REFLECTION FROM, AND TRANSMISSION THROUGH, ROUGH SURFACES.

By A. F. Gorton.

IT is a matter of common knowledge that matt surfaces, such as ground glass, smoked glass, paper and plaster-of-Paris, which scatter in all directions the light that falls upon them, behave like polished surfaces when viewed at grazing incidence. According to the theory usually advanced in explaining this action, if the light scattered in a given direction by the elevated portions of the surface differs in phase from that returned in the same direction by the hollows or pits in the surface by a quantity small in comparison to $\lambda/2$, the light may be regarded as regularly reflected. The light thus reflected will be diminished in intensity, depending on the magnitude of the phase difference. Lord Rayleigh[1] showed this experimentally by sending light from a Welsbach lamp upon a thermo-couple after reflection from two parallel plates of silvered ground glass. A third ground and silvered plate was found to reflect as much energy as a polished silvered mirror. This experiment is in a sense qualitative, for it does not tell with what intensity the individual wave-lengths are reflected.

A study of rough surface reflection has been made recently by Meyer,[2] but his experiment also may be looked upon as qualitative in the sense referred to above. He employed a rather interesting scheme for showing that rough surfaces reflect like mirrors for sufficiently long waves. Light scattered by the matt surface was received by a concave mirror and focused on the slit of a fluorite prism spectrometer, which threw approximately monochromatic light on a thermo-couple. A galvanometer in series with the thermo-couple measured the amount of energy received from the matt surface. By rotating the concave mirror, the blurred image could be gradually thrown off the slit, first in one direction, then in the other. With the spectrometer set for wave-length 8 μ, measurements taken with the rough surface in question showed a sharp decrease in intensity as the image was shifted off the slit,—this decrease being very nearly as sudden as that obtained when a polished mirror was

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[1] Nature, 64, p. 385, 1901.

[2] T. J. Meyer, Verh. Deutsch. Phys. Ges., p. 126, Feb., 1914.

substituted for the rough surface. As the wave-length was decreased, this drop in intensity became more and more gradual. In other words, waves longer than $8\,\mu$ are regularly reflected and therefore sharply focused on the slit; while the shorter waves are scattered, and form a broad, diffuse image.

Though Meyer's experiments tell us how a surface of a certain degree of roughness behaves towards waves of different lengths, the method is not directly designed to show the reflecting power of such a surface throughout the spectrum. The experiments described in the following pages were undertaken with the idea of ascertaining the reflecting power, for the range of wave-lengths $.6\,\mu$ to $14\,\mu$, of matt surfaces which can be easily and quickly prepared, and thereby showing how well such surfaces are fitted to act as screens for cutting off the short waves. Not only reflection, but also transmission experiments (using roughened plates of rock-salt) were performed. It is not necessary to remark that a reflection "screen" is preferable to a transmission cell because it is good for an unlimited range of wave-lengths in the infra-red, whereas rock-salt and other so-called "transparent" substances possess regions of opacity. Besides these experiments on rough surfaces, some work was done on the reflecting power of polished glass, quartz and Iceland spar, in the regions of metallic reflection, as a function of the angle of incidence. The curves obtained have been included in this paper, together with a brief discussion of their bearing on the reflection of plane-polarized light.

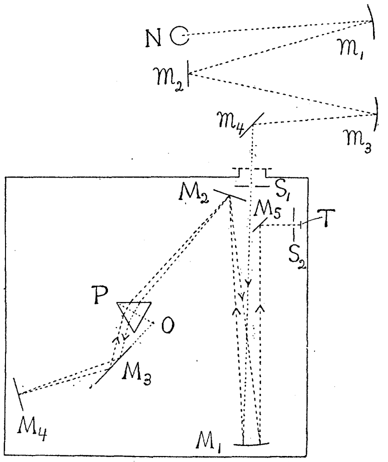

Fig. 1.

