ChemComm

COMMUNICATION



View Article Online View Journal | View Issue

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Cite this: Chem. Commun., 2022, 58, 11284

Received 16th June 2022, Accepted 11th September 2022

DOI: 10.1039/d2cc03398d

rsc.li/chemcomm

Synthesis and ⁸³Kr NMR spectroscopy of Kr@C₆₀†

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Synthesis of Kr@C₆₀ is achieved by quantitative high-pressure encapsulation of the noble gas into an open-fullerene, and subsequent cage closure. Krypton is the largest noble gas entrapped in C₆₀ using 'molecular surgery' and Kr@C₆₀ is prepared with >99.4% incorporation of the endohedral atom, in *ca.* 4% yield from C₆₀. Encapsulation in C₆₀ causes a shift of the ⁸³Kr resonance by -39.5 ppm with respect to free ⁸³Kr in solution. The ⁸³Kr spin-lattice relaxation time *T*₁ is approximately 36 times longer for Kr encapsulated in C₆₀ than for free Kr in solution. This is the first characterisation of a stable Kr compound by ⁸³Kr NMR.

Endohedral fullerenes (endofullerenes) are compounds in which atoms or small molecules are encapsulated inside fullerenes, providing a unique opportunity for study of the confined species in the isolated cavity.^{1*a*-*d*} The noble gas endofullerenes of C₆₀ and C₇₀ (denoted *e.g.* Ng@C₆₀ for the former case) are a specific group that have been the subject of sustained research activity, as compounds of great interest for study of the interactions between the encapsulated species and the encapsulating cage,^{2,3} the quantised energy level structure of the endohedral noble gas atom,² and the effect of the noble gas upon the properties and reactivity of the fullerene cage.^{4*a*,*b*} Many theoretical studies have addressed these areas,^{5*a*-*h*} and our interest in the practical synthesis of noble gas endofullerenes is motivated by both the opportunity for direct study of these materials, and the value of resulting data as a test of theoretical models.

Early methods for preparation of Ng(0)C₆₀ compounds relied upon direct encapsulation by exposure of C₆₀ to the gas under high temperature and pressure, and led to approximately 0.1% incorporation of a single endohedral atom of He, Ne, Ar or Kr, and just 0.03% of Xe.⁶ Under similar conditions, an improved level of direct encapsulation into C₆₀ ground with KCN was achieved, of 1% He and approx. 0.3% Ar, Kr or Xe.^{7*a*-*c*} Enriched samples have been obtained using recycling HPLC, of *ca*. 0.1–1.0 mg Kr@C₆₀ with 90–99% purity.^{8,9} and *ca*. 0.3 mg Xe@ C₆₀ with 50% purity.^{7*b*} Resulting ¹³C NMR, UV-visible absorption, infrared, Raman, X-ray absorption and ¹²⁹Xe NMR studies have confirmed a weak interaction between the noble gas atom and interior cage surface,^{7*b*,8} and observed the endohedral atom to influence cage vibrational and rotational properties.^{5*d*,9}

With the development of the 'molecular surgery' method of endofullerene synthesis, high incorporation to facilitate spectroscopic studies on a macroscopic (multi-milligram) scale has become possible, the synthesis of $H_2@C_{60}$ and ${}^{4}He@C_{60}$ being early examples.^{10,11} Murata's open-fullerenes 1 and 3 (Fig. 1)^{12,13} are key intermediates for 'filling' in the syntheses of HF@C₆₀, $H_2@C_{60}$ and $H_2O@C_{60}$ (1), Ar@C₆₀ and CH₄@C₆₀ (3),¹³⁻¹⁷ and we recently developed a one-pot filling and partial closure of a phosphorous ylid derivative 2 that enabled efficient synthesis of noble gas endofullerenes ${}^{3}He@C_{60}$, ${}^{4}He@C_{60}$ and Ne@C₆₀.¹⁸ Incorporation of approx. 50–60% of the noble gas was accomplished, and enrichment of Ne@C₆₀ to >99.5% encapsulation of the noble gas atom was achieved by recycling preparative HPLC.

