EXPERIMENTS ON THE WAVE-LENGTHS OF SCATTERED X-RAYS

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Abstract

Intensity distribution of scattered x-rays as a function of wave-length.—(1) *Molybdenum rays.* Specially built tubes enabled the radiators to be placed only 1.6 cm from the target, so that reliable measurements were obtained from small radiators. An ionization spectrometer (methyl iodide) with a calcite crystal was used. For Li and Al, curves are given for various scattering angles. The results are similar to those obtained by previous observers for carbon, the shift of the maximum intensity of the modified band agreeing with the theory of A. H. Compton. Simultaneous irradiation by two x-ray tubes permitted scatterers to be employed that were small enough to allow a fairly accurate estimate of the *width of the modified band.* This width (for lithium) was thus found to be greater than that permitted by Compton's equation. The curves obtained show that the intensity of the unshifted line relative to the general radiation is less in the scattered spectrum than when obtained direct from the target of the tube. Less detailed experiments with Be, C, Na, NaCl, Mg and S are in agreement with the theory as far as shift is concerned and show that the relative intensity of the modified band decreases as atomic number increases. (2) *Tungsten rays.* In this case the radiator could not be placed nearer than 10 cm, so less reliable results were obtained. However the shifts are in general agreement with theory.

PRELIMINARY reports of these experiments have appeared elsewhere.[2,3] The experiments were performed with one of the ionization spectrometers in this laboratory which has been previously described.[4,5] The preliminary reports mentioned the use of special water-cooled x-ray tubes, similar to those first designed by A. H. Compton,[6] and of the multiple slits devised by Soller.[7] The water-cooled molybdenum targets in the special x-ray tubes were of the type furnished by the General Electric Company in the apparatus manufactured for experiments on x-ray diffraction. These targets were sealed into long, narrow, glass tubes constricted and made thin-walled in a region near the focal spot. With such tubes the scattering substance should be brought within 1.6 cm of the center of the focal spot. No great difficulty was experienced in evacuating these tubes

[1] National Research Fellow.
[2] Allison and Duane, Proc. Nat. Acad. Sci. **11**, 25 (1925).
[3] Allison and Duane, Phys. Rev. **25**, 235 (1925).
[4] Allison and Duane, J. Opt. Soc. Amer. and Rev. Sci. Inst. **8**, 681 (1924).
[5] J. C. Hudson, ibid., **9**, 259 (1924).
[6] A. H. Compton, Phys. Rev. **22**, 409 (1923).
[7] Soller, Phys. Rev. **23**, 272 (1924).

so that they could be sealed off and run at 50 kv and 20 milliamp. from the high potential storage battery.

The multiple slits were constructed with 15 vanes of spring steel, 1 cm wide by 50 cm long, and .015 cm thick. These vanes were held between brass plates in which parallel grooves had been cut. Thus 14 parallel slits 50 cm long were produced, each slit .07 cm broad and 1 cm high. The calculated angular width of the beam from the slits was therefore 9.6 minutes of arc. The width of the unresolved Mo $K\alpha$ doublet should then be 12.1 minutes of arc in the first order. The observed width agreed well with this calculation.

The composite beam from these slits was 1 cm wide and necessitated therefore a crystal face 8.7 cm long in order to reflect the whole beam at an angle of incidence of 6°30′. (The critical angle of reflection of the Mo $K\alpha_1$ line is 6°43′.) An old face on a calcite crystal 9.2 cm long was finally adopted. This face was shown not to give spurious reflections by examining the Mo $K\alpha$ lines direct from the target of the tube.

In the course of the work a set of curves was obtained which showed the change of wave-length of the modified radiation with scattering angle in the case of the scattering of molybdenum rays by lithium. Later these experiments were repeated with the beam defined only by two single slits and reflected from one of the crystals previously used for wave-length determinations in this laboratory. The curves obtained in this way confirmed completely the results from the multiple slits and large crystal, and also showed that the increase in intensity obtained by the use of multiple slits is really surprisingly small.