Apparatus.—The arrangement of apparatus is shown in Fig. 1. The source of light was a Nernst glower *N*, suitably protected from air currents by a metal cover. The glower was operated on a 110-volt storage battery, and the constancy of its radiation was found to be ample for the short period of time (5 minutes or less) required for taking measurements at a definite wave-length. The light was focused by a concave silvered mirror m_1 (7.5 cm. in diameter and 26 cm. focal length) upon the rough surface m_2, whence the light was received by m_3 (a duplicate of m_1) and focused on the first slit S_1 of the spectrometer. Although the diagram shows the arrangement for throwing a converging beam of light on the rough surface, all the earlier experiments were performed using strictly parallel light. In both cases the spectrometer receives that proportion of the light which is scattered by the rough surface at the same angle (angle of incidence = angle of reflection) as that at which light is regularly reflected by a polished mirror. The matt surface was pressed firmly by a spring against three screws held in a suitable framework—a device which ensured the exact replacement of one mirror by another. In addition, this framework, together with m_1 and N, rested upon a brass plate which rotated about a vertical axis passing through the middle point of the surface m_2, so that it was possible to alter the angle of reflection from 0° to 90° without changing the relative positions of N, m_1 and m_2 or of m_2, m_3 and m_4.

The spectrometer was of the usual type, consisting of a rock-salt prism P (area of faces 5×9 cm.), mounted with the plane silver mirror M_3 according to Wadsworth's arrangement for minimum deviation on a prism table whose axis of rotation passed through O. The table was turned by means of a device used by Mendenhall—a micrometer arrangement (not shown in the drawing) by which angular displacements of 1/10 second could be accurately read. The concave mirror M_1 (the only one used in the spectrometer) was of speculum metal, of 10 cm. aperture and 58 cm. focal length, figured by Brashear. The parallel beam of light reflected by M_1 reached the prism P after striking the plane silvered mirror M_2, which was introduced in order to decrease the astigmatism and thus improve the definition of the image. With the idea of doubling the resolving power, it was decided to return the light through the prism, so that the same effect was obtained as from two prisms in series. This was accomplished by inserting the plane silvered mirror M_4, which received the light from M_3 and returned it over approximately the same path, so as to reach the thermo-couple by way of M_1 and M_5. The edge of M_5 was beveled, so that the angle between the incident and return beams was as small as 2°. This slight departure from the strict conditions for minimum deviation caused no appreciable shift in the spectrum, as shown by the observed positions of the CO_2 emission bands ($2.7\,\mu$ and $4.4\,\mu$), the bands of metallic reflection of quartz ($8.5\,\mu$ and $9\,\mu$), and the Iceland spar band ($6.7\,\mu$) agreeing with the calculated positions. The thermo-couple T was a 3-junction compensated instrument, of bismuth-tin alloy, with a receiving surface 12 mm. long and 1 mm. wide; and the galvanometer was of the D'Arsonval type with a silver wire suspension. Both instruments were constructed by Dr. A. H. Pfund.[1] The thermo-couple-galvanometer system

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[1] Phys. Zeit., 13, 1912, p. 870.

had a sensibility of 150 cm. scale deflection for a candle at 1 meter, the scale distance being 4 meters. Throughout the work but little trouble was experienced with the galvanometer, which was not magnetically shielded. Over periods of time as long as 15 minutes the zero was constant to within 0.1 mm., and at all times readings could be repeated to within 0.3 mm., though such accuracy was not needed in view of the larger experimental errors inherent in the method employed. This steadiness is thought to be due in part to the care taken to protect the thermo-couple from stray radiation. An air-tight cover of galvanized iron, wrapped with a thick layer of felt, and provided with a small window for admitting the incident light, fitted securely over the whole spectrometer. After the initial adjustment for minimum deviation, this top was screwed down and the spectrometer permanently closed, save for the short intervals of time (30 seconds) when the window was opened for the purpose of taking readings. Dishes of sulphuric acid and calcium chloride were placed near the prism to remove moisture.

