

Highlight Review

A New Route to an Endohedral Fullerene by Way of σ -Framework Transformations

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Abstract

The molecular surgical approach has been shown to be applicable to preparation of an endohedral fullerene. Thus, an orifice large enough to insert an atom or molecule has been constructed on the surface of fullerene C_{60} . The orifice has been enlarged to a 13-membered ring by insertion of a sulfur atom on the rim, and 100% encapsulation of molecular hydrogen has been attained. Then, the size reduction of the orifice, without the loss of incorporated hydrogen, and complete closure of the orifice have been achieved to afford a new endohedral fullerene, $H_2@C_{60}$.

Introduction

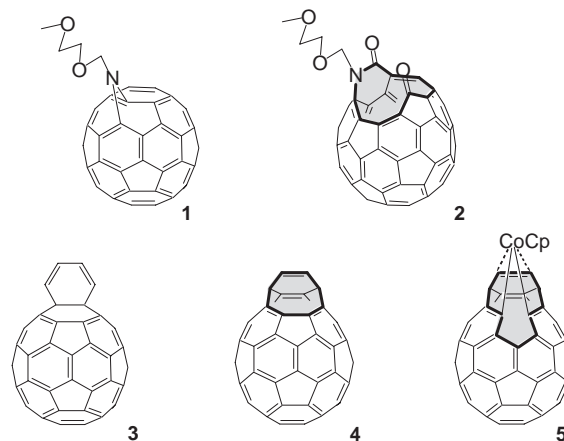
Almost 15 years have passed since fullerene C_{60} was isolated as a *real* material in macroscopic quantities.¹ During this period, numerous studies have been conducted in the field of organic chemistry to elucidate the reactivity of C_{60} , and consequently various types of reactions are now known to be applicable to derivatization at the outside of the cage.² In contrast to a wealth of researches dealing with outside π -system of the fullerenes, the science concerning the inside of fullerene, i.e., that of "endohedral fullerenes" appears to be much less developed in spite of great interest in these particular class of fullerenes both from basic and application viewpoints.³ This situation could be ascribed to the fact that their production has so far relied only on the physical method such as hard-to-control co-vaporization of carbon and metal atoms³ or high-pressure/high-temperature treatment with noble gases⁴ ending up only in milligram quantities of pure product after laborious isolation procedures. In order to bring about a breakthrough into this situation, an entirely different approach for the production of endohedral fullerenes is needed.

One approach would be the use of organic synthesis by a strategy of "molecular surgery," in which the fullerene cage is opened and then closed after insertion of a small atom or molecule. In order to establish this methodology, acquirement of the technique for transformation of the σ -framework of fullerenes is indispensable. This account summarizes developments in this area and our recent success in completion of the molecular surgical technique to produce a new endohedral fullerene encapsulating molecular hydrogen.

Open-cage Fullerenes

In 1995, Wudl and co-workers reported the synthesis of a first open-cage fullerene, i.e., ketolactam **2** having an 11-membered

