History of Li@C\textsubscript{60}

Abstract  Whereas endohedral metallo[60]fullerenes with lanthanide and alkaline earth metals were formed by laser vaporization or arc discharge, endohedral alkali metal-containing [60]fullerenes were produced by colliding ion beams or plasma with C\textsubscript{60}. In experiment colliding a lithium ion beam with C\textsubscript{60}, a mass peak assignable to Li@C\textsubscript{60} was detected. Potassium plasma was also used, and a peak assignable to K@C\textsubscript{60} was detected by mass spectrometry. Campbell and co-workers developed ion implantation method based on repeated irradiation of C\textsubscript{60} with a lithium ion beam with the aim of isolating Li@C\textsubscript{60}. After applying this method, Li@C\textsubscript{60} was extracted from the deposited film, and a fraction containing predominantly Li@C\textsubscript{60} was separated by HPLC. Some physical properties of Li@C\textsubscript{60} were investigated. The measured second-harmonic generation response of Li@C\textsubscript{60} in the film as well as the third-order susceptibility of Li@C\textsubscript{60} suggested that Li in the C\textsubscript{60} cage enhances its second hyperpolarizability. The resistivity of the Li@C\textsubscript{60} film was measured as 1.5 k\textOmega cm, about four orders of magnitude smaller than that of C\textsubscript{60} films (ca. 50 M\textOmega cm).

Keywords  Alkali metals · Lithium ion beam · Lithium plasma · Ion implantation method · Collision energy

2.1 Introduction

Apart from endohedral metallo[60]fullerenes, the general method for producing endohedral metallofullerenes involves heating graphite rods containing a metal source to high temperature by using laser irradiation or an arc discharge [1]. Then, the metal atoms are encapsulated into the fullerene cage during the formation of fullerenes, which affords endohedral metallofullerenes of various sizes. Another approach involves forcibly putting atoms into the fullerene cages that are prepared in advance. This method is usually used to produce endohedral [60]fullerenes
containing noble gases, as described in Chap. 1. Furthermore, researchers have attempted to produce endohedral fullerenes by applying a strong electric field instead of high temperatures since the early stage of fullerene science.

This chapter describes the production, purification, and physical evaluation of alkaline metal-containing [60]fullerenes, in particular Li@C_{60}, prepared by the ion implantation method, which was first reported in the late 1990s to early 2000s. Although some experimental data are inconsistent with those obtained after the recent successful isolation of Li@C_{60} as a solid (Chap. 7), the materials obtained in this early research undoubtedly involved the Li@C_{60} structure and provided valuable information for further research on Li@C_{60}.

### 2.2 Detection of Alkali Metal-Containing C_{60}

Anderson and co-workers performed collision experiments using Li, Na, and K ion beams to collide with fullerenes [2], while collision experiment had previously been attempted using other types of ion beams [3–6]. A mixture of C_{60} and C_{70} was vaporized at approximately 340 °C, metal ion beams were irradiated onto the evaporated fullerene mixture, and then the products and unreacted ions were analyzed by mass spectrometry. A molecular ion peak corresponding to the alkali metals plus C_{60} as well as peaks for species with elimination of C_{2} units was observed, and the peak ratio varied as the applied energy of the ion beams was changed. For example, the molecular ion peak for the LiC_{60}^{+} reached a maximum at approximately 20–30 eV, and irradiation with larger energy produced peaks for fragmentation ions such as LiC_{58}^{+} with the loss of a C_{2} fragment as well as peaks for C_{60−2n}^{+} (n = 0, 1, 2, …) with the loss of the lithium atom. The observed mass spectra for ion beam collision energies of 35 and 74 eV are shown in Fig. 2.1. As shown in the figure, there is an optimal metal ion collision energy, above which molecules decompose by fragmentation. The amount of the product obtained by the reaction of ion beams with fullerenes is very small. As in studies of other endohedral fullerenes in early fullerene research, the generation of LiC_{60} was detected by mass spectrometry only.

