the gauge should be increased as much as possible so as to use low vapor pressures, and (2) the gauge should be kept at as high a temperature as possible. Several runs with different galvanometer sensitivities and with different ionization gauges were made before it was found possible to prevent condensation in the gauge. Condensation was always indicated by an unsteady drift of the galvanometer off the scale, and if the condensation became very great, by a marked decrease in the filament to grid current.

By using the gauge at a filament to grid current of 36 m.A. in conjunction with the more sensitive galvanometer, which increased the sensitivity of the gauge by a factor of approximately 21 and allowed the use of much lower vapor pressures, this difficulty was overcome.

Fig. 8 shows a set of curves obtained for cadmium reflected from sodium chloride. They were taken at a beam temperature of  $480^{\circ}\text{C}$  and crystal temperatures of  $350^{\circ}\text{C}$  and  $50^{\circ}\text{C}$ . The deviation from the specular position is not as large as usually observed for mercury incident at the same angle. However, individual crystals of sodium chloride show such a deviation in the angle of the reflected beam that one cannot be certain of this point.

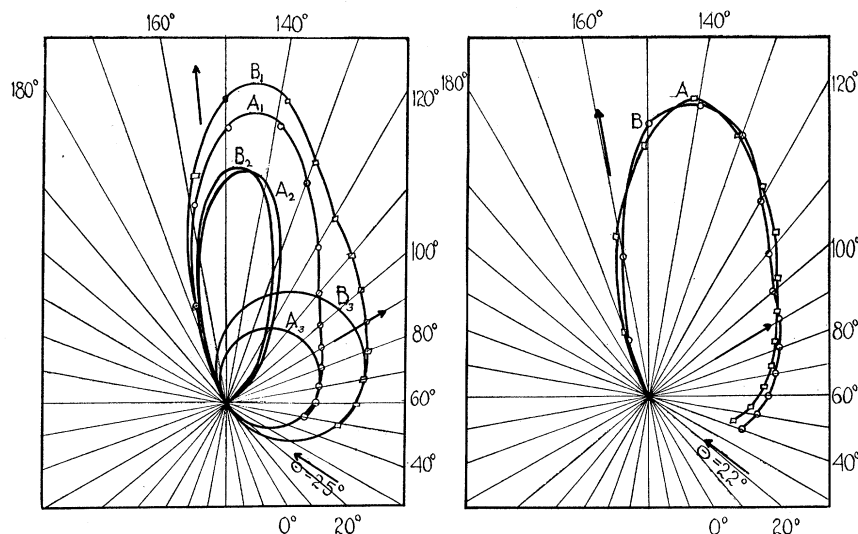


Fig. 8. Distribution of cadmium atoms from sodium chloride as a function of the crystal temperature. Table I.

Fig. 9. Distribution of mercury atoms from sodium chloride as a function of the vapor pressure at the gun opening.

#### VI. Effect of varying pressure in atom-gun on the reflected beam

Fig. 9 shows two curves for mercury reflected from sodium chloride at different boiler pressures. Curve *A* was taken at a pressure of 0.35 mm corresponding to a mean free path of approximately 0.6 mm. Curve *B* was taken at a pressure of 3 mm corresponding to a mean free path of approximately 0.075 mm. The two curves show no appreciable difference. Other curves (not shown) and the data obtained by Zahl and Ellett<sup>4</sup> show very little difference up to a boiler pressure of 10 mm. This indicates that the deviations from a Maxwell distribution which occur in this range of pressure are not significant as far as these experiments are concerned.

#### VII. Variation in random scattering from a cold crystal with time

Fig. 10a shows the scattering of a beam of mercury atoms from a sodium fluoride crystal at  $50^{\circ}\text{C}$  as a function of time. The crystal was heated at a temperature of  $550^{\circ}\text{C}$  for several hours while outgassing the system. Curve *A* was taken immediately after the crystal had been cooled to  $50^{\circ}\text{C}$ . Curve *B* after remaining at this temperature for 20 minutes and curve *C* after 60 minutes. The curves show an increase in the random scattering with time, the

positions of the quasi-specular beam apparently remaining unchanged. Fig. 10b shows the distribution as the crystal was reheated. The crystal was heated to 275°C and curve *B* taken. The temperature was then increased to 400°C and curve *C* taken.

