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The structure and optical behaviour of iridescent shells

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1. Introduction

As is well known, the innermost layer of the shells of numerous molluscan species consists of a material known as nacre or more familiarly as mother-of-pearl. The outer opaque layers covering the nacreous substance may usually be removed without difficulty and its surface thus exposed may be smoothed and polished, thereby enabling its characteristic lustre and iridescence to be fully displayed. Large shells of the molluscan species *Margaratifera*, *Turbo*, *Haliotis* and *Nautilus* thus prepared are magnificent objects. Some twenty years ago, one of us became interested in the optical phenomena exhibited by these shells. An extensive collection of material was got together, and the studies made with the same, revealed many facts of interest.[1,2,3] It was shown that the colours of internal reflection and of exterior diffraction at the surface of the shells are so related that the monochromatic light-beam arising from the mutual interference of the reflections from the successive layers of the nacre has the same direction as the diffracted beam of that wavelength in the spectrum of the same order. A notable part was also found to be played by the diffusion of light in the nacreous material arising by reason of its structure which consists of discrete crystallites of aragonite imbedded in a cementing network of conchyolin and arranged in a series of equidistant layers. The size, orientation and ordering of the crystallites in the layers is altogether different in the different classes of mollusca, viz, *Bivalvia*, *Gastropoda* and *Cephelopoda* and differs in detail even as between the different species within the same class. These structural differences are made evident in a very striking way by the variation in the nature of the diffusion halo observed in the different cases when a bright source of light, preferably a sodium vapour lamp, is viewed through a thin plate of nacre. The actual appearance of an iridescent shell in any given set of circumstances was found to be profoundly influenced by the diffusion and absorption of light within its material, apart from the internal reflections at the successive layers of the structure.

Recent issues of these *Proceedings* have contained papers describing the results of investigations on the structure and optical behaviour of various solids exhibiting structural colours. The phenomena encountered in those investigations suggested that further studies on the same lines with iridescent shells might prove fruitful, and this has actually been found to be the case. Some noteworthy results have emerged which are reported in the present paper. Of special interest is the discovery that the monochromatic reflections and extinctions bifurcate at oblique incidences and appear in the spectrum as separate components which are polarised differently. This result could have been anticipated as a consequence of the strong birefringence of aragonite. Secondary maxima of reflection and extinction accompanying the principal components have also been observed and recorded. The diffusion haloes referred to in the foregoing paragraph have also been found to exhibit remarkable changes in their geometric form and their state of polarisation when a source of light is viewed obliquely through the plate of the material. Closely connected with these diffusion phenomena is the polarisation of the transmitted light which is observed and which is of the opposite character to that ordinarily exhibited by a pile of plates at oblique incidences. In these and various other effects that have been noticed, the individual features in the structure of the nacre in the different species of mollusca come very prominently into evidence.

2. The structure of the nacreous material

The lamellar structure which is responsible for the iridescence of nacre is on a very fine scale. Nevertheless, it is often possible to observe and enumerate the individual layers, because in their natural form the shells are curved and hence when a plate is cut and polished *flat*, the successive layers meet the surface obliquely and exhibit the contours of the form on which the material of the nacre was originally laid down. These contours can be readily observed through a magnifying lens or a low-power microscope. They appear as a series of circles, ellipses, hyperbolae or other curves following each other in great number. From the inclination of the lamellae to the surface and their observed separation, the spacing of the stratifications can be determined.

That the nacre consists of discrete crystallites becomes evident when a small bright source of light is viewed normally through a thin polished plate of the material. Overlying the original source of light we observe a diffusion halo which, as mentioned above, exhibits totally different characters in the different orders of mollusca. In the *Gastropoda* which include such well known shells as *Turbo*, *Trochus* and *Haliotis*, we observe a circular halo with faint extensions outside and a dark area inside surrounding the source. The halo of *Turbo* is reproduced as figure 1 of plate I. In the *Bivalvia* on the other hand, the halo consists of two diffuse spots, one on either side of the image of the source, with a distinct bright corona overlying the latter. This is illustrated in figure 5 of plate II. The most interesting halo of all is that given by *Nautilus*. This shell is remarkably opaque and has to be thinned down very considerably to enable the halo to be seen. It is of peculiar form, consisting of two circular but incomplete arcs of about 60° angle, one on either side of the direct beam. In the outer regions we observe faint extensions, including especially a pair of brushes extending out obliquely from the terminations of each of the circular arcs mentioned above. A picture of the halo of *Nautilus* as observed in the normal setting of the shell is reproduced as figure 8 in plate III.

In all cases, if the source of light is monochromatic, the haloes exhibit a finely mottled structure as can be seen in plates I, II and III. On the other hand, if the source of light is white, we notice long coloured streaks radiating out from the centre, the most intense portions of these forming the observed halo. From these facts it is clear that the haloes arise from the interference of the light diffracted by the individual crystallites of aragonite in their setting of conchyolin. From their configuration one can deduce the size, shape and ordering of the crystallites in the individual layers of the nacreous material.

