OPTICAL NOTES.

By Wm. W. Coblentz.

I. Reflection and Refraction at the Interface of two Media Having Intersecting Dispersion Curves.

OCCASIONALLY there appear notices of methods for making objects invisible by selecting combinations of media having about the same index of refraction as the immersed solid. This subject was first investigated by Christiansen[1] in 1884. His object was to show that white powders are transparent. For this purpose he used a mixture of ground glass, benzene and carbondisulphide. The transmitted light varied in color from violet to red, depending upon the size of the glass particles, upon the quantity of carbondisulphide mixed with the benzene, and also upon the temperature. That wave-length, for which there is an equality of the indices of refraction of the mixture, is transmitted without reflection or refraction. It varies with the temperature, is fairly homogeneous, and is called " Monochrome " by Christiansen. The reflected and refracted colors bear his name.

The most recent notice on this subject is by Wood,[1] who dissolved chloralhydrate in glycerine. This solution has almost the same dispersion as glass, and finely powdered glass, in it, is transparent without showing a trace of Christiansen's colors.

The object of the present communication is to call attention to a phenomenon connected with media having intersecting dispersion curves, hence the same index of refraction for a certain wave-length of light.

While investigating the infra-red absorption spectrum of eugenol, $C_{11}H_{14}O_2$, it was found that the liquid had decomposed on standing exposed to the light, the color having changed from a light to a deep reddish brown. As a film between two plates of rock salt,

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[1] Christiansen, Ann. der Phys., 23, p. 298, 1884.

[2] Wood, Phys. Rev., Vol. XV., p. 123, 1902

observed at a varying angle of almost grazing emergence of the light, one sees a brilliant series of spectral colors — reddish brown for the reflected, and violet for the transmitted rays. Safrol, $C_{10}H_{10}O_2$, which is light straw-color also shows this effect while carvacrol $C_{10}H_{14}O$, also straw-color, does not. At first this seemed likely to be due to "Resonance." But the directly transmitted light showed no peculiarities as viewed in a direct-vision spectroscope. Furthermore, the same films between glass plates lost this property. It was then suggested by Professor Nichols that this is probably due to the near equality of the refractive indices of the two media.

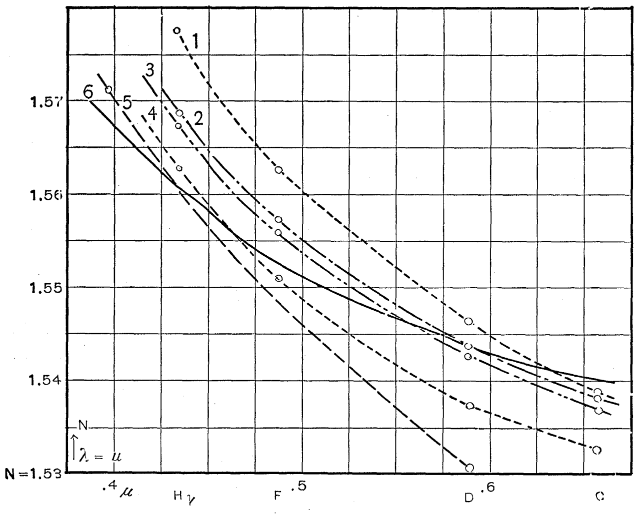

Fig. 1.

Dispersion curves : 1 = benzaldehyde ; 2 = eugenol ; 3 = safrol ; 4 = methyl eugenol ; 5 = cuminol ; 6 = rock salt.

A glance at the dispersion curves[1] of rock salt and the liquids, in Fig. 1, explains the question. In fact they contain more information than was first anticipated. In the region to the *right* of their intersection with the rock salt dispersion curve, the indices of refraction of the liquids are *less* than for rock salt, while to the *left* of their intersection they are *greater*. To the *right* of this intersection, as the rays pass from rock salt to the liquid, we have the ordinary case of total internal reflection, which can occur only when

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[1] Indices from Landolt & Börnstein, Physical Tables.

a ray, traveling in a given medium, falls upon the boundary separating it from a less refracting medium at an angle of incidence greater than the critical angle. To the *left* of the intersection, in the same manner, the rays pass from a less to a greater refracting medium, and we have the ordinary case of refraction.