The gain in intensity due to the narrow x-ray tubes enabled us to use small radiators, or, what amounts to the same thing, to select for examination radiation from a portion of the scatterer in which the range of scattering angle is small. The importance of this has been previously considered,[2] and will be illustrated later.

In examining the scattering of molybdenum rays we have made more or less isolated experiments using scatterers of Be, C, Na, NaCl, Mg, and S. We have made more extensive studies of the scattering by Al and Li. The results confirm those of other experimenters who have published curves or photographs representing the scattering of Mo x-rays in a similar manner.[8–12] They show that in addition to scat-

[8] A. H. Compton, Phys. Rev. **21**, 483 (1923) et seq.
[9] P. A. Ross, Proc. Nat. Acad. Sci. **9**, 246 (1923) et seq.
[10] Compton and Woo, Proc. Nat. Acad. Sci. **10**, 271 (1924).
[11] J. A. Becker, Proc. Nat. Acad. Sci. **10**, 342 (1924).
[12] Kallman and Mark, Naturwiss. **14**, 299 (1925).

tered radiation having the same wave-length as the primary, as demanded by the classical theory of scattering, there is, at least for the light elements, a large portion of the scattered radiation which is shifted in wave-length and obeys the simple quantum theory advanced by A. H. Compton and independently by P. Debye. Recently curves have been obtained which show that there is an appreciable wave-length breadth of the shifted radiation, as announced by Compton,[6] which cannot all be accounted for by the range of the scattering angle. Such an effect has been theoretically treated by Jauncey[13,14,15] and ascribed to the binding of the electrons to the nucleus and their motion in the Bohr orbits in the atoms of the scattering substance.

The early, unpublished work by Bergen Davis and the photographs taken by Ross lead to the conclusion that the ratio of the intensity of the modified line to the unmodified decreases with increasing atomic number, and the experiments reported here support this conclusion.

The investigation of the scattering of molybdenum rays by heavy elements is made difficult by the extremely low intensity of the *scattered* radiation from these elements. Thus in our experiments on Mg and S, the intensity of the scattered radiation was so small that reliable curves were obtained only with great difficulty. This effect may perhaps be ascribed to the rapid increase of true or fluorescent absorption with rising atomic number, while by comparison the scattering per electron remains approximately constant.

The question of the variation in the intensity ratio of the modified to the unmodified line with angle of scattering for a given element and given incident wave-length has been theoretically investigated by Jauncey.[14] The experiments reported here unfortunatly give no quantitative information on this interesting problem. Some experiments of Ross[16] seem to indicate that at small scattering angles the ratio of the modified to the unmodified line is decreased, and Compton[6] has also reported such an effect.

Experiments with Aluminium

The change of wave-length of the modified line with scattering angle is a fundamental part of the quantum theory of scattering advanced by A. H. Compton. Compton[6] has obtained curves showing this

[13] Jauncey, Phys. Rev. **24,** 204 (1924).
[14] Jauncey, Phil. Mag. **49,** 427 (1925).
[15] Jauncey, Phys. Rev. **25,** 314 (1925).
[16] Ross, Proc. Nat. Acad. Sci. **10,** 304 (1924).

effect in the scattering of Mo x-rays by carbon. In the present experiments a set of curves was obtained using aluminium radiators at various angles of scattering, and molybdenum primary rays. These are shown in Fig. 1. Simplified diagrams, showing to scale the relative positions

