Brilliant Whiteness in Ultrathin Beetle Scales

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The colored appearances of animals are invariably controlled by pigmentation, highly periodic ultrastructure, or a combination of both (*1*, *2*). Whiteness, however, is less common and is generated by neither of these methods, because it requires scattering processes appropriate for all visible wavelengths. We report the identification of whiteness resulting from a three-dimensional (3D) photonic solid in the scales of *Cyphochilus* spp. beetles. Their scales are characterized by their exceptional whiteness, their perceived brightness, and their optical brilliance, but they are only 5 μm thick. This thickness is at least two orders of magnitude thinner than common synthetic systems designed for equivalent-quality whiteness.

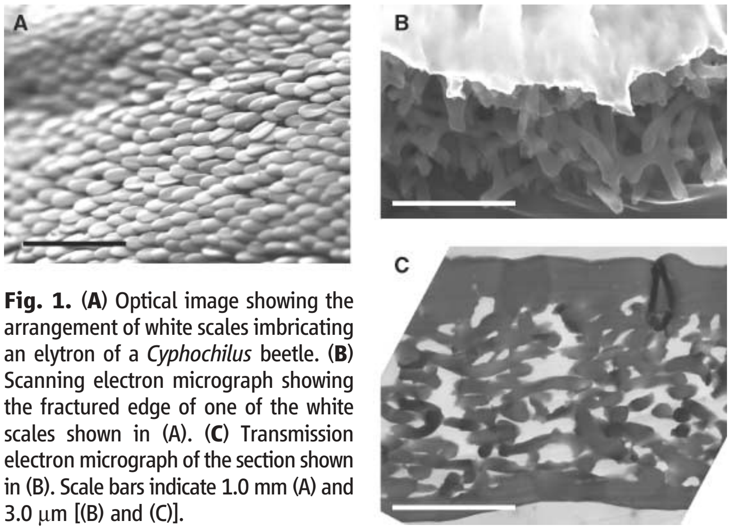

Fig. 1. (**A**) Optical image showing the arrangement of white scales imbricating an elytron of a *Cyphochilus* beetle. (**B**) Scanning electron micrograph showing the fractured edge of one of the white scales shown in (A). (**C**) Transmission electron micrograph of the section shown in (B). Scale bars indicate 1.0 mm (A) and 3.0 μm [(B) and (C)].

Archetypal brilliant whiteness that is not augmented by fluorescence, such as whiteness from snow or milk, is the result of multiwavelength scattering arising from aperiodic and multiply oriented interfaces between low-absorbance media of appropriately different refractive index (*3*). The whiteness of *Cyphochilus* spp. originates from elongated flat white scales that imbricate its body, head, and legs (Fig. 1A). These scales are about 5 μm thick, 250 μm long, and 100 μm wide. Their interiors are composed of a random network of interconnecting cuticular filaments with diameters of about 250 nm (Fig. 1B and fig. S1).

Two-dimensional fast Fourier transforms (FFTs) of electron microscope images of the scales' interior (Fig. 1C) confirmed an absence of well-defined periodicity. Wave vector space maps produced by this transform [Supporting Online Material (SOM) text] were free from any single spatial component of refractive index variation (fig. S2A). Experimentally this was confirmed by recording the diffraction pattern associated with light incident on individual scales. By mounting specific white scales on separate needle tips and directing low-intensity focused laser light exclusively through the center of each scale, we imaged the reflection and transmission diffraction patterns on spherical screens (fig. S2B). The resulting diffraction patterns closely matched the FFT maps of the scales' interior (fig. S2C) and confirmed the cuticular filament network as the origin of the whiteness. The intrascale cuticle volume occupancy is about 70%. This appears to optimize scattering intensity by maximizing the scattering center number density while avoiding substantial unfavorable optical crowding (*4*). Optical crowding occurs when the radiation fields associated with individual scattering centers overlap. It causes the system to adopt characteristics of fewer and larger scattering centers when the distance between individual scatterers becomes too small. The relatively high void fraction in this *Cyphochilus* beetle's scales appears to be a vital part of the system's ability to scatter light. It is this, as well as the system's aperiodicity and index contrast of about 0.56, that create such intense optical whiteness for very limited thickness.

The quality of the beetle's whiteness and brightness was quantified according to International Organization for Standardization national standards (SOM text). Its whiteness and brightness values (*5*) were measured to be 60 and 65, respectively, quantitatively indicating remarkable multiwavelength scatter for systems that are only 5 μm thick. In synthetic systems where whiteness is desirable, far more substantial structure is necessary. For example, conventional white uncoated wood-free papers (comprising random networks of bleached cellulose fibers) can be upward of 25 times thicker than these beetle scales but return only an 8% superior brightness. Carbonate or kaolin crystal inclusions and optical brightening agents (blue fluorescing dyes) are added to paper coating formulations to enhance scattering contrast and to improve the perceived appearance of white. However, individual isolated 5-μm-thick calcium carbonate coating layers have a brightness of only 40 to 50, with such poor opacity that its whiteness value is meaningless. Similarly, the whiteness of human teeth is dominated by multiwavelength scattering from packed hydroxyapatite crystals in up to ~2 mm of tooth enamel. Although they are generally considered to be white, their best natural whiteness and brightness are relatively low; typical human milk teeth exhibit a whiteness under 40 and a brightness of about 53, reflecting relatively low index contrast and high absorption at blue wavelengths.

For proportionally insignificant supplementary thickness, the addition of these scales' form of photonic solid would strongly enhance the desirable quality of whiteness in these and many other systems. Additionally, it offers a permeable, flexible, and fault-tolerant ultrathin layer with which to back large-area white light–emitting devices (OLEDs) and control their emission direction.

The phenotypic color of this *Cyphochilus*, credited for cryptism among white fungus, arises from an aperiodic form of structure that might appear to contrast strongly with the highly periodic structure in narrow-band colored weevil scales (*6*). However, they do share several important features: a cuticular filament network with typical filament diameter of the order from 200 to 250 nm, a scale thickness of about 5 μm, and similar extrusion from single epidermal cells into the sealed parcels that comprise each scale. The form of the photonic solid in these white beetle scales confirms that the transition from high-contrast saturated color (SOM text) to optically brilliant whiteness is largely a matter of structural order.

References

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Supporting Online Material
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SOM Text
Figs. S1 to S4

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