However the occurrence of total reflection, and of refraction at the boundary of two media, at the same time, by breaking up and dispersing a non-homogeneous ray of light is rather unique, and is so easily observed that it seems worth mentioning. It impresses us the more with the question of what occurs at the interface of two media, of optical density, etc., which will be considered presently.

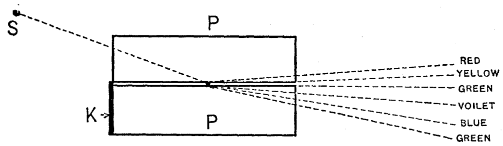

Fig. 2.

Let us first consider what has really been observed when non-homogeneous light passes into a combination of media like a film of eugenol (from oil of cloves or benzaldehyde from bitter almond-oil; the essential oils might answer the purpose), held between the two plates of rock salt, as indicated in Fig. 2, where p, p, = plates, s = the source of light, k = an opaque screen to prevent light from entering from below and thus confusing the resultant distribution of light. It was found, on viewing the surface of the films of eugenol at an angle of almost grazing emergence, as shown in Fig. 2, that the totally reflected light was a reddish brown, which changed to a greenish yellow as the angle with the normal was increased. Viewed end on a light green was visible. Moving the eye farther along so as to get the transmitted light, a quite deep blue appeared which changed to a blue-green, and finally light green as the eye was moved farther around the edge. For benzoldehyde, following in the same order, the reflected light was a deep red, cardinal, reddish brown to orange, then blue to green for the transmitted rays. In the same manner the colors for safrol were reddish brown, orange to light green for reflection, then violet, blue green to light green for the transmitted ray. Most interesting of all is cuminol, $C_{10}H_{13}O$, which, as will be noticed in the dispersion curves, Fig. 1, intersects the rock salt curve towards the violet. For this compound, the reflected rays, observed in the usual order, appeared in succession brownish red, yellow, green, and light green, while the transmitted rays were deep violet then blue to deep green.

It is to be noticed that the arrangement of the spectral colors appears anomalous, *i. e.*, red, yellow, green, then violet, blue, green.

However, since we are *looking at* the transmitted light we see the virtual spectrum in which case the violet appears the least refracted.

A quotation from Rayleigh[1] seems in order there, since the media in question show continuity as well as discontinuity when we consider their dispersion curves. This combination might possibly be used to study the question of a finite reflection at the interface of two media having different dispersive powers, at the point where the indices are the same.

The present cursory examination shows qualitatively how dependent the reflected wave-lengths are upon the relative difference in the refractive indices. Thus for benzaldehyde where the intersection of the dispersion curves is toward the red no green is reflected while for cuminol all wave-lengths up to the deep green are reflected.

The experiment is simple and easily performed. Rock salt is easily obtained. The natural cleavage surfaces last the longest, and are usually just as plane as the hand polished. The few striations will do no harm if the plates are put together at their common cleavage face. The splitting of the plates is most easily done by applying a thin, sharp-bladed knife, and tapping it gently with a light hammer. The size of the plate produced depends upon the dexterity of the manipulator as well as upon the homogeneity of the crystal. A plate 2 x 3 x .2 cm. will answer the purpose, unless a lantern projection is desired. A few drops of the liquid is placed

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[1] Rayleigh, Light, Encyc. Britt., 9th ed., 24, p. 458, 1888. "The whole problem of reflexion is so much concerned with the condition of things at the interface of two media about which we know so little. . . . Reflection depends entirely upon an approach to *discontinuity* in the properties of the medium. If the thickness of the transitional layer amounted to a few wave-lengths there would be no sensible reflexion at all. Our theories take no account of the fact that one at least of the media is *dispersive*. . . . We may thus expect a finite reflexion at the interface of two media if the dispersive powers are *different* even though the *indices* be absolutely the same for the waves under consideration, in which case there is no refraction."

on a plate, which is then covered with a second plate and the two held together in a clamp or by means of a wire wrapped around them. The liquids mentioned have high boiling points, hence are convenient to manipulate. The incident light should not be too intense. Daylight has sometimes been found most serviceable. The bottom, one end, and the two sides of the lower plate should be protected from stray light. The incident light is then permitted to enter from above, and viewed from the other end, as already described. Such plates will last for several months provided the surfaces have not been rubbed hard, nor scratched in cleaning.