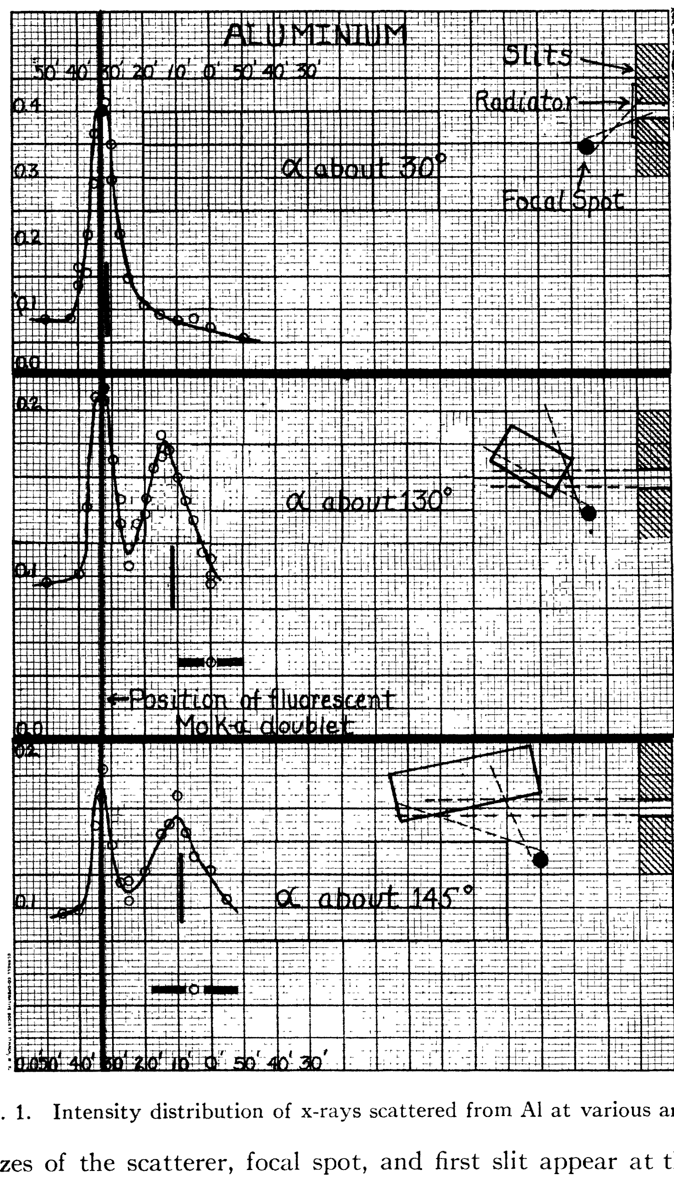

Fig. 1. Intensity distribution of x-rays scattered from Al at various angles.

and sizes of the scatterer, focal spot, and first slit appear at the right. The experiments were performed at a constant storage battery voltage of about 40 kv and 20 m-amp. of current. The spectrometer scale was frequently calibrated by determining the position of the fluorescent molybdenum $K\alpha$ doublet from a strip of molybdenum mounted in place of the scatterer. The position of this peak remained unchanged throughout the course of the experiments with aluminium and is indicated in the figure. The points below the curves taken at larger scattering angles show the ionization current obtained when the beam reflected by the crystal did not enter the ionization chamber slit. They therefore represent the height of the baseline due to natural leak of the electrical apparatus and to x-rays scattered by the crystal as an amorphous substance, etc. The position of the modified peak calculated from the Compton equation

$$\lambda - \lambda_0 = .0242 \quad (1 - \cos\alpha)$$

is shown by a heavy vertical line in each case. Since the finite size of the focal spot and radiator made quite a range of scatteıing angles possible, the position of the modified line agrees within experimental error with that predicted by the quantum theory of scattering.

It may be demonstrated from these curves that the intensity of the unmodified line relative to the general radiation under it is less than in the case of the radiation from the target direct. This ratio depends on the slit widths and the voltage. From the central curve of Fig. 1 ($\alpha = 130^\circ$) the value 3 to 1 may be calculated for this ratio. Spectra obtained from the target direct with the same slit width and voltage show that in this case the ratio is much greater, being about 18 to 1. The reason for this difference is not yet quite clear.

