On the Origin of Colored Lustre Exhibited by Metallic Wood-Borer, *Chrysochroa elegans*[1]

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Introduction

It is well known that two kinds of colored lights are exhibited by every sort of insects. One of them is diffuse light due to the absorption in hypodermis of an insect and the other is brilliant one attributable to the surface color or structural one. It appears to us the former no longer affords any scope for discussion, but the latter is open to discussion. The origins of the brilliantly colored light apparently resembling metallic lustre, have been discussed for a long time. In the first place, Michelson[1)] pointed out the existence of a colored layer showing very intensely selective absorption, and on the other hand demanding still further experiments, Lord Rayleigh[2)] proposed his opinion that the cause of bright iridescent light was the result of interference of light in the cuticula of an insect constructed of multiple layers.

Numerous subsequent attempts inquiring into the subject have been carried out mainly tending to explain the cause of colored lustre by the interference of light, but the subject is still under discussion. From their experiments carried out in detail, Jean-Paul Mathieu and Mlle. N. Faraggi[3)] concluded that the cause was the interference of light in multiple layers of a coleoptera's integument. On the other hand the micrograph[4)] of wing covers of *Serica sericea* photographed by an electron microscope showed line grating on its surface, by which the interference of light could be occured as the cause of colored light. We also tried to bring our research to a decisive conclusion about the origin of colored lustre exhibited by a metallic wood-borer, *Chrysochroa elegans*.

1 Absence of interference by surface structure

We studied spectrographically the reflected lights on the various surfaces of *Chrysochroa elegans*—the upper surface of its fore wing, notum and sternum of thorax, and sternum of abdomen. As the greenish blue upper surface of the fore wing has a strip tinged with red, we

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1 Contribution from Department of Physics, Faculty of Science, Ochanomizu University, No. 5

divided it into two parts and called them roughly blue and red parts according to their apparent colors.

To begin with, we cut off a nearly plane lamina from the blue part of a fore wing and photographed the spectra of lights scattered in various directions by its fixed surface on which a white light was thrown under a certain fixed angle of incidence. We found that the intensities of scattered lights had clearly three maxima and two minima in the region of visible ray. The wave lengths for both maximum and minimum intensities displace continuously to the smaller with the increase of reflected angle.

The first purpose of the above experiment was to determine the wave lengths of diffracted rays in different diffracting angles on some grating, if any, on the surface of the wing, but the distributions of maximum and minimum intensities were not similar to those of usual interference on a plane reflecting grating. Any attempt is positive in denying the assumption that the color of the fore wing of *Chrysochroa elegans* originates in its surface grating. Looking into the surface of the wing under an optical microscope, it is easy to find that the surface

