ON IRIDESCENT SHELLS.

Part II. Colours of Laminar Diffraction.

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1. *Colours of Stratified Films.*

THE late Lord Rayleigh[1] was the first to draw attention to the special character of the iridescence exhibited by regularly stratified films, namely that a narrow region of the spectrum is strongly and selectively reflected. Several examples of such iridescence are known, *e.g.*, Lippmann's spectrum photographs in natural colours, twinned crystals of potassium chlorate, fiery opals and the metallically coloured wing-cases of certain beetles.[2] In the case of iridescent shells, we have three special features which distinguish it from the examples cited: (1) the internal laminations are nearly always inclined to the external surface instead of being parallel to it; (2) the laminæ are granular and not homogeneous in structure; (3) considerable thicknesses of the material have usually to be considered and not thin films. Before we consider the special effects arising from these causes, it is useful to recall the features exhibited by the simpler cases mentioned above.

The theory of the reflection of light by a stratified film has been discussed by Rayleigh.[3] His investigation indicates that the permissible cases fall into one or another of two classes, the first in which the reflection tends to become complete as the number of laminæ becomes large, and the second in which the reflection and transmission remain fluctuating however great this number may be. Whether the one or the other state obtains is determined by the relation between the reflecting power of the individual laminæ and the phase relation between the reflections occurring at the successive laminæ. If the reflecting power of each lamina be small, many laminæ are required even with the most favourable phase-relations to give a tolerably complete reflection and a nearly complete cut-off in transmission. The reflection is at the same time highly selective in respect of its spectral character. On

[1] Rayleigh (I), *Scientific Papers*, 3, 1, 190, 204, 264.

[2] Old decomposed glass also shows a marked iridescence due to a stratified film covering it.

[3] Rayleigh (I), *Proc. Roy. Soc.* (A), 1917, 93, 565; also *Scientific Papers*, 6, 492.

the other hand, if the individual reflections be strong, fewer laminæ suffice to give a strong reflection, and a correspondingly broader spectral range of reflection is obtained. The effects of varying the factors involved, namely the spacing of the laminæ, their reflecting power and their number, may be studied with the examples of stratified films already mentioned. The spectrum of the reflected light frequently includes not one, but several bands, these representing successive orders of interference. The light reflected at nearly normal incidence exhibits comparatively narrow bands in its spectrum ; as the angle of incidence is increased, these bands move towards shorter wave-lengths and increase rapidly in width. Very interesting effects are noticed when the number of laminæ operative is limited ; in such cases, the bands of maximum reflection in the spectrum of the reflected light are accompanied by subsidiary bands of smaller intensity on either side of them. The appearance of these secondary maxima is readily understood by analogy with the secondary maxima observed in diffraction spectra with gratings having a finite number of rulings.

2. *Laminar Diffraction Spectra.*

As is well known, Sir David Brewster who investigated the colours of mother-of-pearl classified them under two heads, what he called transferable and non-transferable colours. The former could be transferred to gelatine or other soft substances employed to take an impression of the surface of the material, and hence it was inferred that they were due to diffraction by grooves on the exterior of the nacreous substance. The non-transferable colours on the other hand were regarded as interference or thin film colours due to the internal reflecting layers. The grooves on the surface capable of diffracting light were interpreted as the outcrops of these internal stratifications. Later writers have accepted Brewster's classification without comment. A little consideration will show, however, that this separation of the optical effects into two independent and superposable phenomena is not justifiable. Assuming that the laminæ meet the surface at an angle and that in consequence the surface is grooved, diffraction effects must arise not only when the light is incident externally on the surface, but also when it emerges at the surface after suffering reflection at the internal laminations. The non-transferable diffraction effects arising in this way should be quite as important as the transferable effects associated with the comparatively weak reflection at the external surface. Further, as both the externally and internally reflected wave-trains are derived from the same original beam, the effects arising from them would be coherent and capable of interfering with each other and not simply superposable. These considerations indicate that the phenomena observed should be considered as a whole, and that the optical effects exhibited by a cast of the surface would be very different from those actually observed at the surface of the shell. Even if the latter were perfectly plane, the laminations meeting the surface obliquely would in effect form a grating giving rise to diffraction effects of a non-transferable character.

The full significance of the foregoing remarks is best indicated by the results of a simple experiment. A narrow pencil of light is allowed to fall on the polished surface of an iridescent shell. A polished piece of *Turbo* shell serves admirably for this purpose, and in fact *Turbo* was the species of shell with which the observations to be described were first made, though other species may also be successfully employed. The pencil of light after falling on the surface and being reflected by it is received on a white screen. It is then found that the reflected pencil is accompanied by diffraction spectra. With the particular specimen of *Turbo* shell, three spectra were conspicuously observed on one side of the reflected light, and only one on the other (Fig. 1). The first-order spectra on both sides showed the complete set of colours present in white light. But the second-order and third-order spectra which were present only on one side did not show all the colours of the spectrum, and the third-order spectrum in particular, though very intense, exhibited only one pronounced colour, namely that of the characteristic green iridescence of the shell for the particular angle of incidence. In other words, *the characteristic iridescence of the shell appeared as the third-order diffraction spectrum due to the laminar grating formed by the surface of the shell.*

An interesting variation on the experiment is made by cementing a thin microscope cover-slip of glass with a little Canada-balsam on the surface of the shell and reflecting a pencil of light from it at the same angle of incidence as previously (Fig. 2). It will be noticed that all the diffraction spectra disappear except the third-order spectrum on one side which remains in identically the same position. The effect of the Canada-balsam is virtually to suppress the grooves present externally on the surface of the shell. But the periodic internal structure persists and gives rise to the characteristic reflection at the same angle of diffraction as previously. Examination of the third-order spectrum with a pocket spectroscope shows that only a comparatively narrow region of the spectrum has an appreciable intensity in it. Experimenting with different shells and even with different areas on the same shell, it is found that *the characteristic iridescence may sometimes appear as the diffraction spectrum of the second order instead of as the third. A superposition of the second and third orders for wave-lengths near the two ends of the visible spectrum may also be observed in certain cases. The iridescence then appears as a mixed colour instead of being monochromatic.*

That the direction in which the light of appropriate wave-length reflected by the internal laminations emerges should be identical with that of one of the diffraction-spectra produced by the surface of the shell is intuitively evident and may be readily proved theoretically. In Fig. 3 (*a*) and (*b*) we have the internal laminations meeting the surface at an angle α. If d is