Fig. 2 shows the curve obtained when the range of scattering angle is large and includes the region about 90° where the wave-length of the modified line is changing most rapidly. Here every small volume of the radiator in the path of the slit is emitting an unmodified ray of constant wave-length, and a modified ray of a wave-length which depends on its scattering angle. Under these conditions, the theory indicates, and the experiment shows, that the shifted radiation is drawn out into a band whose intensity is low compared to that of the unmodified ray. This illustrates the difficulty in obtaining evidence of the Compton effect with large radiators.

In Fig. 2 and in every curve reproduced, *all* the readings of one experiment are plotted that were obtained in the angular range through which the curve extends. Due to mechanical or electrical disturbances of some kind, whose effects were appreciable relative to the very low intensities in the spectrum of the scattered x-rays, readings were occasionally obtained (as in Fig. 2) which were difficult to include in a smooth curve. Such readings were repeated later, as is indicated by two or more points for the same angular setting, and almost invariably then gave values consistent with the general trend of the curve.

Experiments with Lithium

A set of curves similar to those of Fig. 1, but with lithium as the scattering substance is shown in Fig. 3. The much greater intensity of the modified line with respect to the unmodified is at once apparent. These experiments were performed with two single slits defining the

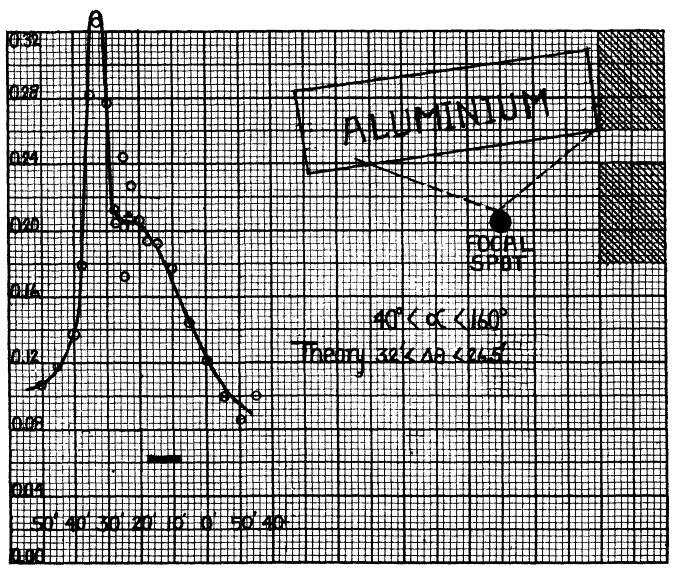

Fig. 2. Intensity distribution when the range of scattering angle is large.

beam. The results agree closely with those of similar experiments performed with multiple slits. With lithium as a scattering substance the intensity is much greater than with aluminium, and the curves, therefore, are more reliable. The lithium used appeared to be fairly free from oxide, and was kept coated with a paraffin oil during these experiments. The scattering from the carbon in this oil may have affected the relative intensity of the two lines somewhat. The slight shelf in the curve in which the angle of scattering is about 100° at the position of the unmodified peak was repeated several times and is undoubtedly present.