Reactions involving treatment of C_{60} with potassium plasma rather than ion beam irradiation were reported by Hatakeyama, Sato, and co-workers [7]. Potassium plasma, which was generated by surface ionization of K atoms on a hot plate, was reacted directly with the C_{60} vapor. Mass spectra of the obtained thin films exhibited a peak assigned to KC_{60}. They surmised that electrons in the plasma reacted with C_{60} to generate C_{60}^{−}, creating a potassium–fullerene plasma that reacted with K^{+} to produce K@C_{60}. Although this process produced only a small amount of endohedral metallo[60]fullerenes, the plasma method became the basis for manufacturing an apparatus for Li@C_{60} production.
2.3 Ion Implantation Method and Purification

With further improvement of Anderson’s ion collision method, Campbell and co-workers conducted scale-up experiments using a deposited C\textsubscript{60} films and ion beams and reported the synthesis of endohedral metallo[60]fullerenes in sufficient quantities for handling in 1996 [8]. Figure 2.2 shows their vacuum deposition apparatus for production of endohedral metallo[60]fullerenes [9]. The vapor-deposited C\textsubscript{60} film on a substrate shown on the right-hand side of the figure is transferred to the left-hand side and irradiated with a Li\textsuperscript{+} ion beam with its collision energy controlled by an applied bias voltage. The substrate is transferred back to the right-hand side, and C\textsubscript{60} is vapor-deposited again over the existing film. They reported that alternating deposition of C\textsubscript{60} thin films and exposure to the Li\textsuperscript{+} ion beam produced 15–20 μg of Li@C\textsubscript{60} per hour. The amount of Li@C\textsubscript{60} was estimated by laser desorption ionization time-of-flight (LDI-TOF) mass spectrometry (Fig. 2.3a). A peak at \( m/z = 727 \) to the right of the C\textsubscript{60} peak (\( m/z = 720 \)) was assigned to Li@C\textsubscript{60}. This mass spectrum was obtained for a sample prepared with a collision energy of 30 eV and a 6:1 molar ratio of irradiated Li to deposited C\textsubscript{60}. The amount of Li@C\textsubscript{60} obtained was significantly influenced by the energy of the Li\textsuperscript{+} ion beam. Figure 2.3b shows a plot for the ratio of produced Li@C\textsubscript{60} to C\textsubscript{60}, as

![Mass spectra of Li\textsuperscript{+} + C\textsubscript{60} at collision energies of a 35 eV and b 74 eV. Reprinted with permission from Ref. [2]. Copyright (1993) American Institute of Physics](image)
obtained from the ratio of molecular ion peaks for Li@C₆₀ to C₆₀, versus irradiated beam energy. The production of Li@C₆₀ was found to reach a maximum around 30 eV.

Using the repeated ion beam irradiation method, Campbell and co-workers enthusiastically produced Li@C₆₀. In the following year, 1997, they reported the extraction of Li@C₆₀ from the deposited films with carbon disulfide and the purification of Li@C₆₀ by HPLC [10]. During the HPLC separation, they used also carbon disulfide as the mobile phase with a Buckyprep or 5PBB (pentabromobenzyl) column (Nacalai Tesque), both of which are well known for fullerenes purification. Figure 2.4a shows an HPLC profile when the 5PBB column was used.
Mass spectra for fractions 1, 2, and 3 are shown in Fig. 2.4b. A fraction containing Li@C_{60} eluted after elution of C_{60}. They also reported thin films showing good solubility in carbon disulfide. As mentioned above, optimal molar ratio of Li^+ to C_{60} was 6:1 for the formation of Li@C_{60} as judged from mass spectra for deposited thin films. However, they found that the thin film prepared with a Li^+:C_{60} ratio of 1:1 showed better solubility than the one prepared with a 6:1 ratio. With a condition of the 1:1 materials ratio, the amount of empty C_{60} in the deposited film is increased, but they found this condition is more efficient for production of Li@C_{60} with the higher solubility of deposited films.