The arrangement described above for returning the light through the prism—a combination Wadsworth-Littrow mounting—possesses several advantages over the ordinary type of infra-red spectrometer: it yields double the resolving power afforded by a single passage of the light through the prism, and, for a prism of given size, delivers four times as much energy as the ordinary type of spectrometer with double the focal length; it involves the use of only one concave mirror, which, however, must be carefully figured; and it permits of an extremely compact spectrometer. As an illustration of the resolving power of the present instrument, a curve showing the transmission of pure ethyl alcohol is given below (Fig. 2). This curve is taken from some unfinished work of the writer's on the absorption spectra of organic substances during chemical reaction. Fig. 4, which shows the transmission of a film of alcohol 0.01 mm. thick, is copied from Coblentz's "Infra-red Absorption Spectra." (The percentage transmission is plotted as ordinates, and wave-lengths in μ as abscissæ.) It will be observed (see Fig. 2) that there are three small absorption bands between 2 μ and 3 μ, and perhaps five from 4 μ to 6 μ, while the great band at 3.5 μ is plainly double, one component being at 3.3 μ and the other at 3.7 μ, with a slight intermediate maximum at 3.5 μ (see magnified view in Fig. 3).

Experimental Procedure.—In the work on the reflection from rough surfaces, the procedure adopted was as follows. With the spectrometer set at a particular wave-length, the galvanometer deflection obtained with the rough surface in position (m_2, Fig. 1) was noted, together with the deflection observed when the matt surface was replaced by a polished plane mirror of the same substance. The ratio of the two deflections may be termed the "relative" reflecting power of the matt surface in question. Proceeding in this manner throughout the spectrum, a curve was drawn with wave-lengths as abscissæ and "relative" reflecting powers as ordinates. Then the angle of incidence was changed (but at all times the angle of incidence equalled the angle of reflection) and a new curve drawn. Having obtained a number of curves at different angles of incidence, a rougher (or smoother) surface was substituted and the same procedure repeated. In this way the effects of the two factors—angle of incidence and degree of roughness—could be analyzed separately, and the most suitable method of roughening the surface ascertained. In view of the fact that the object of the experiments was to develop an infra-red screen, it may seem more logical to get the absolute reflecting power of the matt surfaces, either by a direct method, or by comparison with a plane silvered mirror. This was not done for several reasons. In the first place, it was found convenient to use ordinary plate glass in grinding most of the surfaces. Though some of the surfaces were afterwards silvered, the result was not a success, because the customary polishing with rouge could not be resorted to. Since the absolute reflection curve of glass is not only very low (4 per cent.) in the transparent region, but is complicated by a curious maximum near 9 μ, it is clear that the absolute reflection curves of rough glass, taken at various angles, would not be very illuminating. Moreover, it was deemed advisable to ascertain if the character of the substance used in making the surface had any influence on the shape of the reflection curves. This could be done only by the method first described.

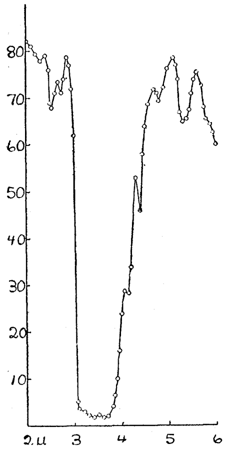

Fig. 2.

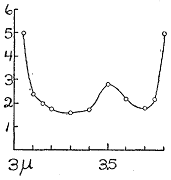

Fig. 3.

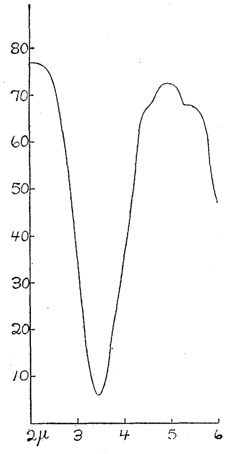

Fig. 4.