The disappearance of an object when immersed in a medium having the same refractive index is less exactly shown by placing powdered rock salt in one of the liquids mentioned. (Ordinary salt will not behave thus.) A blue color is visible for the transmitted light, while patches of totally reflected red are also apparent — "Christiansen colors." Applying heat the whole becomes opaque, but again becomes transparent on cooling. For a lantern projection it is best to have the rock salt split into parallelopipeds having edges, say .5 to 1 cm. These are placed in a flat, glass cell and covered with benzaldehyde. In this case the reflected and refracted rays (for light passing through the liquid) at the interface, are just the reverse of the case already considered when the liquid was between the rock salt plates. Here we have violet, blue, green for reflection, then green, yellow, red for refraction, observed in the order already described.

At the same time that one observes this effect at the upper surface of the rock salt cube, the phenomena already described for a film of liquid between the plates can be seen at the lower surface if precaution has been taken to avoid stray light from entering the sides and the bottom of the cell. To demonstrate this most successfully it is best to have one large parallelopiped of rock salt in the liquid, covering its sides and the upper half of one end with tinfoil to avoid confusion from stray light. Even then it is difficult to repeat one's observations, and the method of placing the liquid between plates of rock salt seems preferable. However, for the spectacular, the display of colors from the parallelopipeds of rock salt in benzaldehyde rivals that obtained by interference of polarized light in piles of mica plates. Rock salt is about the only transparent mineral from which such regular solids with plane, highly polished faces, can be obtained cheaply. The effect is rendered still more conspicuous by placing ground rock salt in the bottom of the cell and the parallelepipeds above, thus projecting both upon the screen at the same time. As the cell grows warmer from the lantern the wave-lengths transmitted without reflection or refraction will shift in a very striking manner.

II. The Infrared Absorption Spectrum of Selenium.

About a year and a half ago the absorption spectrum of a film of selenium, melted between rock salt plates, was found. Commercial vitreous selenium was used. It was found that the transmission varied with the age of the film, for the first few days, hence it seemed wise to repeat the work. Since then, through the courtesy of Dr. Carveth, of the Chemistry Department, an opportunity was granted to repeat the observations on very pure selenium prepared by A. P. Saunders.[1] The results seem worth recording, since they complete the exploration of the spectrum from the ultraviolet to 14 μ in the infrared.[2]

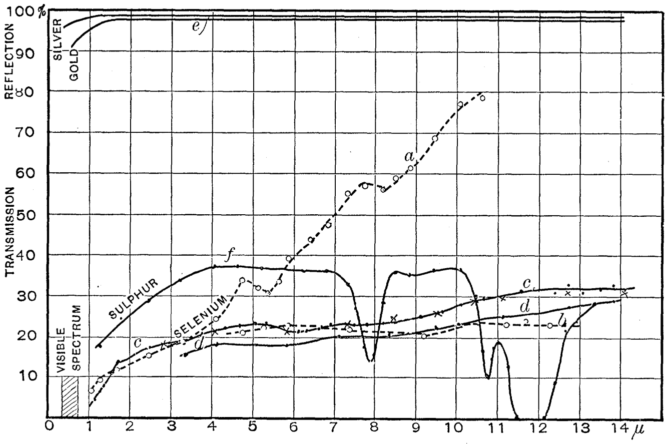

Fig. 3.

The results are shown in Fig. 3, in which curve *a* shows the

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[1] Saunders, Allotropic Forms of Selenium, Jour. Phys. Chem., Vol. 4, p. 423, 1900.

[2] A mirror spectrometer, rock salt prism, and radiometer were used. Described in the Phys. Rev., Vol. XVI., Nos. 1 and 2, 1903.

transmission for the commercial material. The transparency at this time increased with increase in wave-length. Two days later the film was reëxamined, curve *b*, when a constant transmission of about 20 per cent. was found throughout the spectrum. This it continued to do, as was found on subsequent examination.