Useful information regarding the structure of nacre is also forthcoming from a variety of other sources. In particular, should be mentioned the appearance of thin sections of nacre under the microscope. Studies of this kind accompanied by numerous microphotographs are described in a paper by V S Rajagopalan.[4] As has been shown by him, the results are in full accord with the inferences derived from a study of the diffusion haloes. Of particular interest are the photographs of the conoscopic figures of different specimens of nacre also recorded and reproduced in the same paper. The figures exhibit the birefringence of the material very clearly and represent the integrated effect of the crystallites. For the *Gastropoda*, the figures observed in convergent polarised light are indistinguishable from that of a uniaxial crystal cut normal to the optic axis. On the other hand, the *Bivalvia* show figures resembling that of a biaxial crystal but with varying optic axial angles. *Nautilus* gives a biaxial figure with a very small axial angle.

These observations indicate that in the *Gastropoda*, the crystallites are orientated at random in the plane of the stratifications, while on the average, their *c*-axes are normal to that plane. On the other hand, in the *Bivalvia*, it is evident that the crystallites are set in more or less precisely defined orientations in the plane of the stratifications, while their *c*-axes lie normal to that plane on the average. The case of *Nautilus* is of a more complex character. Observations under the microscope with high powers exhibit a twinning of the crystallites which appear ordered in the layers in a fairly regular manner. However, fairly large errors in orientation are indicated by the fact that no complete extinctions are observed under crossed nicols.

The foregoing inferences regarding the orientation of the crystallites in the nacreous shells receive support from X-ray diffraction studies. Numerous examples have been investigated by S Rama Swamy[5,6] in different settings of the specimens using monochromatic X-radiations. The patterns recorded are found to be totally different for the *Bivalvia*, *Gastropoda* and for *Nautilus* respectively.

They also show that the orientation of the individual crystallites fluctuates observably about the average in all cases.

3. The reflection-diffraction spectra

As remarked earlier, the laminations of nacre, in general, meet its external boundary obliquely. As a consequence, the surface of the material is usually corrugated and gives rise to diffraction spectra accompanying the reflected light. Simultaneously also, the incident beam penetrating into the nacre is reflected backwards by the stratifications, and since the latter are regularly spaced, there is a selective monochromatic reflection, the direction of emergence of which is determined by the inclination of the stratifications to the surface and the refractive index of the material. Since both effects have their origin in the same incident beam, they are necessarily coherent, and it is easily shown[2] that the internal reflection emerges in a direction coinciding with one of the orders of the diffraction spectra of the same wavelength produced by the surface of the shell. Further, the order of the diffraction spectrum in which it appears is also the order of the interferences giving the characteristic internal reflections. All that is necessary to determine the latter is to allow a thin pencil of white light to fall on the surface of the shell and to receive it after reflection on a white card. The iridescent reflection then appears in its proper place in the sequence of diffraction spectra produced by the corrugated surface.

The coherence of the internally reflected and externally diffracted radiations also exhibits itself in other ways. A faint diffraction spectrum of a higher order than the characteristic iridescence is frequently observed and this is usually monochromatic. Further, the distribution of intensity in the spectra of the lower orders is modified and may be very different from that observed in a normal spectrum. Such an effect is clearly seen in figures 14, 15 and 17 in plate IV.

Four reflection-diffraction spectra obtained with *Margaratifera*, *Turbo*, *Nautilus* and *Haliotis* are shown as figures 14, 15, 16 and 17 respectively in plate IV. In each figure the diffraction spectrum of zero order appears as the most intense and best defined spot. Owing to the asymmetric configuration of the surface, the diffraction spectra are far more intense on the one side than on the other. In each figure the last bright spot to the right is the characteristic reflection. In figure 14 it appears in the diffraction spectrum of the fourth order, in figure 15 in the third, and in figures 16 and 17 in the second order.

Some special points of interest may be mentioned in this connection. The iridescent reflection usually appears surrounded by a halo of scattered light. The angular diameter of this halo is large and its intensity is low for *Margaratifera*. Indeed it is hardly visible in figure 14. On the other hand, it is of smaller dimensions and more intense in the case of *Turbo* (see figure 15). These differences are explicable in terms of the size of the crystallites which are much smaller in

Margaratifera than in *Turbo*. The diffusion halo overlying the iridescence in the case of *Nautilus* is very intense as can be seen from figure 16. This is evidently a consequence of the special structure of the nacre in this mollusc and is closely connected with the extreme opacity of its shell referred to earlier.

It is evident that the reflection colours exhibited by nacre would be more lively if they arise from interferences of a lower order than in the case of higher orders. There are however also other factors which require to be considered in this connection. One of them is the intensity and colour of the overlying diffusion of light already referred to. Another factor is the specific absorption of light by the organic matter present in the nacre. The effect of such absorption would be to diminish the intensity of the diffuse light emerging from within the shell and hence would help to make the coloured reflections more vividly observable. *Per contra*, the absence of such material or a specially strong diffusion would reduce the vividness of the iridescence. As examples of the working of these factors, we may mention a few cases. The iridescence of *Turbo* is more vivid than that of *Margaratifera* evidently as a consequence of the interferences being of a lower order. The brilliant colours often seen with the shells of the Californian abalone may likewise be ascribed to the interferences being of a still lower order, namely the second. They are further enriched when absorbing material is present in the shell. *Nautilus*, on the other hand, presents a silvery appearance and a generally inconspicuous iridescence, clearly because of the intense diffusion of light by the material.