In the experiments on transmission through rough surfaces, a slight change was made in the disposition of apparatus. The framework used for holding the matt surface m_2 (Fig. 1) was removed, and the brass plate supporting N and m_1 was rotated so that the light traveled directly from m_1 to m_3, being brought to a focus midway between the two mirrors. At this focal point was introduced the roughened plate of rock-salt whose transmission was desired. The ratio of the deflection obtained with the rock-salt plate in position to that observed when the plate was removed gave the percentage transmission.

In the supplementary work on the reflecting power of polished glass, quartz and Iceland spar as a function of the angle of incidence, comparison was made with a plane silvered mirror, whose reflecting power was found later by a direct method, and the reflecting powers relative to silver were thus reduced to absolute values.

Results.—The simple theory given above tells little about the behavior of ordinary rough surfaces towards waves of different lengths, for the reason that such surfaces are extremely irregular in structure. This fact is brought out by examination with the microscope, and is shown also by the absence of decided interference minima in the reflection curves. Such minima are exhibited by a surface of regular topography—for instance, a plane reflection grating placed with its grooves parallel to the plane of the incident and reflected beams of light. The writer used a small speculum grating, of 7,000 lines to the inch, ruled by Dr. J. A. Anderson. The grating was placed with its lines horizontal and its reflecting power, at 23°, compared with that of polished speculum. The result is shown in Fig. 5. (Wave-lengths in μ are plotted as abscissæ, "relative" reflecting power in per cent. as ordinates.) A deep minimum is noticed in the curve at 0.71 μ, where the relative reflecting power is

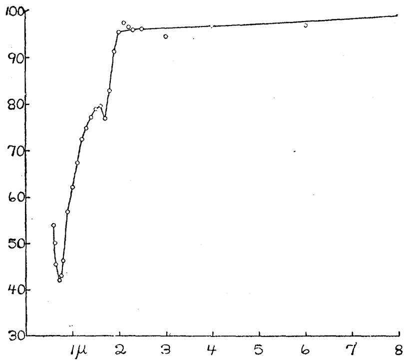

Fig. 5.

42 per cent., and a second one, less marked, at 1.7 μ. If we assume for the sake of simplicity that the grooves are all shaped like the letter V, it is a simple matter to calculate their probable depth. The condition for the principal interference minimum is $2H \cos i = \lambda$, where H = depth of groove, i = angle of incidence. Substituting the values $\lambda = .71\ \mu$, $i = 23°$, H is found to be .38 μ, or 1/66,000 inch.[1]

Rough Surface Reflection.—Various processes of preparing matt surfaces were tried, but only one—that of grinding with the finest emery and water—was found satisfactory. Glass plates which had been roughened with the sand-blast and others which had been etched were tested, but some were found to be too coarse and all were lacking in uniformity. The attempt was made to plot the reflection curves of smoked glass at various angles of incidence, in order to draw a comparison between this type of matt surface and the ordinary ground surface, the former being topographically the reverse of the latter. Uniform films of smoke of any desired thickness are easily produced, but, as one might expect, their reflecting power, even at large angles of incidence and for waves as long as 10 μ, is very small. Some observations were made on smoke films which had been gold-plated cathodically, but they proved disappointing, perhaps because the deposit of gold was too thin to increase the reflecting power appreciably. The surfaces whose curves appear in Figs. 6, 7, 8 were all prepared by the method first described. Two pieces of ordinary plate glass $\frac{1}{4}$ inch thick were ground together, using the finest grade of Bausch & Lomb emery and enough water to prevent sticking. A few minutes' grinding yielded a fairly fine and very uniform surface. Much smoother surfaces were obtained by washing off the emery and continuing the grinding with water alone, but great care had to be taken to avoid scratching. In order to increase the reflecting power and to see if the material of the surface played a rôle, some of the plates were coated cathodically with gold, platinum and silver. Some typical curves are shown in Fig. 6. Curve I. gives the "relative" reflecting power at 23° of a comparatively rough plate which had been silvered; Curve II. was taken at 70°. Curve III. shows the relative reflecting power of a much finer surface, also silver-plated, at 45°. (In all the reflection curves values of the relative reflecting power, *i. e.*, the reflecting power of the rough surface divided by that of a polished mirror of the same material, are plotted as ordinates, and wave-lengths in μ as abscissæ.) In the case of both surfaces, the comparison mirror was silvered simultaneously with the matt surface, to ensure films of equal

