Synthesis and Characterization of a Water-Soluble Endohedral Metallofullerol

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A water-soluble endohedral metallofullerol, $Pr@C_{82}O_m(OH)_n$ ($m \approx 10$ and $n \approx 10$), was successfully synthesized through the reaction of a pure endohedral metallofullerene, $Pr@C_{82}$, with a concentrated nitric acid and a subsequent hydrolysis process. The formation of endohedral metallofullerols $Pr@C_{82}O_m(OH)_n$ is thought to involve a NO_2 radical formation step, in much the same way as the reaction of empty fullerenes. FT-IR, XPS, and LD-TOF MS techniques were employed to characterize the structure of the endohedral metallofullerol from the above reaction.

Introduction

Endohedral metallofullerenes show promise as a new type of functional materials with many applications. In particular, their interesting guest−host structure has attracted much attention from the biomedicine community.[1−3] Since the first observation of a metallofullerene species, $La@C_n$, using laser desorption time-of-flight mass spectrometry,[4] significant progress has been made in isolating and characterizing a wide variety of endohedral metallofullerenes in pure form.[5−22]

One of the most interesting aspects of metallofullerenes is the functionalization of these species, which could lead to a host of metallofullerene derivatives. Some work has been reported along this direction. Preliminary results from these studies indicate that endohedral metallofullerenes show distinctive chemical properties.[23−26] In this paper, we report the synthesis and characterization of a new water-soluble endohedral metallofullerol, $Pr@C_{82}O_m(OH)_n$ ($m \approx 10$ and $n \approx 10$) from the reactions of pure metallofullerenes. This was made possible by the increasing availability of pure metallofullerenes.[27−30]

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Water-soluble endohedral metallofullerene derivatives are very important, given the expectation that they could be used in biomedicine as new types of bio-radical scavengers, radiotracers, magnetic resonance imaging agents, and “missile” medicines.[31] In order for endohedral metallofullerenes to be useful in biomedicine, it is essential to make them soluble in nature’s solvent—water. There have been several reports on water-soluble endohedral Gd- and Ho-containing fullerols, focusing on the prospect of their biomedical applications.[26,32−33] We aimed to synthesize and characterize the water-soluble endohedral metallofullerol Pr@$C_{82}O_m(OH)_n$. Our approach to the exohedral hydroxylation is through the reaction of a pure endohedral metallofullerene, Pr@C_{82}, with a concentrated nitric acid and the subsequent hydrolysis process. It is believed that the reaction involved a NO_2 radical addition process, in much the same way as in the reaction of empty fullerenes.[34] FT-IR, X-ray photoelectron spectroscopy (XPS), and laser-desorption time-of-flight (LD-TOF) MS analysis of the reaction products are consistent with the formation of a multihydroxyl endohedral metallofullerol.

Experimental Section

The production procedures for the pure metallofullerene Pr@C_{82} used in this study were described previously.[21] Only a brief description is given here. Soot containing metallofullerenes was produced by the standard arc-vaporization method. A composite rod with an atomic ratio of Pr/C $\cong$ 0.01 was used as the anode for arc burning. The “in situ activating” and “back burning” [35] techniques were employed during the arc vaporization to increase the yield of metallofullerene species. The dc contact-arc discharge was carried out at 80−100 A and 25−30 V in a He atmosphere of 100 Torr. The raw soot was collected and extracted in a Soxhlet extractor with *N,N*-dimethylformamide (DMF, 99.9%, BDH) at its boiling point for 8 h. The DMF was evaporated in a vacuum and a black powder was obtained. The soluble fraction was redissolved in toluene and injected into an HPLC. A buckyprep column (4.6 mm × 250 mm; Cosmosil, Nacalai Tesque Inc.) was used for the isolation of metallofullerene Pr@C_{82}, and the mobile phase was toluene. The injection volume was 1 mL and the elution rate was 1 mL per min. The purity of the collected Pr@C_{82} was estimated to be more than 99.5%, judging from the HPLC profiles and DCI negative ion mass spectra.[21]

