Fine Structure Constant Defines Visual Transparency of Graphene

R. R. Nair,[1] P. Blake,[1] A. N. Grigorenko,[1] K. S. Novoselov,[1] T. J. Booth,[1] T. Stauber,[2] N. M. R. Peres,[2] A. K. Geim[1]*

There are few phenomena in condensed matter physics that are defined only by the fundamental constants and do not depend on material parameters. Examples are the resistivity quantum, h/e^2, that appears in a variety of transport experiments, including the quantum Hall effect and universal conductance fluctuations, and the magnetic flux quantum, $h/2e$, playing an important role in the physics of superconductivity (h is Planck's constant and e the electron charge). By and large, it requires sophisticated facilities and special measurement conditions to observe any of these phenomena. In contrast, we show that the opacity of suspended graphene (*1*) is defined solely by the fine structure constant, $\alpha = e^2/\hbar c \approx 1/137$ (where c is the speed of light), the parameter that describes coupling between light and relativistic electrons and that is traditionally associated with quantum electrodynamics rather than materials science. Despite being only one atom thick, graphene is found to absorb a significant ($\pi\alpha = 2.3\%$) fraction of incident white light, a consequence of graphene's unique electronic structure.

It was recently argued (*2*, *3*) that the high-frequency (dynamic) conductivity G for Dirac fermions (*1*) in graphene should be a universal constant equal to $e^2/4\hbar$ and different from its universal dc conductivity, $4e^2/\pi h$ [however, the experiments do not comply with the prediction for dc conductivity (*1*)]. The universal G implies (*4*) that observable quantities such as graphene's optical transmittance T and reflectance R are also universal and given by $T \equiv (1 + 2\pi G/c)^{-2} = (1 + \frac{1}{2}\pi\alpha)^{-2}$ and $R \equiv \frac{1}{4}\pi^2\alpha^2 T$ for the normal light incidence. In particular, this yields graphene's opacity $(1 - T) \approx \pi\alpha$ [this expression can also be derived by calculating the absorption of light by two-dimensional Dirac fermions with Fermi's golden rule (*5*)]. The origin of the optical properties being defined by the fundamental constants lies in the two-dimensional nature and gapless electronic spectrum of graphene and does not directly involve the chirality of its charge carriers (*5*).

We have studied specially prepared graphene crystals (*5*) such that they covered submillimeter apertures in a metal scaffold (Fig. 1A inset). Such large one-atom-thick membranes suitable for optical studies were previously inaccessible (*6*). Figure 1A shows an image of one of our samples in transmitted white light. In this case, we have chosen to show an aperture that is only partially covered by suspended graphene so that opacities of different areas can be compared. The line scan across the image qualitatively illustrates changes in the observed light intensity. Further measurements (*5*) yield graphene's opacity of $2.3 \pm 0.1\%$ and negligible reflectance (<0.1%), whereas optical spectroscopy shows that the opacity is practically independent of wavelength, λ (Fig. 1B) (*5*). The opacity is found to increase with membranes' thickness so that each graphene layer adds another 2.3% (Fig. 1B inset). Our measurements also yield a universal dynamic conductivity $G = (1.01 \pm 0.04)\ e^2/4\hbar$ over the visible frequencies range (*5*), that is, the behavior expected for ideal Dirac fermions.

The agreement between the experiment and theory is striking because it was believed that the universality could hold only for low energies ($E < 1$ eV), beyond which the electronic spectrum of graphene becomes strongly warped and nonlinear and the approximation of Dirac fermions breaks down. However, our calculations (*5*) show that finite-E corrections are surprisingly small (a few %) even for visible light. Because of these corrections, a metrological accuracy for α would be difficult to achieve, but it is remarkable that the fine structure constant can so directly be assessed practically by the naked eye.

