STRUCTURAL COLORS IN FEATHERS. II

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Iridescent Feathers

In addition to white and blue, the structural basis of which has been recognized for some time, another type of color claims our attention. Iridescent or "metallic" colors occur in feathers of peacocks, humming birds, trogons, pheasants, pigeons, ducks, chickens, grackles, etc., and are characterized by their brilliancy and lustre, and by the marked change in color which they show with changing positions, as well as by their occurrence in the barbules alone. The uniformly opaque brownish appearance of these feathers when held against the light shows that more than ordinary pigmentation is present. The variety of causes to which these colors have been ascribed is sufficient justification for the present study, which is an attempt to evaluate the numerous theories which have been advanced. Structures similar to prisms, to diffraction gratings, or to thin plates, have all been suggested as causing the iridescent colors, while selective reflection (surface color) has been considered by some investigators to account for these colors. Of so many possibilities, including all the ordinary types of structural color, one ought to fit the facts, without the need of postulating a type of structural color not yet discovered. For this reason, these various causes suggested will be examined in some detail, as a basis for comparison with the properties of iridescent feathers. Although there are other types of structural colors, such as resonance, Christiansen effect, etc., these show their colors only by transmitted light, whereas we are concerned with colors which are observed only

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by reflected light, since it is only thus that the iridescent colors of feathers are seen.

Prismatic structure is assumed by Gadow[1] to be the cause of the iridescence of feathers. He observes that the colors which a feather shows by reflected light change "from the violet toward the red end of the spectrum" as the angle of incidence of the reflected light is increased from normal toward grazing, and gives a diagrammatic drawing of the cross-section of a barbule having a prismatic ridge along the outer surface. This drawing which shows the paths of the rays of light of different color seems to have clinched his argument, from the extent to which it has been copied in dictionaries of birds and similar works, though how a prism, in the position shown, could refract any light from a beam falling on the outer surface of the barbule at any angle, to the eye of the observer on the same side of the barbule, requires more than the known laws of refraction for its explanation; as Strong[2] points out, the light refracted by the prism to the eye would always have to make an angle of more than 180° with the incident ray—a physical impossibility, as far as the structure shown by Gadow is concerned, and absolutely at variance with the behavior of feathers. Incidentally, none of the iridescent feathers studied in the present work show such prismatic structure. Walter[3] also points out that a prism, to produce color, requires a narrow illuminating beam of light, and gives no color whatever with diffuse light. He emphasizes the fact that with the most highly dispersive transparent substances known, the whole spectrum only occupies a few degrees, "so that if we are to account for the gradual and continuous change of the tints of the surface colors when the angle of incidence varies between 0° and 90°, we must postulate an almost infinitely large number of prisms arranged in a very peculiar way, with the refracting edges all parallel. Even then one would have accounted for the play of colors only in one plane, for light falling perpendic-

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[1] Proc. Zoöl. Soc. London, **1882,** 409.
[2] "Mark Anniversary Volume," 263.
[3] "Die Oberflächen- oder Schillerfarben," (1895).

ular to the refracting edges. In order to have the same effect in all other directions there must be an infinite number more of these prisms, or twice infinity all told."

Gadow explains the fact that every feather does not show the whole spectrum, by the barbules acting as screens to cut out all but a part of the spectrum, or by the spectra from two neighboring prisms partly overlapping. However, the color of the isolated barbules is the same as that which they show in the feather.

There is no need of continuing further; it is obvious that Gadow's explanation cannot possibly be correct and that the colors of iridescent feathers are not caused by prismatic dispersion. The properties of these feathers given on subsequent pages only emphasize this. It is unfortunate that Gadow's paper has been so widely quoted without the inadequacy of these theories being perceived by the readers, particularly since the inadequacy ought to be apparent to anyone who subjects them to the least critical examination.

It has been suggested that the colors of iridescent feathers are due to some structure similar to that of a diffraction grating, since grating colors show a marked change with angle and are of considerable brilliancy. However, no trace of the system of fine, regular, parallel, striations characteristic of diffraction gratings is visible on most iridescent feathers, although the rulings of a diffraction grating are readily resolved by the microscope. A diffraction grating requires sensibly unidirectional light for the production of color, and this light must fall across the striations, not parallel to them, while iridescent feathers show their colors from whatever direction the light is coming. A diffraction grating shows no color in uniform light, such as that of a clouded sky, but the iridescent colors of feathers are unaffected by this illumination. The colors of a diffraction grating are visible, not in the path which the directly reflected or refracted rays would take, but considerably to one side of these rays. Thus a grating shows brilliant colors when illuminated from the side and examined from above and gives no color when examined with a vertical illuminator used in connection with a microscope. On the other hand, the iridescent barbules of feathers show no colors unless at such an angle as to reflect the light which falls on them to the eye of the observer; they give intense colors with vertical illumination under the microscope. Hodgkinson,[1] in an admirable paper, emphasizes these differences. The colors of a diffraction grating approach the red end of the spectrum (increase in "order") as the angle of incidence increases, while those of iridescent feathers approach the blue of the spectrum (decrease in "order") with increasing angle of incidence. The very marked change in color shown by a diffraction grating with change of angle is in marked contrast to the relatively slight change observed in feathers.

The marked differences in properties outlined above make the differences between diffraction colors and the colors of iridescent feathers very apparent. We may conclude that there is no connection between the iridescent colors of feathers and the colors produced by a diffraction grating.

Interference Colors of Thin Films

More detailed study of the properties of thin films and those of selectively reflecting media is necessary, for sufficient similarity exists to make the distinction very confusing, and indeed, the greatest division of opinion exists as to whether the iridescence of feathers is due to one or the other of these two possibilities.

The colors of thin laminae or films are caused by the destructive interference of certain of the wave lengths of the incident light, part of which is reflected from the outer surface of the film, and part from the other surface, after traversing the film. The portion of the light which traverses the film and is reflected back from the under surface through the film again, suffers a certain amount of retardation, dependent upon the thickness of the film, which may be just sufficient to put certain of the wave lengths out of phase with the same wave

[1] "Manchester Memoirs," [4] **2,** 193 (1889).

lengths reflected from the upper surface. Interference as a result of this retardation may result in the destruction of one of the component colors of the reflected light. If the incident light is white, the destruction of any wave length will cause a color due to the remaining components. Examples of this type of color are oil films on water or asphalt pavement, iridescent soap bubles, Egyptian glass, Newton's rings, etc.

Since the film itself must be fairly transparent, these colors are not seen plainly unless most of the light from the opposite side of the film is cut off. Otherwise the light passing through the film to the eye is much stronger than the reflected light, in which the color is found, and the color is obscured. Thus oil films on wet asphalt pavement appear much more brightly colored than oil films on clear water, because the dark background prevents any light from below from lessening the apparent intensity of the colors. The colors of thin films, viewed by transmitted light, are the true complements of those seen in the reflected light, but are not readily seen on account of the admixture of a large proportion of the white light which passes through the film unchanged as to color. The brightest color effects are seen against dark or dull backgrounds. The color seen when the film is illuminated with white light depends on the difference in refractive index between the film and the surrounding medium, on the thickness of the film, and on the angle from which it is viewed. (Dispersion may be neglected in thin films.)

Newton was the first to study these colors and they are often given his name. He arranged them in a series, in order of increasing retardation (or effective thickness) of the film, thus:

Black, white, yellow, red; violet, blue, green, yellow, red; purple, blue, green, yellow red; green, red; greenish blue, red; pale greenish blue, pale red, etc.; the colors corresponding to the thicker films approaching more and more toward white. Such a list of names is of little value, for the colors of the different "orders" (separated by semicolons) cannot be described adequately by naming them. Excellent colored charts of this series of interference colors have been prepared for use in petrography, and may be found in such books as Johannsen—"Determination of Rock-Forming Minerals," Winchell—"Elements of Optical Mineralogy," Lévy et Lacroix—"Les Minéraux des Roches," Finlay—"Igneous Rocks," and similar works.

Even these charts fail to represent the brilliant "metallic" lustre and intense coloring, which can best be observed with films prepared by allowing a drop of oil to spread on water, wet slate, etc., or by covering a dark object with a thin film of varnish or other material. Permanent films may be made by dipping a plate of black glass (or clear glass coated with a smooth film of India ink) into a *very* dilute collodion or gelatine solution. The excess liquid is allowed to drain off, and the plate is carefully dried. Unless the solution is too concentrated, a series of brilliant colors (Newton's colors) will be observed on the plate, the upper ones corresponding to the thinner part of the film, which is wedge-shaped and increases gradually in thickness toward the lower edge of the plate. By varying the concentration of the solution films of different thicknesses may be obtained and the colors corresponding to different parts of Newton's series may be examined. If the film is prepared on transparent glass the colors will be found to be very faint; the dark background is essential to their brilliancy, and to their distinctly metallic lustre. Thin films may also be prepared by blowing glass into exceedingly thin bulbs, or by cleaving mica. These films should be examined against a dark background to show their colors most plainly. The uncolored character of the transmitted light may be observed when the dark backing is absent.