4. Spectral character of the reflections and extinctions

In plates V and VI are reproduced the reflection and extinction spectra respectively of iridescent shells in typical cases. They exhibit several features of interest which will now be described.

Figure 18(a) in plate V is a record of the spectrum of the light reflected at nearly normal incidence from the outer convex surface of a large well-polished shell of *Margaratifera*. The reflecting area chosen was located on a part of the shell in which some absorbing material was present which in consequence was quite dark when viewed by diffuse light and *per contra* exhibited vivid colours by reflection. Other areas where there was no such absorption appeared silvery white by reflected light with scarcely any visible colour. Figure 18(a) shows the third and the fourth order reflections in this case. The latter is highly monochromatic and is accompanied by secondary maxima. Figures 18(b) and (c) recorded with a polaroid before the slit of the spectrograph in two perpendicular settings give no indication of any polarisation of the spectrum at the incidence employed. On the other hand, the spectra recorded with the same shell and with the light incident at an angle of about 50° and reproduced in figure 19 show such an effect in a striking manner. Figure 19(a) gives the whole of the reflected light, while figures 19(b) and (c) were recorded with a polaroid in front of the slit with its vibration directions respectively perpendicular and parallel to the plane of incidence. The splitting of the spectral reflection into two polarised components, each accompanied by its own secondaries, is thus clearly demonstrated. A similar effect is shown by figures 20(a), (b) and (c) recorded in a similar manner, of the reflection from a piece of *Turbo* at oblique incidence. Figures 21 and 22 in plate VI are similar records of the transmission spectra of a thin polished plate of *Turbo* at normal and at oblique incidence respectively. The former exhibits the high monochromatism of the extinctions, the secondaries accompanying them, as also the absence of any polarisation. But in figure 22(a) which was recorded in oblique transmission through the plate, the splitting of the extinctions into two components appearing at λ 4380 and λ 4520 respectively is very clearly seen. It is also apparent from figures 22(b) and (c) that the two components are polarised differently; the extinction at λ 4520 is very prominent in figure 22(b), while that at λ 4380 is hardly visible; in figure 22(c), on the other hand, the extinction at λ 4520 is not perceptible while that at λ 4380 is distinctly visible.

The splitting of the reflections and extinctions into polarised components in oblique reflection and transmission is readily understood when the birefringence of the nacre is taken into consideration. The refractive index of aragonite for vibrations parallel to the *c*-axis is 1·530 while for vibrations parallel to the *a*- and *b*-axes are respectively 1·681 and 1·685. The values for nacre would, of course, be modified by reason of the presence of conchyolin. We may, as a first approximation, ignore the difference in the refractive indices for vibrations along the *a*- and *b*-axes and treat the nacre as equivalent to a negative uniaxial crystal. Such an assumption would be strictly correct for the *Gastropoda* and approximately so for the *Bivalvia* and for *Nautilus*. The monochromatism of the reflections and extinctions at normal incidence and their splitting into two components at oblique incidences with the component of shorter wavelength vibrating in the plane of incidence follow as consequences of this situation.

It may be mentioned that the splitting and polarisation of the spectral components can be observed visually with a pocket spectroscope. It can also be demonstrated in an objective manner with the aid of the reflection-diffraction spectra illustrated in plate IV, when these are observed at oblique incidences with a polaroid placed in the path of the reflected light.

The high degree of monochromatism of the reflections exhibited in figure 18(a) calls for remark. The theory of the reflection of light by a periodically stratified medium was discussed by G N Ramachandran in these *Proceedings*[7] some years ago. His paper considers the influence of the several factors which influence the observed results, viz., the reflecting power of the stratifications, the relative thicknesses of the alternate layers, the total number of strata and so forth. As was shown by him, the sharpness of the spectral maxima cannot be indefinitely increased by increasing the number of the stratifications but is limited by their reflecting power. In the present case, the difference in the refractive indices of aragonite and conchyolin at normal incidences is very large. In these circumstances, the observed spectral sharpness of the reflection maxima is, at first sight, a very surprising fact. An explanation of this is to be found in the circumstance that the layers of conchyolin separating those of aragonite are very thin in comparison with the latter. Thus, in spite of the large difference in the refractive indices of the two materials, the reflecting power of an individual stratification is small. The light can therefore penetrate to considerable depths and bring effectively into operation a large number of strata and thereby sharpen the spectral bands of reflection.