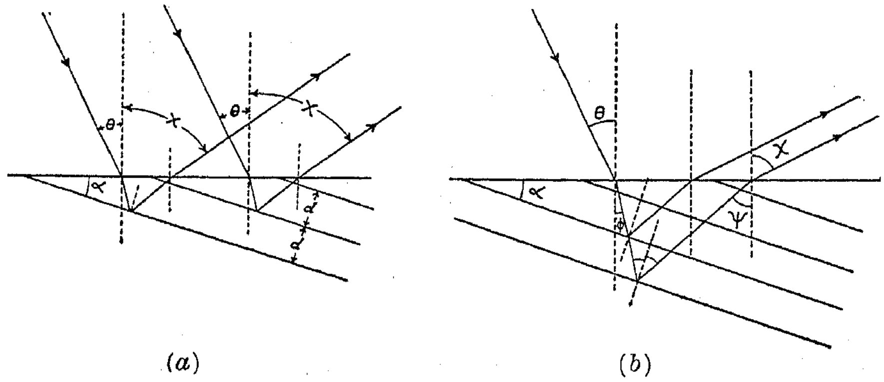

FIG. 3. Identity of Direction of Iridescent Reflection with Diffraction Spectrum.

the thickness of the laminations, the grating space on the surface is d cosec α. We denote by θ and ϕ the angles of incidence and refraction of the in-falling light, and by ψ and χ the angles of incidence and refraction of the beams emerging from the surface of the shell.

For the diffraction at the surface of the shell, we have the usual grating formula [Fig. 3 (*a*)]

$$d \operatorname{cosec} \alpha \, (\sin \chi - \sin \theta) = \pm n\lambda \quad \ldots \quad (1)$$

The beam of light entering the substance of the shell is incident on the internal laminations at the angle $(\phi+\alpha)$, and the wave-length of the characteristic reflection is given by the usual formula [Fig. 3 (*b*)]

$$2\mu d \cos(\phi+\alpha) = n\lambda \quad \ldots \quad (2)$$

But $\sin \theta = \mu \sin \phi$, and $\sin \chi = \mu \sin \psi$, where $\psi = \phi + 2\alpha$ .. (3)

Substituting these in formula (1), the latter assumes the form

$$2\mu d \cos(\phi+\alpha) = \pm n\lambda \quad \ldots \quad (4)$$

which is identical with (2) except for the presence of the alternative signs $\pm$. In other words, *the internal reflection emerges from the surface of the shell in a direction coinciding with one of the orders of diffraction spectra produced by the surface of the shell,* on the side corresponding to a positive value of n $(\chi > \theta)$. The order of the spectrum which exhibits the characteristic colour is also the order of interference of the light reflected from the successive internal laminæ.

The foregoing formulæ admit of ready experimental check. The grating space d cosec α may be directly measured on the surface of the shell by observation under the microscope. The angles of incidence and emergence θ and χ at the surface of the shell can be measured on a divided circle. The order of interference n is directly accessible to observation, and the wavelength of the iridescent reflection can be read off with a pocket spectroscope having a scale in the eye-piece. The quantities appearing on both sides of formula (1) are thus completely accessible to observation and should check each other. The three equations (3) contain four unknowns, ϕ, ψ, α and μ, and one additional observation should therefore enable all the quantities to be determined. For instance, if μ were determined by some independent method, the formula would enable us to evaluate ϕ and α, and therefore also from (2) the value of d. What the measurements would enable us to do in effect is to check the assumption that the spacing of the laminæ visible on the surface should agree with that calculated from the internal spacing of the laminæ meeting the surface obliquely at a known angle. That such a check would not be superfluous is indicated by a discrepancy encountered by Lord Rayleigh (II) who found that he had to multiply by two the optically determined spacing in order to obtain a value for the spacing of the laminations agreeing with that observed microscopically in a cross-section of mother-of-pearl. Rayleigh endeavoured to explain this on the assumption that the alternate layers of aragonite and of organic material have equal thickness and the same refractive index, and that the optical spacing should therefore be half that observed under the polarisation microscope.[4] According to Schmidt, however, whose conclusions are supported by strong evidence, the organic layers are excessively thin in comparison with the aragonite layers and the spacing observed under the microscope and deduced optically should be identical. It appears likely that the discrepancy encountered by Rayleigh is not real but is due to the difficulty of interpreting the microscopic appearances.

As an illustration of the foregoing theory and of its agreement with the facts may be mentioned some observations made with a piece of *Turbo* shell which gave a greenish-blue iridescence appearing in the third-order diffraction spectrum. The following were the observational data:

$$\theta=0°, \ \chi=24°8', \ n=3, \ \lambda=5000 \text{ A.U.}$$

[4] Rayleigh's argument (*Proc. Roy. Soc.* (A), 1923, **102**, 677) appears a little difficult to follow. The refractive indices of the aragonite and conchyolin layers must differ at least slightly for any reflection to be possible. Phase changes must, therefore, occur in reflection which are different at the alternate boundaries. The optical spacing would, therefore, in any case be determined by the thickness of both layers considered together and not that of either layer separately. As will be remarked later, the effects observed when the surface of iridescent shell is examined under the "ultra-opak" microscope support Schmidt's view of the structure of nacre.

From these data, the grating space on the surface was calculated. The refractive index of the material was determined by observing the Brewsterian angle of complete polarisation of the reflection from the polished surface of the shell and was found to be 1·66. Using this value of μ, α is calculated from equation (3), and hence from equation (4) d can be calculated. It is thus found

$$d=0\cdot456\times10^{-3}\ \text{mm.},\quad \alpha=7^\circ9',\quad d\ \text{cosec}\ \alpha=3\cdot66\times10^{-3}\ \text{mm.}$$

The grating space on the surface directly observed under the microscope was $3\cdot69\times10^{-3}$ mm. showing satisfactory agreement with the optically determined value.

3. *Effect of Grinding and Polishing on Surface Structure.*

Nearly all nacreous shells which exhibit iridescence do so in their natural state on their inner concave surfaces. In some cases it may be possible to expose the other (convex) surface of the nacreous layer by simple mechanical removal of the super-incumbent layers. It is thus possible, at least in many cases, to study the iridescence of the material in its natural state. This procedure is, however, not very convenient. Owing to the curvature of the surfaces and their inevitable optical imperfections, the shells in their natural state do not lend themselves to optical investigation so well as material prepared therefrom by cutting, grinding and polishing. As is well known, mother-of-pearl lends itself readily to mechanical working and takes a good polish, and indeed its practical utility as a decorative material depends to a great extent on these valuable properties. So far as the optical effects arising from the internal structure of the material are concerned, it is obvious that optical preparation of the external surfaces would facilitate rather than interfere with their study. It is very remarkable that even the surface or diffraction effects are more conveniently studied with artificially prepared material. Why this is so will presently be explained. It may be remarked that the general appearance of an iridescent shell as well as the more recondite phenomena observed on detailed examination are largely determined by the inclination of the internal laminations to the external surface of the shell. The form of these laminations depends on the shape and structure of the shell and is of course fixed, while the exterior surface of the shell (and, therefore, also the angle at which it meets the laminations) can be artificially determined by grinding and polishing the material. How greatly the form of the internal laminations may vary in different species of shell is evident on a comparison of Figs. 1 and 2 in Paper I of this series which represent the ground and polished convex surface of two abalone shells. The ripplings which form so conspicuous a feature in Fig. 2 are due entirely to light reflected by the internal laminations and do not exist on the external surface.