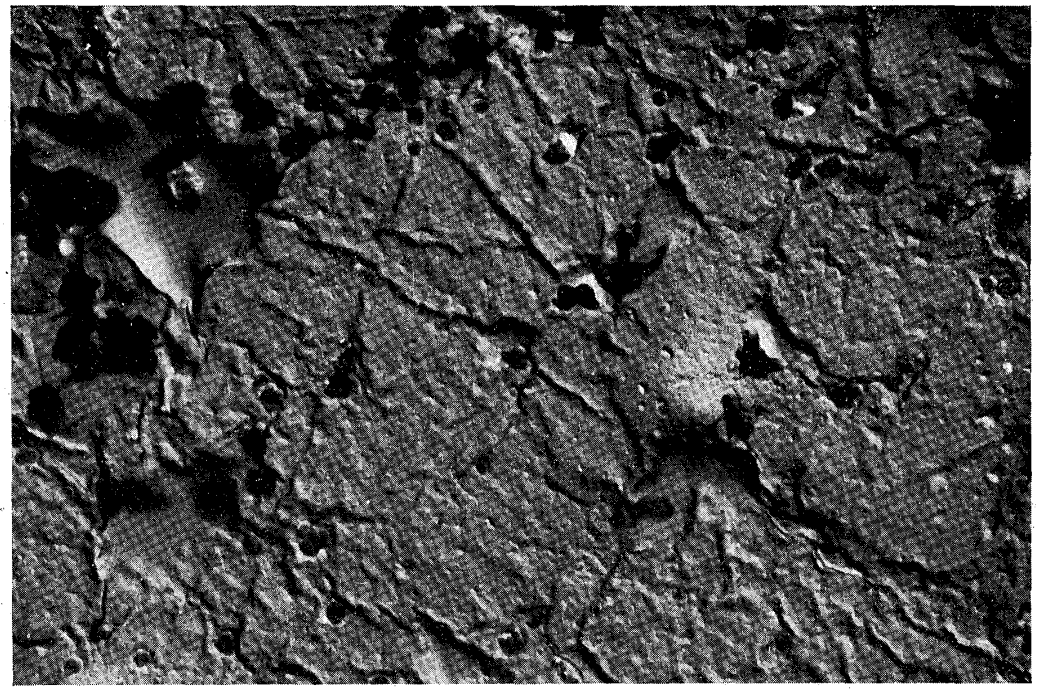

Fig. 1

is partly covered with almost regular hexagonal grating. On our calculation supposing the effect of the interference by the hexagonal grating, we can recognize the difference of the effects according to the change of plane of incidence of an incident ray thrown on the surface of the wing. But among the photographs taken for various planes of incidence, we could not distinguish one from the others. At the same time, micrographs[2] of various portions in the upper surface of the wing photographed by electron microscope showed the irregularity of hexagonal grating and also unevenness of the surface which were inadequate to regular interference. Moreover the difference between dimensions of the hexagons on a blue part itself is comparable to one between the blue and the red parts.

Therefore it necessarily follows by the experimental results that the brilliant color at least on the wing of *Chrysochroa elegans* is not affected by the surface structure. Fig. 1 is one of the micrographs of the blue part of the surface of its fore wing magnified 7200 times and shows the irregularity and unevenness with protrusions, cavities and lines. The mere sight will deny the regular interference of light on its surface.

2 Consideration of the origin of colored lustre

In the next place, the cause of the brilliant color was considered once to be the metallic reflection as shown by some dyestuffs. To verify this assumption, we flayed thin integuments which had a thickness of about 7μ from the wing by treating with concentrated nitric acid. In the case of suitable treatment, the integument could be flayed practically without changing the intensity and the color of brilliant lustre of its upper surface, and at the first glance the skinned surface reflecting very diffuse and weak ray, showed an egregious discrepancy in its quality with the upper layer.

Concerning the relation between the colors of reflected and transmitted lights, we could not find any regularity. If the brilliant color were originated from either the strong selective absorption or the interference in the total layer of integument, any relation between them would be expected. But it is difficult to find appreciable difference even between transmitted rays through blue and red parts. Then it remains to us to decide whether the origin of brilliant color is attributable to the interference of light in the upper layer composed of a single or multiple film, or to the intense selective absorption in a certain layer adjacent to the upper layer, that is to say, the layer skinned or another one if it were allowed to exist. It is difficult to determine which is true, for we can not flay the integument further. But by a strong pressing of an integument inserted between two glass plates, looking from a certain direction it seems that the colors change slightly. From the phenomenon, the interfering effect should be expected one way or another. With respect to the lower layer, there is nothing but to

2 The photographs were taken by Dr. K. Kanaya and others, Electron Microscope Section in Shibabashi Electrotechnical Laboratory with methyl-metaacril-alminium replica method.

conclude that it seems to be impossible for this layer to take part in the interference or the strong absorption, for its surface reflects only diffuse and weak light.

3 Interference in thin layer

According to the above consideration, to determine whether the interference of light in the thin film is possible or not, we photographed the spectra of the so-called reflected rays in the direction of regular reflection on the specimen under the various angles of incidence. The distribution of maximum and minimum intensities in regard to wave lengths in the spectra was appreciably equal to those which had been obtained in the previous experiment. It tells us that the appearance of maximum and minimum intensities in spectra in the previous experiment is due to scattering of lights by the irregularity of the surface and not by the surface grating.