C. V. Boys[1] in a little book on "Soap Bubbles" discusses the colors in some detail. A film to produce interference colors must be less than about 1.5μ in thickness, while the brilliant colors of the "second order" must correspond to thicknesses between about 0.3μ and 0.7μ, for films having a refrac-

[1] "Soap Bubbles," 148, 151.

tive index of 1.5. He points out that the retardation (effective thickness) varies with the cosine of the angle which the refracted ray of light makes with the normal to the plane of the film; if the color of the reflected light from a thin film held perpendicular to the line of vision is compared with the color observed when the film makes an acute angle with the line of vision, the color in the latter position corresponds to that of a thinner film. In other words, increasing the angle of incidence is equivalent to thinning the film, and causes a corresponding change in the color reflected.

The actual color to be obtained at grazing incidence from a thin film may be calculated rather easily from the relationship:

Retardation (effective thickness) = 2 θ cosine r where θ is the thickness of the film, and r the angle of refraction of the incident light. For a film of thickness θ, of refractive index 1.5, the maximum angle of refraction (critical angle) is about 42°, and calculating the retardation for $r = 0°$ (vertical incidence) and $r = 42°$ (grazing incidence) the retardation at grazing incidence is found to be about 75% of that at vertical incidence; that is, the effective thickness is less at grazing incidence by about 25%.

From a table of retardations corresponding to the different colors of the series the color at vertical incidence may be recognized, and its retardation noted;[1] the color at grazing incidence will be the color corresponding to a retardation about 75% of this value. This works out very nicely on color-producing films prepared as above.

This change of color with angle, or *iridescence*, is the most striking characteristic of thin film colors. For example, a film which is purple at normal incidence may change through red and yellow to green as the angle of incidence approaches grazing, a yellow film may pass through green and blue to violet, or a green film may change to red. These changes may all be predicted by means of a chart of Newton's colors. In

[1] Johannsen: "Manual of Petrographic Methods," 333 (1918).

the series given above, the colors preceding any given color are those of thinner films, so the color of a given film will always change to colors listed before it, usually through only one or two, or, at the most, three of the colors immediately preceding it in the series. Such a change is often referred to as "lowering of the order of the color," while the reverse change is called a "rise in order." The change in color is slight for inclinations less than about 30° from normal incidence, but as the angle increases toward grazing the colors change in a very striking manner, which is readily observed by the eye.

When the angle of incidence is small, a nicol prism shows no change in color of the reflected light vibrating in different planes. The color change as the angle increases is not affected. At about 60° from normal incidence, however, the reflected light, examined through the nicol in position to transmit the vibrations in the plane of incidence, is seen to decrease markedly in intensity. The light vibrating perpendicular to the plane of incidence is also decreased in intensity. At a definite angle the light vibrating in the plane of incidence almost disappears, and the film appears dark. This angle does not depend on the thickness of the film, for a film of variegated color darkens as a whole at the proper angle, which appears to be in the neighborhood of the "polarizing angle" (the tangent of which is equal to the refractive index of the substance).

If the angle of incidence is further increased, the color of the light vibrating in the plane of incidence appears complementary to that of the light vibrating perpendicular to this plane; it is also complementary to the color seen without the nicol, and to that of the light vibrating in the plane of incidence at angles less than the apparent "polarizing angle" noted above.

The optical properties of thin plates have been rather completely studied from a mathematical standpoint. Preston[1] gives a full discussion of the optical behavior of thin plates, in which he shows that the light reflected, at angles greater than the polarizing angle, is elliptically polarized, and that a

[1] Preston: "Theory of Light," 373 (1912).

complementary change in color takes place at the polarizing angle for vibrations in the plane of incidence.

The elliptical polarization of the light reflected from a thin film at angles greater than the "polarizing angle" may be detected by a "quarter-wave plate," which converts elliptically polarized light into plane polarized light. If the light, reflected at an angle greater than the "polarizing angle" of the thin plate, is passed through such a quarter-wave plate, and then examined through a nicol prism, in position to transmit the vibrations in the plane of incidence, the color observed is that seen without the nicol and quarter-wave plate. In other words, instead of a color *complementary* to that seen without the nicol, or with the nicol at lesser angles, or with the nicol perpendicular to the plane of incidence, the *same* color as that observed under these conditions is seen when the quarter-wave plate is combined with the nicol in position to transmit the vibrations in the plane of incidence. The interposition of the quarter-wave plate under these circumstances, with the resulting change from the complementary to the original color constitutes a very simple means of detecting the elliptical polarization of the light from thin films at angles greater than the polarizing angle. Theoretically, if the reflected light is all elliptically polarized, the quarter-wave plate ought to render it all plane polarized, and it shoud be cut off completely by the nicol in one position. Actually the elliptical polarization of the reflected light is not complete, and rotating the nicol when the quarter-wave plate is in position under these circumstances does not destroy the color.

The above changes in color with change in the angle of incidence may be easily observed by inclining the color-producing film in front of a source of diffuse white light, while viewing it through some sort of telescope combined with a nicol prism. In this work a Fuess Universal Stage Petrographic microscope was used. This instrument permits measured angular rotation of the specimen about a number of different axes, as well as providing a nicol prism and quarter-wave plate for the study of the reflected light. Since the films as prepared are usually of varying thickness and color, it is necessary to fix the attention upon a very small area of uniform color in order that the changes may be accurately observed. Points of reference may be marked on the film with a needle.

It should be borne in mind that the colored light is reflected from thin films as white light is from a mirror; the angles of incidence and reflection are equal; if the film is smooth images may be seen in it as in a mirror; no scattering takes place, and if the light from a point falls on a thin film only a colored point of light is seen. In order that the whole surface of the film shall appear colored, light from an infinite number of points—that is, diffuse light, is necessary. This is quite the opposite of the diffraction grating, with which a point of light is necessary for maximum color, and no color is seen in diffuse light.

This reflection which is essential to the production of color by thin films is, of course, dependent on the difference in the index of refraction between the film and the surrounding medium; thin films surrounded by a medium of refractive index near their own show no color. Colors of thin films can be completely destroyed by surrounding these films with the medium of the same refractive index. Liquids which do not affect the film itself should be chosen for demonstrating this.

A thin film of gelatine or collodion changes its color to that of a thinner film if subjected to considerable pressure, under a smooth convex surface. More striking effects are obtained by swelling. Gelatine or collodion films may be swelled by breathing on them or by exposing them to steam for a moment. The color produced by swelling is invariably that of a thicker film. Usually the color does not change through more than two colors adjacent in the series, and by examining the swelled film with grazing light (which is equivalent to decreasing its effective thickness) the original color of the untreated film may generally be observed. The color changes from swelling are reversible, and the original color is restored by drying the films.

Although maximum color is obtained from clear, transparent, colorless, thin films, very good effects may be observed with films made from turbid or highly colored material. For instance, black asphaltum varnish forms films on water almost as brilliantly colored as those from pale or colorless oils and varnishes. The asphaltum varnish is far from opaque in films of this thickness, yet the brown color of a thin layer of it is fairly pronounced.

If color-producing films of different refractive indices are superposed, the color produced depends on the relative thicknesses of the films as well as on their refractive indices. If two or more such thin films, each giving the same color, are combined the resultant color is the same in hue but occupies a smaller portion of the spectrum. These "multiple films"[1] except for the increased purity of their colors, have essentially the same properties as the single films. If the films which are combined are of different colors no such purity of color results, but rather a dulling or increase in order toward white.

Surface Colors

Surface color, which is a result of selective reflection, is possessed by certain substances, such as solid aniline dyes, highly colored crystals, metals, etc., and gives to the substances a peculiar brilliant metallic color, in appearance somewhat like the iridescent coloring of certain feathers.

Thin layers of these intensely colored substances transmit certain of the components of white light, and the light which passes through the substances appears colorless. Those wave lengths which are transmitted compose the "body color" of the substance. Of the wave lengths not transmitted, some are absorbed, while others are reflected from the surface layer of the substance, almost as perfectly as from a mirror. These reflected wave lengths make up the *surface color*, this phenomenon being called selective reflection.[2]

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[1] Rayleigh: Phil. Mag. **26,** 256 (1888).

[2] Wood: "Physical Optics," 439 (1911).

The statement is often made that the selectively reflected light is complementary in color to the transmitted light (Haidinger's Law) but it is evident that reflected light = white light (incident light) − absorbed light − transmitted light, so that unless absorption is negligible, the transmitted and reflected colors are really not complementary, though they often nearly appear so. For instance, solid fuchsine transmits red and reflects greenish yellow, as may be seen by allowing a warm concentrated alcoholic solution of the dye to evaporate on a glass plate. Cyanine, however, transmits purple, and reflects nearly the same color. Wood[1] emphasizes the fact that the wave lengths most reflected are not necessarily the ones most absorbed.

Of the substances which give selective reflection, all which have been studied show anomalous dispersion,[2] that is, the shorter wave lengths (blue) are not refracted as highly as the longer ones (red). This is the opposite of the behavior of the ordinary refracting substances, such as glass, water, etc. This anomalous dispersion is very marked, the refractive index varying greatly with the wave length of the light refracted. Thus cyanine has refractive indices from 0.83 to 2.68. If the selectively reflecting substance were in contact with a transparent substance of the same refractive index as its own for all wave lengths, no light would be reflected by it. It is actually possible to match the refractive index for a particular wave length, which then fails to be reflected, and does not appear in the reflected light. The result is a change in the color of the reflected light. The surface color of fuchsine changes from yellow-green to blue if the surface is covered with balsam or cedar oil.