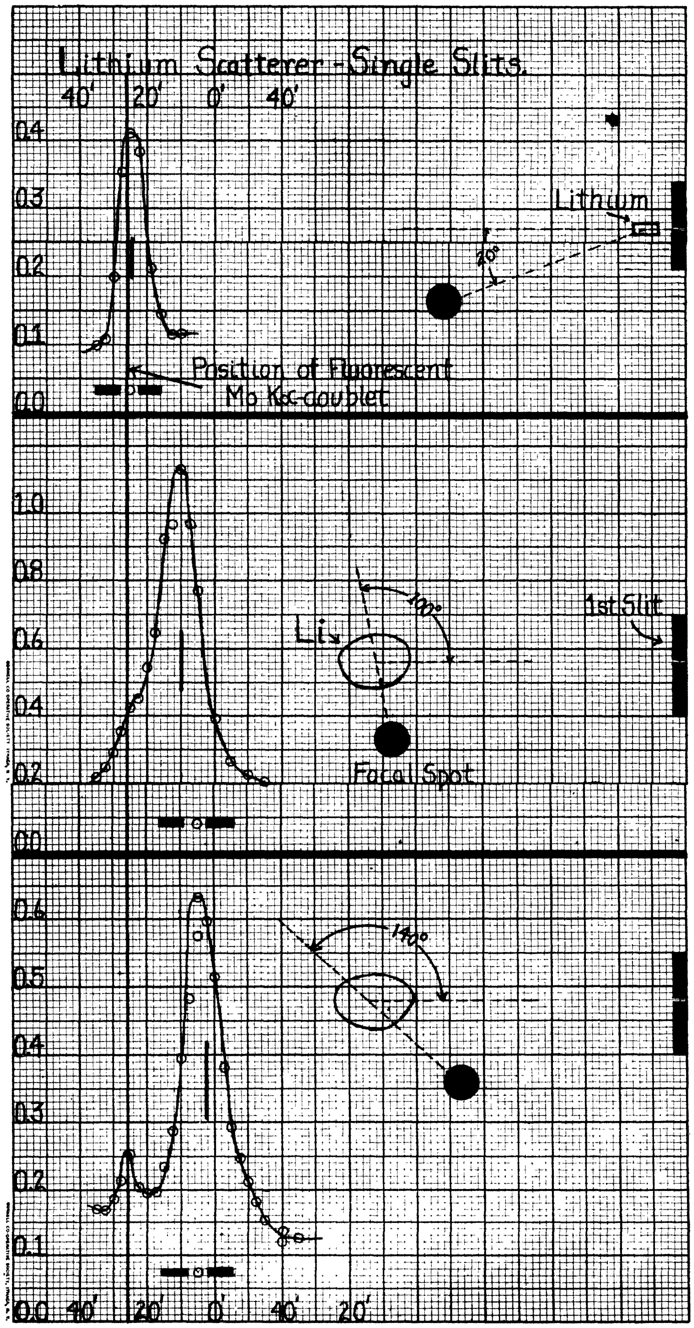

Fig. 3. Curves for scattering from lithium.

Experiments with Tungsten Primary Rays

Spectrometer measurements on the scattering of tungsten rays have been reported by Compton[6] and by Ross.[17] Ross has found that the relative intensity of the modified line to the unmodified for a given element is much greater for tungsten rays than for molybdenum rays. M. de Broglie[18] has reported measurements of the Compton effect using tungsten primary rays.

We have not found it possible as yet to operate a narrow x-ray tube with a tungsten target at sufficient voltages to bring out the tungsten

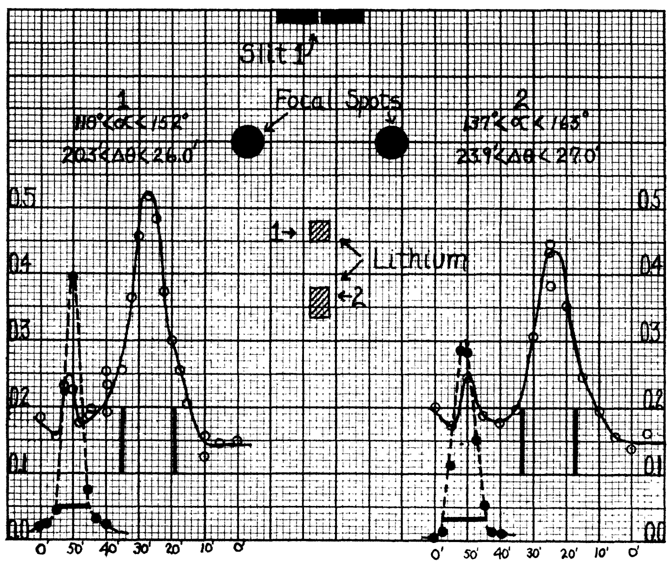

Fig. 4. Scattering from lithium irradiated from two Mo targets simultaneously.