The toluene solution of pure metallofullerene Pr@C_{82} appeared dark green. A brown powder of Pr@C_{82} was collected after vacuum evaporation of the toluene. It was redissolved in a much more inert solvent, carbon tetrachloride (CCl_4, Nacalai), and a light green solution was obtained. Concentrated nitric acid (with a concentration of 65%) was added into the CCl_4 solution of Pr@C_{82}. The nitric acid solution was in the top layer, since it is not miscible with the light green CCl_4 solution of Pr@C_{82} in the bottom layer. The mixture was stirred vigorously and heated to reflux for 12 h. The color of the bottom CCl_4 layer started to fade slowly and eventually became colorless. The top layer of nitric acid solution appeared slightly yellow. The mixture was evaporated in a vacuum to remove CCl_4 and nitric acid. A yellow powder was obtained and showed good solubility in water, giving a yellow brown aqueous solution with a pH value of 2−3. The solution was reevaporated and redissolved in water, yielding an aqueous solution of endohedral metallofullerol with a pH value of 6.5.

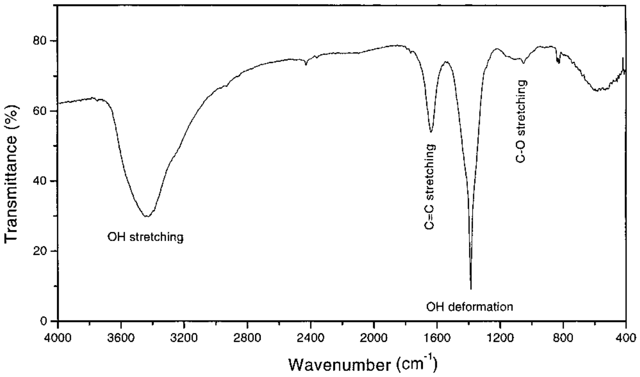

Figure 1. FT-IR transmission spectrum of the water-soluble endohedral metallofullerol Pr@$C_{82}O_m(OH)_n$.

The formation of endohedral praseodymium metallofullerol was confirmed by the FT-IR, XPS, and LD-TOF mass spectrometry techniques. The aqueous solution of metallofullerols was evaporated to remove water. The yellow powder obtained was dried in a vacuum at 40 °C for 24 h and mixed with dry KBr. The mixture was pressed for the FT-IR analysis. For the XPS study, a uniform film of metallofullerols was prepared on a gold substrate. The concentrated aqueous solution of metallofullerols was dropped onto gold foil. Evaporation of water left a uniform film of endohedral praseodymium metallofullerol on Au in an area of $\sim$0.5 cm^2. The film was dried and washed with *n*-hexane. XPS measurements were taken using monochromatized Al Kα radiation ($h\nu = 1486.6$ eV), with an energy resolution of $\sim$0.6 eV. For the LD-TOF mass spectrometry analysis, the aqueous solution of metallofullerols was dropped onto a Cu target and the solvent was evaporated. A nitrogen laser ($\lambda = 337$ nm) was used to desorb and ionize the sample. The laser beam was attenuated to a low energy of 3−5 μJ. Negative ions were collected for more than 50 single laser shots.

Results and Discussion

Figure 1 shows the FT-IR spectrum of the reaction product. Clearly identifiable are five characteristic peaks centered at 3420 cm^{-1} (strong and broad), 1634 cm^{-1} (medium and sharp), 1384 cm^{-1}(strong and sharp), 1050 cm^{-1} (weak and broad), and 580 cm^{-1} (medium and broad). The first four peaks can be assigned to the OH stretching vibration, C=C stretching vibration, OH deformation vibration, and C−O stretching vibration, respectively. No peaks corresponding to the vibrational frequencies of other functional groups can be observed in the FT-IR spectrum, indicating that only the OH, C−O, C=C functional groups exist in the product. The peak positions and shapes are found to be similar to those of water-soluble multihydroxyl fullerols $C_{60}(OH)_n$,[34,36−38] suggesting a similar multihydroxyl endohedral metallofullerol structure for the reaction product.