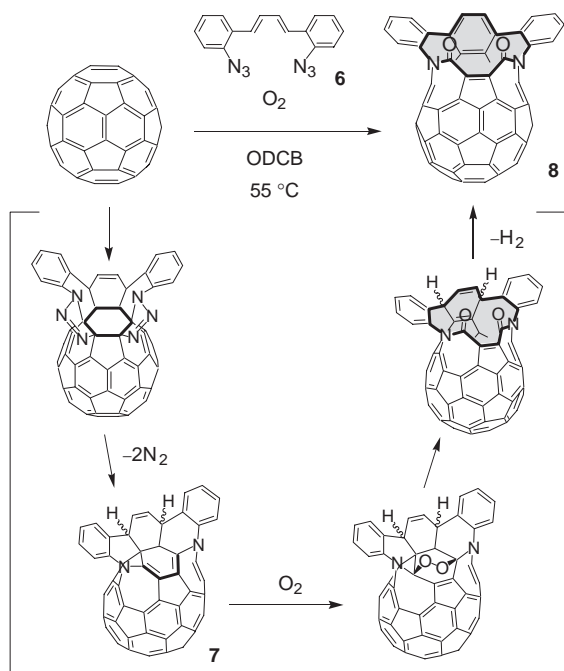
ring orifice, through the reaction of [5,6]-azafulleroid **1** with singlet oxygen.⁵ However, the orifice was found to be too small even for a helium atom to pass through at the temperature as high as 200 °C.⁶ In 1996, Rubin and coworkers synthesized another open-cage fullerene **4** possessing an eight-membered ring orifice via sequential intramolecular [4+4] and retro [2+2+2] rearrangements from *in situ* generated C_{60} derivative **3** fused with 1,3-cyclohexadiene.⁷ Compound **4** was transformed to cobalt complex **5**, whose structure was determined by X-ray crystallography.⁷ Although the cobalt atom is ideally seated on top of the orifice, activation such as heating up to 400 °C⁶ or pressurizing up to 40 kbar⁸ was not effective to push in the cobalt atom through the orifice.



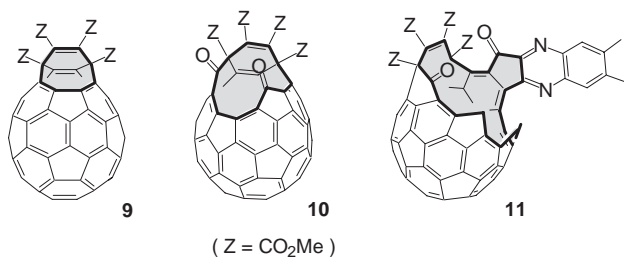
Later in 1999, Rubin's group reported an open-cage fullerene **8** having a 14-membered-ring orifice. Upon treatment of C_{60} with diazidobutadiene **6** in *o*-dichlorobenzene (ODCB), an initial reaction of **6** (involving both a [4+2] cycloaddition and two 1,3-dipolar additions) takes place with three double bonds in a same six-membered ring, which is followed by extrusion of two nitrogen molecules and rearrangements involving nitrogen migration to give **7**. A reaction of the resulting electron-rich butadiene unit with oxygen and following dehydrogenation can yield the open-cage fullerene with a bislactam structure **8** (Scheme 1).⁹ The orifice of **8** is rather elliptic in shape, but the insertion of a helium atom in 1.5% and a hydrogen molecule in 5% through the orifice was successfully conducted by applying high-temperature/high-pressure conditions (288–305 °C/ca. 475 atm and 400 °C/100 atm, respectively),¹⁰ thus giving a first piece of evidence that the molecular surgical approach is actually feasible.

At this point, it should be noted that a group in Nagoya

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University has also succeeded in synthesis of an open-cage fullerene with an eight-membered ring **9** through a [4+2] cycloaddition reaction of a palladacyclopentadiene derivative and C_{60} .¹¹ By photochemical oxidation of one of the double bonds at the rim of the orifice¹² (vide infra) and a following reaction of the resulting open-cage fullerene **10**, possessing a 12-membered-ring orifice, with an excess of 4,5-dimethyl-1,2-phenylenediamine, the largest orifice of a 20-membered ring was produced on the original fullerene's surface (compound **11**).¹³ Now the molecular shape of **11** is close to a bowl, and a water molecule was found to be incorporated in up to 75% of all the molecules of **11** in a solution in 1,1,2,2-tetrachloroethane- d_2 , as demonstrated by a ^1H NMR signal at such a high field as $\delta -11.4$ ppm.¹³ However, such a severely ruptured π -system in **11** does not seem suitable to be restored into the original structure of C_{60} .



