aurates(I) $[MAu_4][M_3AuO_2]$ (M = Rb, Cs), formed by the disproportionation of gold into Au^+ and Au^-,[17] requires the synthetic cluster chemists to extend their work to the construction of nanoscale high-nuclearity homo- and heterometallic clusters. Through the strategy of employing bridging ligands, whether soft such as sulfide or selenide or hard such as amides, the nuclearity of the gold clusters can be increased easily, in a uniform, systematic, and controllable fashion. The versatility of the synthetic design strategies can be further elaborated by using the metalloligand approach. With such an ability and the potential to assemble new multinuclear supramolecular arrays, gold has important implications for the future design and development of advanced nanomaterials.

[1] a) *Gold: Progress in Chemistry, Biochemistry, and Technology* (Ed.: H. Schmidbaur), Wiley, Chichester, **1999**; b) H. Schmidbaur, *Gold Bull*. **1990**, *23*, 11; c) H. Schmidbaur, *Chem. Soc. Rev*. **1995**, 391.

[2] See, for example: a) A. Deveson, S. Dehnen, D. Fenske, *J. Chem. Soc. Dalton Trans*. **1997**, 4491; b) J. F. Corrigan, D. Fenske, *Angew. Chem*. **1997**, *109*, 2070; *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 1981; c) J. F. Corrigan, D. Fenske, W. P. Power, *Angew. Chem.* **1997**, *109*, 1224; *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 1176; d) V. W.-W. Yam, K. K.-W. Lo, *Comments Inorg. Chem*. **1997**, *19*, 209.

[3] a) G. Marbach, J. Strähle, *Angew. Chem*. **1984**, *96*, 695; *Angew. Chem. Int. Ed. Engl.* **1984**, *23*, 715; b) S.-P. Huang, M. G. Kanatzidis, *Angew. Chem*. **1992**, *104*, 799; *Angew. Chem. Int. Ed. Engl.* **1992**, *31*, 787.

[4] a) C. Kowala, J. M. Swan, *Aust. J. Chem*. **1966**, *19*, 547; b) P. G. Jones, G. M. Sheldrick, E. Hädicke, *Acta Crystallogr. Sect. B* **1980**, *36*, 2777; c) K. Angermaier, H. Schmidbaur, *Chem. Ber*. **1994**, *127*, 2387; d) F. Canales, M. C. Gimeno, P. G. Jones, A. Laguna, *Angew. Chem*. **1994**, *106*, 811; *Angew. Chem. Int. Ed. Engl.* **1994**, *33*, 769.

[5] F. Canales, M. C. Gimeno, A. Laguna, P. G. Jones, *J. Am. Chem. Soc.* **1996**, *118*, 4839.

[6] a) V. W.-W. Yam, E. C.-C. Cheng, K.-K. Cheung, *Angew. Chem*. **1999**, *111*, 193; *Angew. Chem. Int. Ed*. **1999**, *38*, 197; b) V. W.-W. Yam, E. C.-C. Cheng, Z.-Y. Zhou, *Angew. Chem.* **2000**, *112*, 1749; *Angew. Chem. Int. Ed*. **2000**, *39*, 1683.

[7] D. Fenske, T. Langetepe, M. M. Kappes, O. Hampe, P. Weis, *Angew. Chem.* **2000**, *112*, 1925; *Angew. Chem. Int. Ed*. **2000**, *39*, 1857.

[8] a) P. A. Bates, J. M. Waters, *Acta Crystallogr. Sect. A* **1987**, *43*, C194; b) P. Pyykkö, *Chem. Rev.* **1997**, *97*, 597.

[9] C. E. C. A. Hop, R. Bakhtiar, *J. Chem. Educ*. **1996**, *73*, A162, and references therein.

[10] a) V. Ramamoorthy, P. R. Sharp, *Inorg. Chem*. **1990**, *29*, 3336; b) A. Grohmann, J. Riede, H. Schmidbaur, *J. Chem. Soc. Dalton Trans.* **1991**, 783.

[11] a) K. Angermaier, H. Schmidbaur, *Chem. Ber*. **1995**, *128*, 817; b) A. Shiotani, H. Schmidbaur, *J. Am. Chem. Soc*. **1970**, *92*, 7003.

[12] S. D. Bunge, O. Just, W. S. Rees, Jr., *Angew. Chem.* **2000**, *112*, 3199; *Angew. Chem. Int. Ed*. **2000**, *39*, 3082.