characteristic rays strongly. Our experiments indicate that if this could be done, large intensities could be easily obtained. We have used a Universal type tube, operated at 100 kv and 6 m-amp. With this tube the radiators could not be placed nearer than 10 cm to the target. When the multiple slits were used, the rays were reflected internally from a thin slab of calcite placed across the beam. This solved the difficulty of obtaining a crystal long enough to take in the full beam by surface reflection at the small glancing angles involved. Aluminium and graphite radiators were used. The curves obtained were of low intensity, and not reliable as to details of shape, but showed

[17] Ross, Phys. Rev. **25**, 235 (1925).

[18] De Broglie, Compt. Rend. **178**, 908 (1924).

that the radiation was shifted as expected, and that the relative intensity of the shifted peak was greater for a given element than in the scattering of molybdenum rays, as reported by Ross.

The Breadth of the Shifted Line

Experiments have been recently performed in which the radiator was irradiated from two molybdenum target tubes simultaneously. Some curves that have been obtained are shown in Fig. 4. The curve marked 1 was taken when each tube was running at 47.5 kv and 20 m-amp. from the storage battery. Curve 2 was taken at about 40 kv and the same currents. The relative positions of the tubes, radiator, and slit are shown on the diagram. Single slits were used. The diagram refers to a horizontal plane through the top of the slit, which was 2.5 cm high.

With the extra intensity supplied by the second tube, it was possible to use smaller radiators than before, from which we could make a good estimate of the maximum range of scattering angle possible. In making this estimate, we have assumed that the entire button of molybdenum in the target of the tube acted as a source of x-rays, and have taken account of the vertical dimension of the slit in calculating the minimum scattering angle possible.

The width of the slits was calibrated by taking the fluorescent radiation from a molybdenum plate. This is shown in dotted lines. The heavy lines at the base of the fluorescent peaks show the angular widths at which the excess intensity due to the characteristic lines has fallen to about 1/20th of its value at the maximum. From this width, and the minimum and maximum scattering angles permissible, the angular range in which the modified peak should rise and fall to 1/20th its value above the general radiation have been calculated from the simple Compton equation. These angular ranges are between the vertical lines underneath the modified peaks. It seems evident that the modified peak is broader than that predicted by the simple Compton theory, extending certainly to longer wave-lengths than Compton's equation permits. This effect is presumably connected with the binding of the electrons to the nucleus,[13] and therefore should be less marked in lithium than in other heavier elements. The high intensities obtainable from lithium, however, have made the use of this element desirable.

It appears on consideration that all the experiments reported here contain a slight element of uncertainty in view of the fact that methyl iodide was used in the ionization chamber and the second order of the iodine critical ionization wave-length occurs in the region of the shifted peak from Mo Kα. This observation applies to all the experiments of previous observers in which ionization measurements were made with methyl iodide gas. The curves taken at small scattering angles (Fig. 1) indicate fairly well, however, that such an effect is practically negligible. The extent of the discontinuity introduced into the baseline depends on the fraction of the energy in the iodine critical absorption wave-length (.3737A) which is absorbed in the chamber. It is very much smaller in second order reflections than in first.

These experiments indicate that the shifted radiation should be considered to be a band with a sharp intensity maximum which obeys the laws deduced from the simple quantum theory of the scattering by free electrons. In any given atom, the rays scattered by the loosely bound electrons may be considered to give the modified radiation obeying more or less approximately the simple Compton equation. The rays scattered by the more firmly bound electrons may well produce the major part of the unmodified line and contribute most of the breadth of the shifted line in excess of that due to the range of scattering angle.