We, on the other hand, found that the thermal reaction of C_{60} with polyaza-aromatic compounds having nitrogen atoms at adjacent positions can proceed via [4+2] cycloaddition, extrusion of nitrogen, formal [4+4], and retro [2+2+2] reactions, as shown in Scheme 2, to form an eight-membered-ring orifice on the fullerene surface, as in **12**,¹⁴ **13**,^{15a} and **14**.¹⁶ As shown in the X-ray structure of **12** (Figure 1), the double bonds on the rim of the orifice are considerably distorted (twist angle of two $\text{C}=\text{C}$ double bonds, 39.0° and 38.8°), and the coefficients of the HOMO are relatively high on these carbons. Thus, singlet oxygen generated by irradiation of visible light selectively adds

to each of these double bonds, resulting in enlargement of the orifice through the formation of a 1,2-dioxetane^{15b} to give **15a** and its isomer **15b** with a 12-membered-ring orifice, in 60% and 31% yields respectively.¹⁴

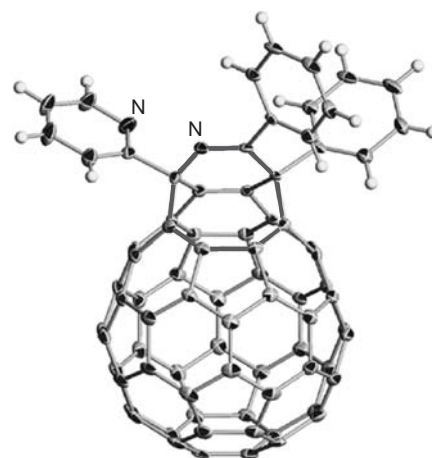
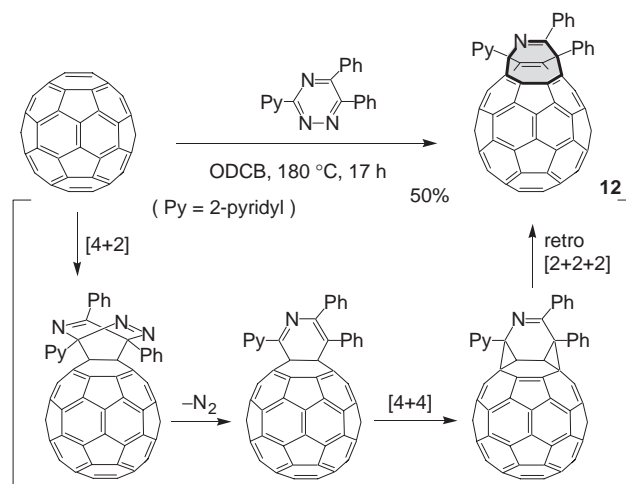
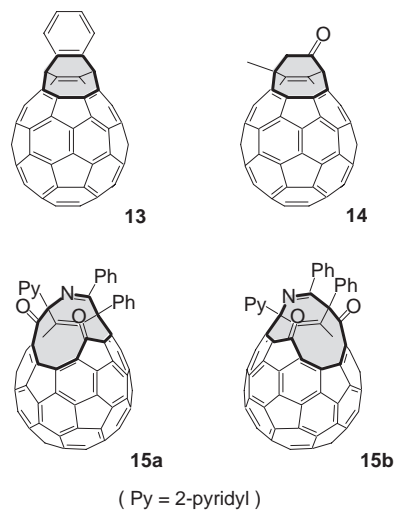


Figure 1. X-ray structure of **12** (50% probability for thermal ellipsoids).



We were interested in the redox behavior of open-cage fullerenes **12**, **15a**, and **15b**, with such severely torn out π -systems. To our surprise, **15a** and **15b** were found to undergo reversible stepwise reductions with the first reduction potentials even lower than that of C_{60} by nearly 0.2 V as shown in Table 1. This is in agreement with low LUMO levels calculated for these compounds possessing two carbonyl groups. Thus the open-cage fullerenes **15a** and **15b** are regarded as good π -electron acceptors.