With the aim of elucidating the energy level structure of a confined noble gas atom and its interaction with the interior



Fig. 1 Open-cage fullerenes **1–3** are key precursors to 'filling' by a single atom or molecule in reported syntheses of $H_2O@C_{60}$, $HF@C_{60}$, $H_2@C_{60}$, (1),^{11,16,17} $HD@C_{60}$, $D_2@C_{60}$, ³ $He@C_{60}$, ⁴ $He@C_{60}$, $Ne@C_{60}$ (2),¹⁸ $CH_4@C_{60}$, $Ar@C_{60}$ (3).^{14,15}

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cage surface in detail, our syntheses of 3 He@C₆₀ and 4 He@C₆₀ have so far enabled characterisation of internuclear interactions in the form of the "non-bonded" *J*-coupling (${}^{0}J_{HeC}$) and experimental interaction potential – each evaluated against theoretical models.^{2,3} We now describe preparation of pure Kr@C₆₀ on a scale of tens of milligrams suitable for detailed study, including by 13 C and 83 Kr NMR discussed herein. We also report upon current limitations to the application of molecular surgery methods for synthesis of Xe@C₆₀.

Synthesis of Kr@C₆₀ was carried out according to the methods we have reported for preparation of CH₄@C₆₀¹⁵ and Ar@C₆₀,¹⁴ and is described in Scheme 1. The bis(hemiketal) hydrate of open fullerene **1** was prepared from C₆₀ using our recent optimisation¹⁸ of the cage-opening steps earlier described by Murata and co-workers,^{13,19} before dehydration to give **1** and insertion of sulfur to furnish **3**.¹² DFT calculations (see ESI†) indicated $\Delta H_{entry}^{\ddagger} = 87$ kJ mol⁻¹ and $\Delta H^{bind} = -57$ kJ mol⁻¹ for encapsulation of krypton by **3**, similar to the values for CH₄. Accordingly, heating powdered **3** under >1500 atm of krypton gas for 14 h gave Kr@**3** with >99% filling estimated from the ¹H NMR and ESI+ mass spectra.

Encapsulation of xenon by 3 was calculated to have $\Delta H_{\text{entry}}^{\ddagger} = 152 \text{ kJ mol}^{-1}$ and $\Delta H^{\text{bind}} = -56 \text{ kJ mol}^{-1}$, and attempted preparation of Xe@3 by heating 3 at 212 °C under 1850 atm of xenon gas for 17 h gave <1% xenon incorporation, from the ESI+ mass spectrum. Higher temperature or a longer reaction time led to substantial decomposition, so xenon 'filling' of 3 does not constitute a viable route for the synthesis of Xe@C₆₀ for which a larger cage opening is needed.

The rate of first-order thermal dissociation of Kr@3 was measured between 433 and 453 K. Arrhenius and Eyring plots are shown in the ESI.† All parameters for loss of krypton from the fullerene (E_a exit = 138.5 \pm 5.6 kJ mol⁻¹, ΔH^{\ddagger} = 134.8 \pm 5.6 kJ mol⁻¹, ΔS^{\ddagger} = -40.1 \pm 14.6 J K⁻¹ mol⁻¹, (log)A = 11.3 and ΔG^{\ddagger} = 152.4 \pm 0.1 kJ mol⁻¹ at 165 °C, closely matched those for loss of CH₄ from 3.²⁰

Oxidation of Kr@3 gave sulfoxide Kr@4 cleanly, and photochemical desulfinylation of Kr@4 led to the ring-contracted product Kr@1, isolated as its hydrate Kr@5 with >99% encapsulation. Separation of Kr@C60 and H2O@C60 is possible using recycling preparative HPLC so it was unnecessary to conduct exhaustive drying of Kr@5 or to use conditions for the following step that avoid re-encapsulation of traces of water (cf. our Ar@C₆₀ synthesis).¹⁴ The final ring-closure steps for conversion of Kr@5 to Kr@C60 were therefore conducted under the conditions we originally reported for the synthesis of $H_2O@C_{60}$;¹⁷ involving dehydration to Kr@1, intramolecular Wittig reaction of the phosphonium ylid Kr@2 to give Kr@6, then similar Wittig closure of a phosphite ylid upon heating Kr@6 with $(i PrO)_3 P$. Reaction with N-phenylmaleimide in a final step that involves sequential [4 + 2], retro[4 + 2] and [2 + 2 + 2] cycloaddition completed the cage closure. Removal of H2O@C60 and enrichment of the krypton encapsulation, was achieved by recycling preparative HPLC.^{8,21a,b} Overall, Kr@C₆₀ was recovered with >99.4% incorporation of the noble gas, and in 3.6-4.1% yield from C₆₀ over repeated batch syntheses. A crystal structure of the nickel(II) octaethylporphyrin/benzene solvate of $Kr(@C_{60} was obtained, in which the noble gas atom is centred$ in the cage (see ESI[†]) as in the previously reported structure of ca. 9% filled Kr@C₆₀ {Ni^{II}(OEP)} $2C_6H_6$.^{21a}