5. The diffusion haloes and their polarisation

As remarked in the introduction, the diffusion haloes observed when a source of light is viewed through a plate of nacre undergo most remarkable changes in respect of their geometric form and state of polarisation when the plate is tilted from the normal position to one in which the light traverses it obliquely. These changes are illustrated by a series of photographs in plate I for the case of *Turbo*, in plate II for the case of *Margaratifera* and plate III for the case of *Nautilus*. Certain features common to all the three cases may first be mentioned. When the light traverses the plate normally, neither the source of light itself nor the halo seen around it exhibit any polarisation. In other words, if a polaroid covers the source of light and is turned round in its own plane, no change is observable in the field. However, when the plate is tilted, polarisation effects immediately become visible. The source itself as seen by the transmitted light is weakened in intensity, the component of vibration lying in the plane of incidence much more so than the other: indeed, the former component is nearly extinguished when the plate is held sufficiently obliquely. This effect is exactly the opposite to that exhibited by a pile of plates and also appears at much smaller angles of incidence than in the latter case. The explanation of the phenomenon is evidently to be found in another effect which is noticed at the same time, viz., the appearance of an increasingly intense diffusion halo seen covering the source of light and which is strongly polarised in the opposite sense, that is, with its light vibrations predominantly in the plane of incidence. The extinction of the same component in the transmitted light is thus revealed to be a direct consequence of the strong diffusion of the same component at oblique incidences. In all three cases, however, part of the diffusion halo as seen at oblique incidence is found to be polarised with the vibrations perpendicular to the plane of incidence. Both the configuration of the halo and the state of polarisation in the different parts of the field alter progressively with the increasing obliquity of the plate.

The case of *Turbo* illustrated in plate I shows the most rapid changes of the diffusion halo as the incidence is made oblique. To observe the circular halo represented in figure 1, the orientation of the plate has to be precisely normal to the light-beam from the source. A slight tilt of the plate causes the disappearance of a part of the circular halo and the simultaneous appearance of a corona of light surrounding the source with the consequence that the picture is strongly asymmetric (figure 2 in plate I). With a further tilt, the surviving part of the circular halo divides into two spots which shift towards a diametral setting with reference to the central corona which then appears with greatly enhanced intensity. The picture is then rather reminescent of the planet Saturn with its rings protruding on either side. Seen through a polaroid, the two outer spots are strongly polarised, being visible in one setting and completely absent in a perpendicular setting; the central corona is also partially polarised but in the opposite sense. These two cases are represented respectively in figures 3 and 4 of plate I. It will be noticed from the latter figure that the central corona has a distinctly elliptic shape with its major axis in the plane of incidence.

In the case of *Margaratifera*, a tilt of the specimen away from the normal results principally in an enlargement and intensification of the central corona covering the source of light. There is however an important difference in its shape and extension according as the tilt of the specimen is about the line joining the two outer spots of the halo or about a perpendicular line. In either case, the extension of the corona is greater in a plane perpendicular to the axis about which the plate is tilted. If the corona extends more along the line of the spots, it tends to overlap and cover them up. Figure 6 corresponds to this case and figure 7 to the other case.

The most remarkable changes are those observed with *Nautilus* and illustrated in figures 8 to 13 of plate III. Some of the features noticed in this case resemble those noted above in the case of *Turbo*, while others resemble the effects observed with *Margaratifera*. The phenomena are totally different in the two cases in which the axis about which the plate is tilted is respectively parallel or perpendicular to the line joining the centres of the two short circular arcs seen in the normal setting. Taking first the parallel case, we find as with *Turbo* a shortening of the circular arcs; they appear to drift to one side or the other according as the tilt is in one sense or the opposite. The pattern thus becomes distinctly unsymmetrical with reference to the image of the source of light. This asymmetry becomes most clearly evident when the pattern is seen through a polaroid. The two outer arcs alone and the source of light are seen in one setting of the polaroid, while in the other perpendicular setting a bright central corona with a diffuse outlying patch is seen. The extraordinary perfection of the polarisation of this corona will be realised on a comparison of figures 10 and 11 in plate III which represent the diffusion halo as seen through the polaroid respectively in two mutually perpendicular settings. Figure 9 is the diffusion halo in the same situation but photographed without a polariser. It will be noticed that the outer arcs have shifted distinctly downwards with respect to the centre of the corona; on the other hand, when the tilt of the plate is in the opposite sense, they drift upwards with respect to it. The latter case is represented by figure 12. When the axis about which the plate is tilted is perpendicular to the line joining the centres of the circular arcs seen in the normal setting, we observe the strikingly asymmetric pattern reproduced in figure 13, one of the arcs being then much more intense and elongated than the other.