The relations of wave lengths for maximum and minimum intensities between the experimental values and calculated ones, which were estimated by assuming the interferences in thin film in the upper layer of integument, are shown in Fig. 2. In this figure full lines and broken lines show the calculated wave lengths for maximum and minimum intensities respectively and crossed marks show the observed ones for each angle of incidence. Judging from the shape and settled position of the specimen, it may be justly accepted to think the specimen as a plane lamina, when the ray is reflected by its surface in the plane of incidence along the length of the wing. So we calculated simply the phase difference between two beams of the light interfering to each other by

$$\frac{4\pi}{\lambda} d\sqrt{n^2-\sin^2 i}, \qquad n=f(\lambda),$$

where λ is the wave length of light in air, d the thickness of the thin film, i the angle of incidence and n the relative refractive index of the film to air. When the plane of incidence is perpendicular to the length of the wing, we calculated it by

$$\frac{4\pi}{\lambda} \rho \sin\theta \left\{ \frac{n^2}{\sin^2 i} \left(1-\frac{d}{\rho}\right) - \sin(i+\theta) \right\},$$

in which ρ is the curvature of surface of the specimen as a cylindrical one, and θ the angular aperture of the whole surface. As ρ is very large in comparison with linear dimension of the specimen and θ is very small quantity, it has no meaning except the case of small angle of reflection.

It is very difficult to determine experimentally the value of n, for the reflected ray on the specimen is not simply linearly polarized light but combined with elliptically polarized light, and therefore it does not obey exactly to Brewster's law. If we accept the interference of light in a thin film in the case of the reflection of each monochromatic ray, the observation does not offer sufficiently decisive value of n, for the layer is not uniform. We calculated the value n by making use of the positions of different series of maximum and minimum intensities represented by the same wave length in the spectra of reflected rays. The calculation gives the value 1.48 with respect to D-line in the case of