Campbell and co-workers then sought to characterize the purified Li@C_{60}. In 2003, they reported IR and Raman spectra of eluents containing Li@C_{60} fractionated by HPLC [11]. These spectra were intricate and showed numerous peaks. They hypothesized the existence of dimer and trimer structures with C_{60} cages bonding to the Li@C_{60} component based on their spectroscopic data and previous reports describing the behavior of Li@C_{60}.

Fig. 2.4  a HPLC profile of the CS_{2} extract of thin films containing Li@C_{60}. b LDI-TOF mass spectra for the fractions 1, 2, and 3. Reprinted with permission from Ref. [10]. Copyright (1997) Royal Society of Chemistry

2.3 Ion Implantation Method and Purification
2.4 Properties of Li@C₆₀ in Early Research

Although the amount of Li@C₆₀ obtained by the Campbell’s method was not large by today’s standards, the necessary amount for evaluation could be prepared by repeatedly applying their method. With several milligrams of materials in hand, they evaluated various physical properties of Li@C₆₀. They measured thermal properties including thermal desorption spectroscopy [12] and thermal stability [13]. In addition, they observed thermal elimination of Li@C₆₀ and Li₂@C₆₀ molecules from films prepared by low-energy ion bombardment of C₆₀. The binding energy between fullerenes was increased by lithium ion beam irradiation. In other words, this treatment made elimination of C₆₀ from the film difficult. Li@C₆₀ was found to be less thermally stable in solution (e.g., fractions 2 and 3 in Fig. 2.4a) than in the solid state. It would gradually decompose in solution accompanied by elimination of Li and dimerization.

In 1998, large hyperpolarizability of Li@C₆₀ was estimated in theoretical studies, and the second-harmonic generation (SHG) response of Li@C₆₀ within the film was reported [14]. In 1999, the third-order susceptibility of Li@C₆₀ was also reported [15]. These data suggested that the Li atom in the C₆₀ cage enhances its second hyperpolarizability.

Electrical measurements of Li@C₆₀ were also performed [16]. A sample purified by HPLC (as described in the Sect. 2.3) was vapor-deposited on silicon substrates and subjected to resistivity measurement, showing a resistivity value of 1.5 kΩ cm, several orders of magnitude less than that of C₆₀ films (ca. 50 MΩ cm). This observation suggests that charge transfer from the encapsulated Li atom to the fullerene cage increases conductance. This resistivity value for the Li@C₆₀ films was measured under high vacuum, but increased to 4 MΩ cm upon exposure to air for 2 min and to a value comparable with that of C₆₀ films upon exposure to air for 1 h. The measurement configuration and I–V characteristics are shown in Figs. 2.5 and 2.6, respectively.

Electron paramagnetic resonance (EPR) was measured for Li@C₆₀, and a small signal was observed at $g = 2.0025 \pm 0.0005$ [16]. A similar signal was also observed for the C₆₀ solid. In the case of C₆₀, this signal is assigned to a very small amount of C₆₀⁺ present. This observation implies that valence electrons originating from the Li atom contribute to bonding between fullerene cages. The electron spin–lattice relaxation time was different between Li@C₆₀ and C₆₀, presumably because of the symmetry reduction caused by encapsulation of the Li atom in the fullerene cage.
2.5 Conclusion

Li@C\textsubscript{60} was produced by Li\textsuperscript{+} ion beam irradiation onto vapor-deposited C\textsubscript{60}. Some studies investigated the physical properties of isolated Li@C\textsubscript{60}. However, in absolute terms, the amount of material that could be prepared by this production method was still small for full chemical and structural characterization, including NMR measurements, elemental analysis, and X-ray crystallography. The existence of Li@C\textsubscript{60} was confirmed by only mass spectrometry. To account for the difficulty...
of characterization, researchers considered the possibility of dimer or trimer formation. In 2016, full chemical and structural characterization of endohedral lithium-containing [60]fullerene was, at long last, achieved through isolation and purification of lithium-ion-containing [60]fullerene (Li+@C60), followed by its reduction to neutral lithium-containing [60]fullerene (Li@C60) [17].

References


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