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[1] *Note.*—It is to be observed that the curve (Fig. 5) in reality gives the energy distribution in the principal image of the grating.

thickness. One notices that increasing the angle of incidence from 23° to 70°, in the case of the rougher surface (Curves I. and II.), increases the steepness of the curve and eliminates the horizontal portion at the short-wave end, but causes no considerable increase in reflecting power beyond 10 μ. It is also plain that the curve for a smoother surface (Curve III.) is steeper than that for a rougher one even at a greater angle of incidence. These and other facts are brought out better by Figs. 7 and 8. Fig. 7 gives the relative reflecting power of a surface not quite

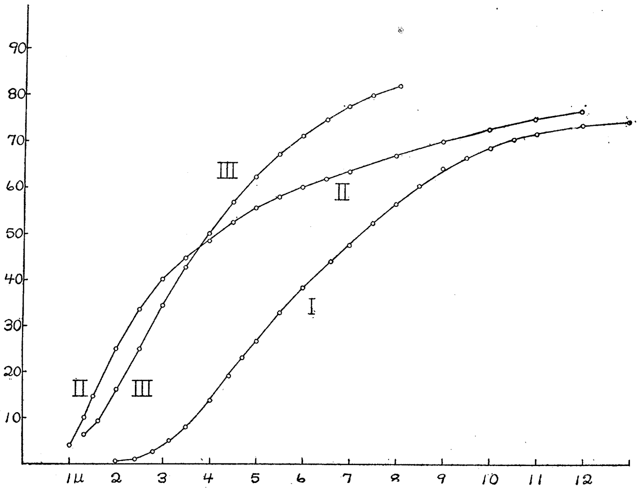

Fig. 6.

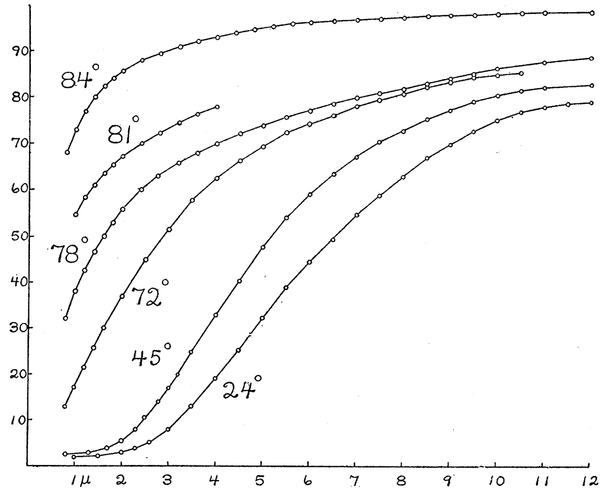

Fig. 7.

as coarse as the first one described above, which was platinized cathodically, and Fig. 8 shows the results obtained with an exceedingly fine surface of ground glass which was not covered with any metallic deposit. The former was compared with a polished mirror platinized simultaneously with the rough surface, and the latter was compared simply with a polished plate of glass. The angle of incidence is marked on each curve. In order to show, for a given rough surface, how the relative reflecting power for a fixed wave-length varies with the angle of incidence, some points were taken from the curves in Fig. 8 and plotted as shown in Fig. 9. A glance shows that the relative reflecting power increases most rapidly at 1 μ for angles between 75° and 80°.