Krypton is the largest noble gas so far encapsulated in C_{60} by the 'molecular surgery' methods described here, enabling synthesis on a suitable scale for detailed NMR characterisation. The ¹³C NMR resonance of Kr@C₆₀ in 1,2-dichlorobenzene- d_4 has a chemical shift of δ_c = 143.20 ppm at 298 K, deshielded by +0.390 \pm 0.001 ppm relative to empty C₆₀ (Fig. 2a). Yamamoto *et al.* reported a consistent value of $\Delta \delta$ = +0.39 ppm in benzene d_6 ,⁸ and it has been previously noted that deshielding of the cage ¹³C NMR resonance in the noble gas@C₆₀ series, with respect to C₆₀, becomes greater with the increasing van der Waals radius of the trapped atom.^{1*a*,18}

We observe a pair of side peaks to the main ^{13}C NMR resonance (Fig. 2b), due to minor isotopomers of Kr@C_{60} that each contain two adjacent ^{13}C nuclei separated by either a hexagon–pentagon (HP) or shorter hexagon–hexagon (HH) bond, present in a 2:1 ratio respectively. One-bond secondary isotope shifts of $^{1}\Delta_{\rm HP}$ = 12.45 \pm 0.01 ppb and $^{1}\Delta_{\rm HH}$ = 19.77 \pm 0.02 ppb, shielded relative to the main Kr@C_{60} peak, are smaller than those measured for empty C_{60} ($^{1}\Delta_{\rm HP}$ = 12.56 \pm 0.01 ppb and $^{1}\Delta_{\rm HH}$ = 19.98 \pm 0.02 ppb)²² and are the smallest secondary isotope shifts yet measured for atomic or molecular endofullerenes.^{3,14,18,22}

The only stable krypton isotope with a nuclear spin is ⁸³Kr (I = 9/2, 11.58% natural abundance) and ⁸³Kr NMR has been used to study the surface and void adsorption properties of porous nanomaterials.^{23*a,b*} Hyperpolarised ⁸³Kr gas is used for MRI imaging of the lungs, despite the relatively short spin-lattice relaxation time of the quadrupolar ⁸³Kr spin.^{24*a,b*} To our knowledge, Kr@C₆₀





Fig. 2 (a) ¹³C NMR spectrum of Kr@C₆₀ (99.44 mol% krypton) in 1, 2-dichlorobenzene- d_4 at a field of 16.45 T (¹³C Larmor frequency = 176 MHz) and 298 K, acquired with 912 transients. An asterisk marks empty C₆₀ (0.56%). (b) Expanded view of the base of the Kr@C₆₀ resonance to show side peaks arising from minor isotopomers with two adjacent ¹³C nuclei that share either a hexagon-pentagon (HP) or hexagon-hexagon (HH) edge.

offers the first opportunity for ⁸³Kr NMR spectroscopy of a stable compound of krypton. The ⁸³Kr NMR spectrum of Kr@C₆₀ in 1, 2-dichlorobenzene- d_4 solution with dissolved krypton gas at 298 K is shown in Fig. 3. The $\delta = 0$ origin of the ⁸³Kr NMR chemical shift scale corresponds to low-pressure Kr gas on the unified IUPAC referencing scale,²⁵ but using an updated Ξ parameter for ⁸³Kr as determined by Makulski (see ESI†).²⁶

The ⁸³Kr chemical shift for ⁸³Kr@C₆₀ in 1,2-dichlorobenzene- d_4 solution is $\delta_{\rm Kr} = 64.3 \pm 0.1$ ppm, shifted by -39.5 ppm with respect to the resonance of free ⁸³Kr in solution. For comparison ³He@C₆₀ and ¹²⁹Xe@C₆₀ are reported at -6.04 and -16.5 ppm respectively from the dissolved gasses in this solvent.²⁷ In benzene- d_6 solution ⁸³Kr@C₆₀ is at $\delta_{\rm Kr} = 64.3 \pm 0.3$ ppm, shifted by -32.7 ppm from the dissolved gas (see ESI†). The reported shifts of ¹²⁹Xe@C₆₀ in benzene are 179.2 ppm from Xe gas, and -8.89 ppm relative to dissolved gas.^{7b} The shift of ³He@C₆₀ is -6.3 \pm 0.15 ppm in 1-methylnaphthalene or CS₂ with respect to either dissolved or free gas.²⁸