Table 1. Reduction potentials^a and calculated LUMO levels^b

Compound	E_{red} (V vs Fc/Fc ⁺) ^a				LUMO ^b /eV
	E_{red}^1	E_{red}^2	E_{red}^3	E_{red}^4	
C_{60}	-1.17	-1.59	-2.06	-2.56	-3.23
12	-1.21	-1.62	-2.11	-2.62	-3.03
15a	-0.97	-1.40	-2.01	-2.43	-3.32
15b	-0.98	-1.39	-2.00	-2.44	-3.34

^aDetermined by differential pulse voltammetry (sample 1 mM with 0.05 M Bu_4NBF_4 in ODCB, scan rate 0.02 V s⁻¹).

^bCalculated at the B3LYP/6-31G* level of theory.

As shown in Figure 2, the LUMO coefficients of **15a** were found to be relatively high on the butadiene unit on the rim of the orifice. It was therefore anticipated to be possible to insert a sulfur atom into the central part (bond *a*) of the butadiene unit in order to enlarge the size of the orifice when the molecule was activated by addition of a typical π -electron donor such as tetrakis(dimethylamino)ethylene (TDAE). Under such conditions, the sulfur insertion reaction successfully proceeded to give **16** with a 13-membered-ring orifice as a single product in 77% yield (Scheme 3).¹⁴ The versatility of this method to enlarge an orifice of fullerene has been confirmed by Orfanopoulos for Wudl's compound **2**.¹⁷

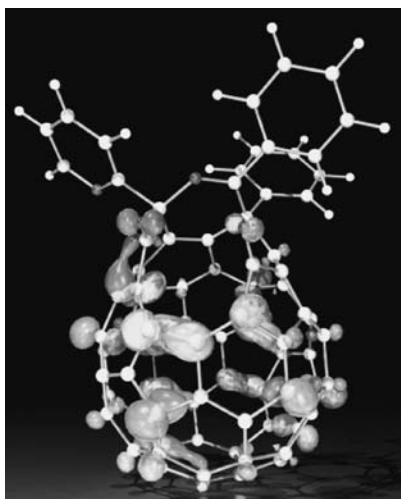
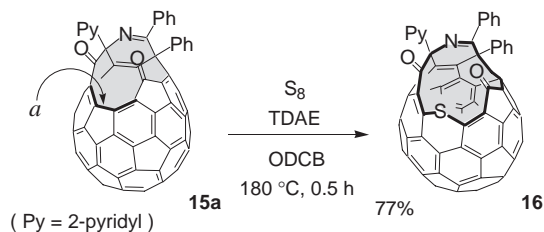


Figure 2. The optimized structure of **15a** with the contour of the LUMO at the B3LYP/6-311G** level of theory.

◆ Insertion of Molecular Hydrogen

As shown in Figure 3, the X-ray crystallography on **16** indicated that the shape of the orifice is somewhat more like a circle rather than an ellipse when compared with **8**. The required ener-



Scheme 3.

gy calculated (B3LYP/6-31G**//B3LYP/3-21G) for a hydrogen molecule to enter through the orifice is 30.1 kcal mol⁻¹ for **16**, which is about 10 kcal mol⁻¹ lower than that for **8** (41.4 kcal mol⁻¹). However, the space-filling model (Figure 3b) and a cut-out view of the transition state (Figure 4) show yet how small this orifice is for a hydrogen molecule to pass through. Upon actual experiment, treatment of powder of **16** with hydrogen gas (800 atm) at 200 °C for 8 h resulted in 100% encapsulation of hydrogen in an fullerene cage for the first time.^{18a} The encapsulated hydrogen was detected as a singlet signal at such a high field as -7.25 ppm in ¹HNMR.¹⁸ It was also directly observed to be located at the center of the cage by synchrotron X-ray crystallography and MEM (maximum entropy method) analysis.¹⁹ The hydrogen-incorporating complex, H₂@**16**, is quite stable at room temperature, but it releases hydrogen slowly at a temperature range of 160 to 190 °C (*t*_{1/2}, 54.4 and 4.2 h at 160 and 190 °C, respectively). The rate follows the first-order kinetics and the activation energy was determined as 34.3 kcal mol⁻¹. Note that this value is rather close to the value calculated for hydrogen insertion (vide supra).