However, it is interesting to notice some subtle differences in the FT-IR spectra of endohedral metallofullerols and fullerols. Compared with fullerols, the OH deformation vibration peak (1384 cm^{-1}) of metallofullerols shows a much higher relative intensity, while

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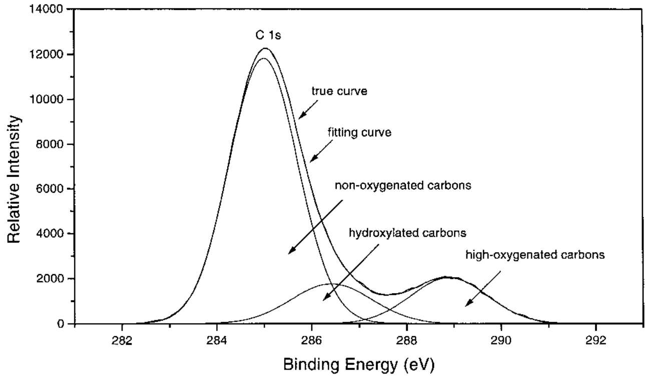

Figure 2. C1s XPS spectrum of the water-soluble endohedral metallofullerol Pr@$C_{82}O_m(OH)_n$.

the C−O stretching vibration peak (1050 cm^{-1}) is somewhat broader, weaker, and shifted to a lower frequency.[34] The differences are attributable to the different molecular electronic structure of endohedral metallofullerols compared to that of fullerols. For example, there is a three-electron transfer in the endohedral metallofullerol from the encapsulated Pr atom to the outer fullerene cage, whereas this cannot be the case in empty fullerenes.[21]

The XPS spectrum of the metallofullerol film shows two main peaks in the regions of C1s (54%) and O1s (40%). Peaks for $Pr3d_{3/2}$ and $Pr3d_{5/2}$ could also be observed. The peak position of $Pr3d_{5/2}$ is somewhat shifted to a lower binding energy than that of Pr@C_{82} and has a broader and stronger shoulder peak. It should be pointed out that the relatively low signal-to-noise ratio of the XPS data in the Pr3d region prohibited detailed analysis. Since no other carbon-containing chemical reagents or solvents were used in our synthesis, the carbon peak in the spectrum should be solely ascribed to the metallofullerols. It follows that the analysis of the carbon peak provides an important insight into the structural nature of carbon atoms comprising the metallofullerols. Figure 2 shows the XPS pattern of endohedral praseodymium in the core level region of C1s. A simple curve-fitting analysis shows that three peaks are required to fit the core level (C1s) features of metallofullerols, implying the presence of two different carbon oxidation states in addition to the normal oxidation state (nonoxygenated carbons) associated with the main peak. The peak at a binding energy of 284.99 eV (71.9%) is assigned to the nonoxygenated carbons, while the peak at a binding energy of 286.32 eV (13.8%) is assigned to the carbons linked with a single hydroxyl group. Another peak is located at a binding energy of 288.88 eV (14.3%), which is nearly 4 eV higher than that of the main peak, suggesting the existence in the metallofullerols structure of possible dioxygenated or cyclooxygenated carbons, as reported previously on the XPS study of fullerols.[34,36−38] Due to the lack of carbonyl absorption bands in the IR spectrum (Figure 1), it is most likely that this peak originates from the hemiketal (RO−C−OH) or cyclooxygen (C−O−C) structures. They might be formed in the oxidation step by the nitric acid or in the heating process for the XPS sample film preparation, during which dehydration may have occurred. A simple calculation of the relative XPS peak intensities reveals that the metallofullerol contains approximately 10 hydroxyl groups and 10 hemiketal (RO−C−OH) or cyclooxygen (C−O−C) groups. The molecular formula of the endohedral praseodymium metallofullerol can therefore be written as Pr@$C_{82}O_m(OH)_n$ ($m \approx 10$ and $n \approx 10$)