As a consequence of the high dispersive power the color at grazing incidence will be different from that at normal incidence. In the case of a substance with its refractive index for a certain wave length less than that of air, total reflection may take place for this wave length at large angles of incidence.

[1] "Physical Optics," 440 (1911).

[2] Wood: "Physical Optics," 113 (1911).

with an accompanying change of color, which might be enough to be perceived by the eye. The change in relative intensity of different wave lengths with increasing angle of incidence and of reflection may be calculated from Fresnel's formula

$$\frac{\text{Reflected light}}{\text{Incident light}} = \frac{1}{2}\left[\frac{\sin^2 (i-r)}{\sin^2 (i+r)} + \frac{\tan^2 (i-r)}{\tan^2 (i+r)}\right]$$

where "i" is the angle of incidence and "r" the angle of refraction, but the change in relative intensity for the different wave lengths is not great, and indeed can barely be detected by the eye. It is calculated that the change in color should be toward blue, and this corresponds to what apparent color change is observed, but the effect is so slight that different observers cannot agree as to whether there is an actual change of color or only a darkening of the color seen at normal incidence. If the film of selectively reflecting material is formed on glass the body color may be mingled with the surface color unless care is taken to cut off all transmitted light. In any case, the supposed change of color is not observed except at almost grazing incidence; at angles less than this the change of color observed with the naked eye is almost inappreciable.

Examined through a nicol prism, the light reflected vibrating perpendicular to the plane of incidence shows no appreciable change of color with increasing angle of incidence. The light vibrating parallel to the plane of incidence shows marked change in color, always toward the blue end of the spectrum but never from green to red in any of the cases examined, as it sometimes does in thin-film colors.

To cite a few examples—*Gentian Violet* has a purple body color, yellow-green metallic surface color, which possibly becomes slightly more bluish at grazing incidence. No change in color with angle, examined through the nicol perpendicular to the plane of incidence. With the nicol parallel to the plane of incidence, the color changes to greenish blue at grazing incidence.

Fuchsine (magenta).—Body color—red, surface color—yellowish green. Very slight if any change toward blue with increasing angle of incidence, examined without the nicol or with the nicol perpendicular to the plane of incidence. Surface color changes to greenish blue with increasing angle, if the nicol is parallel to the plane of incidence.

Aniline Blue.—Body color purple, surface color reddish brown (bronze). No perceptible change in color with angle, except when examined through the nicol parallel to the plane of incidence, when color changes to dark greenish-bronze.

Malachite Green.—Body color green, surface color coppery pink. With the nicol parallel to the plane of incidence surface color changes toward yellow as angle of incidence is increased.

Cyanine.—Body color blue, surface color reddish purple. With the nicol parallel to the plane of incidence, surface color changes to greenish blue as angle of incidence increases.

The above examples show how the colors selectively reflected from typical substances showing surface color are not even approximately complementary to those which these substances transmit (body color). The almost inappreciable change in color with angle, except when the colors are examined through a nicol parallel to the plane of incidence, is also worth noting. The change thus observed appears to be always toward blue.

Metallic reflection results in elliptical polarization of the reflected light,[1] the extent of this polarization depending on the angle of reflection. This may be shown in the case of the above selectively-reflecting substances by inserting the quarter-wave plate in front of the nicol set to transmit vibration in the plane of incidence; the color observed without the quarter-wave plate, which is markedly different from that seen without the nicol or with it rotated through 90°, is changed by the interposition of the quarter-wave plate, not to a complementary color but to a color similar to the color without the nicol or with it transmitting vibrations perpendicular to the plane of incidence. This change takes place at any angle where the difference in color between the reflected light vibrating in the

[1] Wood. "Physical Optics," 456 (1911).

two different planes is appreciable, but the color change is by no means a complementary one, nor does it occur only at angles greater than a definite value, as in the case of thin-film colors. Apparently the surface color is elliptically polarized, to a greater or less degree, at any angle, while thin film reflections are elliptically polarized, to about the same extent, at all angles greater than the polarizing angle, but are not even partially elliptically polarized at angles less than this, as shown by the quarter-wave plate. Actually and theoretically, there is no darkening of the light selectively reflected at a definite angle, and no change to a complementary color at slightly greater angle, though, in the case of thin-film colors, the changes are shown both by observation and from theoretical considerations.

The very great absorbing properties of substances showing selective reflection must be emphasized. Even films a fraction of a micron thick show strong color by transmitted light. Films for the study of the transmitted and reflected light of these substances may be prepared by dipping glass plates into their warm alcoholic solutions, and allowing the plates to drain and dry. No matter how thin the film is, its body color is apparent in all cases where the film is thick enough to show any surface color whatever. The surface color is seen best when the film is against a black background. Against a light background the body color is mixed with the surface color, except in the case of very thick, almost opaque films.

All the dye stuffs which we know to give surface color are soluble in water, alcohol, ether, or other organic solvents, and are readily bleached. In the solid state or in concentrated solution in solid material their colors are not affected by pressure. Their optical properties appear to be the same whether they are dissolved in dry films of collodion, or in extremely concentrated solution in some liquid solvent, or simply as a film of the solid dye stuff.

The distinction between the properties of thin, color-producing films, and those of substances showing surface color are marked enough so that, in spite of their superficial similarities, it is possible to decide which is the type of color represented in iridescent feathers.

Structure and Physical Properties of Iridescent Feathers

Detailed study of the tail feathers of the peacock, typical iridescent feathers, is of particular interest because of the variety of colors represented in the pattern of a single feather. Examination of the structure is of the utmost importance, both for the detection of any color-producing structure, and because of the influence which structure may have on surface colors, and on tests for their identification.

The iridescent color of the feather is wholly in the barbules; the barbs are a dark, dull brown, and show no color effects. The iridescent color of the barbules is visible from both surfaces; but it is not seen if the feather is held between the eye and the light. Brown is the only color seen in this position, the iridescence not being observable.

The barbules vary considerably in size in the different parts of the feather, but all show the same structure, and appear as thin, narrow, curved, segmented ribbons or elongated plates. In the loose parts of the feather no hooks are found on the barbules, but in the denser parts of the "eye" some of the barbules may have hooklets on their ends. The barbules on the outer surface of the feather in its dense parts present a smooth surface, for they overlap like shingles, and form an approximately plane surface in the general plane of the feather. Actually the surface of the individual barbule is far from plane; they are curved longitudinally, convex-concave in cross-section, and the segments are individually of slightly greater thickness at their ends than at their centers, appearing to overlap somewhat like shingles. The barbules of the peacock feather are much larger than those of any other iridescent feather, being 0.8–3 mm long, 60 to 80 microns wide, 4 to 5 microns thick, with segments 30–50 microns in length.

Cross-section of the barbules, prepared by the paraffin method, were obtained sometimes as thin as about 5μ, though the small size, smooth surface, and brittle nature of the barbules render them very difficult to imbed firmly and to section satisfactorily. While sections thinner than this would be very desirable for accurate interpretation of such a minute structure, a fairly good idea of the internal structure of the barbule may be obtained, considering that the resolving power of the microscope sets a definite limit to the size of the details which can be studied. Such cross-sections are best examined without freeing them from the paraffin, for otherwise they are likely to lie on their sides rather than standing on end. The paraffin supports the section of the barbules so that their cross-section is readily observable and permanent preparations may be made by simply covering the paraffin sections with xylol-balsam and covering with a cover glass. The paraffin remains in position to support the section of the barbule, while the xylol-balsam partially clears the preparation.

The cross-section shows a central pith or core about 2μ thick, which appears to be of somewhat fibrous or granular character. Enveloping this core are three thin layers or laminae, of equal and uniform thickness, apparently in contact with each other. Since the total thickness of these three layers is only a little more than a micron, they are close to the limit of the resolving power of the microscope, and considerable care has to be taken to avoid incorrect interpretation. However, there seems to be no question but that there are actually three of these thin layers, each about 0.4μ–0.5μ thick, of great uniformity. The inner and outer layers appear dark while the middle layer appears light or transparent. That these are not simply diffraction effects seems to be proved by the fact that they appear in spite of various manipulations of the illumination, and moreover, are sometimes found separated where the broken portion of the barbule has been sectioned.

The barbules may be split by pressure or teasing, often in their principal plane, particularly since the core does not appear to have any great tenacity. Either half of the split barbule may show the iridescent colors. If the barbules are swelled to partial disintegration, by potash, ammonia, or sodium hypochlorite, the thin outer layers swell, pucker, split, and loosen from the core, which has a segmented appearance like flattened, short-joint bamboo. On drying, the loosened envelope shrinks back onto the core again, though not without considerable puckering and unevenness. Such severe treatment usually destroys the iridescence as well as removing some of the brown coloring.

No differences in structure between barbules of different colors were observed. The above properties fit all the different colored barbules which the peacock feather possesses. Study of other iridescent feathers (bronze-winged pigeon, Monaul pheasant, cock, trogon, etc.) by sectioning, teasing, and swelling, showed essentially the same structure, though the barbules of these feathers are smaller than those of the peacock, and generally are not so highly curved.

The laminated outer layer of the barbules, as shown by cross-section, is particularly characteristic, and is not found on non-iridescent feathers of the same bird where these are available for examination. In all cases a definite structure is associated with iridescence. The barbules are always broad and flattened, distinctly segmented, with blunt ends, and are generally much more heavily pigmented than adjacent, non-iridescent barbules of the same feather.