When MALDI-TOF MS was conducted on H₂@**16** at a laser power adjusted slightly above the threshold for the ionization of **16**, the molecular ion peak of H₂@**16** was clearly observed, along with a peak for empty **16** formed by escape of hydrogen molecule upon laser irradiation. When a higher laser power was used, the peak height for the molecular ion decreased and, instead, the formation of C_{60} and H₂@ C_{60} (in a molar ratio of about 3:1) was clearly observed. This result demonstrates that a highly modified C_{60} derivative such as **16** can regenerate the pristine C_{60} cage by self-restoration upon application of high laser power. We next concentrated our efforts on actualization of this process by laboratory experimental procedures.

◆ Encapsulation of Molecular Hydrogen in C_{60} by Organic Synthesis

It was expected that the transformation of H₂@**16** to H₂@ C_{60} would be attained by removal of the sulfur atom on the rim of the orifice and following chemical closure of the orifice. In order to attain these procedures without significant loss of encapsulated hydrogen, the use of high temperature must be avoided from the experimental results described above.

First, the sulfur atom of H₂@**16** was oxidized by *m*CPBA at room temperature to give the sulfoxide H₂@**17**. The sulfinyl group was then removed by photoirradiation with visible light also at room temperature to yield H₂@**15a** having a 12-membered-ring orifice. The MALDI-TOF MS of H₂@**15a** now exhibited the molecular ion peak of H₂@ C_{60} as a base peak, indicating its enhanced accessibility from H₂@**15a** as compared with H₂@**16**. The spectrum, however, also showed the presence

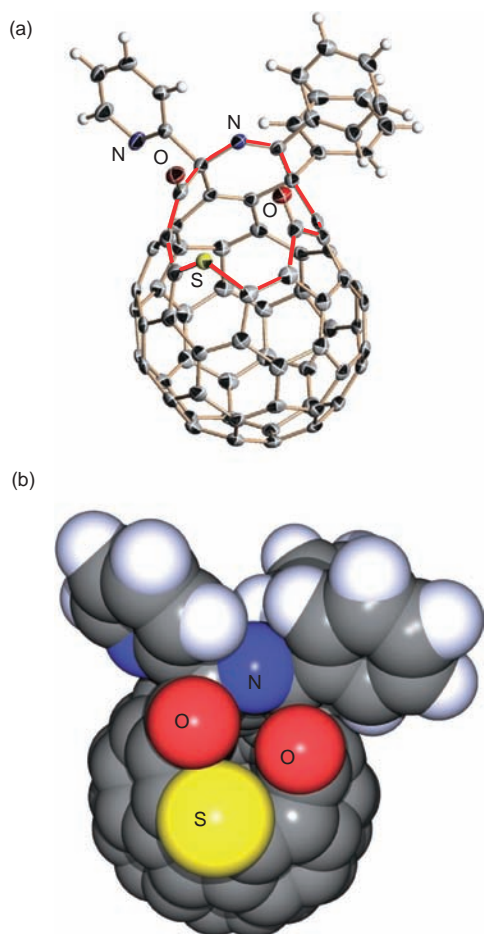


Figure 3. X-ray structure of **16**; (a) the thermal ellipsoid model with 50% probability levels and (b) top view of the space-filling model.