[13] a) P. Miele, J. D. Foulon, N. Hovnanian, J. Durand, L. Cot, *Eur. J. Solid State Inorg. Chem*. **1992**, *29*, 573; b) P. B. Hitchcock, M. F. Lappert, L. J.-M. Pierssens, *Chem. Commun*. **1996**, 1189.

[14] A. M. James, R. K. Laxman, F. R. Fronczek, A. W. Maverick, *Inorg. Chem*. **1998**, *37*, 3785.

[15] A. Vogler, H. Kunkely, *Chem. Phys. Lett*. **1988**, *150*, 135.

[16] E. Cerraga, M. Contel, A. D. Valencia, M. Laguna, T. Gelbrich, M. B. Hursthouse, *Angew. Chem.* **2000**, *112*, 2443; *Angew. Chem. Int. Ed.* **2000**, *39*, 2353.

[17] A.-V. Mudring, M. Jansen, *Angew. Chem.* **2000**, *112*, 3194; *Angew. Chem. Int. Ed*. **2000**, *39*, 3066.

Single Fullerene Molecules and the Wave – Particle Dualism

K. O. Greulich

In the past, new developments in physics often have fostered progress in applied chemistry. Now it is applied chemistry which boosts physics in one of its central questions: wave – particle dualism. C_{60} and C_{70} molecules, fullerenes, help solve two of the most important questions of physics: "Is the wave – particle dualism also valid for large objects?" and "Can particles interfere with themselves?"

C_{60} molecules have a molecular weight of approximately 1000 Dalton. This corresponds to a peptide of 8 – 9 amino acids or an oligonucleotide of 3 – 4 monomers. The linear dimension of such a fullerene is equivalent to four carbon atoms (since $4^3 = 64$), namely, three C–C bonds or five Ångströms. Objects of this size can be visualized with good scanning – tunneling or atomic force microscopes. Most readers would probably agree that these are true particles.

If it were possible to show that fullerenes of this size also have wave properties, this would represent a major breakthrough in one of the most basic questions of physics. Exactly this is reported by the group of Anton Zeilinger, Vienna.[1]

Recall that when a (plane) wave encounters a double slit, part of it will move through slit A, the other one through slit B. When the slit width as well as the distance between the slits are of the order of the wavelength, both slits are the origin of spherical waves which interfere with each other, that is, they generate regions of amplification and regions of extinction. A screen in the path of such interfering waves will register an intensity pattern with maxima and minima. One

[*] Prof. Dr. K. O. Greulich
Institut für Molekulare Biotechnologie
Postfach 100813, 07708 Jena (Germany)
www.imb-jena.de/greulich
Fax: (+49) 3641-656-410
E-mail: kog@imb-jena.de

  1433-7851/00/3923-4242 $ 17.50+.50/0

can model this process easily in a basin with still water: Holding the thumb and ring finger of one hand in a fixed position at a water surface, oscillation of the hand will model the two spherical waves emanating from two slits. A clear interference pattern is seen with regions of heavy wave motions and regions of quiescence. Double-slit experiments with light (Young, Huygens) have, in the 19th century, proven that light is a wave. A more general rule is: Whenever two or more paths are possible and interference patterns result, this is evidence for waves. So far, everything is straightforward—only the mathematics describing the process is perhaps somewhat difficult.

Problems arose with the advent of quantum mechanics: The latter postulates, that interference occurs also when a beam of particles, instead of waves, passes the double-slit arrangement. This occurs even when the beam is attenuated so much that only one particle at a time can pass the apparatus. This is no longer interference of a partial beam travelling through slit A with a partial beam travelling through slit B. Some hidden information must organize this process. Alternatively, single particles interfere with themselves, as it was mentioned above.

For decades, most experiments of this kind were performed with light, which, for this purpose, was regarded as a beam of photons, and photons were thought to be strict particles. Phrases such as "when light is attenuated so much, that only one photon at a time is in the apparatus" can be found in many textbooks, even in quite new ones. However, such an experiment has never been made. The reason is that a light source, be it a laser or a cheap light bulb, always generates wavetrains. Since in such wavetrains, for example with green light, the temporal distance between two photons is 1.6 femtoseconds and techniques which might resolve such short times[2] have never been used in a double slit experiment, one can never say if there were really single photons or if two or more photons were in the apparatus, which might have interfered classically, as described. Even so-called single-photon detectors can never ascertain if they have observed a single photon or just the first photon of a more-or-less short wavetrain. Therefore, all double-slit experiments which were used to discuss the above-mentioned quantum mechanical questions are disputable.