Newbigin[1] has pointed out the structural differences between iridescent and non-iridescent barbules, which are very noticeable in most feathers where both types of barbules are present. The bronze-winged pigeon, for example, has sharply defined iridescent patches on gray feathers, and microscopic examination shows the boundary of the patches to be very distinct, both types of barbules often existing side by side on the same barb. These structural differences are so apparent, that, after a little practice, it was found possible to pick out from the collection of drawings of barbules in Chandler's paper[2] those which were of the iridescent type, and comparison with the description of the coloring of the feather revealed very few errors, though the drawings cover almost all species, and include many feathers not possessing any non-iridescent barbules for comparison. This shows clearly that the same sort of structural modification occurs in connection

[1] "Colour in Nature," Chap. xiii (1898).

[2] Univ. of Cal. Pub. Zoöl., **13,** No. 11 (1914–16).

with iridescence, irrespective of the species of the bird to which the feathers belong.

The iridescent barbules of feathers do not usually have hooklets developed on them to any considerable extent and when these are present they are usually only on the segments nearest the tip of the barbule. The distal barbules in a feather of dense structure are so placed that, instead of being seen edgewise as the feather is viewed from a point normal to its surface, they present their broad surfaces to the observer, and give a smooth, overlapping "shingled," satiny appearance to the feather, few gaps or openings being visible in this approximately plane surface, even under the microscope; in the looser, more open types of feathers both the distal and proximal iridescent barbules present their flat surfaces to the eye in the above manner, though less closely overlapping. This satiny "shingled" surface is so different from that of a non-iridescent feather that it is not to be wondered at that Altum[1] made the statement that "in the case of the iridescent feathers with metallic lustre, the peculiar color is always accompanied by a peculiar structure. Wherever we find this type of color, we find a feather structure which feels hard, smooth, and metallic. It does not require a delicate sense of touch to distinguish blindfolded those parts of the feathers which show metallic colors, if one runs the hand, for instance, up and down the back and breast of *Cuculus cupreus* or of the different red-breasted trogons, etc. The metallic lustre is always associated with the peculiar, hard, and smooth texture. A blind man could easily pick out all the birds with metallic lustre in a collection of any size. He would even be able to arrange them according to the intensity of the lustre and other peculiarities."

The surface formed is so smooth and so nearly plane in many feathers that it gives them an almost mirrorlike or metallic appearance, and it is noticeable that practically no light is reflected from such a surface unless it is held so that the light may be reflected to the eye as from a mirror, the angles of incidence and reflection being equal.

[1] Jour. Ornithologie, **2,** 19 (1854).

Optical Properties of Iridescent Feathers

Whatever their colors by reflected light, the barbules of the peacock feather appear brown by transmitted light. The thinness is such that they are fairly transparent under the microscope. The shade of brown does not appear to be different in barbules of different color by reflected light.

By reflected light, the gorgeous colorings show plainly. They include copper-red, brass-yellow, yellow-green, blue-green, and purple, as seen when the plane of the feather is normal to the line of vision. These colors change very markedly with inclination of the feather from this position, an inclination of about 30° from normal causing the red parts to appear green in color, the yellow to appear blue-green, the blue-green to appear purple, and the purple to appear almost reddish. This variation is further increased by increasing the angle of incidence still more.

Microscopic examination by reflected light shows that what appears to the naked eye as a region of uniform color in the feather is really a composite, and that the color of the individual barbules in such a region varies considerably, any color from yellow to green appearing in the brass-yellow part of the feather. The color of the individual barbules is often far from uniform, showing distinct variations in different segments, and some lack of uniformity of coloration is noticeable even within the segments, though the boundaries between the different colors are not sharp, but blend gradually together. The coloring is further complicated by the curvature of the surfaces of the barbules, for, since the line of vision cannot make the same angle with all parts of the curved surface, part may be viewed at normal incidence while another part is seen at an angle as great as 30° from this position. Thus a curved red barbule may appear red at the base and green at the tip, solely on account of this difference in the angle at which these two parts of its curved surface are seen. Flattening the barbules under a cover glass when examining them helps to bring all parts of the barbule into the same plane. The transverse curvature of the barbules, which gives them a convex-concave cross-section, is more marked than their longitudinal curvature, and results in more noticeable variation of the color for this reason. Sometimes a barbule presents almost a spectrum across its surface, the red being on the part of the surface which is viewed normal, while the colors shade through yellow to greenish-blue on the part of the surface which makes an acute angle with the line of vision. Flattening the barbule brings all parts into approximately the same plane, and this variation of color due to curvature is destroyed.

Examination by means of a microspectroscope shows the light reflected from the barbules to consist of a region of the spectrum rather than being made up of lines or bands. The spectrum in general shifts toward the blue as the obliquity of the barbule to the line of vision is increased. Nothing more significant seems to be revealed by the microspectroscope than can be observed with careful study of the colors by the microscope alone.

On account of this complexity of surface, the color changes with angle can best be studied from single barbules flattened in wax on a slide, but not covered with a cover glass. Even then, the observations are best made on a single point at a time, rather than on the surface of the barbule as a whole, though, if its surface is smooth and approximately plane, good results may be obtained by study of the entire feather. A Universal Stage microscope provides for all possible orientations, while diffuse light may be supplied by an opal glass bulb, with white reflector, behind a white translucent screen, from which light can fall on the barbules from widely differing angles so that, whatever their position may be, it will be reflected in the eye of the observer.

Increasing the angle of incidence from the normal, little change in the color is noted with or without the nicol, at angles less than 30°, but as the angle of incidence exceeds this the color changes are marked. If the nicol is inserted so as to transmit light vibrating in the plane of incidence, the color is seen to darken as the angle of incidence is increased and at a slightly greater angle the complement of this color appears.

The color thus seen at an angle of incidence of about 60° is the complement of that seen at the same angle without the nicol, or with the nicol placed to transmit vibrations perpendicular to the plane of incidence. Also, if a quarter-wave plate is inserted, the color observed in this position is no longer complementary to, but is the same as the color seen without the nicol, or with it in the other position but without the quarter-wave plate. At angles of 60° or greater with the quarter-wave plate in position, rotating the nicol does not cut off the reflected light, showing that not all of the light has been rendered plane polarized by the quarter-wave plate, which means that the reflected light is only partially elliptically polarized.

In all the cases studied the changes in color and polarization with the angle follow the above rules. Indeed, after a little practice, one is able to predict, with considerable success, the color changes which any feather will show with increasing angle of incidence. The color changes of some typical iridescent feathers will be tabulated after the effect of swelling has been discussed.

Effects of Pressure and Swelling

Since the barbules are composed of fairly dense material, and apparently have no cavities, considerable pressure is necessary to produce any effect on dry, untreated barbules. It is noticeable, however, that their color by reflected light is changed by pressure, and in general this change is toward the blue end of the spectrum, or, more exactly, toward the color seen at grazing incidence. Barbules which have been softened by soaking in water or swelled by alkalies, etc. show much more noticeable changes in color with pressure. In this case the change of color with pressure follows the same rule.

The barbules are swelled markedly and softened by dilute ammonia or sodium hydroxide solutions. If they are mounted in water and the alkali is allowed to diffuse through the preparation the swelling takes place gradually and may be observed under the microscope. The swelling action causes marked changes in the color of the barbules as observed by reflected light, and all gradations of these changes are sometimes shown on a single barbule, one end of which may have been acted on by the reagent while the other end as yet was not reached by the diffusion. Thus a single barbule may appear blue at one end (its original color), shading through green and yellow to copper-red at the point acted upon longest by the swelling reagent.

In general the colors of the barbules change toward the red end of the spectrum though this is not the case for the barbules of feathers of some other birds than the peacock. The swelled barbules show the color change with angle, and other optical properties, corresponding to the behavior of the untreated barbules. It is always noticed that the color of the swelled barbules seen at grazing incidence is very nearly identical with the color of the untreated barbules seen at normal incidence. In some instances this color is reached at angles of incidence somewhat less than 90° (grazing), when the color of the swelled barbule at grazing incidence is very similar to that of the untreated barbule at an angle of incidence somewhat less than grazing.

The color changes of some typical iridescent feathers may be listed as in the following table:

The above list might be continued but the instances given are sufficient to show the nature and extent of the color change, and to illustrate the generalizations given in the preceding paragraphs. The similar behavior of similar colors in different birds is also worthy of note.

The application of pressure to the swelled barbules restores the original color, the color changes which take place being just the opposite of those passed through during the swelling process. More severe pressure may cause the color to go beyond that of the untreated barbule, generally toward the red end of the spectrum.