These curves show the peak shifted toward the normal from its position with the crystal at 50°C but very little change in the amount of random scattering. Curve *D* taken at 600°C shows the peak still farther shifted toward the normal and the amount of cosine scattering very greatly reduced.

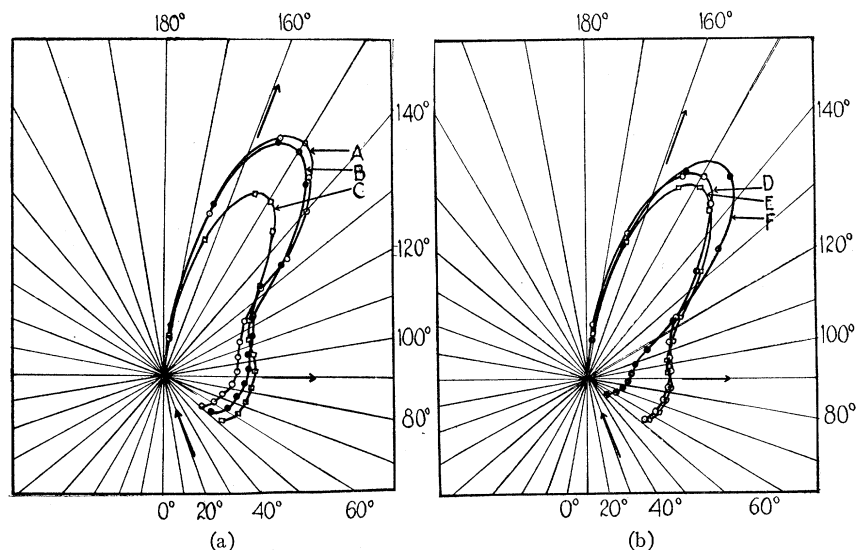


Fig. 10. Distribution of mercury atoms from a sodium fluoride crystal as a function of time and temperature of crystal.

It should be noted that when a crystal of sodium fluoride was exposed to air when placed in the apparatus it was always necessary to heat it at a temperature of at least 550°C for approximately an hour before a directed beam could be obtained.

The tables show the results obtained for the various cases discussed above. The relative number of atoms in the directed beam and in the random scattering were computed by the method described by Zahl and Ellett.<sup>4</sup>

#### CONCLUSION

A directed beam has been obtained for all the cases investigated. The former unsuccessful attempts to detect a directed beam from crystals of potassium iodide are shown to have been due to contamination of the crystal surface by overexposure to air, particularly to moist air, when it was placed in the apparatus. (The writer found no evidence of a directed beam in several attempts before the method of mounting in an atmosphere of dry nitrogen was developed.)

When a crystal surface was exposed to air, even for periods as short as two or three minutes, it was necessary to heat the crystal to drive off the

TABLE I. Reflection of mercury from alkali-halide crystals.