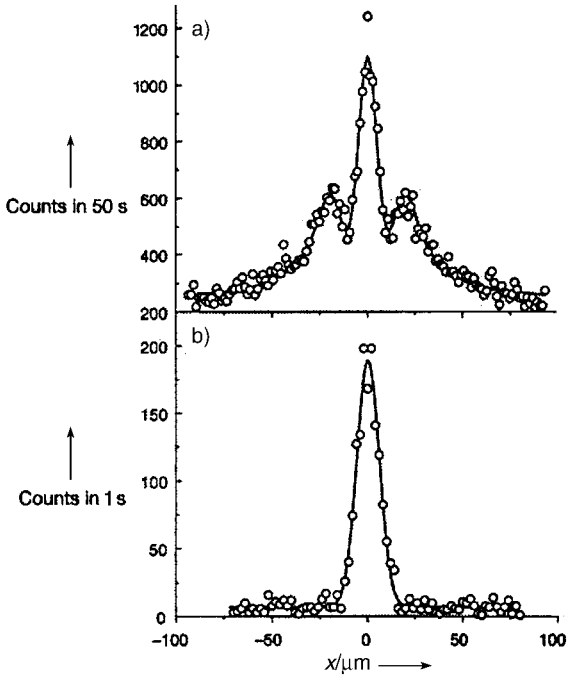

Figure 1. Experimental interference results, collected with (a) and without (b) the grid present. Note that the count rate scales are different. The solid line is calculated from theory. (Reproduced from ref. [1].)

Less disputable are the Zeilinger experiments with fullerenes: There is little doubt that we have a true single-molecule experiment. Nevertheless, when fullerenes are sent through a double slit (or, for practical reasons, through a grid with more than two slits), molecule by molecule, particle by particle, the result is the one shown in Figure 1a: Obviously interference!

The Experiment

Commercial fullerene C_{60} molecules (purity 99.5%) were purchased. After heating in an oven to 900 or 1000 K, those molecules which migrate in the wanted direction are collimated in vacuum (5×10^{-7} mbar) by two 10 μm slits 1.04 m apart from each other (Figure 2a). Immediately after the second collimation slit, a grating with 50 nm wide slits and a grid constant of 100 nm was inserted into the path. The detection system was positioned 1.25 m further (Figure 2b). The fullerenes were first ionized with a focused 24 W argon-ion laser and then detected with a beryllium–copper conversion electrode combined with a channeltron detector. The dark count rate for this system is less than one count per second.

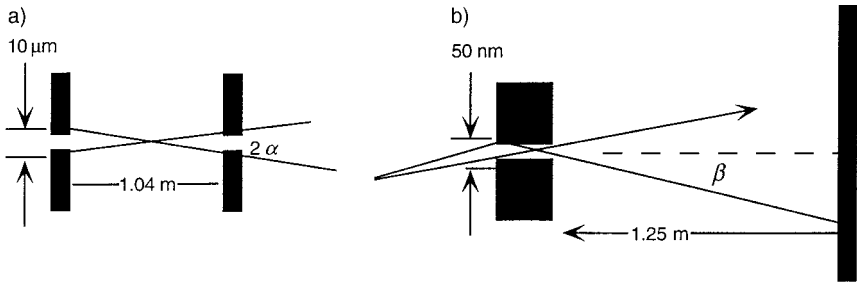

Figure 2. Experimental set-up for the collimation (a) and the collection (b) geometries, showing the collimation and collection angular deviations, α and β, respectively.

Are "Trivial" Interpretations Possible?

In such an important scientific question as discussed here, we should thoroughly check if some trivial interpretation is perhaps possible. In fact, we should ask a few obvious questions. In the collimator, a small angular divergence remains. One can easily verify that the numerical value of this divergence α is 10 μm per 1.04 m or about 10^{-5}. On the other hand, the width of the single slits of the grid is 50 nm.