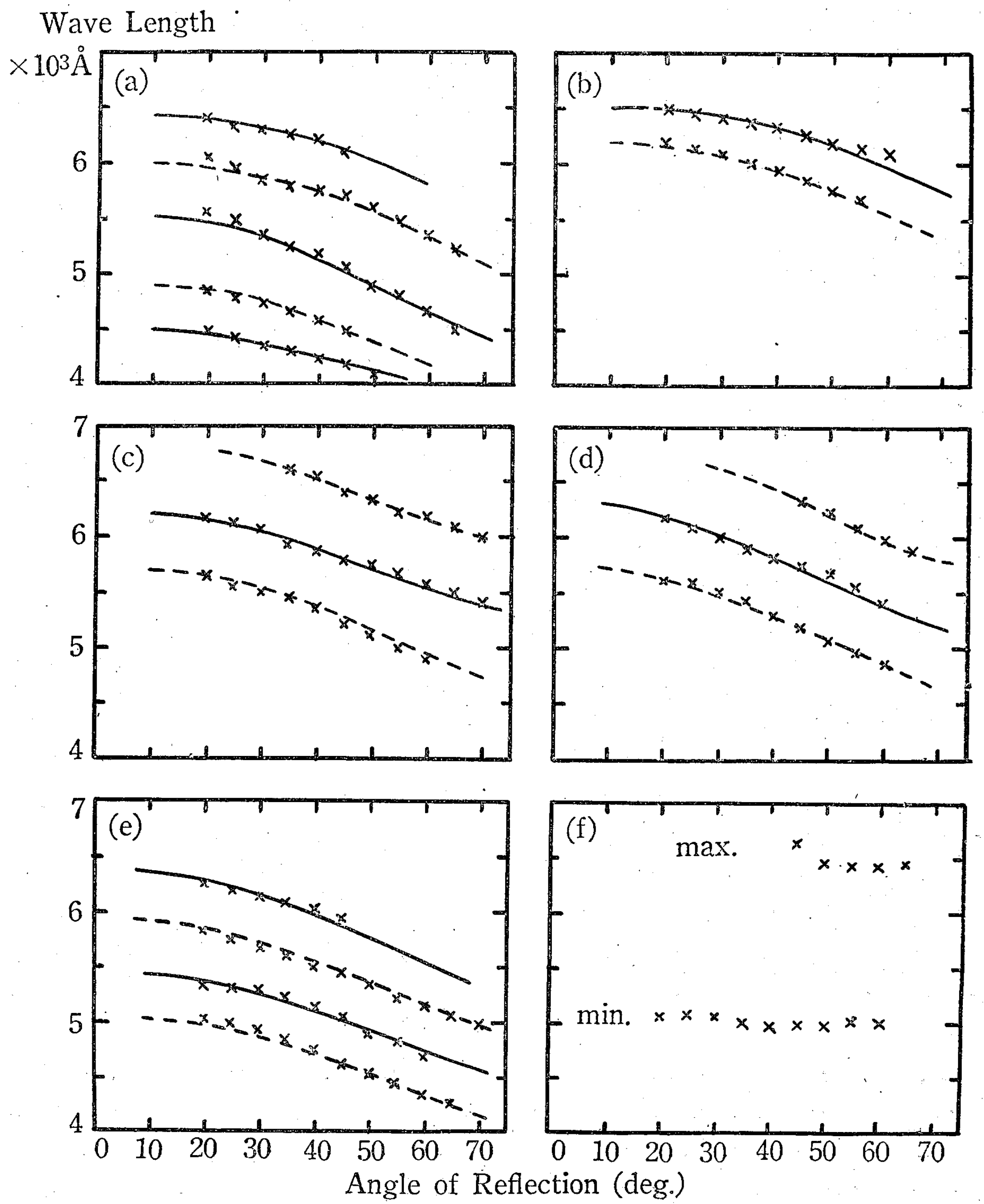

Fig. 2

the blue part of the wing. In the blue part, the value of n increases gradually and monotonically to 1.54 with decrease of wave length till 4000Å, but the decrease of n is so rapid that it may readily be imagined for anomalous dispersion to exist. At the wave length of 6400Å it must turn into 1.35 according to our calculation. Accepting these values of n, we obtained the results shown in Fig. 2 (a).

As shown by the plotted curve it seems to be explained that the origin of brilliant color takes rise in the interference in thin upper layer, but it is not clear whether this thin layer has a single film of thickness d or a pile of films. We shall call d the effective thickness and estimate it about 0.74μ in the case of the blue part of the wing. On the blue part of the wing, considering from the wave lengths at the three maximum and two minimum intensities, we can assume the phase differences of interfering beams of light at their extremum intensities as 6π, 8π, 10π and 7π, 9π respectively, and consequently the refractive index of layer adjacent to the upper one must be greater than that of the latter.

Aside from the lower layer, the construction of the integument is conceived to be complicated one, but it is not difficult to imagine that its construction becomes considerably clear through the photograph by electron microscope, judging from its moderate effective thickness d. But here we shall refrain from the speculative discussion. The photographing of a section of the wing of *Chrysochroa elegans* by electron microscope is now carrying out to test our calculations and it will become clear in due course of time.

At our experiment a broad band is observed especially for the maximum intensity in almost all cases. It may throw once a question, but it will be attributable to the irregularity of specimen taken from an insect and especially to the luck of uniformity of thickness of the layer in the integument. In almost all cases, the regions of the minimum intensities are sharper than those of the maximum ones. The fact struck us with the imagination that the polarized rays reflected on the surface of specimen might be influenced by reflection and refraction in the prism, as we utilized a spectrograph with Pellin-Broca's constant deviation prism, but we examined in vain this effect.

In the case of the blue part of the wing we could gain comparatively in detail the result, but in the red part of the wing, the reflected light was very weak in comparison with that of the blue part and showed only one maximum intensity and one minimum available for the calculation. So the result on the red part represented in Fig. 2 (b) may not be accurate, but it is sufficient to conclude that the colored light is also due to the interference of light. The value of n is nearly equal to that of the blue part and the effective thickness is about 0.77μ and therefore the phase differences between interfering beams of light at the maximum and minimum intensities are also comparable to those of the blue part. Therefore it can be considered that the disparity of apparent colors between two parts is based only on the difference between their effective thickness. It is natural to imagine that the color of the red part hemmed with narrow strips tinged with orange and yellow is due to the high gradient of thickness at the strips like the colored fringes of interferences.

The reflected rays on some parts such as abdomen, sternum and notum of thorax of this insect were also photographed. The effective thickness and other characteristics of corresponding portions of several pieces of *Chrysochroa elegans*, which are of the same kind but have somewhat different appearances of colors with naked eye, are dissimilar to a certain extent. Photographs of reflected rays on the abdomen, tell us that their several pieces have almost equal characteristics. Regularities of their maximum and minimum intensities in the spectra agree with their appearances with naked eye, uniform in every portion of them, therefore lay us under the necessity of consideration that the layers have comparatively a uniform effective thickness.