Crystal	Figure identification number	Angle of incidence	Angle of reflection	Temperature of crystal	Change in angle of reflection due to change in crystal temperature	Temperature of mercury beam	Curve describing directed beam	Intensity of directed beam	Intensity of cosine scattering	Total intensity	Percent of atoms contributing to directed beam
(1) LiF*		18°	32°	470°C		285°C	cos 3.3°	23.34	75	98.34	23.8
(1) LiF		18	26	50	6	285	cos 4.0°	16.90	68	84.90	19.9
(1) LiF	3(a), A	18	32	470		375	cos 3.8°	31.5	75.3	106.8	25.9
(1) LiF	3a, B	18	25.7	50	6.3	375	cos 5.5°	20	81.6	101.6	19.7
(1) LiF	3b, A	18	29	470		525	cos 3.8°	25.5	67.8	93.3	33.2
(1) LiF	3b, B	18	25	50	4	525	cos 5.0°	15.8	88.3	104.1	15.4
(1) LiF		36	40.6	470		285	cos 3.6°	26.52	70.8	97.32	27.2
(1) LiF		36	34.7	50	5.9	285	cos 4.0°	30.36	92.4	122.76	24.4
(1) LiF		35	39	470		375	cos 3.8°	47.1	75.6	122.7	38.3
(1) LiF		35	33	50	6	375	cos 4.8°	27.9	94.0	121.9	23
(1) LiF		34	35	470		525	cos 4.4°	25.87	75.3	101.17	25.6
(1) LiF		34	31	50	4	525	cos 4.6°	25.05	77.85	103.9	24.3
(1) LiF		56	52	470		285	cos 3.6°	26.1	42.4	68.5	38.1
(1) LiF		56	48	50	4	285	cos 4.8°	24.01	70.2	94.21	23
(1) LiF		56	55	470		375	cos 4.4°	28.4	64.4	92.8	30.7
(1) LiF		56	53	50	2	375	cos 4.6°	26.9	72	98.9	27.8
(1) LiF	4a, A	57	55	470		525	cos 4.7°	30.51	56.62	87.13	34.6
(1) LiF	4a, B	57	53	50	2	525	cos 5.5°	18.8	89.6	108.4	17.7
(2) LiF		39	48	700		500	cos 4.0°	12	17.3	29.3	41
(2) LiF		39	43	50	5	500	cos 5.7°	8.77	25.1	33.87	26
(2) LiF		39	45	50	3	360	cos 5.2°	7.97	22	29.97	26.6

TABLE I. (Continued).

Crystal	Figure identification number	Angle of incidence	Angle of reflection	Temperature of crystal	Change in angle of reflection due to change in crystal temperature	Temperature of mercury beam	Curve describing directed beam	Intensity of directed beam	Intensity of cosine scattering	Total intensity	Percent of atoms contributing to directed beam
(3) NaF	5c, A	22	37	550		475	cos 2.8 $\ominus$	39.75	46.9	86.65	45.7
(3) NaF	5b, A	22	33	50	4	475	cos 4.4 $\ominus$	6.14	77	83.14	7.4
(3) NaF	5b, B	37	42.5	550		475	cos 3.2 $\ominus$	15.4	42.6	58	22.7
(3) NaF		37	38	50	4.5	475	cos 3.6 $\ominus$	12.6	53.5	66.1	19.2
(3) NaF		52	49	550		475	cos 2.8 $\ominus$	43.5	42.5	86	50.6
(3) NaF		52	47	50	2	475	cos 3.6 $\ominus$	14	54.5	66.5	25.7
(3) NaF	5c, A	22	40.5	550		280	cos 3.2 $\ominus$	12.2	49	61.2	19.8
(3) NaF	5a, A	22	35.5	50	4.7	280	cos 3.6 $\ominus$	10.6	72	82.6	12.9
(3) NaF	5a, B	37	45.5	550		280	cos 3.2 $\ominus$	17.4	62.8	80.2	21.7
(3) NaF		37	43	50	2.5	280	cos 3.6 $\ominus$	11	76	87	12.3
(3) NaF		52	53	550		280	cos 3.2 $\ominus$	19.7	45.7	65.4	30
(3) NaF		52	51	50	2	280	cos 4 $\ominus$	9.8	52	61.8	15.8
(4) NaF		21	32.5	700		500	cos 2.8 $\ominus$	15	18.9	33.9	43.3
(4) NaF		46	45	700		500	cos 3 $\ominus$	11.2	18.9	30.1	37.5
(5) LiCl	6b, B	22	33	500		500	cos 3.2 $\ominus$	8.82	29.8	38.62	22.9
(5) LiCl	6a, A	22	31	50	2	500	cos 3.4 $\ominus$	7.4	32.6	40	18.5
(5) LiCl	6a, B	22	35	500		260	cos 3.2 $\ominus$	8.48	25.2	33.68	25.1
(5) LiCl	6b, A	22	35	500		260	cos 3.2 $\ominus$	8.48	25.2	33.68	25.1
(5) LiCl		50	54**	500		500					
(5) LiCl		50	52**	500	2	500					
(5) LiCl		50	55**	500	2	260					