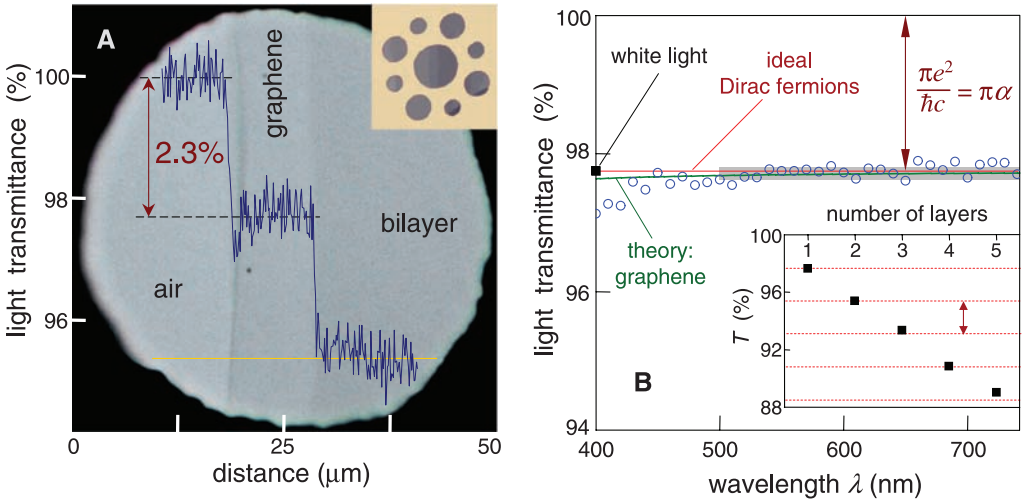

Fig. 1. Looking through one-atom-thick crystals. (**A**) Photograph of a 50-μm aperture partially covered by graphene and its bilayer. The line scan profile shows the intensity of transmitted white light along the yellow line. (Inset) Our sample design: A 20-μm-thick metal support structure has several apertures of 20, 30, and 50 μm in diameter with graphene crystallites placed over them. (**B**) Transmittance spectrum of single-layer graphene (open circles). Slightly lower transmittance for $\lambda < 500$ nm is probably due to hydrocarbon contamination (*5*). The red line is the transmittance $T = (1 + 0.5\pi\alpha)^{-2}$ expected for two-dimensional Dirac fermions, whereas the green curve takes into account a nonlinearity and triangular warping of graphene's electronic spectrum. The gray area indicates the standard error for our measurements (*5*). (Inset) Transmittance of white light as a function of the number of graphene layers (squares). The dashed lines correspond to an intensity reduction by $\pi\alpha$ with each added layer.

References and Notes

1. A. K. Geim, K. S. Novoselov, *Nat. Mater.* **6**, 183 (2007).
2. T. Ando, Y. Zheng, H. Suzuura, *J. Phys. Soc. Jpn.* **71**, 1318 (2002).
3. V. P. Gusynin, S. G. Sharapov, J. P. Carbotte, *Phys. Rev. Lett.* **96**, 256802 (2006).
4. A. B. Kuzmenko, E. van Heumen, F. Carbone, D. van der Marel, *Phys. Rev. Lett.* **100**, 117401 (2008).
5. Materials and methods are available on *Science* Online.
6. J. S. Bunch *et al.*, *Science* **315**, 490 (2007).

7. We are grateful to A. Kuzmenko, A. Castro Neto, P. Kim, and L. Eaves for illuminating discussions. Supported by Engineering and Physical Sciences Research Council (UK), the Royal Society, European Science Foundation, and Office of Naval Research.

Supporting Online Material

www.sciencemag.org/cgi/content/full/1156965/DC1
Materials and Methods
SOM Text
Figs. S1 to S5
References

25 February 2008; accepted 26 March 2008
Published online 3 April 2008;
10.1126/science.1156965
Include this information when citing this paper.

[1]Manchester Centre for Mesoscience and Nanotechnology, University of Manchester, M13 9PL Manchester, UK. [2]Department of Physics, University of Minho, P-4710-057 Braga, Portugal.

*To whom correspondence should be addressed. E-mail: geim@man.ac.uk