THE COLORS OF MOTHER-OF-PEARL.*

BY

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At the request of the U. S. Bureau of Fisheries the following work was undertaken to ascertain the cause of the iridescence of mother-of-pearl. While numerous investigators have studied this problem, their results have been largely of a qualitative nature. Probably the first in the field was Sir David Brewster who, as early as 1853, arrived at conclusions which are in substantial agreement with those held to be correct at the present day. As a result of the present investigation quantitative measurements, substantiating the original conclusions of Brewster, are presented. These results are made possible in consequence of extending the observations into the infra-red region of the spectrum where conditions are much simplified. Incidentally it is shown that much information on this subject may be gained entirely without the use of a microscope.

By following the course of procedure to be outlined it is possible to subject almost the entire surface of an iridescent shell to study. Since, however, the primary purpose of this work is to ascertain the cause of iridescence it was deemed advisable to confine the investigation to clear-cut cases, therefore specimens of shell showing extremely brilliant colors were chosen. Since these specimens formed parts of ornamental pictures and jewelry it is out of the question to ascertain the types of shell from which the specimen were taken.

STRUCTURE OF SHELL.

The structure of the shell of a fresh-water mussel (*Abovaria ellipsis* (Lea)) is shown in Fig. 1.² This is a perpendicular section of the shell (near its growing edge) and shows the disposition of the various layers. Roughly speaking, the shell may be said to consist of three layers:

* Communicated by the Author.

¹ "Optics," by Sir David Brewster (1853), pp. 137-149.

² Drawing prepared by Dr. R. E. Coker.

1. An outer horny layer (*a*) (periostracum) which is composed of organic matter (conchiolin).

2. An intermediate layer (*b*) of minute prisms of CaCO_3 separated by thin layers of conchiolin. This layer is termed the "prismatic layer."

3. An inner layer (*c*) composed of alternate laminæ of CaCO_3 and conchiolin. This is the true mother-of-pearl or "nacre."

That minute layers of conchiolin exist between those of

FIG. 1.

Diagrammatic camera lucida drawing of section of fresh-water mussel shell (*Abovaria ellipsis* (Lea)).

CaCO_3 is shown by placing a shell in hydrochloric acid. The calcium carbonate disappears, leaving a flabby, honeycombed mass of conchiolin in practically the form of the original shell.

DIFFRACTION COLORS.

Whereas the minute layers of nacreous matter are continuous on the inside of the shell, they terminate abruptly on the outside. Each layer projects slightly beyond the edge of its predecessor hence the outside of the nacreous portion will show innumerable steps or ridges running parallel to the growing edge of the shell. Such a surface structure is identical with that of a diffraction grating, hence, in case the spacing is sufficiently regular, diffraction colors might be looked for on the outside of a shell.

In order to study these colors it is first necessary to grind off the horny and prismatic layers and polish the nacreous layers by means of a buffing wheel. By permitting the light from an incandescent lamp to be reflected from this surface, pure diffraction colors are observed. As a rule these colors are rather inconspicuous since they are masked by the flood of light coming from the underlying portions. These phenomena may be studied most readily by means of celluloid copies or replicas which are

FIG. 2.

Rowland grating. 7230 lines per inch.

Shell

9000 lines per inch.

made by flowing celluloid dissolved in amyl acetate over the surface of the shell. After the amyl acetate has evaporated the shell is immersed in water for about 20 minutes. The celluloid is then removed and dried on a plate of clear glass.

A microphotograph obtained from such a replica is shown in Fig. 2. For the sake of comparison a similar photograph of a replica taken from a Rowland diffraction grating having 7230 lines per inch, is shown. Since the scale of enlargement is the

same in both cases it appears that the steps or ridges on the outside of the shell are spaced at the rate of about 9000 per inch. This particular shell belonged to a mussel taken from the Mississippi River. As might be expected replicas taken from the inside of the shell revealed no grating structure.

It is obvious that the microscope may be dispensed with entirely in a study of the spacing of these lines for, by measuring the angle of diffraction of light of known wave-length, the grating space may be obtained at once. If a piece of cardboard with a pin-hole 0.5 mm. in diameter be placed in contact with the replica and if a Nernst lamp be viewed through this opening, the two first order diffraction spectra may be seen. If the pin-hole be moved perpendicular to the direction of the lines a study may be made of the striking periodicities in the spacing of the lines. At intervals the lines will be spaced at the rate of 6-8000 lines per inch while the regions in between will show a spacing of 15-20,000 lines per inch. This is not the place to discuss the question as to how these layers are deposited by the living mussel or what the cause of the periodicity giving rise to layers of such remarkable uniformity is. Yet, a study of these questions might be much facilitated by the use of replicas which, when viewed in the white light from a small, intense source, show extremely brilliant colors and color changes over the surface, thus enabling one to tell at a glance where the spacing is coarse or fine.

INTERFERENCE COLORS.