The nature of the structure existing at the surface of the shell and the effects produced on it by grinding or polishing the material are obviously very relevant to our investigation. That all the diffraction spectra other than that corresponding to the characteristic iridescence disappear on covering the surface with a layer of Canada-balsam and a glass cover-slip indicates that the surface even after grinding and polishing is not optically plane, but is of grooved form. The explanation of this is to be found in the fact that the material is not very hard and is readily abraded even by the mildest agents. Examination under the microscope indicates a strongly pronounced tendency for the material to break off under the action of an abrasive, leaving the surface in the form of terraces or steps with sharp edges. Polishing tends to round off the edges of these terraces but only very slowly. Very prolonged polishing is required before all trace of periodicity on the external surface is lost.

Very interesting changes are observed in the relative intensity of the diffraction spectra produced by the surface of the shell during the process of polishing. When the surface is still rough with pronounced terraces, the ordinary white light reflection is very weak, and most of the light is thrown into the first-order diffraction spectrum on one side which is intermediate in direction between the ordinary (white) reflection and the characteristic (iridescent) reflection from the surface of the shell. The iridescent reflection is also rather weak and diffuse. In a general way, these facts are readily understood, if we recollect that the appearance of terraces with sharp edges on the surface *ipso facto* involves an inclination of the level of the surface to the surface of the individual terraces. The diffraction effects produced by the rugosities on the surface must, in these circumstances, be very pronounced and at the same time very unsymmetrical. As the polishing proceeds, the ordinary reflection brightens up, the first-order spectrum on the one side falls off in intensity and the first-order spectrum on the other side begins to appear. The iridescent reflection also brightens up and becomes better defined in direction. The asymmetry of the diffraction pattern, however, persists even after prolonged polishing, being evidently the result of the inclination of the internal laminations to the external surface.

An interesting example of material prepared by grinding and polishing for the investigation of iridescence is the box covered by pieces of abalone shell (ground, flat and polished from the natural material) a photograph of which is reproduced as Fig. 4 of the present paper. The photograph was taken under the oblique illumination from a mercury lamp, and a patchiness due to the internal reflections being at various angles is very noticeable, the brighter areas representing places where the iridescent reflections occurred in such directions that they reached the lens of the camera. Fig. 17 represents one end of the same box photographed under the 4358 A.U. radiation of the mercury lamp. The illumination in this case was approximately normal but indirect being due to a large sheet of Bristol board with an aperture in it encircling the lens of the camera. The appearance of the surface as seen by reflected light is made more uniform by this arrangement, but even so, it will be noticed that considerable areas of the mosaic are quite dark, and these represent areas where the coloured internal reflections were quite strong but so oblique that they could not be caught by the camera. Very interesting and conspicuous features are the ring-shaped structures seen in many pieces of the mosaic. These consist of lustrous areas of nacre separated by dark regions which do not exhibit any iridescence. In each case, the centre of the ring system represents an area where the coloured reflections are normal to the surface, while in the surrounding rings, they occur at greater obliquities. Each ring-system, in fact, presents by reflected light, the illusion of a hollow cup viewed from the concave side. Actually, the illusion has some correspondence with reality, as it indicates that the laminations responsible for the iridescence take the form of concave surfaces which meet the polished exterior of the plate at various angles. Most of the pieces of shell in the mosaic which showed ring-systems presented the illusion of a hollow cup while only three presented the illusion of a *convex* surface. It is evident that these three pieces unlike the others, had been polished flat from the convex side of the natural curvature of the shell.

4. *Observations with the Ultra-opak Microscope.*

Very remarkable effects are observed when the abalone box illustrated in Fig. 4 is examined on the stage of the Leitz Ultra-opak microscope. The latter instrument has already been referred to in a paper in these *Proceedings*[5] on the colours of birds' feathers. It is essentially an opaque illuminator of the kind used for metallurgical work, the source of light being an 8-volt lamp in a side tube attached to the microscope. The beam of light consists of a hollow cylindrical pencil of rays which is reflected downwards and instead of, as in metallurgical microscopes, passing through the objective, envelopes the latter and is focussed as a hollow cone of rays having its vertex on the surface under examination. The instrument thus combines the principles of opaque lighting and of dark-ground illumination, and is exceptionally

[5] C. V. Raman, *Proc. Ind. Acad. Sci.*, 1934, **1**, 1.

suitable for examining optical surfaces that reflect and diffract light. A very useful device supplied with the instrument is a diaphragm with a variable sector opening which can be inserted in the path of the cylindrical beam of light before it goes down the microscope tube. By narrowing the sector, and turning it round, we can arrange that instead of a complete hollow cone of rays being focussed on the surface, only a sheaf of rays of any desired angular opening adjacent to a particular generator of the cone is used to illuminate the surface. A sector of 90° opening is convenient and gives four distinct positions of the illuminating beam as it is turned round to successive quadrants. The unsymmetrical illumination of the surface obtained in this way is very useful. The microscope has a series of objectives and eye-pieces. The angle of the cone of the illuminating beam increases with the power of the objective, and the luminous effects observed with the lower-power objectives therefore differ greatly from those seen with the higher powers. In what follows will be described the effects observed with one of the objectives of higher powers ($\times 11$). (The effects observed with lower powers will be dealt with in later papers of the series.)

Effects observed with Hollow Cone Illumination.—On examining the pieces of abalone shell forming the mosaic on the box, it is noticed immediately that the surface exhibits a large number of sharp luminous lines on a relatively dark field, the lines in many cases exhibiting vivid colours. Photographs of the phenomenon (without the beautiful colour effects) are reproduced in Figs. 5 to 13. It will be noticed that *while the lines are equally sharp in all these figures, the configuration and distance of the successive lines vary greatly.* Very simple and general rules connect the form and spacing of these lines with the optical behaviour of the particular part of the shell under examination. (*a*) If the laminations responsible for the iridescence are nearly plane and parallel to the external surface, the luminous lines seen on the latter are relatively few and far apart; they are then either irregular in shape or else form closed curves, and their colours are less prominent. (See Figs. 5, 6, 7, 9, 10, 11 and 12 for example.) (*b*) If, however, the laminations are rather oblique to the surface, the lines seen on the latter are much more numerous, close together, run approximately parallel to each other in any limited field of view and also exhibit more striking colours. (See Figs. 8 and 13 as examples.) (*c*) If the inclination of the laminæ to the surface is very considerable, the lines are very close and may cease to be resolved by the microscope with the powers used. (*d*) If the inclination of the laminations to the surface is so considerable that the iridescent reflections enter the objective of the microscope, the lines appear superposed on a bright field and may even become invisible. (*e*) Irregularities in the laminations result in corresponding irregularities in the lines seen on the surface, and also in patches of light seen here and there in the field of view. (See Figs. 12, 13 and 16 as examples.)