TABLE I. (Continued)

Crystal	Figure identification number	Angle of incidence	Angle of reflection	Temperature of crystal	Change in angle of reflection due to change in crystal temperature	Temperature of mercury beam	Curve describing directed beam	Intensity of directed beam	Intensity of cosine scattering	Total intensity	Percent of atoms contributing to directed beam
(6) KI	7a, A	19	34	400		170	cos 2.6 $\ominus$	7.8	47.8	55.6	14.8
(6) KI	7a, B	19	31	50	3	170	cos 2.8 $\ominus$	6.9	50.5	57.4	12
(6) KI		27	35	400		170	cos 2.2 $\ominus$	11.6	53.7	65.3	17.8
(6) KI***		27	35	400		170	cos 2.4 $\ominus$	13.2	55.6	68.8	19.1
(6) KI***		27	35	50	2	170	cos 2.6 $\ominus$	9.9	55	64.9	15.2
(6) KI		41	50	400		170					
(6) KI		41	46	50	4	170					
(7) NaCl****	8A	25	36	350		480	cos 3.2 $\ominus$	8.2	31.6	39.8	21
(7) NaCl	8B	25	34	70	2	480	cos 3.4 $\ominus$	4.2	25.1	29.3	14.4
(7) NaCl		34	40	350		480	cos 2.6 $\ominus$	10.2	17.1	27.3	37.3
(7) NaCl		34	37	70	3	480	cos 3.2 $\ominus$	6.1	19.5	25.6	23.8

\* The numbers in column one denote different individual crystals. All data for which the number in this column is the same, were taken in a single run.  
 \*\* These angles represent the peak of the uncorrected beam.  
 \*\*\* After crystal had been exposed to air for 20 minutes.  
 \*\*\*\* The remainder of the data in this table is for cadmium reflected from natural crystals of sodium chloride.