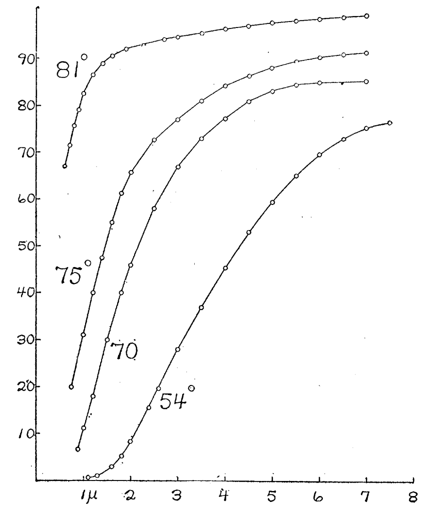

Fig. 8.

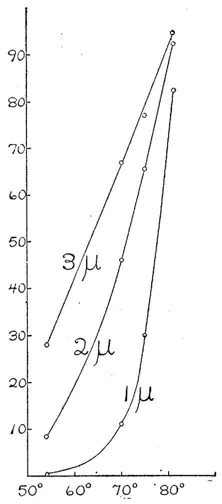

Fig. 9.

Analysis of all the curves brings out the following points:

1. For small angles of incidence the curves are not steep and reach a limiting value considerably below the theoretical value of 100 per cent. This is attributed to the presence in the surface of pits much deeper than the average. For the same angle, the curve for the finer surface is steeper and attains higher values.

2. Increasing the angle of incidence steepens the curve, and the smoother the surface, the greater the increase in steepness.

3. For the purpose of serving as a screen for cutting off the short waves, a rough surface at a large angle is inferior to a smoother surface at a smaller angle.

4. The steepest curves of all are obtained with the finest surfaces used at large angles of incidence.

5. The material of the surface does not affect the shape of the curves for the "relative" reflecting power. Hence if the ground glass surface mentioned above were silver-plated, the curves in Fig. 8 would give absolute values of its reflecting power.

Transmission through Rough Surfaces.—Fig. 10 gives the results of some experiments on the transmission of rough rock-salt crystals. Since both faces of each crystal were roughened, and therefore the light had to pass through two matt surfaces, the curves are steeper than they would be if only one face were rough. Curve I. was taken with a crystal ground with emery, whose surfaces were very rough. Curve II. shows the transmission of a finer plate, which was transparent to red light. Curve III. is for a crystal which was roughened simply by breathing on it for a few seconds. On account of the steepness of the curve, this plate makes a satisfactory transmission screen for eliminating wave-lengths shorter than 1 μ. A curious feature of this particular crystal was that, when held before the Nernst filament, it transmitted only the blue-green,—a striking phenomenon of interference exhibited beautifully by films consisting of minute bubbles,[1] and by gratings whose central images are colored. Viewed under the microscope the surface showed a regular structure resembling that of a honeycomb.

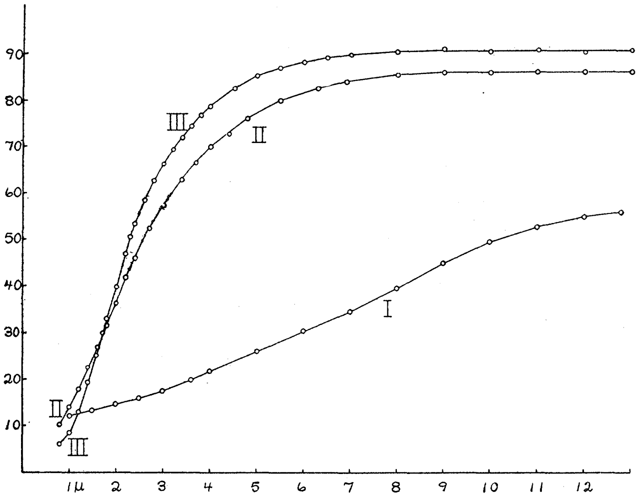

Fig. 10.