The features described above indicate that the luminous lines seen on the surface represent the edges of the terraces on the exterior surface of the shell. This is definitely proved by the fact that the luminous lines weaken or disappear when the surface is covered over with a layer of Canada-balsam and a slip of glass, or if the polishing of the surface be sufficiently prolonged. There seems little doubt also that the edges of the terraces coincide with the curves along which the internal laminations meet the surface of the shell. This point is particularly convincingly shown by examining a ring structure of the kind seen in Fig. 17 under the microscope. It will then be seen that the luminous lines are themselves rings running round the system in approximately the same way as the visible areas of colour. The spacing of the lines is extremely large in the centre of the ring-system and gets closer and closer together in the outer rings, as is to be expected from the increasing obliquity of the laminations to the surface. The sharpness of the edges which is unaffected by their spacing on the surface is most easily understood if we assume that they coincide with the intersections of the surface with the excessively thin organic layers separating the layers of aragonite postulated by Schmidt.

Effects observed with Sector Illumination.—Some very interesting modifications of the effects described above are observed, if instead of using the complete cone of 360° illumination, we use only a sector of small opening, say, 45° in the microscope and place it successively in four positions 90° apart. If a field such as that shown in Fig. 8 or Fig. 13 composed of lines running approximately parallel and close together is observed in this way, we see the following sequence of effects in four positions of the sector 90° apart :—

(*a*) Lines bright and strongly coloured.

(*b*) Lines invisible.

(*c*) Lines weak and yellowish white.

(*d*) Lines invisible.

These changes clearly indicate that the luminosity of the edges is due to diffracted light radiating from them in the form of cylindrical waves, and further that the diffraction is strongly asymmetrical with reference to the normal to the surface of the shell and the diffracting edges.

The same effects can be shown in a different way by observing a field consisting of lines forming closed curves; firstly with the complete cone illumination (see Fig. 10), and then with a sector of 90° opening in two positions 180° apart. The very great difference in the intensity of the lines running parallel to each other but in opposite directions in the two positions of the sector, can be seen on comparing Figs. 9 and 11 which represent identically the same field illuminated by a 90° sector in two positions 180° apart.

5. *Interpretation of the Effects.*

There can be no doubt that the phenomena described in the preceding section are essentially diffraction effects due to the sharply-defined laminar edges producing an abrupt difference of phase in the optical wave-front on either side of them. Such laminar boundaries can easily be obtained by splitting a piece of mica not quite evenly with the result that the thickness of the split mica is not absolutely identical throughout, but differs very slightly in different parts. On examining such a piece of mica under the ultra-opak microscope, the lines separating the parts of the mica with slightly different thicknesses are seen as bright lines in a dark field. On putting in a 45° sector in the illuminating tube and rotating it, a sequence of effects somewhat similar to those described in the preceding paragraphs is observed. The colours of laminar diffraction exhibited by the striæ in mica[6] were observed many years ago and were subsequently investigated by P. N. Ghosh, N. K. Sur and I. R. Rao and described in a series of papers from Calcutta. The effects noticed in the present case, while essentially analogous to those observed with mica exhibit important differences in detail due to the altered circumstances of the case. Instead of a discontinuity of thickness in the surface of a plane-parallel plate, we have in the present case, a series of edges forming a diffraction grating which terminate *sloping* terraces on the surface of the material. Further, we are concerned simultaneously with the light incident externally on the surface and with light emerging after reflection at the internal laminations. The most obvious way of interpreting the effects observed in the ultra-opak microscope and described in Section 4 is to connect them with the laminar diffraction spectra described in Section 2 and illustrated in Fig. 1 of the present paper. The laminar edges are in fact responsible for the diffraction spectra, and all that the microscope does is to collect the diffracted rays and focus them as images of the edges themselves. The colours exhibited by the edges as seen in the microscope are, therefore, determined by the predominant wave-lengths in the bundle of diffracted rays entering the objective of the microscope and focussed by it. The unsymmetrical distribution of intensity of the diffracted rays, and especially the changes of colour and intensity observed as the illuminating sector in the microscope is rotated are naturally interpreted as consequences of the un-

[6] C. V. Raman and P. N. Ghosh, *Nature,* 1918, **102**, 205.

symmetrical distribution of intensity in the diffraction spectra. The edges exhibit the most striking colours when observed by the rays diffracted by them in directions not too far removed from that of the characteristic iridescent reflection. In directions lying on the remote side of the normal to the plate where the higher order spectra are absent, the diffracted rays are weak and do not show any pronounced colour.

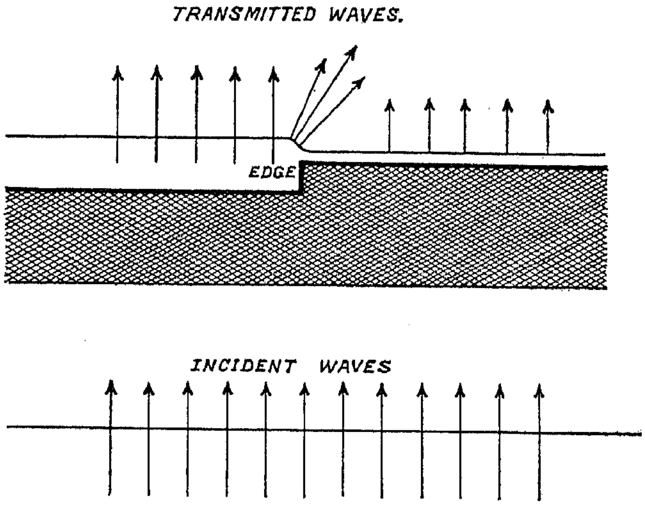

FIG. 18. Asymmetrical Diffraction by Laminar Edge.