The sternum of thorax is the most brilliant part of all surfaces of this insect. Notum is divided into two parts with regard to its apparent colors, one is vivid greenish blue and the other tinged with dark purple. With respect to various reflected angles, the displacements of the wave lengths at the maximum and minimum intensities in their spectra of lights reflected on them are also shown in Fig. 2, where (c) abdomen, (d) sternum of thorax and (e) blue notum. Each refractive index with respect to D-line, effective thickness and several phase differences in regard to the wave lengths of interfering beams of light at each maximum and minimum intensity observed comparatively distinctly, are summarized in the following table together with those referred to the wing.

		apparent color	effective thickness (μ)	refractive index (D-line)	phase difference (π)
wing		blue	0.74	1.47	6, 7, 8, 9, 10
		red	0.79	1.47	6, 7
abdomen		orange	0.66	1.49	5, 6, 7
thorax	sternum	orange	0.85	1.51	7, 8, 9
	notum	blue	0.90	1.49	8, 9, 10, 11

In the above table we must say that the experimental determination of each wave length in a spectrum brings considerable errors. For it is not only unavoidable that each value shows some differences for specimen, cut from an apparently identically colored portion of this insect, but even on a definite specimen we are obliged to recognize considerable displacements of some maximum and minimum intensities especially in the case of smaller angle of reflection with shorter wave length under an intense and convergent incident ray. Therefore the above table is a mere example.

The causes of displacement of positions of some maximum and minimum intensities in a spectrum under a definite angle of incidence are not yet comprehensible. Considering the complexity and luck of uniformity of the layer, we are led to imagine the existence of subdivision of thickness or the participation of the adjacent layer in the effective thickness. In fact those of double refracted rays[5] are already known in the layer of cuticula etc. Therefore the above phenomenon does not necessarily exclude the possibility of the interference, and we are intending to investigate it under the aids of electron microscope.

4 Question of intense selective absorption

In the above section we have imagined an anomalous dispersion in the range of longer wave length. If it were true, though it may be a mere guesswork, we would presume a selective absorption of light in the upper layer at the region near the extremity of longer wave length in visible ray, judging roughly from the shape of graph which shows decrease of n with the increase of λ. But as the anomalous effect is found in the same region of spectra of other portions of the surface of this insect with apparently different color, where it may not be allowable to recognize as the cause of coloring an intense selective absorption in the upper layer. On the purple part of notum both maximum and minimum intensities are so obscure that we are able to plot only observed value in Fig. 2 (f) and can not determine its characteristic values. A question may be thrown concerning to the intense selective absorption in the layer adjacent to the upper one, but we think under the whole circumstances that the ambiguity and irregularity of distribution of maximum and minimum intensities in spectra are due to the ununiformity of thickness of the upper layer and the irregularity of its surface.

5 Conclusion

From the results above mentioned it is concluded but not decidedly that the chief cause of the brilliantly colored lustre exhibited by *Chryso-*

chroa elegans is the interference of light in the upper layer based on its adjacent layer, and a selective absorption of light in the layer adjacent to the upper one may be considered as an additional or secondary cause, if any, for we can not deny it absolutely without flaying an integument further, but the influence of surface grating has no effects at least in *Chrysochroa elegans.*

By the way, we may remark in addition that the reflected rays on this insect traced spectrographically are rather simpler, more regular and less variable than those seen with the naked eye in our usual experience. Not only the ununiformity and complexity of its cuticula but also its varying curvatures and directions lead to its complicated coloring. Moreover as the reflected rays are always polarized, they are exerted influences according to the degrees of polarizations of incident rays. Therefore its coloring changes from place to place.

We wish to express our sincere thanks to Dr. M. Kojima, Tokyo Univ. of Education who afforded many conveniences for our works at our disposal and also to Dr. S. Suzuki and Dr. K. Kanaya, Electron Microscope Section, Electrotechnical Laboratory who kindly hold themselves for the whole microphotography which adduces strong evidence to our works. We express our thanks to Mr. W. Mochizuki and Miss Kobayashi for their assistance.

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