Exposure to phenol vapor for a few days causes color changes similar to those brought about by swelling with alkalies, and the swelled feathers have similar properties. Many

Color Changes from Vertical to Grazing Incidence

	Untreated	Swelled
Monaul Pheasant	Copper-red → yellow-green	Purple → copper-red → olive-green
	Grass-green → greenish blue	Copper-red → grass-green → bluish green
	Light greenish blue → blue violet	Yellowish green → greenish blue indigo
Wood Duck	Dark blue → purplish red	Lighter greenish blue → dark blue → reddish purple
Bronze-Headed Trogon	Green → indigo	Purplish red → bronze-green → blue-green
Common Pigeon	Green → red	Red → green
Black Minorca	Bluish olive-green → purplish blue	Pinkish brown → bluish green → blue
Peacock	Blue-green → indigo → reddish purple	Copper-red → blue-green → blue
	Greenish yellow → bright blue	Orange → green → greenish blue
Bronze-Winged Pigeon	Red → yellowish green	Reddish purple → red → greenish orange
Ptilopus pulchellus, *P. puella*	Green → blue	Orange → green → bluish green
Muscovy Duck (fault bars)	Blue → purple → reddish	Yellow-green → greenish blue
(normal)	Green → blue-green → purple	Orange → yellow-green → green
Nettion brasiliense	Green → blue → purple → reddish	Orange → green → greenish blue → blue
Red King Bird of Paradise	Brilliant green → blue → indigo	Red → yellow → green → bluish green
Peacock Pheasant	Greenish blue → purple → reddish	Orange → green → blue → indigo

organic liquids also cause swelling and color changes of the same sort, and even soaking for a time in water, or exposure to steam will cause considerable change in color due to the swelling of the barbules. Washing and drying of the barbules swelled by liquids, or simple exposure to the air in the case of those acted upon by vapors, is sufficient to restore the original color and properties perfectly. Care must be taken that only very dilute alkalies are employed, for strong solutions have a solvent and disintegrating effect on the feather, and injure its structure and color permanently.

Fault Bars in Iridescent Feathers

Riddle[1] shows that fault bars in feathers are caused by some hindrance of the normal development of the feather, either by mechanical injury or restriction, or by a lowering of the anabolic tonus of the bird by illness, starvation, poisoning, or similar cause. The period of this hindrance is recorded on the feather as a transverse mark or bar. The structure of the feather is much more easily affected than its pigmentation, and structural fault bars are very common in both iridescent and non-iridescent feathers, particularly of the denser types. These fault bars appear as gaps or breaks in the plane of the feather and microscopic examination shows that the barbules are stunted and degenerate, or are absent altogether, while the barbs may also be shrunken, the whole leaving an opening in the feather at this point. All degrees of barring may be noted. The dark brown pigment is only affected by extreme impoverishment, which may cause a lighter color to appear, due probably to decrease in pigment production.

In iridescent feathers fault bars are common, and show the characteristics of those found in ordinary feathers. The barbules are seen to be badly dwarfed or absent in extreme cases. At the edges of such bars, where the stunted appearance begins, the iridescent color is different from that of the normal part of the feather. Where the stunting has been

[1] Chicago Univ. Diss., **46**; Science, 328 (1907–1908).

relatively slight, so that the structure of the barbules is not noticeably dwarfed, only this contrast in color may serve to indicate the fault bars, which in shape and appearance are otherwise the same as those in which the structure is more markedly injured. These iridescent bars, of different colors from the rest of the feather are very noticeable when present. Without exception, in all the cases examined, where color fault bars are found in iridescent feathers, the color of the fault bars observed at normal incidence is the same as the color of the normal part of the feather as seen at angles approaching grazing incidence. The color of the bar may be quite different from that of the rest of the feather but the above rule always holds. The bars themselves show change in color with angle, and, indeed, have all the properties of typical iridescent barbules.

If iridescent feathers showing color fault bars are swelled moderately, by any of the methods given above, the color of the fault bars of the swelled feather is that of the normal part of the unswelled feather. Further swelling may change their color beyond this point, though the relationship given in the preceding paragraph always holds whether the feathers are swollen or not, the color of the fault bar at normal incidence is the same as that of the rest of the feather at a greater angle of incidence.

Most iridescent feathers show fault bars and in all probability they can be found on any iridescent bird if a sufficient number of specimens are available for examination. Chickens, ducks, pigeons, turkeys, pheasants, trogons, humming birds, Jacamar, *Ptilopus pulchellus*, *Ptilopus puella*, *Lamprocolius phoenicopterus bispecularis*, purple grackle, *Nettion brasiliense*, etc. show fault bars the colors of which are in accordance with the above generalizations.

Effect of bleaching Iridescent Feathers

The dark brown pigment (melanin), present in varying amounts in all iridescent feathers except those from albinos, may be bleached by various reagents, though it is markedly resistant to their action. Since all available bleaching agents have deleterious effects upon the structure of the feather, best results are obtained with feathers containing relatively little dark brown pigment, which need not be exposed to the bleaching agent for so long a time. Too concentrated bleaching agents are also to be avoided for the same reason.

Potassium permanganate is a powerful bleaching agent, but is too harmful to the structure of the feather. Sodium hypochlorite is even more active, but swells the barbules badly, as well as rendering them brittle. Hydrogen peroxide (3%) bleaches effectively, with a minimum of injury to the feather, and leaves no harmful products as a result of its action. It is far superior for this work to the methods making use of chlorine, commonly recommended, though it has some swelling action on the feathers, and renders them somewhat brittle. Its action may be stopped at any point by washing with water. Unfortunately, bleached iridescent feathers usually cannot be completely dried without undergoing so much shrinkage and distortion that their structure and color are seriously affected, but they may be studied mounted in water, or permanent mounts may be made in glycerine jelly.

By carrying the bleaching as far as possible without seriously damaging the structure of the barbules, they may be bleached to a pale straw color, almost colorless by transmitted light, yet their iridescent colors resist the action of the bleach, and are changed no more than corresponds to a moderate degree of swelling caused by the soaking to which they are subjected. Such transparent bleached barbules show no appreciable color by transmitted light, but by reflected light against a dark background their iridescent colorings are as brilliant as those of the unbleached barbules. The barbs of the feather are bleached more slowly, but the iridescence of the barbules is very marked when they are held against a dark background. The color changes with angle in accordance with the same rules which apply to the unbleached barbules. Apparently the relatively resistant dark brown pigment of the barbules is affected by the bleaching agent much more markedly than are the iridescent colors.

Bleaching can usually be carried to completion only when the feather is relatively lightly pigmented. Heavily pigmented barbules are generally disintegrated before they are bleached colorless. The green feathers of the bronze-headed trogon bleach perfectly without losing their green iridescence, and show their original changes of color very plainly. The brilliantly iridescent feathers of the bronze-winged pigeon also show their original colorings when bleached almost colorless, as seen by transmitted light. Other iridescent feathers show the same effects to a greater or less degree dependent principally upon the amount of dark brown pigment originally in them.

Effect of Dyeing White Iridescent Feathers

Although only the white iridescent feathers of the neck of the albino and pied (brown and white) pigeon were available for study, there is reason to believe that iridescence is possible in the case of other white feathers from albino or pied varieties of normally iridescent birds, in spite of Chandler's statement[1] that albinism always is accompanied by loss of iridescence and the characteristic structure which accompanies it.

The white neck feathers of the pigeon in mass have a coarse, waxy, appearance, and if examined closely, in bright light, show a slight pearly iridescence.

Microscopic examination shows that the iridescence has the same colors and color changes as seen on normally pigmented pigeons, that is, red at normal incidence to green at grazing, or *vice versa*. These color changes are observed only by careful examination. The white iridescent feathers show exactly the same structure as the pigmented ones, and have the typical, spatulate, segmented barbules which are invariably associated with iridescent colorings. Neck feathers from pied pigeons all show the same structure, and may be all white, or partly white and partly pigmented, or all pigmented. The structure

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[1] Univ. of Cal. Pub. Zoöl., **13,** No. 11 (1914–16).

is uniform throughout the feather, whatever its pigmentation, but only the pigmented feathers or the pigmented parts of partially pigmented feathers show iridescent colors of brilliancy comparable to those of other birds. Even a single barbule may have some segments pigmented while others are colorless by transmitted light, and the structure is the same; the difference in brilliancy of the iridescence of the pigmented and unpigmented segments is very striking. The presence of pigment appears essential to the production of maximum brilliancy.

It is possible to mix alcoholic solutions of aniline dyes so as to produce a color approximating closely the brown of the pigmented, iridescent feathers of the neck of the pied pigeon. When white iridescent feathers are dyed with this solution, dried, and the excess dye on the surface wiped off, they have a brilliancy of iridescence and metallic colorings equalling those of the best of the naturally pigmented feathers of the pigeon. No effect whatever beyond a plain brown body color is produced when similar white feathers, not possessing the structure characteristic of iridescent feathers, are dyed with the same dye. Black dyes may also be used though they act less readily. They enhance the iridescent colors in the same manner as does the brown dye.

White feathers from the albino peacock and turkey have a distinctly stunted and degenerate structure in the barbules, not of the iridescent type, and show no signs of iridescent colorings. Dyeing does not bring out any iridescence in these feathers.

Effect on Iridescent Feathers of Immersion in Liquids

If iridescent feathers are immersed completely in liquids the brilliancy of their colorings is always lessened, and the extent to which their iridescence is darkened appears to depend on the refractive index of the immersion liquid. Liquids of refractive index close to 1.60 cause the colors of a peacock feather to darken so that at first glance they would be said to have disappeared. However, microscopic examination shows that the iridescent colors are not destroyed, but are only much lessened in intensity. If the liquid of refractive index 1.60 is replaced by one of either higher or lower refractive index, the brilliancy of the colors is restored partially. For instance, in alcohol ($n = 1.37$) the colors are very noticeable though still somewhat less brilliant than in air. The most marked disappearance of color appears, in the case of the peacock, in liquid of refractive index 1.60. In general, liquids of refractive indices between 1.55 and 1.60 have the most effect on the colors of feathers, and in many instances careful microscopic examination is required to detect the slight iridescence which remains under these conditions. In all cases, drying the feather restores the original color perfectly.

