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where
\[ K_m = \frac{\varphi_m^T/(RT)}{\beta_mT} \]  
(4)

\[ K_i = \left[ 1/(1-x_m) - (\partial \ln \varphi_i^T/\partial x_m) \right] (\partial x_m/(\partial P)_T - \varphi_i^T/(RT)) - (V_s/V_m) \beta_sT \]  
(5)

In eqs 3-5, \( P \) is the pressure, \( x_m \) is the equilibrium mole fraction of the mobile-phase fluid in the stationary phase, \( \varphi_i^T \) is the infinite-dilution fugacity coefficient of the solute in the stationary phase, \( \beta_m^T \) is the infinite-dilution partial molar volume of the solute in the stationary phase, \( \beta_s^T \) is the isothermal compressibility of the stationary phase, and \( V_s \) and \( V_m \) are the volumes of the stationary and the mobile phases in the column, respectively. The derivation and discussion of eqs 3-5 may be found elsewhere.  

It should only be emphasized here that \( k_i \) in eq 3 is a local value at some particular position within the column rather than the experimentally observed, average value over the pressure drop across the column. In a similar way, the derivative with respect to the molar density of the mobile phase may be written as

\[ (\partial \ln k_i/\partial \rho_m) = Q_m + Q_s + K_m/(\rho_m^2) + K_s/(\rho_m) \]  
(6)

The quantities \( \varphi_i^T \) and \( \beta_m^T \) in eq 4 combine in such a way that straightforward relationships result between \( k_m \) (or \( Q_m \)) and the molecular quantities of eqs 1 and 2. After simple rearrangements, one obtains

\[ \int c_T^m(r) dr = -K_m/(N_A \rho_m \beta_m^T) \]  
(7)

\[ \xi = -RT \rho_m^2 \beta_m^T Q_m \]  
(8)

(26) Roth, M. J. Supercrit. Fluids, in press.

13C NMR Study of the C60 Cluster in the Solid State: Molecular Motion and Carbon Chemical Shift Anisotropy


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13C NMR spectra of solid buckminsterfullerene, the soccerball-like cluster of 60 carbon atoms, have been obtained at temperatures down to 77 K. The ambient spectrum shows rapid isotropic rotational motion. The motion is sufficiently slow at 77 K that a measurement of the chemical shift tensor of the carbon nucleus can be made. The tensor components (220, 186, 40 ppm) have values that are typical for an aromatic carbon. Spectra at intermediate temperatures suggest the possibility of either growth of a low-temperature phase in which C60 rotation is inhibited or a distribution of rotational correlation times.

Raman spectra of C60 strongly support the soccerball geometry for this molecule, and solution NMR spectra of the C60 moiety have shown that the molecule hasicosahedral point group symmetry. The pseudospherical symmetry of this molecule suggests potential for facile isotropic motion in the solid state and solid-state NMR spectroscopy is uniquely suited as a probe of this kind of molecular dynamics.

The sample was prepared by toluene extraction of soot produced by arc heating graphite in 100 Torr of He. The dried powder consists mainly of C60 and C70 in a ratio of 1:4-7. The powdered sample, after being ground and sieved, was then loaded into a 25-mm NMR tube. Spectra at intermediate temperatures suggest the possibility of either growth of a low-temperature phase in which C60 rotation is inhibited or a distribution of rotational correlation times.

Letters

Chemical shift anisotropy is expected to extend over ~200 ppm (3 kHz at 1.4 T), the relevant time scale is ~10^{-4} s. Measurements of the ^{13}C spin-lattice relaxation time at 7.04 T show a T_1 minimum at 233 K, indicating that the correlation time for molecular motion at this temperature is ~10^{-9} s. Thus, C60 molecules must be rotating at rates >10^9 s^{-1} at ambient temperatures. The spectrum at 123 K shows that a broad skirt has developed at the base of the main resonance at 143 ppm. At 100 K, the spectrum is predominantly a powder pattern characteristic of a chemical shift anisotropy^9 with minor intensity in the narrow peak at 143 ppm. At 77 K the same powder pattern is observed with little evidence of the narrow line at 143 ppm. A fit of the powder pattern yields an asymmetric chemical shift tensor^9 as expected for a carbon in the C60 cluster. The components of the tensor, 220, 186, and 40 ppm, confirm the aromatic character of the carbons in C60.839

As shown in Figure 1, as the temperature is lowered, the intensity of the narrow peak due to rapidly rotating C60 decreases while a spectrum reflecting static molecules builds up. This evolution may be explained either by growth, as the temperature is lowered, of a phase in which cluster rotation is inhibited^10 or by a distribution of rotational correlation times and a concomitant distribution of motional barriers.11

In conclusion, we report results that show that the C60 cluster rotates rapidly and isotropically in the solid state at ambient temperatures and that by lowering the temperature this motion can be slowed to the extent that the carbon chemical shift anisotropy can be measured. The resulting chemical shift tensor confirms the aromatic nature of the carbons in C60. The ^{13}C spectra also suggest either growth of a new phase as the temperature is lowered or a distribution of motional dynamics, possibly due to sample heterogeneity. Experiments that may permit us to distinguish between these two possibilities are in progress. A careful study of the temperature dependence of the ^{13}C NMR line shape to probe the details of the motional dynamics is also planned.

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