6. The origin of the diffusion haloes

Two distinct types of diffusion arise when a beam of light traverses the nacreous substance even in the relatively simple case of normal incidence on the stratifications. We have firstly, the diffusion backwards towards the source referred to in section 3, which is due to the fact that the reflecting layers are not continuous and that when considered on a microscopic scale they are not perfectly plane. The second type of diffusion appears in directions adjacent to that of forward travel of the light. This is a consequence of the different retardations of the advancing wavefront produced respectively by aragonite and by conchyolin in each layer of the stratification. As this difference is not negligible, a powerful diffusion would result. Indeed nacre would be completely opaque to light but for the fact that the largest proportion of the area in each layer is occupied by the aragonite crystallites, the conchyolin only filling the narrow gaps between them. It is scarcely to be doubted that the high opacity of the shell of *Nautilus* is to be ascribed to this condition being less perfectly fulfilled than in the other cases, as is indeed evident from the microphotographs of thin sections of the material.[4]

The linear fibrous grouping of the crystallites in *Margaratifera* results in the diffusion appearing principally in a plane perpendicular to the fibre direction. As a consequence of the approximate uniformity of the size of the crystallites, the nacre behaves somewhat in the manner of a diffraction grating: a central corona appears surrounding the source of light and is accompanied by two bright spots on either side. On the other hand, the central corona is very weak in the normal patterns of *Turbo* and almost completely absent in that of *Nautilus*. The pattern for *Turbo* resembles pretty closely the diffraction pattern due to a large number of circular discs arranged in a plane with a high degree of regularity which is reproduced as figure 3(a) in plate XVI in a paper by Y V Kathavate[8] in these *Proceedings*. We may therefore infer a remarkable combination of random orientation with regularity of spacing of the crystallites of aragonite in *Turbo*. The special form of the diffusion halo in *Nautilus* is likewise to be ascribed to the peculiar shape and very characteristic arrangement of the crystallites in its structure revealed by microscopic and X-ray studies.

When the characteristic monochromatically reflected beam travels backwards towards the source of light, it would necessarily suffer a diffusion of the second type. This would be characterised by its being also monochromatic and would thus be different from the backward diffusion of the first type which would be white in colour. The overlapping of the two effects would determine the colour of the backward diffusion actually observed.

7. The case of oblique incidences

We now have to consider the explanation of the remarkable changes in the general configuration of the diffusion pattern, as also the striking polarisation effects exhibited by it in different areas, consequent on a tilting of the plate with respect to the light beam. There could scarcely be any doubt that the latter feature arises from the birefringence of the crystallites of aragonite. When the light traverses them normally, the refractive index is effectively the same or nearly the same for all directions of vibration in the wave front. Hence, the diffusion haloes cannot be expected to exhibit any polarisation; and indeed no such effect is observed. On the other hand, when the light traverses the plate obliquely, the refractive indices of the aragonite differ notably for the two components. There is therefore no reason to anticipate that either the transmission or the diffusion of the light through nacre would exhibit identical features in respect of both components. What is remarkable, however, is that in certain parts of the field the diffused radiation is predominantly polarised in one way and in the rest of the field predominantly in the opposite sense. We have now to ask ourselves why this is the case.

In order that there should be either a high concentration of intensity or a nearly vanishing intensity of the diffracted light in any particular part of the field, it is clearly necessary that the scattered radiations from the crystallites should be in regular phase relationships with each other in the corresponding directions, mutually reinforcing or mutually cancelling out each other's effects by interference, as the case may be. The retardation of phase of the light-waves in passage through a crystallite would be different for the two components of vibration, and it is readily seen that the fluctuations in such retardation due to the varying orientation of the crystallites would be much larger for the vibration component in the plane of incidence than for the other component. It follows that the features in the pattern arising from the coherence-in-phase of the effects of the individual crystallites would be most clearly evident for the component perpendicular to the plane of incidence; *per contra*, the results of their incoherence would be most marked in the parallel component. Pursuing this line of thought, one can readily understand in a general way the phenomena described above for the different species of nacre. A preferential extinction of the parallel component in the transmitted light follows as a consequence of the same train of ideas. This effect is very evident on a comparison of figures 22(b) and (c) in plate VI, which represent the spectra of the transmitted light for the two components respectively and which were recorded with identical exposures.

8. Optical behaviour of transverse sections

So far, we have been concerned with the passage of light through nacre in directions either normal or moderately inclined to the stratifications. Very beautiful effects which appear worthy of record are also noticed when a pencil of light passes through a thin plate of nacre cut transversely. Such a section, in effect, constitutes a diffraction grating. As a consequence, when a narrow pencil of light passes through it and is received on a screen, diffraction spectra are observed, one on either side of the transmitted beam, in directions making fairly large angles with it. The transmitted beam also shows a distinct measure of polarisation, but the sense of this differs in the two cases of light traversing the section normally and in very oblique directions. Within a certain range of these directions, a bright cross exhibiting brilliant colours with complementary tints in the two arms appears, having the transmitted pencil at the point of intersection of the two arms. The colours change in a remarkable manner with the inclination of the section to the pencil of light. The two arms are also polarised but with their vibration directions perpendicular to each other.

In seeking an explanation for the effects briefly mentioned above, one takes into account the fact that the refractive indices of aragonite and of conchyolin are different, such difference varying both with the direction of travel of the light beam and with the direction of vibration in it. Laminar diffraction effects varying with these factors would arise in consequence. The phenomenon of the cross with coloured arms may be ascribed to the discrete structure of the layers of aragonite. It may be mentioned that the phenomenon is best shown by transverse sections of *Turbo*.