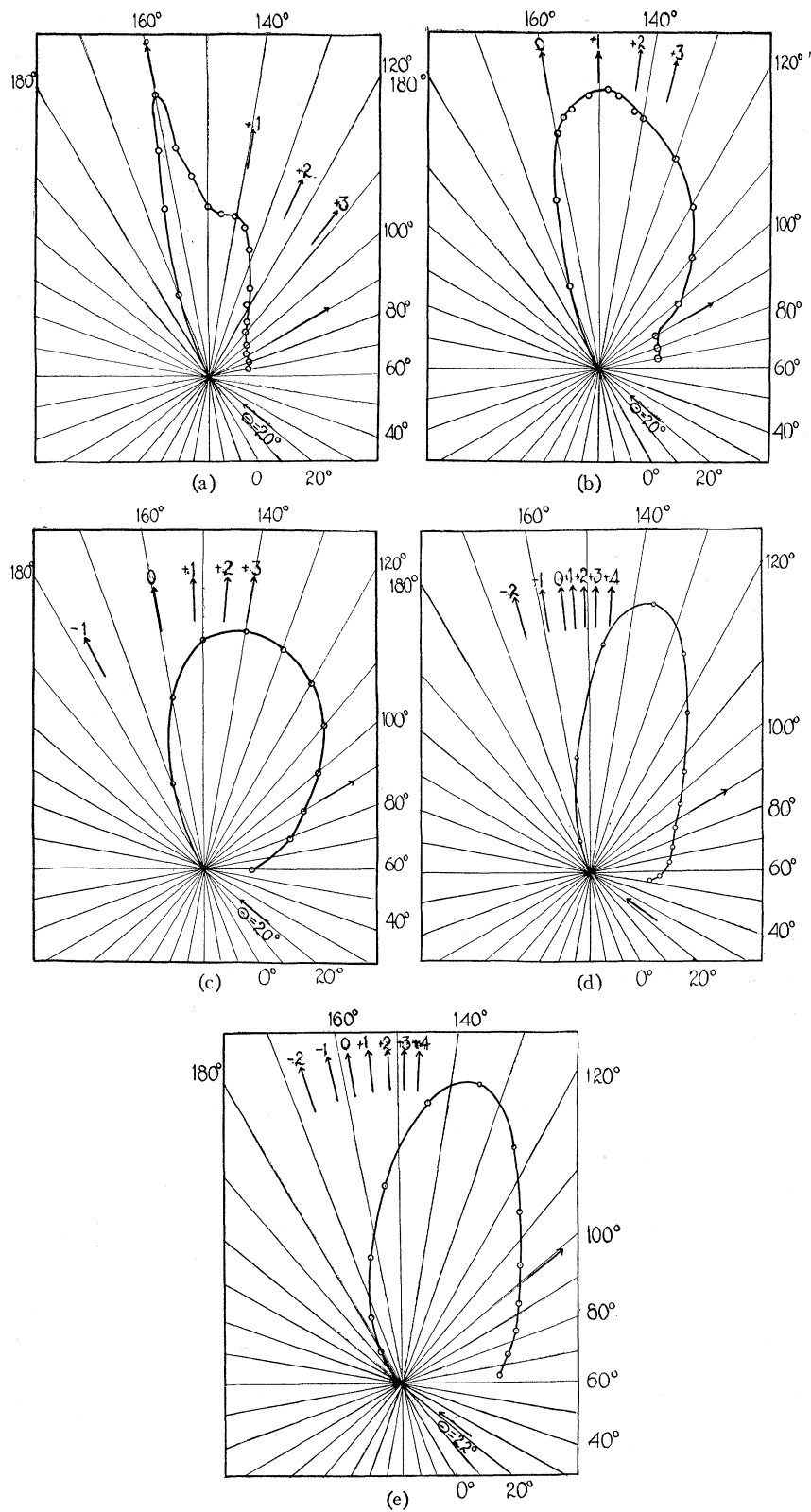


Fig. 11. Distribution of various atomic and molecular beams from sodium chloride crystals; (a) helium, (b) neon, (c) argon, (d) cadmium, and (e) mercury.

adsorbed gas before a directed beam could be obtained. The temperature necessary to accomplish this varied with different crystals, 350°C being sufficient in the case of sodium chloride, for lithium fluoride a temperature of 450°C was necessary and for sodium fluoride a temperature of 550°C was required.

It seems reasonable, as suggested by Zahl and Ellett,<sup>4</sup> that the better definition of the reflected beam at low crystal temperature is due to the decrease in thermal agitation of the crystal and the consequent increased resolving power. The increase in random scattering at low crystal temperatures is evidently largely due to the formation of a gas layer on the crystal surface.

Fig. 11 shows the distribution in the plane of incidence of helium, neon, argon, cadmium, and mercury<sup>9</sup> scattered from sodium chloride. That the asymmetry in the helium curve is due to the presence of a surface grating spectrum incompletely resolved is scarcely to be doubted. It is tempting to infer that the other curves are to be accounted for in the same manner. The maxima of the plus or minus first, the plus or minus second, and the plus third and fourth order spectra of the several beams incident upon sodium chloride would lie at the positions indicated by the arrows. If we take this point of view we will then attempt to account for the temperature shift in the direction of maximum scattering by supposing that it is due to a change in the force field at the surface of the crystal of such a character as to make spectra of positive orders relatively more intense at higher crystal temperatures. Thus the observed phenomena may be interpreted qualitatively at least in terms of surface grating diffraction. However, it is difficult to see, if this interpretation is correct, why rotation of the crystal in its own plane produces so little change in the scattering of mercury. With helium quite radical changes occur while no data are available on neon and argon.

In conclusion the writer wishes to express his appreciation to Professor A. Ellett under whose direction the work was done.

<sup>9</sup> The curves of helium, neon and argon were very kindly loaned to the writer by R. M. Zabel.