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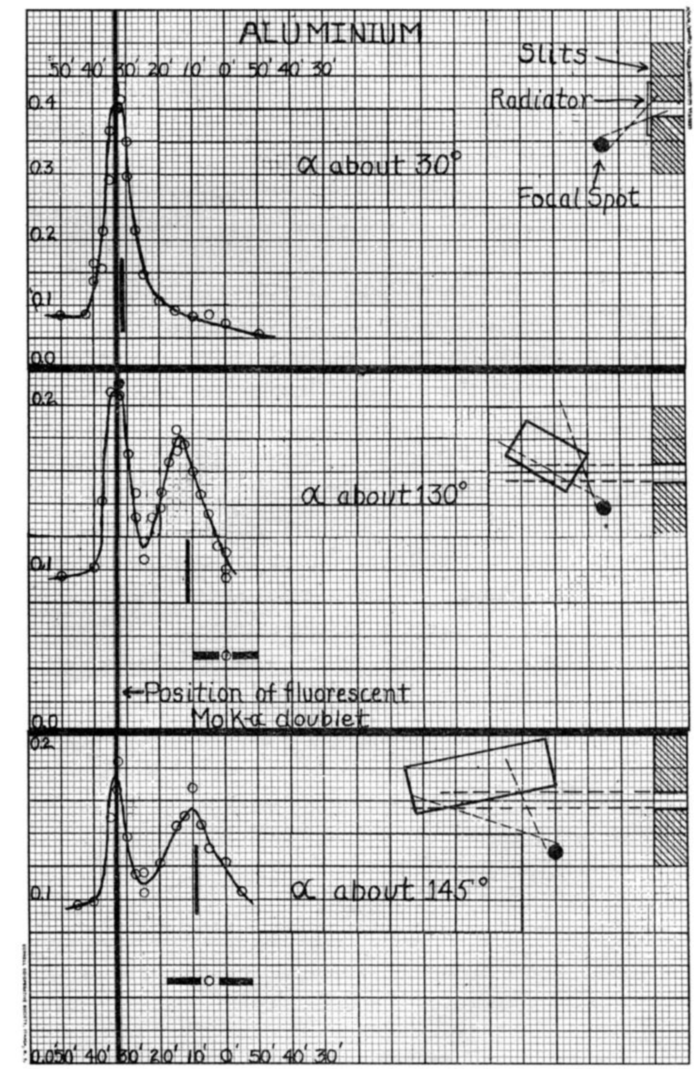