  1433-7851/00/3923-4243 $ 17.50+.50/0

Even with the comparably stable material of which the grid is made (SiN_x), the grid must be some micrometers thick. Figure 2b shows that, in this case, the walls of the slit might act as reflectors for the 0.5 nm large fullerene molecules. In the detector plane, such reflected molecules should be detected [10 μm × (1.25 m/1.04 m) =] 12.5 μm on the right and the left of the central peak, which would be generated by unreflected molecules passing the device. In fact, the side peaks occur at approximately that position (Figure 1a).

Interference of fullerenes—just a trivial geometric problem? Not so! With reasonable assumptions for geometric details, which are, however, not directly evident from the experimental description, the side peaks should be at least an order of magnitude weaker than they are. Thus the trivial explanation seems to be improbable.

More problematic is that in the diffraction experiment only a fraction of all fullerene molecules are counted. The scales in Figure 1a and 1b are very different. The peak of the control experiment has an intensity of 200 counts per second or 10000 counts per 50 seconds (Figure 1b). The intensity of the central peak in Figure 1a is 1100 counts per 50 seconds. Even when considering that the diffraction pattern is broader, a rough estimate indicates that at most 20% of fullerene molecules are counted when the grid is introduced into the path of the fullerene molecules. In a pure wave model, introducing a grid into the experiment should not "swallow" such a large percentage of waves.

We cannot solve this point here, but the data can be explained with high accuracy by Kirchhoff's diffraction theory (the solid line through the data points). It is quite improbable that this agreement would result by chance, with other physical reasons for generation of this pattern. Particularly so, the relative intensities are hardly to be generated by chance. So, with little small remaining doubt, we can accept that the experiment in fact has seen (self-)interference and thus wave properties of single fullerene molecules.

Some Speculation: Are Fullerene Molecules "Soft"?

What is the consequence of interference? A naive answer is that fullerenes are predominantly wavelike and soft! What most of us have accepted for photons, electrons, neutrons, and perhaps single atoms, is obviously also true for these little solid-state bodies consisting of 60 to 70 atoms. Moreover, since we can be quite sure that we had only one fullerene in the apparatus at a given time, we have self interference.

Theoreticians will certainly develop some explanation or they will just tell us "that is nature, we have to accept it!". But let us be somewhat less pessimistic, let us make a speculative assumption: In a way we still have to understand fullerenes may divide into two parts, travelling different paths, and finally reunite, as one can imagine for a droplet of oil when sliced by a knife-like structure.

Is this assumption really so naive that we have to dismiss it immediately? Perhaps not! Perhaps our perception of a particle is incomplete. Everybody accepts that hard cosmic radiation consists of particles. For soft radio waves nobody would dare to suggest this. But the whole edifice of physics would collapse when these two forms of electromagnetic radiation, distinguished only by their wavelengths, were essentially different. Perhaps gamma radiation only appears particle-like since we use objects with a smaller energy density (atoms, nuclei) to detect them. Correspondingly, we perceive radio waves as soft since we use metal rods (antennas) for their detection. Here, we have clear examples that it is rather a matter of perception and not an absolute truth if we see an object as a particle or as a wave. At least elementary particles are no billiard balls.[2] There is a second reason for not immediately dismissing the soft-molecule idea: The droplet model for the atomic nucleus is well accepted and Jensen received the 1963 Nobel Prize for Physics for this idea.

After the 20th century, in which we have learned that particles are waves and Zeilinger's experiment has shown that this is true even for comparably large particles, we should now start to ask a surprisingly simple and yet so difficult question: What is a particle? This goal is now becoming experimentally feasible with the rapid development of single molecule techniques (see, for example, ref. [4]), which allows us to observe and handle single molecules, and applied chemistry is providing the ideal particles to tackle this challenge.

[1] M. Arndt, O. Nairz, J. Vos-Andrae, C. Keller, G. van der Zouw, A. Zeilinger, *Nature* **1999**, *401*, 680; M. Arndt, A. Zeilinger, *Phys. Bl.* **2000**, *56*, 69.
[2] Z. Y. Ou, L. Mandel, *Phys. Rev. Lett.* **1988**, *61*, 54; A. Schenzle, *Phys. Bl.* **1989**, *45*, 25.
[3] J. Maddox, *Nature* **1989**, *342*, 121.
[4] See *Single Molecules*, Wiley-VCH, Berlin, a recently established print and internet journal.

  1433-7851/00/3923-4244 $ 17.50+.50/0