Reflecting Power of Polished Glass, Quartz and Iceland Spar as a Function of the Angle of Incidence.—In mapping the "relative" reflecting power of ground glass, it was thought advisable to plot the reflection

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[1] Wood's Optics, p. 253, new edition.

curves of polished glass at various angles. The results are given in Fig. 11, ordinates being absolute values of the reflecting power, and abscissæ wave-lengths in μ. The curves were taken at the following angles of incidence: I. at 23°, II. at 54°, III. at 60°, IV. at 63°, V. at 70°, VI. at 81°, VII. at 84°. The reflecting power at 23° is low in the visible (4 per cent.), drops to a fraction of 1 per cent. at 8 μ, and rises to a maximum at 9.4 μ, with a slight bulge in the curve near 8.8 μ. Increasing the angle of incidence has the effect of doubling this maximum, and the minimum at 8 μ is accentuated, the rise from 8 μ to 8.3 μ being enormously steepened. In the region of transparency (*i. e.*, below 7 μ), the increase in reflecting power follows the law for the reflection of unpolarized light,

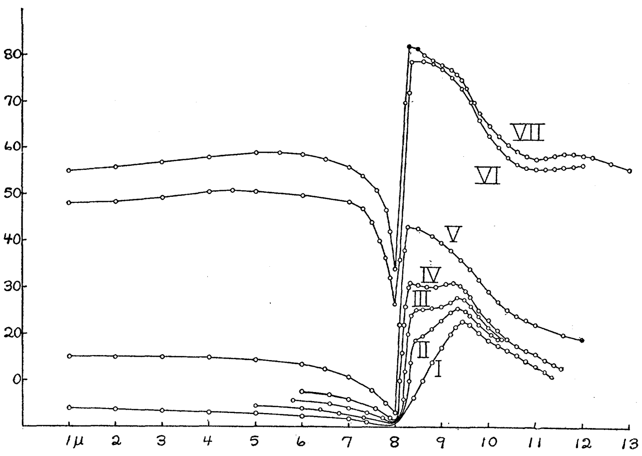

Fig. 11.

$$J = a^2\left\{\frac{\sin^2(i-r)}{\sin^2(i+r)} + \frac{\tan^2(i-r)}{\tan^2(i+r)}\right\}.$$

In the region of absorption (beyond 7 μ), the changes in the index of refraction and the extinction coefficient would appear to be rather complex. That these curious effects are due in part to polarization seems probable for several reasons: (1) The doubling of the maximum begins to be marked in the vicinity of the angle of maximum polarization (56°). (2) Nyswander[1] mapped the reflection curves for the crystals calcite and aragonite, using light plane-polarized in different azimuths, and showed that certain maxima of reflection are due to one component of the incident light but not to the other, while other maxima are due to both.

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[1] Nyswander, PHYS. REV., 28, 1909, p. 291.

Nyswander's results seem to have a direct bearing on the curves for glass given above, and also on those for quartz and Iceland spar, which are given below in Figs. 12 and 13 respectively. At large angles of incidence, the minima on both sides of the maxima become very striking. In the case of quartz (Fig. 12) the minimum at 7.5 μ becomes sharply defined at 78° and is very deep at 84°, while that at 9.6 μ is absent in all but the 84° curve. At 84° the maximum at 8.6 μ is apparently double, and a curious minimum appears at 12.7 μ. In the case of Iceland spar

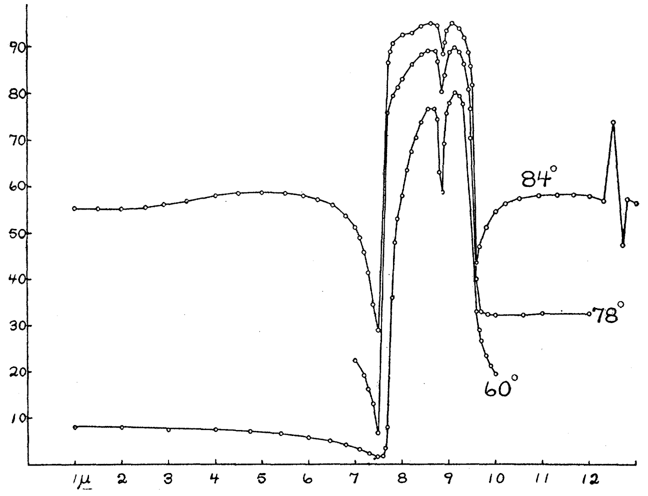

Fig. 12.