Most liquids have some swelling action on feathers, and may change their color somewhat, but the brilliancy depends on the refractive index of the liquid, as may be shown by carefully wiping the feather free from all adhering liquid. By thus removing the liquid the effect due to immersion is destroyed, and the original brilliancy is perfectly restored, though if the liquid has swelled the feather exposure to the air for a few minutes is necessary before the original color is regained.

It has not been possible to destroy the iridescent colors by penetrating the feather with cresol or similar liquids. Apparently there are no cavities in the barbules which might be filled by this liquid, even though they are finely divided, and laid open for penetration by sectioning.

Action of Solvents on Iridescent Feathers

Prolonged extraction of the barbules of iridescent feathers, such as those of the peacock, pigeon, wood duck, Monaul pheasant, chicken, trogon, humming bird, etc., causes no change or diminution of their iridescence. Hot or cold alcohol, alcohol saturated with ammonia, xylene, orthocresol, carbon bisulphide, ether, carbon tetrachloride, acetone, chloroform, and water, have no solvent effect whatever on the iridescent colors during extractions of over 30 hours. The colors of the feathers are not in the least diminished, and the solvents are not discolored.

Only solvents which destroy the feather affect the iridescent colors. Ammonia, sodium hydroxide in aqueous or alcoholic solution, and similar alkalies disintegrate and dissolve the tissue of the feather and the dark brown pigment, but the iridescence persists until the structure of the barbules is damaged seriously by these powerful reagents. Even when the barbules are dissolved completely by the alkali, their solutions are of the same color irrespective of the original iridescent color of the different feathers. Neutralizing with acid does not precipitate a colored pigment, other than muddy brown.

Inadequacy of the Surface Color Theory

If the properties of thin-film colors outlined above, and of iridescent colors of feathers are compared in detail, the resemblances between the thin-film colors and the iridescent colors of feathers will be seen to be rather extensive, while surface color as an explanation of the iridescence presents some irreconcilable differences.

As far as optical properties are concerned, anyone who will take the trouble to compare the changes in color with angle shown by thin-film colors, iridescent feathers, and substances possessing surface color, when examined with unpolarized light, cannot but notice the very striking changes which the first two give, as opposed to the almost inappreciable color change shown by surface colors. If surface color is to be considered as the cause of the iridescence, a pigment showing many times as much change in color with angle as is seen in any known substance must be postulated.

Examination of the reflected light with a nicol prism shows some similarities in the color from these different sources, but also reveals the distinct darkening which films and feathers show at a fairly definite angle; this is not shown by surface colors. Also, as the "polarizing angle" is passed, the reflected vibrations in the plane of incidence change to the complementary color in both thin-film and iridescent-feather colors.

This, again, is not shown by surface color. The elliptical polarization of the reflected light is common to all three sources of color, and, in itself, proves nothing one way or the other.

The fact that true iridescence is shown by albino or bleached feathers, which are colorless by transmitted light presents no incompatibility with a theory of thin-film color, while, if surface color is to be considered as the cause of this iridescence, we must postulate a substance which has marked surface color (selective reflection) but little or no power of absorbing light. This is contrary to all experience and to the theory of the nature and cause of surface color. On the other hand, thin films are transparent and almost perfectly colorless by transmitted light, yet may give intense colors by reflected light.

In connection with this, the action of the brown or black dye, which brings out so strikingly the metallic iridescence in the albino pigeon feathers can hardly be explained on the basis of surface color, for it is noted only in the case of feathers of a definite structure. As a dark background to eliminate the dilution of the reflected colors by transmitted or scattered light, its purpose is analogous to the dark background necessary for the display of the full metallic iridescence of thin films.

While pigments showing surface color, yet resistant to bleaching, might be postulated, such pigments could not be colorless and transparent and yet show surface color. Bleaching cannot remove the color from a thin film, but the bleach may destroy the film, and thus destroy the color. Bleaching of feathers does not destroy the iridescence, though the brilliancy is lessened when the dark brown pigment is bleached, just as the brilliant colorings of thin films are lessened when their dark background is removed.

Swelling and pressure do not change the surface colors of any pigments which we know, and to postulate a pigment so affected would require radical modifications in the present theories of reflection and absorption of light. The color changes can hardly be ascribed to chemical action between the swelling reagent and the pigment, when reagents so widely different chemically all cause the same reversible color change in barbules of a given color, and all cause changes in color which may be predicted on the basis of a thin-film-color theory. Pure water could scarcely change the surface color of a solid pigment from green to red, and this change would hardly be perfectly reversible, yet duplicable by any one of a number of reagents. Thin films, on the other hand, unless made of material not capable of being swelled, are changed readily in color by various swelling reagents; these changes are reversible, and the colors of them may be predicted. Pressure also changes the colors of compressible, thin films; this change is opposite in direction to that caused by swelling, and the colors may be predicted.

The distinctive type of structure found only in iridescent barbules, shows the intimate connection between iridescence and structure in feathers. The structural modification is of such nature that it lends itself to the display of brilliant color very remarkably, and, in its minute details, is in no way incompatible with the presence of thin films as the source of the color.

The modification of the color in fault bars also points to a structural basis of the iridescence, since fault bars are essentially only diminutions in the structures of the feather. The formation of a pigment of different surface color from that of the rest of the feather, in conjunction with the stunting of the growth, seems highly improbable, especially since the color of the fault bars, whatever it may be, is always definitely related to the color of the feather, in the same manner for all colors.

In the preceding paragraphs there are many statements incompatible with the theory of surface color as the cause of the iridescence of feathers. Walter, in an extensive paper,[1] presents among other arguments in favor of the surface-color theory, the statement that thin-film colors "change in intensity, but not in color, with changing polarization of the incident light, while both change in the case of the surface colors." While the second part of this is true, the first is not, for the

[1] "Die Oberflächenfarben oder Schillerfarben" (1895).

change to complementary color at angles greater than the polarizing angle is easily observable, in the case of thin-film colors, and has been demonstrated mathematically.[1]

He admits that thin-film and surface colors have many similarities but fails to bring out their real differences in a very comprehensible manner, finally rejecting the former on the ground that it is inconceivable that films of sufficient regularity should exist. Walter's paper refers particularly to the colors of insects, but he emphasized the fact that many iridescent feathers show a complementary color by transmitted light. Some of his examples are undoubtedly Tyndall blues and greens, the real nature of which was not known at the time of his paper. Because of the yellow color shown by these blues with transmitted light he classes them as lustre (surface) colors on the basis of Haidinger's law, and remarks on the predominance of blues and greens as representatives of this type of color. From this it appears that, in many instances, he did not distinguish between the highly reflecting, metallic, iridescent feathers, and those which we know to be due to Tyndall blue, but perhaps considered them both together.

Michelson,[2] after ignoring Tyndall blue as the cause of the color of non-iridescent blue feathers, states that there are two, important, possible methods of producing color in nature, other than by ordinary pigmentation. These are: A. Interference, including diffraction; B. "Metallic" reflexion (surface color). "The chief characteristics by which 'metallic' reflexion may be distinguished may be summarized as follows:

1. The brightness of the reflected light is always a large fraction of the incident light, varying from 50 to nearly 100 percent.

2. The absorption is so intense that metal films are quite opaque even when their thickness is less than a thousandth of a millimeter.

[1] Preston: "Theory of Light."
[2] Phil. Mag., [6] **21,** 554 (1911).

3. If the absorption varies with the color, that color which is most copiously transmitted will be part of the incident white light which is least reflected, so that the transmitted light is complementary to the reflected.

4. The change of color of the reflected light......follows the invariable rule that the color always approaches the violet end of the spectrum as the incidence increases. If the color of the normal reflexion is violet the light vanishes (changing to ultra-violet) and if the normal radiation be infra-red, it passes through red, orange, and yellow as the incidence increases."

Michelson has applied these qualitative criteria in the study of the iridescent colors of insects and birds and concludes that they support the surface color theory, mainly on the basis of the change of color with angle, which in the case of surface colors, changes "invariably toward the violet end of the spectrum as the incidence increases."

Even if we ignore the fact that feathers change in color far more markedly than do substances possessing surface color, the color changes exhibited by the neck feathers of the common pigeon constitute an exception to the above rule, for they may exhibit any of the following changes as the incidence is increased.

Purplish green—red—green—yellow-green.
Green—purplish green—red.
Red—green—yellow-green.
Red—purplish green—red.

Of these the first two are observed in most feathers; the other changes are less common.

At any rate here is a case of a feather color behaving in direct opposition to one of the important characteristics of surface colors. Some of the iridescent purples of certain ducks and pheasants, which change to reddish or even yellow-orange at grazing incidence, also are at variance with this property of surface color, though it is to be admitted that in most cases the iridescent colors of feathers do change toward violet as the incidence increases. (These are not to be separated from the colors which change toward red, however, as will be shown later.)