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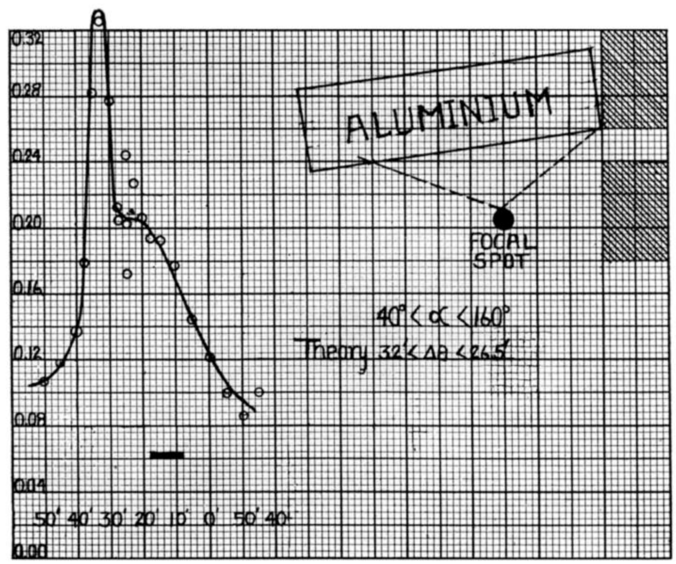
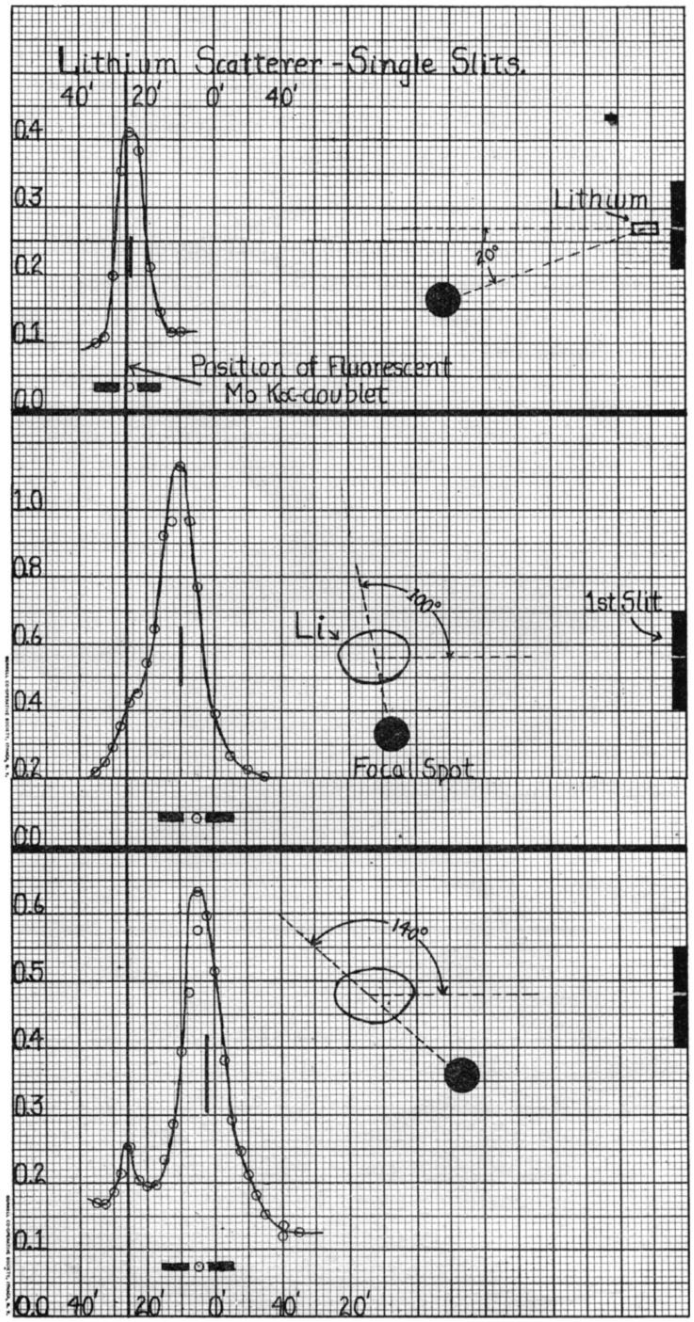


Fig. 2. Intensity distribution when the range of scattering angle is large.



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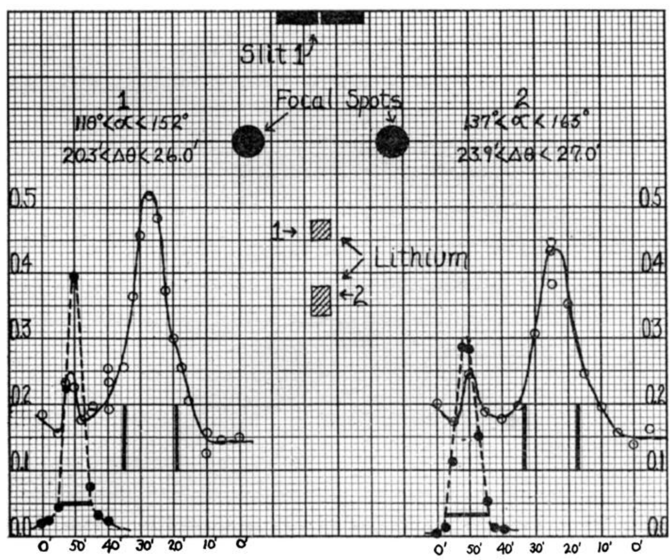

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