There is an alternative and perhaps preferable way of viewing the subject. It is known that a thick laminar edge shows a striking asymmetry[7] in the distribution of the radiations diffracted by it, and the asymmetry of the whole diffraction pattern produced by the sequence of edges may be regarded as a consequence of the behaviour of the individual edges. The reason for the asymmetry will be evident from Fig. 18 which is a diagrammatic representation of the form of a plane-wave before and after passage through a plate containing a laminar edge. Owing to the inflection in the wave-front after passage through the plate, the rays diffracted by the edge towards the *retarded* side of the wave-front would obviously be more intense than those diffracted towards the other side. In our present case we are concerned chiefly with the light emerging from *within* the material after reflection at the internal laminations. Comparing Figs. 18 and 19, it will be seen that the tendency would be for the edges to diffract light unsymmetrically away from the normal and towards the surface of the plate

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[7] I. R. Rao, *Ind. Jour. Phys.*, 1928, 2, 381.

This asymmetry of diffraction by a laminar edge is closely connected with the well-known "Becke phenomenon" which is noticed when such an edge is examined under the microscope.

on the side on which the iridescent reflection is observed. It may be remarked in this connection that by holding a piece of abalone shell in a dark room in the path of a strong beam of light and viewing its surface from various directions, the distribution of the diffracted light may be ascertained qualitatively without any instrumental aid whatsoever. Visual observations made in this way with the abalone box indicate that the laminar edges on the surface of the shell diffract light unsymmetrically through large angles in the manner indicated in Fig. 19.

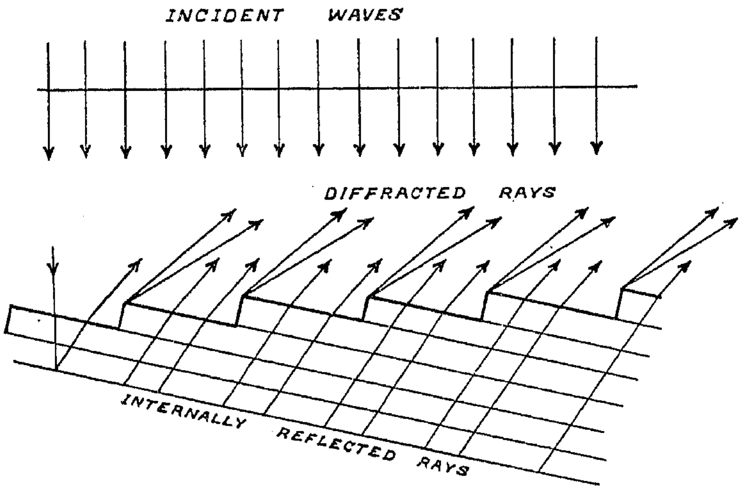


FIG. 19. Asymmetrical Diffraction of Internally Reflected Rays on Emergence.

The effects described and discussed above refer explicitly to the case of abalone shells, which, as mentioned in Part I, exhibit a remarkably pronounced iridescence. Similar, though perhaps less striking, effects are also exhibited by other iridescent shells, particularly those belonging to the *Haliotidæ* and *Turbinidæ* families. It should be mentioned that all iridescent shells whose surfaces have been prepared by grinding and polishing but on which the process of polishing has not been carried too far exhibit luminous lines on their surface when examined on the stage of the ultra-opak microscope, as also the characteristic asymmetry effects with the method of sector illumination (see Fig. 15 for example); the colour phenomena are usually not so striking as with the *Haliotidæ*.

6. *Other Laminar Diffraction Effects.*

Before leaving the subject of laminar diffraction phenomena exhibited by iridescent shells to consider other aspects of the subject, it would be desirable to mention some features of minor importance connected with those already described. If instead of using the principle of dark-ground illumination, the laminar edges on the surface of iridescent shells are examined by the usual methods of microscopic examination, the optical effects are reversed. Instead of the laminar edges appearing as brightly coloured lines on a dark field, they appear as dark lines on a bright field. This reversal may be observed either when the surface of the shell in its normal state is viewed by reflected light under the microscope using any form of opaque illuminator, or when examining a thin section by transmitted light in the usual way. The edges appear as narrow black lines when examined in sharp focus (see Fig. 14), and when put out of focus show the Becke phenomenon of a bright line detaching itself unsymmetrically from the boundary. *It is readily verified that the successive edges seen under the microscope behave in a similar way, supporting Schmidt's view of the structure of mother-of-pearl, namely that the material consists of layers of aragonite separated by immeasurably thin strata of organic matter.*

A few remarks may also be made regarding the laminar diffraction effects observed when a thin plate (not too highly polished) is held up against the eye and a distant source of light viewed through it. It has already been remarked (Section 3 above) that the surface of the shell gives by reflection in similar circumstances a strong first-order diffraction spectrum on one side only of the ordinary white reflection. This is due to the sloping terraces on the surface of the shell which reflect the bulk of the light into a direction different from that of the ordinary reflection. When examining the spectrum given by a thin plate *by transmission*, it must be remembered that there are *two* surfaces to be considered giving rise to diffraction effects. The effect produced by each surface can be examined separately by covering the other with a layer of Canada-balsam and a cover-slip of glass. It will then be found that each surface gives strongly unsymmetrical diffraction spectra in which the first-order spectrum on one side is much stronger than all the others. The two surfaces of the plate give intense spectra on opposite sides of the direct image, and each surface gives a strong spectrum by transmission on the side opposite to that in which it gives a spectrum by reflection. These effects are very readily explicable from optical principles, when we take into account the slope of the terraces on the two sides of the plate, and the opposite deviations produced by reflection and refraction respectively.

A passing reference may also be made to a curious luminous effect which accompanies the diffraction spectra mentioned above and is seen in the immediate neighbourhood of the image of a source of light viewed through a thin piece of mother-of-pearl with imperfectly polished surfaces. A brush of bluish-violet light, with the violet end nearest the source appears to stretch out unsymmetrically from it. This appears to be a secondary diffraction spectrum due to the sloping terraces on the surface of the shell influencing the transmission of light through the plate.