9. Summary

Some remarkable optical effects exhibited by nacreous shells have been observed and reported, the following amongst others: The monochromatic reflections and extinctions split into two polarised components at oblique incidences as a result of the birefringence of the material. Light traversing the stratifications obliquely suffers extinction by reason of diffusion by the crystallites of aragonite, this being most rapid for the component of vibration in the plane of incidence. Striking changes are also observed in the character of the diffusion haloes with increasing obliquity of observation, a particularly noteworthy feature being that the different parts of the diffusion field are differently polarised.

Bibliography

Important studies on the structure of mother-of-pearl were made by W J Schmidt, a summary of whose findings is given in pages 155 to 165 of his book *Die Bausteine Des Tierkorpers in Polarisiertem Lichte*, 1924. The following papers are those referred to in the text.

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4. Rajagopalan V S, *Ibid.*, 1936, **3A**, 572.
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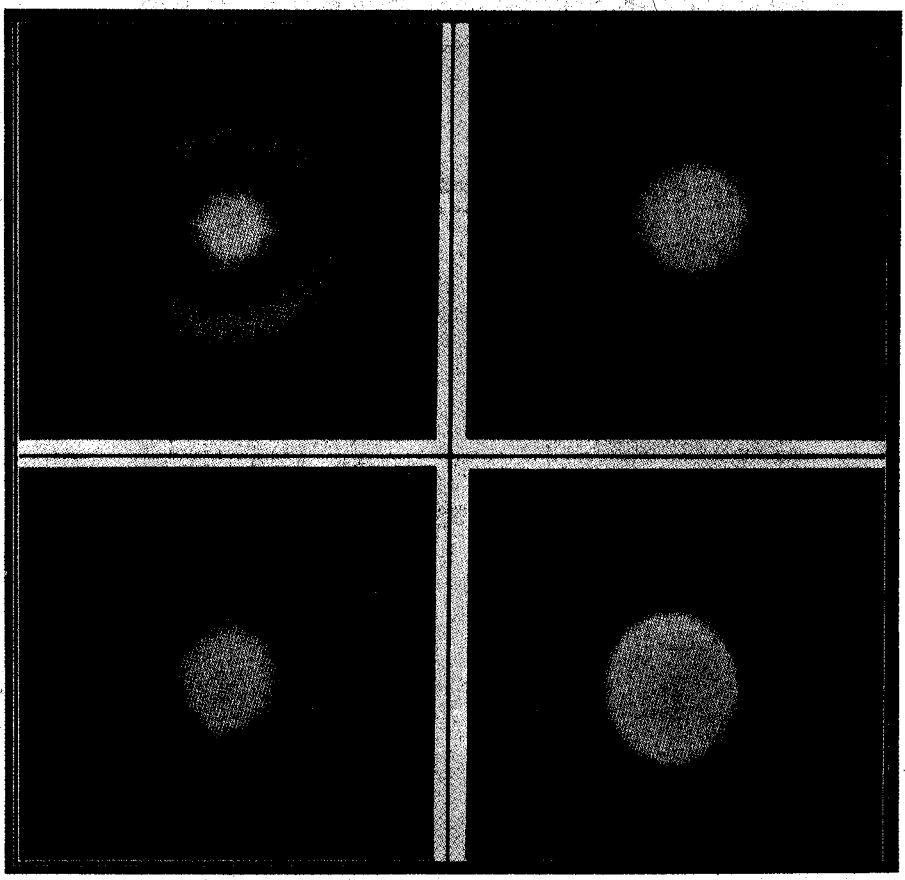
7. Ramachandran G N, *Ibid.*, 1942, **16A**, 336.
8. Kathavate Y V, *Ibid.*, 1945, **21A**, 233.

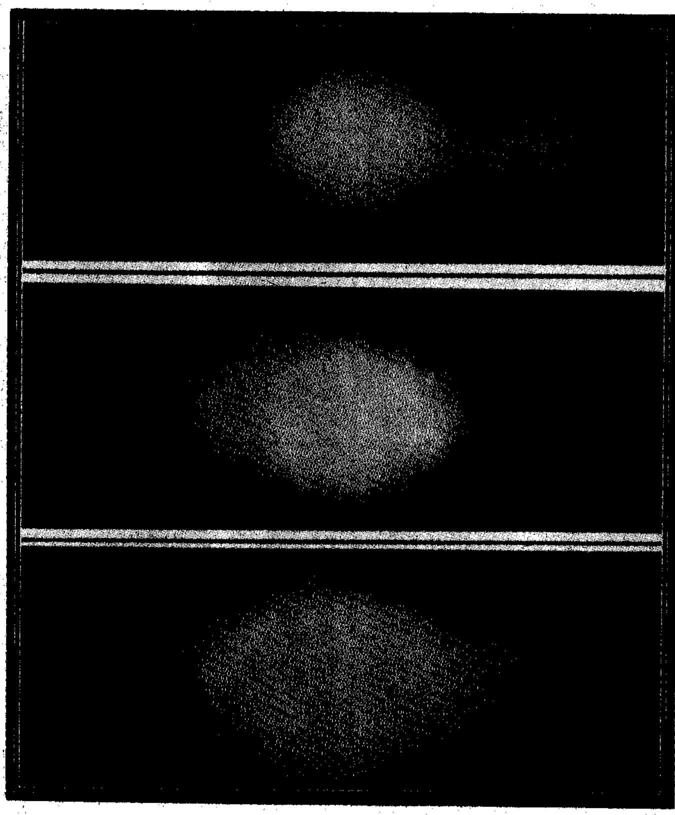
(1) (2)

