

Corrections

Citation: *Physics Today* **53**(7), 77 (2000); doi: 10.1063/1.1308412

View online: <http://dx.doi.org/10.1063/1.1308412>

View Table of Contents: <http://scitation.aip.org/content/aip/magazine/physicstoday/53/7?ver=pdfcov>

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initio calculations have clarified that the microscopic origin of superconductivity in the C_{60} compounds is due to the strong electron–phonon interaction that arises from the curvature of the molecule. In addition, there is a prediction that C_{36} compounds should become superconducting at much higher temperature due to their even larger curvature. That there is no trace of this effect in real C_{36} materials is then explained as being due to difficulties in the preparation.

Unfortunately, there is a tendency to overlook completely the following essential facts, which cannot be addressed by the methods that Bernholc discusses:

▷ Only A_3C_{60} is metallic. A_4C_{60} and other compositions are insulators. (Here, A is an alkali atom.)
 ▷ Fullerene compounds have a very small carrier density (as do the high- T_c superconductors), which is very difficult to incorporate successfully into the Bardeen-Cooper-Schrieffer (BCS) model because the small carrier density leads to a small density of states and to weak screening of the Coulomb interaction.¹ Bernholc argues that the narrow bands may lead to a relative increase in the density of states but, due to the small carrier density, the density of states still remains lower than the best traditional BCS materials.
 ▷ Finally, the BCS theory and the more exact Migdal–Eliashberg theory are intrinsically inconsistent for these systems. In all fullerene compounds the principle of adiabaticity (Migdal’s theorem), on which BCS theory is based, is violated. According to that principle, the effective interaction between electrons and ions is computed assuming that the phonon potential is quasi-static, having slow dynamics and small energy with respect to the rapid, high-energy electronic dynamics. This picture neglects important interference effects that are present if electrons and ions move with similar speed, that is, if their energy scales are similar and their dynamics are correlated in a specific way. In fullerenes and in the other high- T_c materials, the energy scales for the two dynamics are indeed similar. A generalization of the superconductivity theory to the nonadiabatic regime is therefore required.²

In summary, I agree with Bernholc that C_{60} and C_{36} compounds are extremely interesting materials. Their superconductive properties, however, are much more complex and interesting than he describes

and, up to now, first principle calculations have contributed little to their understanding.

References:

1. O. Gunnarsson, *Rev. Mod. Phys.* **69**, 575 (1997).
2. C. Grimaldi, L. Pietronero, S. Strassler, *Phys. Rev. Lett.* **75**, 1158 (1995); *Phys. Rev. B* **52**, 10530 (1995); L. Pietronero, S. Strassler, C. Grimaldi, *Phys. Rev. B* **52**, 10516 (1995).

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BERNHOLC REPLIES: The strength of a material is usually defined as the maximum stress (force per unit area) that the material can support, rather than the maximum strain. In engineering, the maximum elastic (yield) strength is the most important quantity, since at the yield point the strain is still reversible. From Hooke’s law, the yield strength is equal to the product of Young’s modulus and the maximum elastic strain. Nanotubes have an exceptionally large Young’s modulus of 1.25 TPa,¹ while the moduli of silica, silicon, and polyethylene are only 74,² 163,² and 220³ GPa, respectively. Reversible elastic strains of 5.8% have already been measured for single-walled nanotubes.⁴ Furthermore, the computed barriers for the formation of stress-induced defects are very large,⁵ indicating that “perfect” nanotubes should be kinetically stable at much greater strains. Reference 2 has an in-depth review of the factors affecting strength as well as extensive tables of the strengths of various materials.

With regard to Luciano Pietronero’s concerns: Opinions on “computational physics” range from considering this area as a third pillar of physics along with theory and experiment to questioning whether it is needed at all. The extraordinary growth of the field at this time argues positively for its usefulness, but I will not debate the point; I suggest that this debate will be settled in the future.

Although many inventive ideas for superconducting mechanisms were suggested when the C_{60} -based superconductors were found, the general consensus now is that the electron–phonon (intramolecular) interaction is the dominant pairing mechanism. The isotope effect for C_{60} and the lack thereof for Rb, transport properties, and the consistency with theoretical estimates are strong support for this interpretation. The

applicability of the Migdal approximation to low Fermi energy materials referred to by Pietronero has been discussed since the 1960s with a variety of opinions on the scaling parameter and parallel paths for truncation based on the energy dependence of the interactions. That is outside the scope of my article.

The extension of the curvature argument for creating allowed electron–phonon matrix elements extrapolated from the graphite to C_{60} systems is a useful instructional guide but a loose one. However, these couplings were computed for C_{60} and C_{36} systems and as Pietronero has written, “even if there may be appreciable indeterminateness in the absolute values of the parameters (say electron–phonon coupling), the relative difference is much more meaningful.”⁶ This exact approach was used as an argument for suggesting experimental investigation of C_{36} for superconductivity.

Reference:

1. A. Krishan et al, *Phys. Rev. B* **58**, 14013 (1998).
2. A. Kelly, N. H. MacMillan, *Strong Solids*, 3rd ed., (Oxford U. P., New York, 1986), Appendix A.
3. R. S. Porter and T. Kanamoto, *Polymer Eng. & Sci.* **34**, 266 (1994).
4. D. A. Walters et al, *Appl. Phys. Lett.* **74**, 3803 (1999).
5. M. Buongiorno Nardelli, B. I. Yakobson, J. Bernholc, *Phys. Rev. B* **57**, R4277 (1998).
6. L. Pietronero, S. Strassler, C. Grimaldi, *Phys. Rev. B* **52**, 10516 (1995).

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Corrections

May, page 12—Reference 1 of Richard Wilson’s letter should be: R. Wilson, *AAPT Resource Letter*, *Am. J. Phys.* **67** (5), 372 (1999).

May, page 18—The page number in reference 3 should be 2075.

May, page 47—The Indian Institute of Science in Bangalore was actually founded through the vision and drive of Jamshedji Nusserwanji Tata, a prominent industrialist who donated the land. Tata died in 1904, and his sons completed initial construction of the Institute, which opened its doors in 1911. C. V. Raman worked at the Institute from 1933 to 1938, as head of its physics department. ■