Ordinary selenium contains sulphur, and since the latter changes from one crystallographic form to another soon after it has been melted and permitted to cool, this may perhaps explain this change in transparency.

Curve *c* gives the transmission of pure selenium, examined like the preceding. The dots show the first examination just after melting while the crosses show the second one made two days later. It is to be noticed that the two curves coincide.

Curve *d* gives the transmission for this film thirty days later. It likewise is fairly constant in its transmission, being parallel but about 3 per cent. less than for the preceding dates. This, no doubt, is due to the fact that the film had to be remounted on the carrier before the spectrometer slit, while the surfaces of the rock salt plates may have changed by that amount. The results show that the pure material did not change from a varying to a constant transmission, as was found for the commercial article. The film of pure selenium was made by melting between very clear rock salt plates, heated just above the melting point. The film was homogeneous, and its color was a deep ruby-red. Thickness, 0.07 mm.; area, 8 × 14 mm.

It would have been interesting to examine the metallic modification of selenium. But no film could be made procured that was free from rills, so the examination was never made.

The absorption and refraction indices have been determined in the visible spectrum by Quincke,[1] in the visible and ultraviolet by Cornu,[2] and by Wood.[3] The ultraviolet reflecting power has been measured by Nutting.[4] He found that the reflecting power increases abruptly from a low value in the red to a maximum in the yellow, falls off slightly toward the violet and then more rapidly in the ultraviolet, which agrees with Wood's observations. Wood thinks

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[1] Quincke, Wied. Ann., Jubelband, p. 336, 1874.

[2] Cornu, Compt Rend., 108, 917 and 1211, 1889.

[3] Wood, Phil. Mag. (6), 3, p. 607, 1902.

[4] Nutting, PHYS. REV., XVI., p. 129, 1903.

that the violet and ultraviolet regions have several bands with maxima beyond .22 μ. This point is of considerable interest, because of the high dielectric constant, 10.2, of selenium; for according to the electromagnetic dispersion theory, the dielectric constant of any substance is the sum of that of the ions, which by acting on the ether waves cause absorption and dispersion, plus the dielectric constant of the ether. It has been noticed that selenium is quite transparent in the infrared and has no broad absorption bands. Hence, on the above hypothesis we must attribute this high dielectric constant to the ions whose free periods correspond in frequency to the green, blue and ultraviolet rays, as surmised by Wood. He also found that, for a film of selenium which absorbs but little of the red, the violet and ultraviolet is absorbed nearly as strongly as a metal film of the same thickness. This is one peculiarity of selenium, occupying, as it does, a position midway between the metals and non-metals. Like the metals (curve *e*, Fig. 3, from Hagen and Rubens [1]) it has a high reflecting and absorbing power for the visible and ultraviolet rays. Unlike the metals but like the non-metals (except that it has no defined selective absorption bands) it is quite transparent in the infrared. Hagen and Rubens have examined a large number of metals and alloys to 14 μ and found a uniform, high reflecting power throughout the infrared region. They call attention to the enormous influence of the molecular free periods of the metals upon the optical region. The curves impress us with the complexity of the phenomenon of total (of metallic) reflection and the depth of penetration of the same, especially for a metallic film so thin that it is optically transparent in which case the penetration might be considered infinite, *i. e.*, the disturbance is never turned back but is transmitted.

Curve *f*, Fig. 3, gives the transmission of a plate of sulphur 3.6 mm. in thickness. Nothing was known about the direction of the optic axes. Since this is a problem by itself, in pleochroism, it will be sufficient to add that a natural crystal, 1.06 cm. in thickness, transmitted on an average about 50 per cent. where this plate of 3.6 mm., but not so highly polished, transmitted only about 38 per

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[1] Hagen and Rubens, Verh. d. Deutsch. Phys. Gesell., 4, p. 55, 1902; 5, p. 113, 1903.

cent. As is well known, sulphur and selenium have an extraordinary similarity in their properties, but no such similarity is to be found in their transmission curves. Like the metals, selenium is more opaque than sulphur and its absorption is general, while unlike the non-metals it shows no selective absorption as is true of sulphur.

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March 1, 1904.