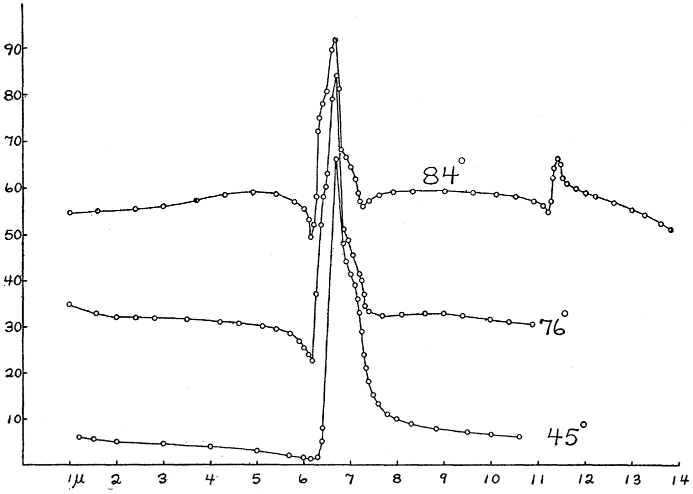

Fig. 13.

(Fig. 13) the maximum at 6.7 μ shows signs of being double at 45°, and is apparently triple at 84°. These distortions of the reflection curves may be traced to the elliptical polarization[1] which is known to take place at the surface of the crystal. Results of theoretical importance in regard to a possible connection between the angle of incidence and the optical constants of the crystal, in the region of metallic reflection, might be hoped for if these experiments were repeated, using plane-polarized light. This the writer expects to do in the near future.

SUMMARY.

1. A study of the reflecting power of matt surfaces at various angles of incidence and of the transmission of roughened plates of rock-salt, in the region 0.6 μ to 13 μ, has been made for the purpose of finding a suitable screen for cutting off the short waves.

2. The best results, in the case of reflection, were obtained with the finest surfaces used at rather great angles of incidence. Experiments showed that a surface of plate glass, which had been ground uniformly with the finest emery and then silvered, when used at an angle of 75°, reflected 90 per cent. at 4 μ, approaching 100 per cent. for longer wavelengths, and only 10 per cent. at 1 μ, less than 5 per cent. in the visible red, approaching zero for the shorter waves. Very similar results were obtained for the transmission of a plate of rock-salt which had been roughened merely by breathing gently upon it. In both cases, the finer the surface, the more suddenly does it cut off the short waves.

3. Increasing the angle of incidence was observed to effect a profound and curious change in the reflection curves of polished glass, quartz and Iceland spar, which may best be described as a quasi-resolution of the bands of metallic reflection. This is thought to be due to a change in polarization at the reflecting surface (*i. e.*, a change probably from plane-polarized to elliptically-polarized light).

4. A description is given of an infra-red spectrometer which is believed to possess better definition and greater resolving power than is usually furnished by instruments of similar type.

In conclusion, the writer wishes to thank all those who have aided him in this investigation. He is under obligations to Professor J. S. Ames, for advice and criticism, and to Dr. J. A. Anderson, for the loan of gratings and mirrors. The mechanical excellence of the spectrometer is due to the skill of Mr. C. M. Childs, one of the mechanicians in this laboratory. To Dr. A. H. Pfund, who suggested and directed the work, the writer is very grateful for his ingenious suggestions, inspiring criticism, and constant encouragement.

JOHNS HOPKINS UNIVERSITY, June, 1915.

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[1] A. H. Pfund, Astrophysical Journal, XXIV., 1, 1906, p. 29.