7. *Acknowledgments.*

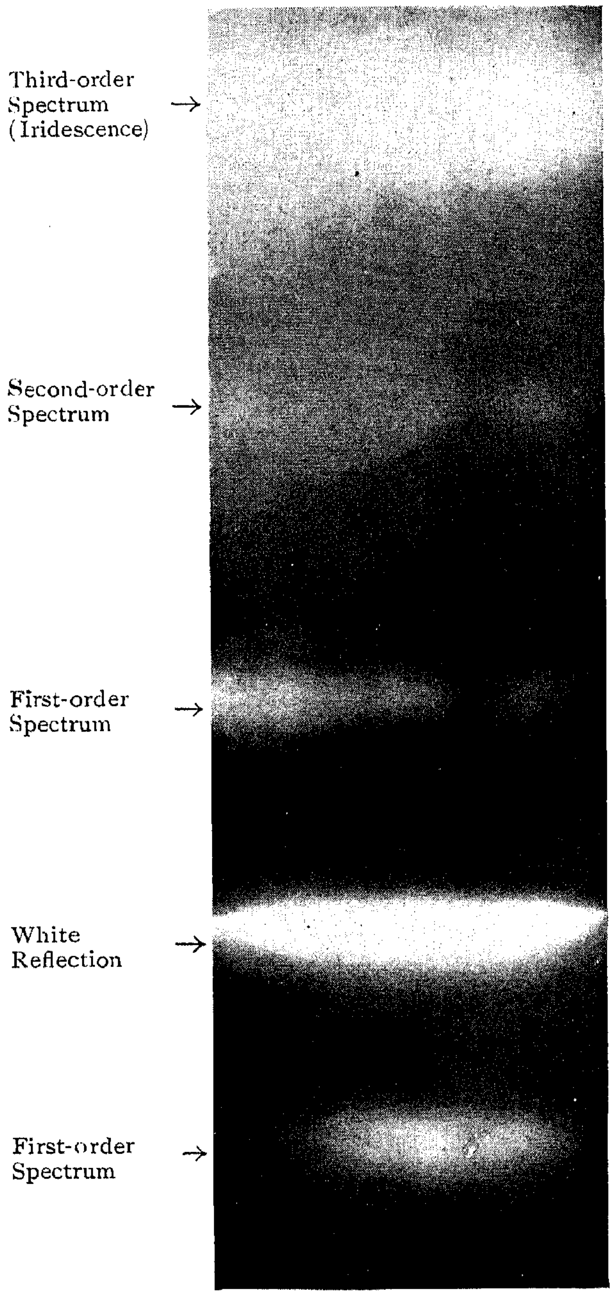
I have to express my appreciation of the valuable assistance rendered by Mr. C. S. Venkateswaran who prepared the photographs illustrating the paper and Mr. P. Pattabhiramayya who prepared numerous specimens and made interesting observations on the behaviour of a nacreous surface during the process of grinding and polishing. I have also to thank Dr. Baini Prashad and Dr. H. Srinivasa Rao of the Zoological Survey of India, Dr. R. P. Paranjpye, Vice-Chancellor, Lucknow University, the Director of Fisheries, Madras and his Research Assistant at Ennur for their kind assistance in obtaining suitable material for the investigation.

8. *Summary of Parts I and II.*

The two communications appearing in the present issue are the first two of a series of papers (of which several more are to follow) describing the results of a study of the iridescence of calcareous shells in relation to their structure. The following is a summary of the material so far published :—

Part I. *Introductory* : Section 1 is mainly historical and indicates the various points of view (optical, crystallographic, colloid-chemical, zoological) from which the study of iridescent shells is of interest. Section 2 surveys the zoological material available for the study. Section 3 summarises the literature on the structure of calcareous shells generally and the work of W. J. Schmidt on the structure of the nacreous substance in particular.

Part II. *Colours of Laminar Diffraction* : Section 1 summarises the known optical effects observed with stratified films. The difference between these and the phenomena of iridescent shells arises from three factors : (*a*) the inclination of the laminæ to the external surface, (*b*) the granular structure of the laminæ, and (*c*) the considerable thickness of the material. Section 2 considers Brewster's classification of mother-of-pearl colours and shows it to have no theoretical justification. Experiment and theory alike prove the characteristic iridescence of shells to be a diffraction effect which appears as one of the orders of spectra produced by the periodic structure at the surface of the shell. Section 3 considers the distribution of intensity in the laminar diffraction spectra and describes the effect of grinding and polishing the surface on the same. Section 4 describes the phenomena exhibited by the surface of iridescent shells when examined under the hollow cone illumination provided by the ultra-opak microscope. Remarkable colour effects are exhibited by the laminar edges which appear as bright lines of light on a dark field. Section 5 interprets these effects



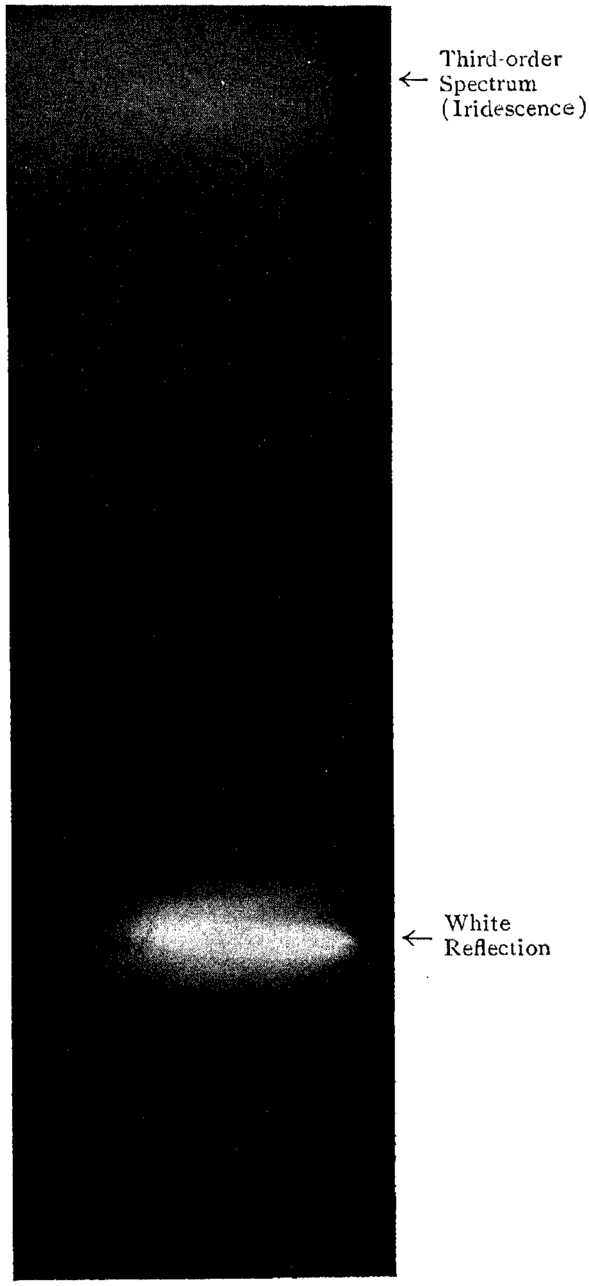


FIG. 1. Without cover-slip. FIG. 2. With cover-slip.

Diffraction Spectra given by Iridescent *Turbo* Shell.

FIG. 4. Box of Polished Abalone Shell.