The iridescence of transparent, albino or bleached feathers is certainly not in accordance with the intense absorption which substances showing surface color possess, while the transmitted color of ordinary iridescent feathers is a plain brown irrespective of their reflected color. As far as the intensity of reflection is concerned, a complex surface such as is presented by a feather would not permit of very conclusive measurements in any case, though quantitative results might be significant if obtained from single, plane, barbules. Anyone who has examined the colors of a thin film backed with black, prepared as directed on a preceding page, will admit that thin films are capable of reflecting as intense colors as those of feathers.

Michelson bases his final conclusion, in favor of "metallic" reflection (surface color) on the similarity in optical properties shown by light reflected from dye stuffs showing surface color and that reflected from feathers or insect wings. Quantitative measurements were made of the "phase differences" in the reflected, elliptically polarized, light, and of the "amplitude ratios," for different angles of incidence. Since the light reflected from thin films is also elliptically polarized, it is unfortunate that similar measurements were not made on it, before thin films were dismissed from consideration as a possible cause of iridescence. Until such measurements are made, the evidence in this quarter leaves much to be desired, and need not be considered as excluding the thin-film theory of the colors of iridescent feathers.

Since the character of the surface influences reflection so pronouncedly, all such measurements, to be comparable, ought to be made on similar surfaces. For instances, the surface colors of dye stuffs painted on dark or neutral-colored feathers might be compared with the iridescent colors of feathers, and with the colors of artificial thin films supported on the uneven surface of dark feathers, and following its irregularities. It is hoped that measurements of such material may eventually be made at Cornell.

Lord Rayleigh[1] has had about the last word on this subject, and in his paper he points out the exceptions to Haidinger's law (of the complementary relationship between surface and body colors) as well as noting that surface colors change too little with angle to correspond with the iridescent colors of feathers and insects. He states that Michelson's four tests for surface color "are as well if not better borne by an interference theory." Rayleigh points out that the absence of a well marked polarization angle may be due simply to the complexity of the surface which produces the color. He also observes that the reflected colors of iridescent feathers and insects are highly saturated as compared with their transmitted colors, while with surface colors the reverse is true. Rayleigh has calculated, on the basis of 1.6 as the index of refraction of the color-producing film, the colors of feathers seen at grazing incidence, from the colors observed at normal incidence, and he remarks upon the very good agreement between the calculated and observed values as a strong point in favor of the thin-film theory. (Cf. p. 422 of this article.) The remarkable variation and range of colors sometimes shown in a small area of the feather, he points out, is easily explicable in terms of structural variation in the color-producing films, though making large demands on a surface-color theory. Rayleigh's conclusion is distinctly in favor of the thin-film theory.

Since the theory of surface color as applied to the iridescence of feathers leaves so much to be explained, and presents so many contradictions with the properties observed in feathers, one is forced to exclude this theory, and to consider, as the cause of the iridescence, the other alternative, namely, thin-film colors, as an explanation.

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[1] Phil. Mag., [6] **37,** 98 (1919).

Similarities between Thin Films and Iridescent Feathers

If the properties of iridescent feathers are compared with those of thin films, the parallelism is very apparent. Perhaps the most striking similarity is that shown with respect to the optical properties studied. The colors of thin films and of iridescent feathers change in the same, very obvious and unmistakable, manner with change in angle of incidence, and all the color changes exhibited in iridescent feathers may be observed with thin films of the proper thickness. This is particularly striking if thin films of gold size, varnish, balsam, asphaltum varnish, etc., are prepared by all owing adrop of the liquid to spread on a smooth water surface. These films are relatively uniform in thickness, and considerable areas often show the same color. Such areas of the film, when hardened by exposure to the air, are strong enough to remain intact when picked up on the surface of a clean non-iridescent feather, and a black or gray feather thus covered by a film requires careful examination to distinguish it from a natural iridescent feather, because the thin film follows closely the complex and uneven surface of the feather rather than remaining as a glassy layer stretched across the tops of the barbs and barbules.

These artificial, iridescent feathers are of importance here because they may be prepared to match any iridescent color found in feathers, and, when thus prepared, show the same color changes with angle as those shown by the natural feather. Their brilliancy and lustre are also quite as intense. Thin films are apparently capable, therefore, of producing colors closely comparable with those of iridescent feathers.

Microscopic study of the colors of individual iridescent barbules also shows the similarity of their colors to those of thin films, for the change of color with angle and with polarization, the existence of a "polarizing angle" at which the color darkens when examined through a nicol, and the elliptical polarization of the reflected light, are alike in feathers and in thin films. The variations of the colors of barbules side by side in the feather correspond to the variations in the colors of thin films due to slight non-uniformity of thickness, and the same is true of the mottling and blending of colors sometimes observed in a single segment of a barbule. These likenesses are all the more significant because not only do the changes and variations of color exist, but they are the same changes and variations found in thin film colors, from which the colors and properties of iridescent feathers may be accurately predicted.

Pressure and swelling cause changes in the colors of thin films and of iridescent feathers and these changes are observed to be similar for similar original colors. Fault bars exhibit colors in feathers which correspond to the colors shown in thin places in color-producing films.

Destruction of films or of the structures of feathers is necessary to destroy their iridescence. Bleaching does not destroy it and solvents cannot dissolve it. Thin films and iridescent feathers may be actually colorless, showing no colors with transmitted light but distinct iridescence with reflected light, and moreover, both have their brilliancy enhanced and exhibit "metallic" lustre when a dark background is present. Such inherent resemblances, particularly in essential characteristics, cannot be ignored, and point strongly toward the identity of the iridescent colors of feathers and of thin films. One fact which needs to be reconciled with this, however, is the moderate effect which immersion in liquids has on the iridescent colors of feathers. An ordinary, single, thin film produces no color when brought in contact with a liquid of its own refractive index, and, even with liquids of refractive index considerably different from this value, the color is very markedly diminished. However, if we have to deal with two or more thin films, of different refractive indices, in contact with each other, only the color due to the film in contact with the liquid can be destroyed by immersion; the color due to underlying films is not affected. This type of color production by "multiple films," is not essentially different, in other properties, from that of a single thin film and corresponds in behavior with the colors of iridescent feathers, so that if more than one film takes part in the production of the color of an iridescent feather we have no incompatibility in this regard.

Iridescence of Feathers on the Basis of Thin Films as the Color-producing Structure

It has been shown that, of the various possible explanations of the iridescent colors of feathers, that involving thin color-producing films is the only one which does not present irreconcilable conflicts with the observed properties of the feathers, and since the similarities between thin films and iridescent feathers are so extensive, it seems justifiable to accept this explanation, and to apply it in detail to the properties of iridescent feathers.

On this basis, the colors of iridescent feathers belong to Newton's series of interference colors, being caused by a laminated or plate-like structure of the barbules, where the color originates. These barbules present broad, flat surfaces forming an approximately plane surface which exhibits the colors with great brilliancy. This invariable, spatulate structure of the iridescent barbules serves to display the colors to best advantage. The color originates in the three layers, each about 0.4 μ thick, which act as a multiple thin film on the surface of the barbule. The thickness of these films is about the value calculated for interference colors of the order observed in feathers, though the whole structure is too small for accurate measurement.

On all the iridescent feathers examined, the colors appear to lie in the upper second or third orders of the series, which include the most brilliant of the interference colors: yellow, red in the upper second order, and dull purple, blue, green, yellow, red, in the third order. Since we have no good method of determining exactly the order of interference and isolated color reflected from a thin film, this was based on matching the colors of feathers with those of artificial films, the colors of which are of known order.

The changes of feathers are summarized in the above series; a feather of given color at normal incidence will appear a color listed ahead of this one when examined at grazing incidence. Hodgkinson,[1] who supports the thin-film theory in

[1] Manchester Memoirs, [4] **2,** 193 (1889).

an admirable paper, was able to predict the color changes of all the humming birds of the Gould collection, South Kensington Museum, and recognized their definite position in Newton's series of colors. In another paper[1] he proposes that the so-called "indescribable" colors of iridescent birds be described as they appear at normal incidence, all their color changes being indicated automatically by the information, in accordance with the above series. The color usually changes through two to three of the colors of the above series, frequently a change "from the blue toward the red end of the spectrum," but these are not spectrum colors, and this generalization does not apply in all cases though it happens to in many. The pigeon, for example, has feathers which change from bluish green through red, to yellowish green with increasing incidence.

Thickening of the color-producing films by swelling results in a color change toward a color listed in the series after the original color, for the thicker the film, the higher the order of color. Thinning by pressure or in fault bars results in a color of lower order (that is, earlier in the series) than the original color of the barbules. Thus the series summarizes the behavior of the colors of feathers on swelling or under pressure.

Bleaching does not destroy the colors, because there is no real color there, but only a structure, and unless this is destroyed the iridescence is uninjured. The "metallic" lustre and brilliancy of iridescent feathers is due to the dark brown pigment in them which serves as a dark background for the thin film colors. The exact distribution of this pigment is not certain, but apparently no special distribution is necessary to give metallic lustre, provided the essential structure is present, for the white iridescent pigeon feathers become metallic by simple dyeing with a brown dye, though detailed study of sections of the dyed barbules does not show any segregation of the dye in one underlying layer, but instead a rather uniform distribution. It is possible that a neutral-

[1] Manchester Memoirs, [4] **5**, 149 (1892).

colored, transparent, thin film may serve to some extent as its own dark background, producing brilliant colors and metallic lustre, as does a colorless film on a dark background. This appears to be true in the case of films of asphaltum varnish, a highly colored transparent substance.