(3) (4)



Figures 1–4. Polarised diffusion haloes of *Turbo*.

Plate I



(5)

(6)

(7)

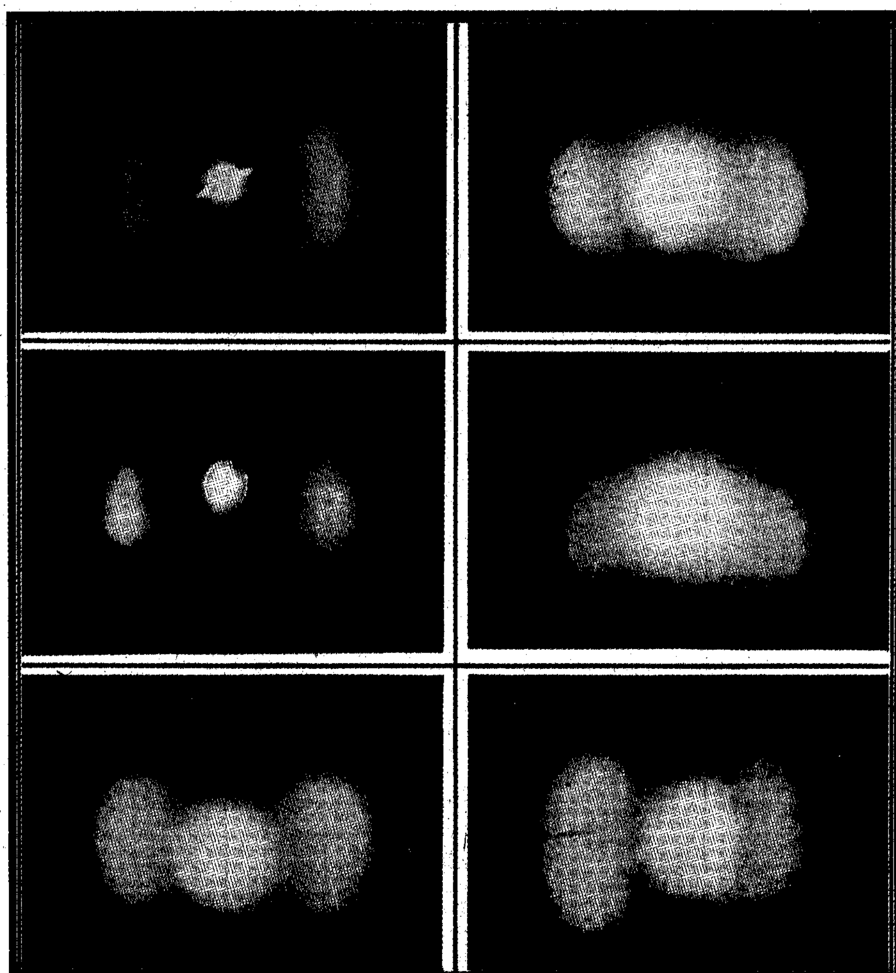
Figures 5–7. Polarised diffusion haloes of *Margaratifera.*

Plate II

(8) (9)

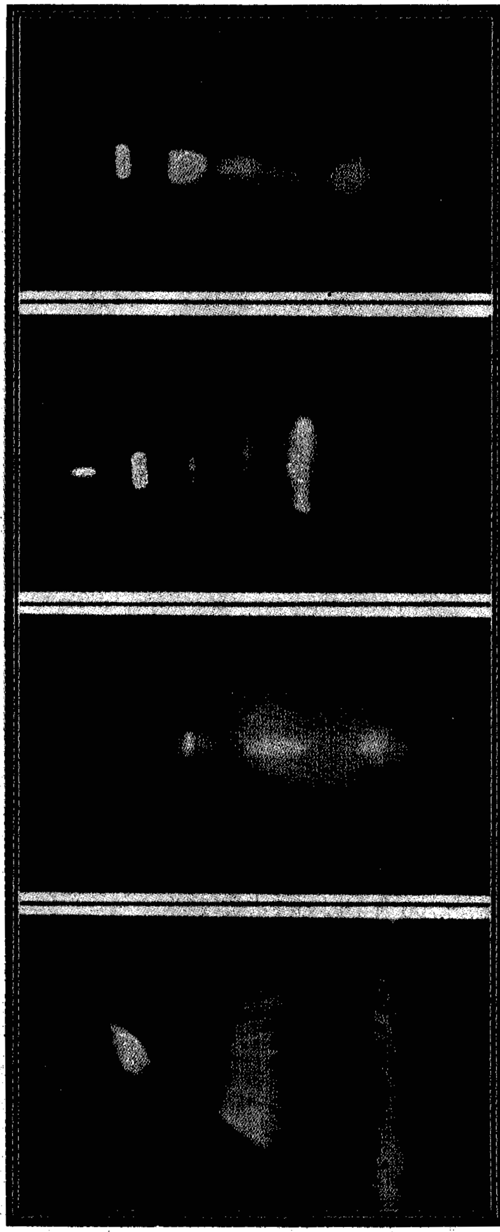
(10) (11)