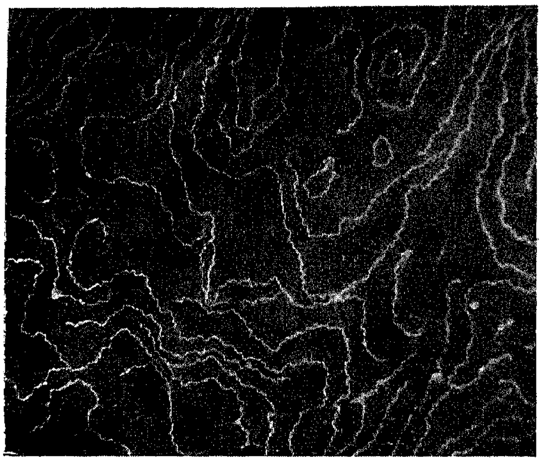


FIG. 5.

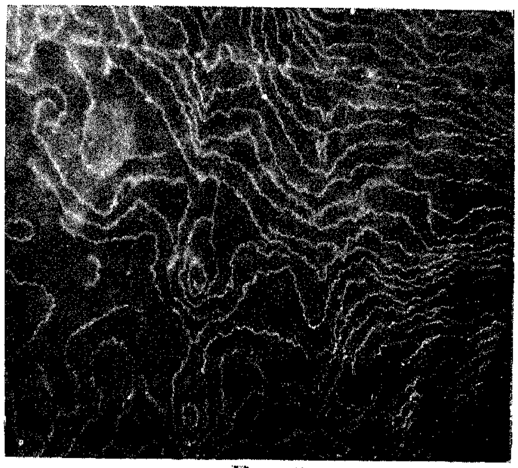


FIG. 6.

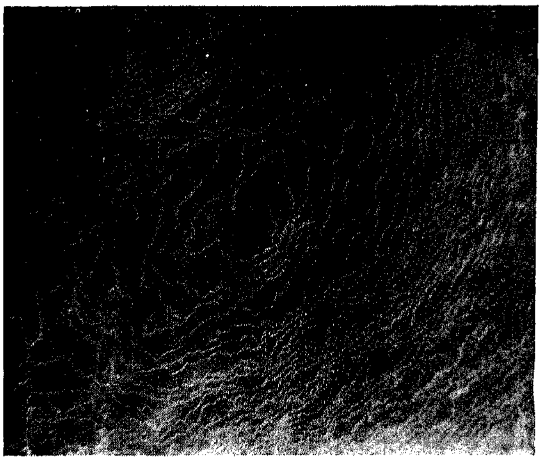


FIG. 7.

FIG. 8.

Abalone Shell under Hollow Cone Illumination.

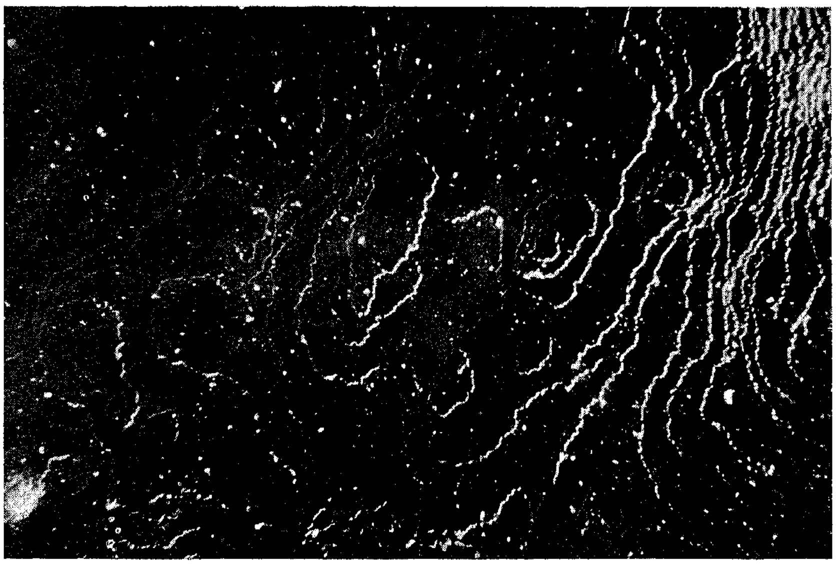


FIG. 9.
Sector Illumination
(From Right)

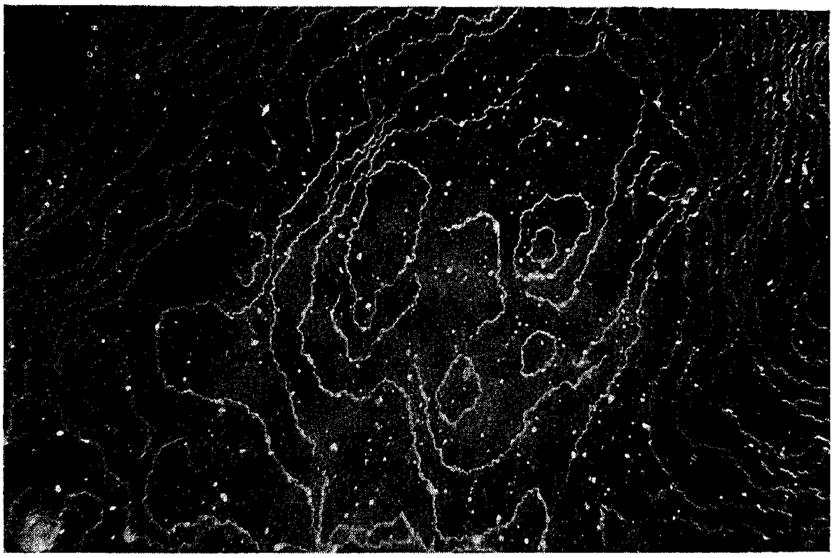


FIG. 10.
Hollow Cone
Illumination

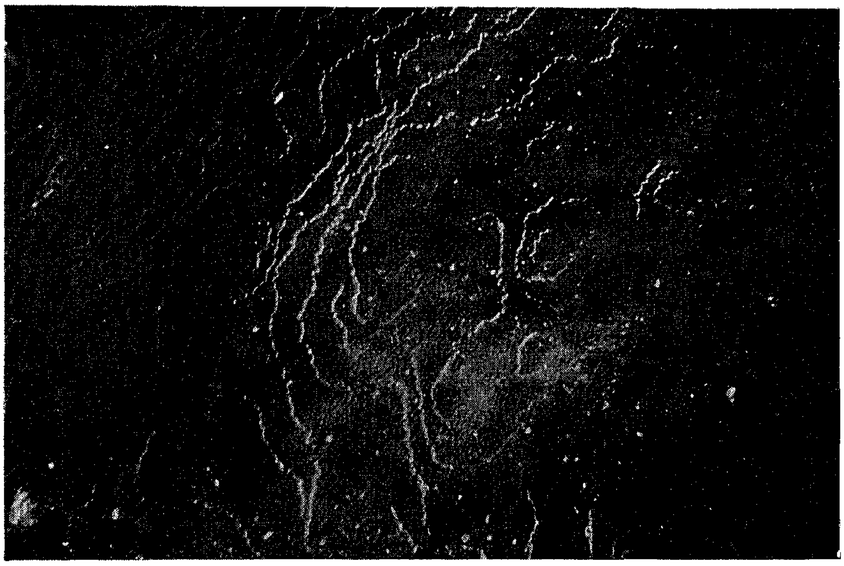


FIG. 11.
Sector Illumination
(From Left)

Abalone Box under Ultra-Opak Microscope.