Upon grinding the surface of mother-of-pearl with fine emery all traces of diffraction colors disappear and the brilliant iridescence alone remains. These colors can, obviously, be due only to interference in the parallel laminae. A rough test of this interference consists in reflecting light almost normally from a patch on the shell appearing red. By increasing the angle of incidence and moving the eye so as to receive always the reflected beam, the color changes in succession to orange, green, and finally blue. The same phenomenon is observed with Lippmann color-photographs and crystals of KClO_3 , whose structure is known to be laminar. In order to prove even more conclusively the correctness of this explanation, white light of great intensity was reflected from the mother-of-pearl into a spectrometer and, by means of suitable apparatus, the intensity of the radiation in the

near infra-red and visible spectrum was studied with the view of finding indications of interference maxima.

In Fig. 3 the parallel layers of CaCO_3 separated by extremely thin films of organic matter are shown. An incident beam of light suffers successive reflections at the various surfaces, each beam lagging behind its predecessor by an amount

$$\Delta = 2\mu e \cos r$$

where μ = refractive index

e = thickness of layer

r = angle of refraction.

Since conditions under which the successive beams are reflected

FIG. 3.

are the same, the phase-change occurring at reflection need not be considered. It is evident that constructive interference will take place whenever $\Delta = \lambda_1, 2 \lambda_2, 3 \lambda_3$, where $\lambda_2 = \frac{\lambda_1}{2}$, $\lambda_3 = \frac{\lambda_1}{3}$, etc. If, therefore, the reflected light should show maxima at the wave-lengths $\lambda_1, \frac{\lambda_1}{2}, \frac{\lambda_1}{3}$, etc., the conclusion may be drawn that interference between parallel laminæ is the cause of the phenomenon.

The arrangement of apparatus used in this experiment is shown diagrammatically in Fig. 4. An image of the straight coil of incandescent tungsten wire in the gas-filled lamp N was projected on the surface of a polished bit of mother-of-pearl P. This was so adjusted that a beam of brilliantly colored light fell

upon the lens L_2 which focused the light on the primary slit of a monochromatic illuminator I. The monochromatic radiation leaving the secondary slit was focused on the vacuum thermocouple T, connected to a D'Arsonval galvanometer G. Without exception the laminae in the mother-of-pearl made a small angle with the outer surface, hence the surface reflection was not superimposed on that coming from the laminae. Since the galvanometer deflections had been shown to be proportional to the intensity of the radiation falling on the thermocouple, such deflections were recorded in the wave-length interval

FIG. 4.

extending from $.5\mu$ (visible green) to 2.5μ (infra-red). On account of the lack of planarity of the laminae no absolute determination of the percentage of energy reflected could be made. Yet by substituting for P a fresh surface of polished silver and by carrying out a similar set of measurements, it was possible to obtain relative values of the reflecting power. A few of the curves obtained are here given. The material used in obtaining the curve shown in Fig. 5 was a polished flake of mother-of-pearl about 0.2 mm. thick. This specimen had a particularly brilliant

spot 1×5 mm. in area and from this the light was reflected. The two maxima lie at the wave-lengths 1.28μ and 0.637μ , respectively. Since these wave-lengths are very approximately in the ratio $1 : \frac{1}{2}$ it is evident that we are dealing with interference maxima of the first and second orders. The sharpness of the maxima indicates a rather remarkable constancy of the thickness of the laminæ.

Practically the same conclusions may be drawn from the curves shown in Figs. 6 and 7. The maxima lie, respectively, at 1.4μ , 0.71μ and 1.86μ , 0.93μ and 0.63μ . As before, the wave-

FIG. 5.

lengths of successive maxima bear the ratios $1 : \frac{1}{2} : \frac{1}{3}$ to a very fair degree of approximation—hence the conclusion may be drawn that the iridescent colors of mother-of-pearl owe their existence to interference of light reflected from the parallel and equidistant laminæ.

It is obvious, without going into details, that these interference phenomena could best be studied in the infra-red spectrum. Not only is the amount of energy great, but the interference maxima are widely separated and hence may be studied readily. A comparison of the curves in Figs. 5, 6 and 7 reveals a marked

difference in the relative intensities of the maxima for one specimen. While a variety of causes may contribute to this effect, the principal ones are:

(1) A difference in the transparency of the nacreous layer to different spectral regions.

(2) Different dispersion curves of the layer of CaCO_3 and conchiolin.

Having investigated highly colored shells it seemed of interest to take up the study of nacreous matter which showed no color but a brilliant "pearly" lustre. A suitable region on the

FIG. 6.

inner surface of a Mississippi River mussel shell was found and from this the reflection curve shown in Fig. 8 was obtained. The lack of sharpness of the maxima indicates that the thickness of the laminae is far from being constant. It is possible to simulate the appearance of such a specimen by heating a piece of mica in a bunsen flame. In consequence of the heating, the mica is split up into numerous laminae of widely varying thickness.