When iridescent feathers are held between the eye and the light no colors are seen, because thin films give no colors appreciable to the eye with transmitted light. Only the dark pigment is seen, and this renders the feather more or less opaque.

Since the colors are not destroyed by immersion of the feather in liquid of any refractive index, multiple films must be postulated, and the structure of the barbules, as shown by cross-sections, appears to bear this out. Unless a considerable number of these films are present, the resulting color will have properties essentially the same as that from a single film, except in this one respect of not being destroyed by immersion in liquid.

The polarizing angle is not observable on the feather as a whole, because the curvature of the barbules makes only different parts of them reflect at different angles and no general darkening is observed, though this may be seen under the microscope on the individual barbules.

The curvature of the barbules, with the resultant complexity of the surface of the feather, results in a softening and blending of the garish colors noticed in plane, thin films, because of the different angles at which different parts of the curved surface are viewed. This causes a mingling of the colors seen at normal and at other angles of incidence, causing added softness and richness of color. The slight local variations in the thickness of the color-producing film also contribute to this effect, by causing a mottling of colors, which mingle and appear to the eye as the mean color of all the various hues. The color which we observe on the feather is thus the result of the mingling of a number of colors adjacent in Newton's series, which produce the effect of a single, softer color.

Strong[1] has explained the colors of the iridescent neck feathers of the pigeon as being caused by Newton's ring effects where the spherical pigment granules within the barbules touch the outer surface, but this cannot be the case, for spheres in contact with a more or less plane surface could not produce a uniform color but rather a series of concentric rings of different colors, in this case so small that they would probably be perceived only as white light, and would not exhibit any consistent color changes. Moreover, the iridescence is noted in parts of the barbules where no spherical granules are present. His statement that the feathers present the phenomenon of "anomalous dispersion" because they are "dark brown by transmitted light and light metallic or yellowish brown by reflected light" seems to be rather far-fetched, in view of the fact that anomalous dispersion can only be detected by spectrometric methods, no record of which is given; anomalous dispersion has not been observed in any thin film colors. Altogether his paper presents no consistent theory which would account for the observed facts, on the basis of our knowledge of the behavior of thin films of the type he suggests. The thin films which cause the iridescence of the pigeon are not of this type, but are of the same character as those of all other iridescent feathers.

Variation in the thickness of the color-producing films also explains the different colors often observed on a single feather, either in the form of a pattern, as in the case of the peacock, or in gradations of color, such as are seen in the feathers of the starling, purple grackle, *Lamprocolius phoenicopterus bispecularis*, and other birds. The latter iridescent feathers show bands of colors which remind one very much of the colors surrounding a drop of oil on asphalt pavement. For instance, some of the feathers of the starling are iridescent, reddish purple at the base, shading to yellowish bronze at the tip; others are yellowish green at the base to greenish blue at the tip, while some feathers of the purple grackle shade from red-

[1] "Mark Anniversary Volume," 263.

dish purple at the base to blue, greenish blue, green, yellow-green, to yellow bronze at the tips. These sequences of shades are undoubtedly produced by a gradual variation in thickness of the color-producing films, for the colors are always adjacent in Newton's series, and, moreover, the colors shift with increasing incidence, just as do Newton's rings, the shift or change in position of a given color being toward the thicker part of the film.

The grosser structure of the feather may influence the appearance of the iridescent colors very markedly. Not only the perfection of the surface formed by the overlapping of the distal barbules, but also the visibility of the color, are dependent on this. For example, the blue-green iridescent barbules of the peacock feather are present in the black center of the "eye" but are arranged so that they are seen edgewise and their color does not appear. The iridescent colors of many birds, particularly humming birds, are often visible only from a position in front of the bird, and are quite invisible when the head of the bird is pointed away from the observer. This again, is due to the barbules which are arranged so that instead of having their planes in the general plane of the feather, they are skewed or tilted somewhat, and lie normal to a direction towards the head of the bird, rather than in the plane of the feather, so that from other positions they are seen edgewise, and give little or no color.

The theory of thin films as the cause of iridescence, although it fits all the observed facts, cannot but inspire one to marvel at the perfection of nature's method of producing these colors with such uniformity through successive generations, especially when a slight general variation in the thickness of the films of the feathers of a bird, such as a peacock, would be enough to alter its coloration completely. Thayer's work on "Concealing Coloration in the Animal Kingdom" emphasizes, by many illustrations, the statement that iridescence is one of the potent devices for effecting "obliteration" against a variety of backgrounds and changing lights. Study of this book makes clear the very great usefulness of iridescent colorings, and throws considerable light on the factors which possibly influenced their development in birds.

The structural foundation of iridescence seems to present a most remarkable case of the regulation of an essential structure within very sharply defined limits of magnitude, not only in numerous individuals but also through many successive generations, and ought to present some interesting problems from a biogenetic standpoint, particularly since very slight structural modifications result in such marked differences in color. Such investigations, however, lie beyond the scope of this paper, as well as outside the training of its author.

Tests for the Identification of Thin-Film Colors in Iridescent Feathers

For convenience a few simple tests are summarized, to the end that any iridescent feather, the nature of the color of which is in question, may be examined systematically in order to decide whether its colors are due to thin films or to some other cause.

If the color of an iridescent feather is due to thin films it should meet the following requirements to a greater or less degree of perfection.

1. The color should change with increasing angle of incidence, to a color of lower order in Newton's series (frequently towards blue) and should be equivalent to colors of the upper second or third order.
2. The iridescent color should be wholly in the barbules.
3. The barbules should be distinctly spatulate in form.
4. The only color seen by transmitted light should be a neutral brown, more or less opaque.
5. The barbules should retain their iridescence in spite of careful bleaching to partial or complete transparency and colorlessness.
6. The color should be changed by swelling to one of the higher order in Newton's series, and this change should be reversible.

7. Pressure on the softened barbules should change their color to one of lower order in Newton's series.

8. If fault bars are present their color should be of lower order than that of the rest of the feather.

9. The lustre of the feather, if it possesses any dark pigment, should be more or less "metallic."

10. Transparent, non-pigmented feathers possessing the proper structure should become iridescent on being dyed with a dye of neutral brown hue.

11. The barbules, if fairly plane, should show a definite polarizing angle, and at angles greater than this the reflected light should be polarized elliptically, with the vibrations in the two planes complementary in color.

12. No system of fine, regular, parallel striations should be visible.

13. The color should not be lost in uniform diffuse light.

14. The colored light should be reflected regularly as from a mirror of complex surface, the angles of incidence and of reflection being approximately equal.

15. Cross-sections of the iridescent barbules should reveal their laminated structure.

16. Extraction should not remove the iridescence, nor should any but a yellowish or colorless extract be obtained.

Iridescent Feathers Studied in this Work

The following feathers were studied and found to owe their iridescence to thin films of the type described above:

Black Minorca and Rhode Island Red Chickens, Bronze-winged Pigeon, Common Pigeon, Green Heron, Wood Duck, Mallard, Sommering Pheasant, Monaul Pheasant, Golden Pheasant, Chinese Pheasant, Peacock Pheasant, Bronze-headed Trogon, Peacock, *Musciroia mexicana*, *Ptilopus puella*, *Ptilopus pulchellus*, *Lamprocolius phoenicopterus bispecularis*, Purple Grackle, Jacamar, Ruby-throated Humming Bird, Red King Bird of Paradise, Wild Turkey, *Nettion brasiliense*, Starling, Muscovy Duck.

Conclusion

The conclusions of this paper are as follows:

1. The iridescence of feathers is caused by thin laminae or films in the barbules, which produce interference colors.

2. No other structural colors and no surface colors due to selective reflection have been identified in iridescent feathers.

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THE FREE ENERGY AND HEAT OF FORMATION OF ZINC IODIDE*

BY T. J. WEBB

Introduction

The directness and definiteness of results obtainable by the employment of the Gibbs-Helmholtz equation in calculating thermal data have given impetus to the measurement of electromotive forces and temperature coefficients of many reversible elements. For the purpose of obtaining the heat of formation of zinc iodide, and for the purpose of subjecting the Nernst Heat Theorem to a still further test (provided sufficient specific heat data are available) the following cell has been set up, and the free energy decrease, as well as the temperature coefficient of the free energy decrease, has been measured—

Zn Amalg. | ZnI_2 (saturated soln.) | AgI-Ag
(10%)

An inspection of the cell will show that the following reaction takes place when current is allowed to flow through an external resistance:

$$Zn + 2AgI = ZnI_2 + 2Ag + Q \text{ cals.}$$

The substitution of the free energy decrease (E × F, E being the voltage of the cell and F a faraday of current) at a given temperature and the temperature coefficient of the free energy decrease, in the Gibbs-Helmholtz equation, $A - U = T\frac{dA}{dT}$, gives immediately the heat of the reaction Q. The addition of the heat of formation of silver iodide (which has been established by various authorities,[1] employing widely differing methods,

* Contribution from the Laboratory of Physical Chemistry, Princeton University.

[1] Braune and Koref: Zeit. anorg. Chem., **87**, 175 (1914); O. Gerth: Zeit. Elektrochemie, **27**, 287 (1921); Taylor and Anderson: Jour. Am. Chem. Soc., **43**, 2014 (1921).