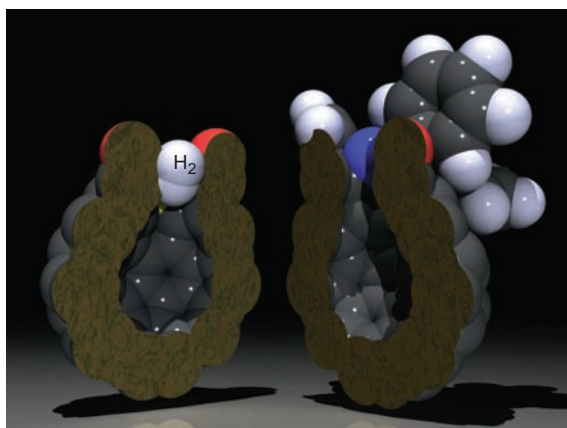
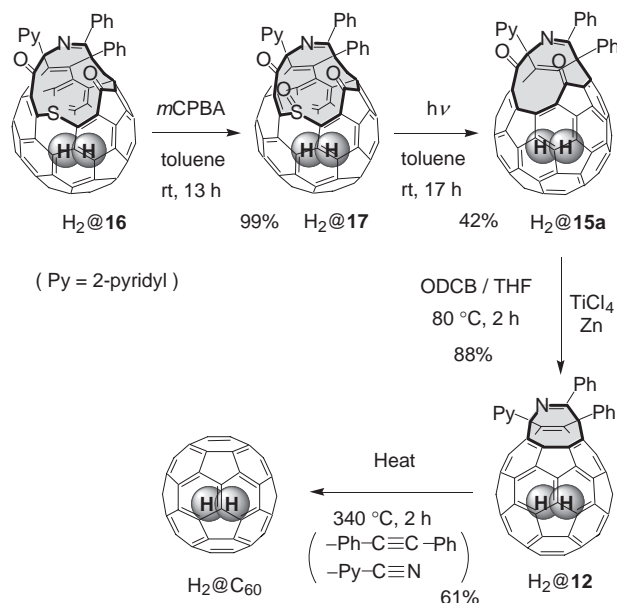


Figure 4. The cut-out view of the transition state for insertion of a hydrogen molecule into **16** calculated at the B3LYP/3-21G level of theory.

of empty C₆₀ in 20% yield relative to H₂@C₆₀ and indicated that further reduction of the orifice size was needed. Then in the next step, two carbonyl groups in H₂@**15a** were reductively coupled by the use of Ti(0)²⁰ at 80 °C to give H₂@**12** having an eight-membered-ring orifice as shown in Scheme 4.

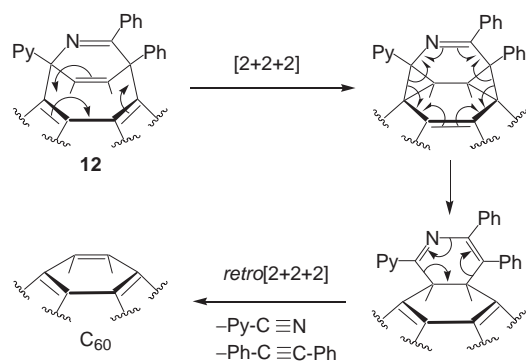


Scheme 4.

At each of these three steps, complete retention of encapsulated hydrogen was confirmed by the integrated peak intensity (2.00 ± 0.05 H) of the characteristically upfield-shifted NMR signals of the inside hydrogen ($\delta -6.18$ ppm for H₂@**17**, -5.69 for H₂@**15a**, and -2.93 for H₂@**12**). The gradual downfield shift of the hydrogen signal, observed upon going from H₂@**17** to H₂@**15a** and from H₂@**15a** to H₂@**12**, reflects the formation at each step, within the fullerene cage, of a fully π -conjugated five-membered ring, which exerts a strong deshielding effect through its paramagnetic ring currents.²¹

Finally, complete closure of the orifice was achieved by heating the powder of H₂@**12** in a glass tube under vacuum at 340 °C for 2 h. The crude product was dissolved in carbon disulfide and passed through a silica-gel column to give H₂@C₆₀ (contaminated with 9% empty C₆₀) in 67% yield. Similar results were obtained when H₂@**12** was heated at 300 °C for 24 h, at 320 °C for 8 h, or at 400 °C for 2 min.²²