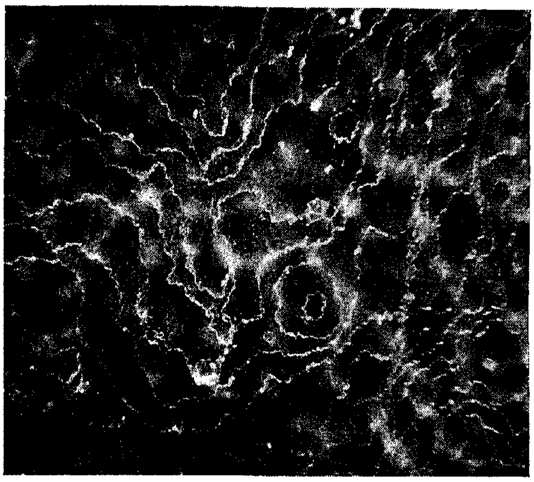


FIG. 12.

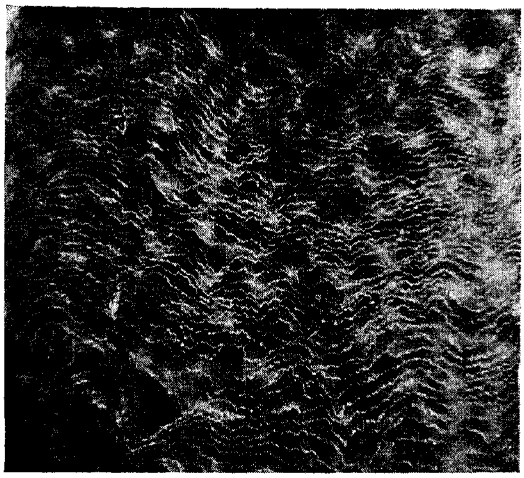


FIG. 13.

Abalone under Hollow Cone Illumination.

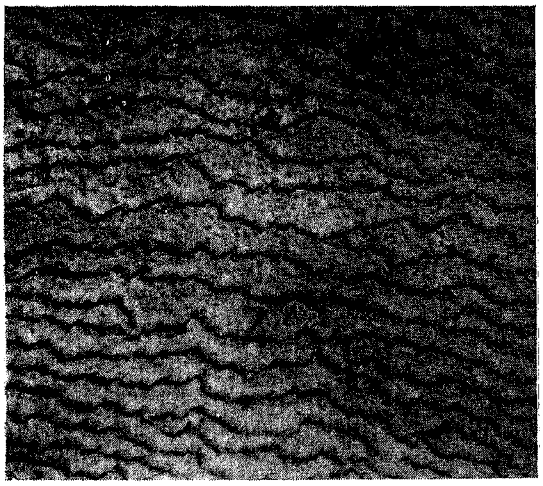


FIG. 14. Transmitted Light.

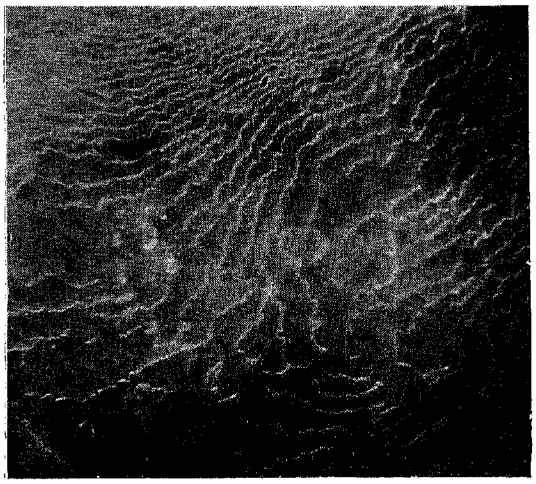


FIG. 15. Hollow Cone Illumination.

Shell of *M. Margaratifera.*

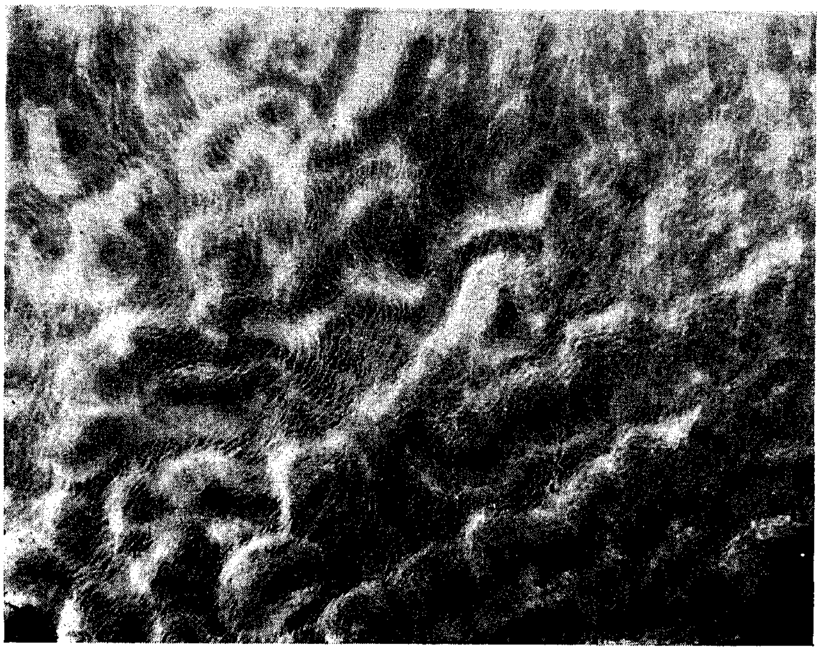


FIG. 16. Abalone under Hollow Cone Illumination.

FIG. 17. Abalone Box in 4358 A.U. Illumination.

and correlates them with the intensity distribution in the laminar diffraction spectra, and with the asymmetrical diffraction by laminar edges. Section 6 considers other laminar diffraction phenomena and shows that the observations generally support Schmidt's view of the structure of nacre, namely that it consists of layers of aragonite crystals separated by immeasurably thin layers of organic matter.

Numerous photographs illustrate the paper.