(12) (13)



Figures 8–13. Polarised diffusion haloes of *Nautilus.*

Plate III



(14)

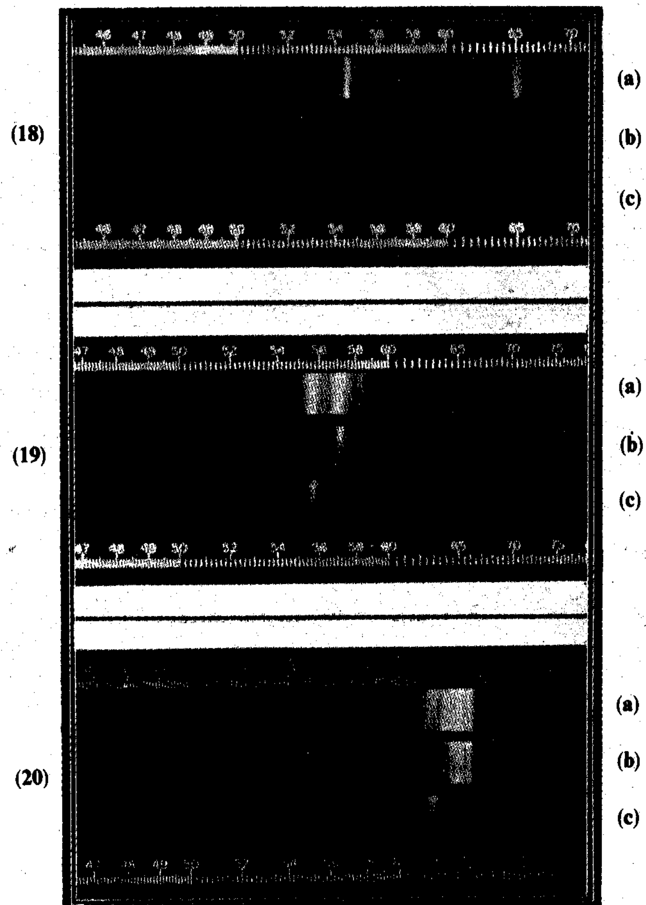
(15)

(16)

(17)

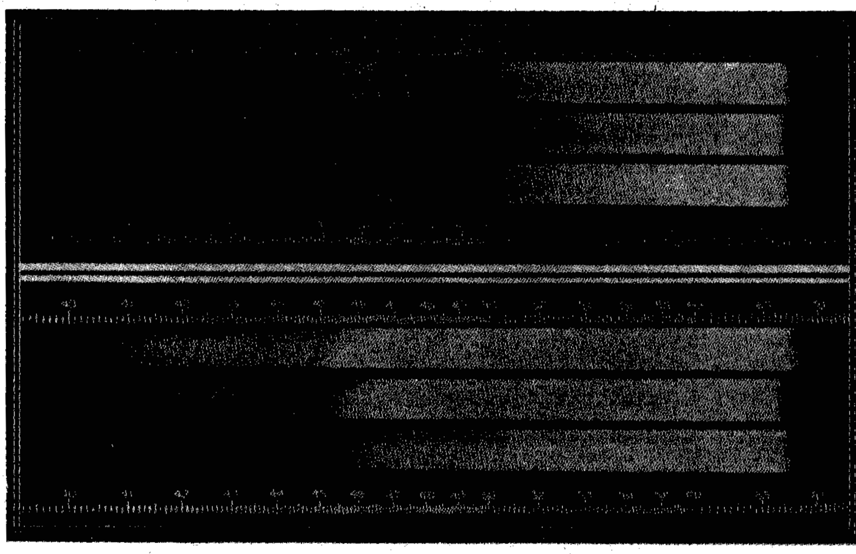
Figures 14–17. Reflection diffraction spectra. **14.** *Margaratifera,* **15.** *Turbo,* **16.** *Nautilus,* **17.** *Haliotis.*

Plate IV



Figures 18–20. Reflection spectra. **18 and 19.** *Margaratifera*, **20.** *Turbo*.

Plate V



(21) (a) (b) (c)

(22) (a) (b) (c)

Figures 21 and 22. Transmission spectra of *Turbo*.

Plate VI