The closure of the orifice is considered to proceed according to the mechanism shown in Scheme 5, which is almost like a reversal of the reactions shown in Scheme 2. The crude product of the thermal reaction exhibited a ¹³C NMR signal for H₂@C₆₀ at δ 142.844 ppm together with a very small signal at δ 142.766 ppm, which corresponds to the signal of empty C₆₀, in an integrated ratio of 10:1. The new endohedral fullerene, H₂@C₆₀, was obtained in a 100% pure form by separation through recycling HPLC on a semipreparative Cosmosil Buckyprep column with retention time of 395 min for C₆₀ and 399 min for H₂@C₆₀. In the MALDI-TOF MS, a good agreement was observed between the experimental and the predicted isotope distribution patterns as shown in Figure 5. The ¹H NMR signal for the encapsulated hydrogen of H₂@C₆₀ was observed at $\delta -1.44$ ppm, which is 5.98 ppm upfield-shifted relative to the signal of dissolved free hydrogen. The extent of this upfield shift is comparable to that observed for ³He@C₆₀ (6.36 ppm) relative to free ³He.^{4a} Thus, the shielding effect of total ring currents of the C₆₀ cage is nearly the same, regardless of the paramagnetic species inside the cage. The only small difference in the ¹³C NMR



Scheme 5.

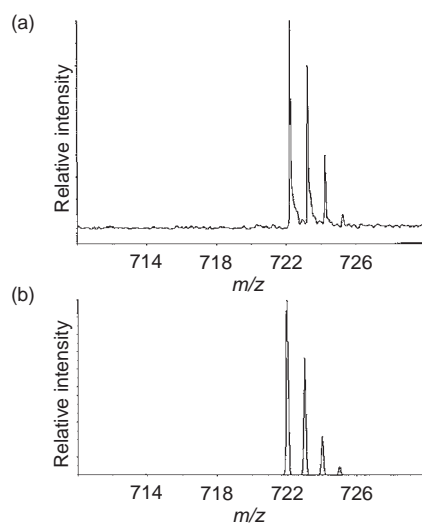


Figure 5. (a) MALDI-TOF MS (positive ionization mode, di-thranol matrix) of purified $H_2@C_{60}$ and (b) predicted isotope distribution pattern for $H_2@C_{60}$.

chemical shift between $H_2@C_{60}$ and empty C_{60} indicates that the electronic and/or van der Waals interaction between the fullerene cage and inside hydrogen is quite small.

◆ Summary and Future Outlook

As described above, the molecular surgical method by the use of organic reactions is shown to be successfully applicable to transformation of C_{60} into an entirely new endohedral fullerene, $H_2@C_{60}$. This should be regarded as the very first step for realization of various yet unknown endohedral fullerenes. This technique can be applicable to other fullerenes such as C_{70} as the outer cage and also to incorporate other small atoms and molecules such as helium,²³ neon, D_2 , HD, etc.

Particularly the compounds encapsulating hydrogen and its isotopes would be used as ideal systems, with which the properties intrinsic to the totally isolated molecular hydrogen can be elucidated: one of such example would be the kinetics for the transformation from *ortho*-hydrogen to *para*-hydrogen. When C_{70} is used as a capsule instead of C_{60} , a possibility to encapsulate two molecules of hydrogen arises. The interaction between the two molecules tightly packed inside the cage is quite intriguing. Moreover, the compound $H_2@C_{60}$ itself can be used as a

sensitive probe, by observing the 1H NMR signal of the encapsulated hydrogen, for the outer fullerene cage undergoing various reactions, as has been used for $^3He@C_{60}$.^{4c}

The most challenging is of course to develop the present method to encapsulate metal ions affording the endohedral metallofullerenes in amounts large enough to investigate their applicability to, for example, a molecular unit in electronic devices.²⁴ If this becomes a reality, this would surely open up a new era in the study of endohedral fullerenes.

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