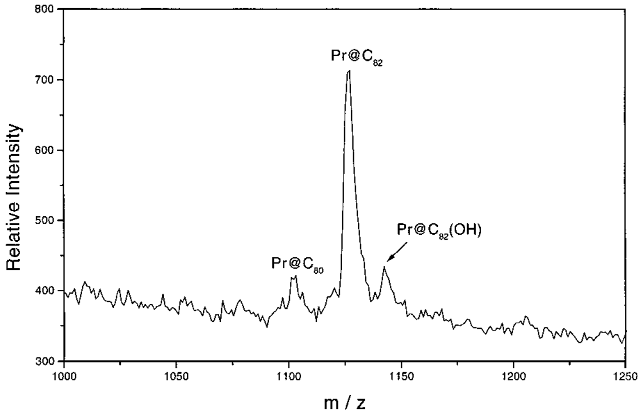

Figure 3. Negative-ion LD-TOF mass spectrum of the water-soluble endohedral metallofullerols Pr@$C_{82}O_m(OH)_n$.

In a way similar to fullerols $C_{60}(OH)_n$, metallofullerols Pr@$C_{82}(OH)_n$ do not display any molecular ion peaks in LD-TOF mass spectra.[39] However, the LD-TOF mass spectra provide a clear and direct evidence of the existence of an intact endohedral metallofullerene cage and multiple hydroxyl groups in the water-soluble products. As shown in Figure 3, an intense peak at *m*/*z* 1125, corresponding to the bare metallofullerene Pr@C_{82}, and two weak peaks at *m*/*z* 1101 and 1142, corresponding respectively to Pr@C_{80} and a monohydroxyl adduct Pr@C_{82}(OH), can be observed. Most probably, these mass peaks are the gas-phase fragment ions from metallofullerols Pr@$C_{82}O_m(OH)_n$ after losing some of their hydroxyl groups, since metallofullerene itself is not water-soluble at all. The existence of these gas-phase fragment ions implies that the endohedral fullerene cage was not destroyed during the reaction.

It appears that the aqueous acid chemistry is very effective for the functionalization of endohedral metallofullerenes and synthesis of water-soluble endohedral metallofullerols. As reported by Chiang et al., aqueous acid chemistry is one of the effective methods to produce fullerols, and the reaction was believed to involve NO_2 radical addition.[36] Roy and Sarkar synthesized multinitric C_{60} derivatives by passing NO_2 gas into a solution of C_{60}, which was readily hydroxylated and converted to fullerol.[40] Sun et al. also produced a multinitric C_{60} derivative through the reaction of C_{60} with concentrated nitric acid.[41] All these experiments show that fullerenes are susceptible to NO_2 radical addition and that the resultant multinitric C_{60} derivative is readily transformed to multihydroxyl fullerols by hydrolysis. We believe that endohedral metallofullerenes exhibit a similar reactivity toward NO_2 as a “radical sponge”,[42]

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although we have not detected the reaction intermediate $Pr@C_{82}(NO_2)_n$, owing to the lack of metallofullerene sample. We believe that a possible formation mechanism of endohedral metallofullerols is analogous to the formation mechanism of fullerols.[36,40−42] In addition, it is also possible that a direct oxidation process may have occurred at the reflux temperature, yielding the fullerenic oxide structures as identified from the XPS data.

Conclusion

In conclusion, a new exohedral adduct of endohedral metallofullerenens—a water-soluble multihydroxyl endohedral metallofullerol, $Pr@C_{82}O_m(OH)_n$ ($m \approx 10$ and $n \approx 10$)—has been successfully synthesized by treatment with nitric acid, followed by hydrolysis. The product was characterized by a variety of spectroscopic techniques including FT-IR, XPS, and LD-TOFMS. All the data acquired so far is consistent with an endohedral metallofullerol structure. Analogous to the same reaction of C_{60}, NO_2 radical addition is considered to be a crucial step for the formation of metallofullerols via the aqueous chemistry.

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