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## FIFTY YEARS AFTER THE IDEA OF C<sub>60</sub> MOLECULE

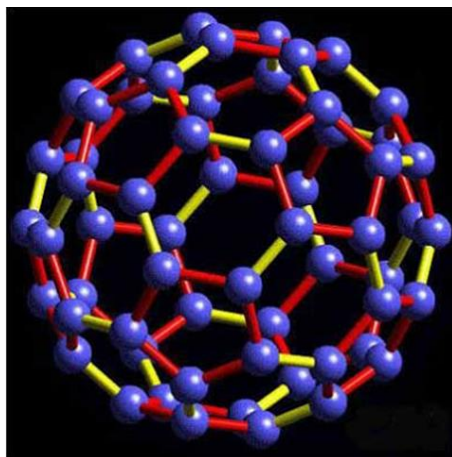
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In contrast to most of the well-known molecules, C<sub>60</sub> fullerene is a brainchild of a fantasy-inclined young chemist. It occurred to me 50 years ago in 1970 [1, 2]. Then, 15 years later, C<sub>60</sub> was spectroscopically observed by Kroto, Smalley and Curl [3] and finally isolated and confirmed by Krätschmer and Huffman [4]. Stunning sphere and well-proportioned symmetry of the molecule instantly attracted large number of scientists all over the world and the so-called fullerene research fever ensued [5].



**Fig. 1** Computer drawing of C<sub>60</sub> molecule. **Purple** = carbon atom, **Red** = single bond, **Yellow** = double bond.

To our disappointment, however, the fever did not last long. In 1996, Kroto, Smalley and Curl were given Nobel Prize of Chemistry for the discovery but in the next year all of them left C<sub>60</sub> and turned to carbon nanotubes. Actually I was faster than them to leave C<sub>60</sub>, finding nanodiamonds more interesting (see below) [6, 7]. As the old Chinese proverb says, "A beauty's life is thin". On the occasion of 50 years anniversary of the idea of C<sub>60</sub>, let me briefly analyze the reason for the sudden decline of C<sub>60</sub> research.

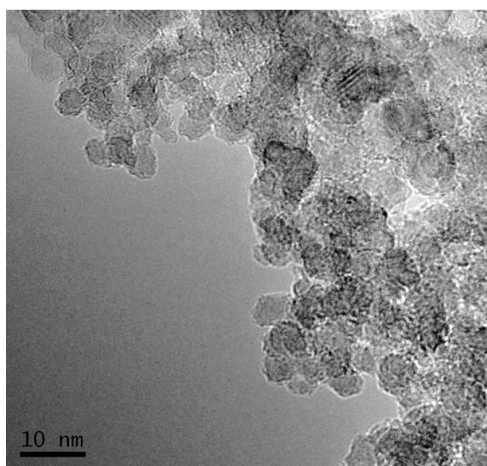
Technically, the production cost was and still remained too high for C<sub>60</sub> to become a commodity chemical. In turn, reason for the high cost is that the formation mechanism still remains unclarified. However, these explanations are only phenomenological. The true reason for the decline of our

interests in C<sub>60</sub> is the fact that no significant industrial application has ever been found. As a matter of fact, in the beginning every one of us believed that there will be soon found truly useful and new applications but this expectation was never fulfilled. The same thing happened with carbon nanotube (CNT) on grander scale. The CNT fever began only a few years later than C<sub>60</sub>, and lasted much longer until very recently involving huge number of researchers.

At the moment, no one can give logical explanation on our failure to find highly attractive applications for these novel network structures of carbon atoms. My tentative explanation invokes the fact that carbon atoms comprising C<sub>60</sub> and CNT have the same electronic configuration of *sp*<sup>2</sup>-hybridization as carbon blacks, the cheapest carbon material. Carbon networks based on *sp*<sup>2</sup>-carbon atoms seems to have inherent and incurable defective properties for use as industrial materials, which cannot be removed by correcting the bulk structure to homogeneous and well-aligned network as in C<sub>60</sub> and CNT.

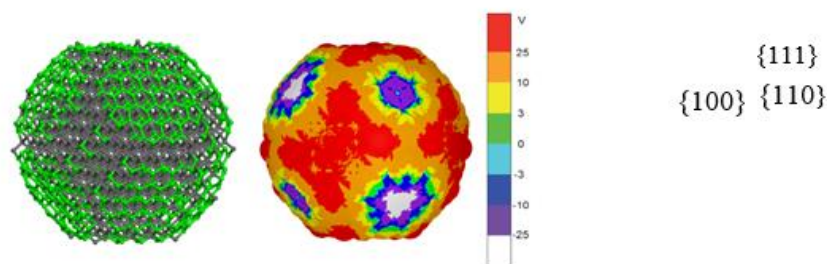
Then, one would ask what the best carbon structure is? At the moment we believe the answer is *diamond in single-nano size*. Note that diamond is chemically composed of *sp*<sup>3</sup>-hybridized carbon atoms, and basically different from *sp*<sup>2</sup>-hybridized C<sub>60</sub> and CNT. So far micron-sized particles and ultra-thin films have been produced on industrial scales, but these were extremely difficult to process. For these diamonds, the final production forms are the final application forms.

We are now working on nanoparticles of diamonds (Photo 1), which can be readily prepared by a number of methods, the best-known one being detonation. *Detonation nanodiamond* has been known since 1963 [8] but the raw product was extremely tight agglutinates of primary particles [9] (Photo 1). We found attrition milling of the aqueous suspension of raw detonation nanodiamond completely disintegrated the agglutinates into polyhedral primary particles with 2.6±0.5nm in diameter (Fig. 2) [10, 11]. These findings comprise a remarkable breakthrough.



**Photo 1** TEM image of primary particles of detonation nanodiamond particles. These have once been dispersed in water by careful attrition milling, but re-aggregated during drying for TEM observation.

Our preliminary studies indicate that solid materials dispersed with the primary particles of detonation nanodiamond acquire high degree of toughness without harming the original elastic and other properties of the host material [12]. It seems that we have finally reached a truly powerful form of carbon material in nanodiamonds after a long detour. Even though the classic beauty of C<sub>60</sub> will remain permanently and remembered by many scientists, I shall, at least for the moment, not come back to this molecule.



**Fig. 2** Geometry-optimized structure drawings of the primary particles of detonation nanodiamond. From left to right, wire-mesh, surface charge distribution, and line drawings. Drawn by Professor A. Barnard.

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