Simple (non-relativistic) calculations for ³He@C₆₀, ⁸³Kr@C₆₀ and ¹²⁹Xe@C₆₀ predict cage induced shifts of -7.0, 29.9 and 71.7 ppm, consistent with the relative order, if not absolute values, observed.²⁹ Recent calculations on ¹²⁹Xe@C₆₀ are in good agreement with the experimental shift.³⁰ Whilst ³He observes the shielding effect of the cage on the field inside, for ⁸³Kr and ¹²⁹Xe the shift is dominated by an increasing direct interaction between the atomic orbitals and the π -electron orbitals of the cage.

The protective effect of the cage is revealed by measurement of ^{83}Kr linewidths and relaxation times. The ^{83}Kr peak of $^{83}\text{Kr}@C_{60}$ has a linewidth of 2.7 \pm 0.1 Hz at half-height, which is much smaller than the linewidth of 10.8 \pm 0.1 Hz for free ^{83}Kr in solution (Fig. 3b and c). Similarly, the ^{83}Kr spin-lattice



Fig. 3 (a) ⁸³Kr NMR spectrum of Kr@C₆₀ (99.44 mol% krypton) in 1, 2-dichlorobenzene- d_4 at a field of 14 T (⁸³Kr Larmor frequency = 23.1 MHz) and 298 K, acquired with 1 02 400 transients. (b) Expanded view of the ⁸³Kr gas peak (dissolved in 1,2-dichlorobenzene- d_4). (c) Expanded view of the ⁸³Kr@C₆₀ peak. Horizontal axes in (b and c) both span 4 ppm, vertical axes are arbitrary.

relaxation time constant of ⁸³Kr@C₆₀ ($T_1 = 860 \pm 24$ ms) is much longer than that of free ⁸³Kr in 1,2-dichlorobenzene- d_4 solution ($T_1 = 31 \pm 2$ ms), and is longer than that reported for ⁸³Kr dissolved in any other solvent at room temperature (Fig. 4).³¹ Presumably the high symmetry and rigidity of C₆₀ greatly reduces the magnitude of fluctuating electric field gradients at the location of the Kr nucleus, which are responsible for quadrupolar relaxation.

In summary, Kr@C₆₀ is prepared in a yield of approx. 4% from C_{60} , with >99% krypton incorporation, using methods which overcome the severe limitation of only 0.1-0.3% direct krypton incorporation that results in very low mass recovery in the previously reported synthesis. An intermediate open-cage fullerene, 3, encapsulates krypton under high pressure but was shown to have a cage opening too small for the entry of xenon gas. The larger scale synthesis of Kr@C60 has enabled measurement of fine structure in the solution-phase ¹³C NMR spectrum, and characterisation by ⁸³Kr NMR spectroscopy – the first example for a krypton compound (*i.e.*, one in which the noble gas cannot escape without breaking covalent bonds). Endohedral ⁸³Kr has a chemical shift of 64.3 ppm in 1, 2-dichlorobenzene- d_4 , with respect to ⁸³Kr gas. This is less deshielded than ⁸³Kr in solution, presumably because the cage protects Kr from direct interactions with the solvent molecules. The ⁸³Kr spin-lattice relaxation for ⁸³Kr@C₆₀ is approximately 36 times slower than for free ⁸³Kr in solution, indicating that



Fig. 4 Inversion Recovery relaxation curves fitted using a monoexponential curve, for 83 Kr spin-lattice relaxation time (T_1) of free 83 Kr (red) and ⁸³Kr@C₆₀ approx. 26 mM (blue) in degassed 1,2-dichlorobenzene- d_4 at a field of 14 T (83 Kr Larmor frequency = 23.1 MHz) and 298 K. 83 Kr solution points were acquired with 2560 transients and ⁸³Kr@C₆₀ points were acquired with 1024 transients.

the cage shields the endohedral atom from fluctuating electric field gradients.

This research was supported by EPSRC grants EP/P009980/1, EP/P030491/1 and EP/T004320/1. The authors acknowledge the use of the IRIDIS High Performance Computing Facility at the University of Southampton.

Conflicts of interest

The authors declare no conflict of interest.

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