An unsuccessful attempt was made to study, in a similar manner, that area on the outside of the shell which exhibits neither color nor pearly lustre. The character of the chalky mate-

rial in the shell was such as to scatter the light diffusely—thus preventing regular reflection from successive laminae. That laminae exist in this region also is certain, for the diffraction colors seen indicate a spacing of the laminae which is practically the same as that shown by neighboring iridescent portions.

In order to determine the actual thickness (e) of the laminae it is only necessary to find the refraction index (μ) and substitute in the expression

$$e = \frac{m \lambda}{2 \mu \cos r}$$

It is, of course, possible to find a fairly transparent portion of a shell and prepare from this an acute-angled prism by means of

FIG. 7.

which μ may be determined. However, it frequently happens that the particular specimen studied is not sufficiently transparent. Then, too, such a determination would only be a grand average which might or might not hold for the small element which was used in the study of the interference maxima. It was soon found that the simplest and most satisfactory method of determining μ was to find the wave-lengths λ_1 and λ_2 at which the first order interference maxima lie when the angles of inci-

dence are respectively i_1 and i_2 . The calculation of μ follows at once from the easily derivable formula:

$$\mu = \sqrt{\frac{\lambda_2^2 \sin^2 i_1 - \lambda_1^2 \sin^2 i_2}{\lambda_2^2 - \lambda_1^2}}$$

The shift of the position of the interference maxima resulting from a change in the angle of incidence is shown in Fig. 9. The specimen studied was taken from an abalone shell. Corresponding to the angles of incidence $i_1 = 11^\circ$ and $i_2 = 50^\circ$ the wave-lengths of the two first order maxima are 1.478μ and 1.288μ . Upon substituting these values in the foregoing formula,

FIG. 8.

the refractive index (μ) found to be equal to 1.54° .³ This value of the refractive-index when substituted in expression (i) yields the value for the actual thickness of one lamina:

$$e = 0.48\mu$$

which is the value of the wave-length of greenish-blue light.—

³The value of refractive index is practically the mean value for that of the ordinary and extraordinary ray in Iceland-spar (CaCO_3) for wave-length 1.45μ . $\mu_o = 1.6361$. $\mu_e = 1.4779$.

Similar determinations of e for other samples of mother-of-pearl all show that the thickness of the lamina is of the order of magnitude 0.4μ to 0.6μ .

Finally, the writer cannot refrain from urging biologists to attack anew the problem of ascertaining the manner in which the layers of nacreous material are deposited. The truly remarkable constancy of thickness of the laminæ demands explanation. That periodic variations in external conditions such as light and darkness, tides, temperature, &c., should be responsible for the deposition of discreet layers seems improbable since the total number of laminæ possessed by a shell of known age is entirely too great to

FIG. 9.

be accounted for on any such hypothesis. Possibly the animal, as such, has nothing to do with the periodicity which gives rise to the laminæ—for, just as the crystals in the minute laminæ exhibited by KClO_3 grow only to definite thickness, so may the minute crystals of CaCO_3 , surrounded by conchiolin, grow only until a certain thickness is reached. These suggestions are merely offered for what they are worth.

SUMMARY.

1. Mother-of-pearl owes its colors to two causes:

(a) Diffraction of light due to a grating-like structure of the terminal edges of successive laminæ.

(b) Interference of light due to reflection from numerous parallel laminæ of sensibly equal thickness.

2. By means of "replicas" the study of diffraction colors was carried out. Interference measurements were obtained in the infra-red region of the spectrum where conditions are much simplified. From these data the thickness of the laminæ for many different samples was found to lie between the limits 0.4μ and 0.6μ .

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Fuses on Short-circuit. ANON. (*The Electrician* (London), vol. lxxviii, No. 19, p. 568, February 9, 1917.)—It is well recognized that the object of a fuse on an electric circuit is two-fold: Firstly, to prevent overloading of the circuit, and, secondly, to prevent damage to the wiring through short-circuits. On ordinary networks the fuse is called upon mainly to play the part of protector against overloading and against the milder forms of short-circuit; but it is nevertheless realized that every fuse should be capable of taking care of what is termed a "dead short-circuit." The fuse takes a certain time to act—this, in fact, being one of its virtues—but, owing to this characteristic, the current that is carried before actual fusion occurs may be very high under certain conditions, and a state of affairs may be reached in which a small variation in the time constant of the circuit and other factors may make a very considerable difference in the maximum current. This seems to be the explanation of effects observed by Mr. Sydney W. Baynes, the chief electrical engineer of the St. Pancras Borough Council.

Mr. Bayne has found that service fuses have become much less satisfactory in recent years—in fact, since the advent of the steam turbine. The currents that may arise on dead short-circuits through 5-ampère or 10-ampère fuse have now become very heavy, this possibly being partly due to the fact that a momentary overload has a less mechanical effect on a steam turbine than on a reciprocating engine, and partly, no doubt, to the much smaller reactance of the turbo-generator. Experiments show that, owing to the heavy currents that may result, there is a tendency for the arc to flash to any earthed metal in the vicinity of the fuse. Consequently fuses of the cartridge type are favored, and for this reason concrete service boxes have been adopted for all service on the St. Pancras network.