Deuterium Isotope Effects

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Is Deuterium Always Smaller than Protium?**

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Is deuterium smaller than protium? The question is, strictly speaking, meaningless. Nevertheless, we can think of "effective" size—the amount of space taken up by an atom or molecule without overlap with other atoms or molecules. Overlapping of atoms in different molecules generally corresponds to repulsion. In this sense, it has been widely accepted for some time now that repulsions involving deuterium atoms are smaller than those for hydrogen atoms at the same internuclear distance, in other words that deuterium has effectively a smaller packing radius than hydrogen.[1–3] In essence, the lower zero-point energy of deuterium implies a smaller vibration amplitude and hence a smaller effective radius (van der Waals radius) than that of protium. This picture has been the basis for explanations of kinetic isotope effects, such as in the well-known example of the racemization of optically active 9,10-dihydro-4,5-dimethylphenanthrene, where replacement of protium by deuterium in the methyl groups leads to an acceleration in the rate of racemization.[4] Other more recent examples include the observation of a smaller unit cell for perdeuterotetracyanoanthraquinodimethane ([D_8]TCAQ) compared with normal TCAQ.[5] In this case the smaller steric demand of deuterium results in an intramolecular flattening, although the effects of temperature were not studied. Similarly, an equilibrium deuterium isotope effect for the interconversion between the two chair isotopomers of 1,1,3,3-tetramethylcyclohexane, observed by NMR spectroscopy and predicted theoretically,[6] is rationalized in terms of steric hindrance between neighboring methyl groups.

The simple picture described above neglects the effect of temperature. The Boltzmann distribution over the energy levels of a quantized harmonic oscillator leads to an expression for the mean-square displacement amplitude [Eq. (1)], where ν is the frequency and μ the mass (or

$$\langle u^2 \rangle = (h/8\pi^2\mu\nu)\coth(h\nu/2kT) \tag{1}$$

reduced mass) or moment of inertia for a rotational oscillation. The first factor on the right-hand side of Equation (1) is due to the zero-point motion; it is seen to be inversely proportional to μ and hence smaller for a deuterated molecule than for the lighter isotopologue. For a harmonic oscillator, the frequency ν is inversely proportional to the square-root of the reduced mass and hence also smaller for the deuterated molecule. On combining these two variables, the zero-point motion is seen to be inversely proportional to the square-root of the mass, and hence smaller for the more massive isotopologue. The influence of temperature arises from the second factor, the hyperbolic cotangent function. This can be written as coth$x$, where $x = h\nu/2kT = 0.7194\omega/T$ and with the frequency expressed in cm^{-1}. For small values of T the value of the hyperbolic tangent is unity, and for higher values of T it becomes proportional to T with a slope $1.390/\omega$. For an oscillator with a frequency around 100 cm^{-1} the mean-square amplitude at 100 K is then almost 40% larger than that of the zero-point motion; the lower the frequency, the larger the amplitude. This is another way of saying that for low-frequency oscillations with increasing values of T, the higher vibrational levels become more populated for deuterated molecules than for their proton isotopologues. Of course, in a real system with low-frequency vibrations, the potentials are likely to be anharmonic to a greater or lesser degree. This will complicate matters but the softening of the potentials at larger vibrational amplitudes can be expected to lead to an enhancement of the frequency effect (larger amplitude of D versus H) over the mass effect (larger amplitude of H versus D). Thus, although the zero-point motion always leads to a smaller effective size for deuterium than for protium, the effect of temperature is to expand the effective size of deuterium faster than that of hydrogen. For a system with low-frequency vibrations, deuterium may even appear to be larger than hydrogen at sufficiently high temperatures.

The benzene crystal offers an opportunity to test these ideas. It is known that at normal pressure both C_6H_6 and C_6D_6 have the same crystal structure (*Pbca*, $Z = 4$) from 4.2 K up to the melting point.[7–13] The structure (Figure 1) is essentially a close packing of oblate ellipsoids with several low-frequency lattice vibrations[14–16] around 100 cm^{-1}. A thorough study of the electron distribution and molecular motion, by combining X-ray diffraction data on C_6H_6 with multitemperature neutron diffraction data on C_6D_6, has been made.[17] Here we concentrate on the temperature dependence of the unit-cell volume and the molecular volume of the two isotopologues.

The unit cell volume V_c can be determined with high accuracy and the molecular volume V can be taken as $V_c/4$. Figure 2 shows the molecular volume V in Å^3 as recently determined by high-resolution neutron powder diffractometry as a function of temperature for benzene (C_6H_6) and perdeuterated benzene (C_6D_6). It is clear that it fulfills expectations based on the above theoretical arguments: at

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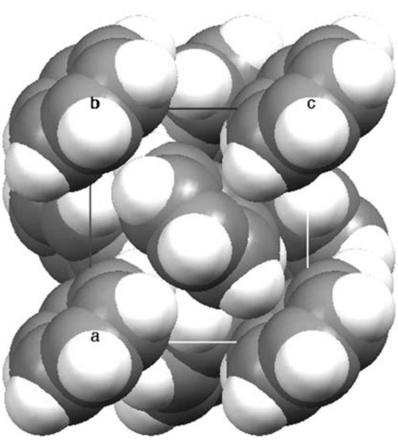

Figure 1. The structure of benzene viewed down the crystallographic *b* axis.

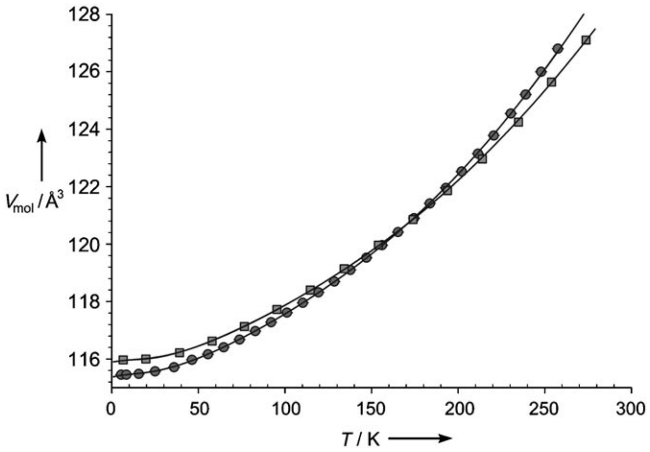

Figure 2. Molecular volume *V* of benzene (C_6H_6, squares) and perdeuterated benzene (C_6D_6, circles) versus temperature *T*. Solid lines show single-Einstein plus single-Debye model function fits to the data (see text, coefficients are given in Table 1).

5 K the molecular volume of C_6D_6 is 115.452(1) Å^3 compared with 115.967(2) Å^3 for C_6H_6; the difference decreases with increasing temperature, and around 170 K the two volumes become equal; at higher temperatures the molecular volume of C_6D_6 is greater than that of C_6H_6.

The temperature variation of the molecular volume can be fitted in a number of ways. The high precision of the experimental data enables detailed fitting to be carried out by using Einstein and Debye functions that are more typically associated with the analysis of heat capacity data (see for example Ref. [18]). In these models, quantum theory is applied to the oscillations of individual atoms about their equilibrium postions, assuming a single frequency in the case of the Einstein model or a kind of average over frequencies in the Debye model, leading to characteristic Einstein and Debye temperatures, θ_E and θ_D, respectively (see for example Ref. [19]). In the present case for benzene, an almost exact fit can be obtained by using a single-Einstein plus single-Debye model temperature [Eq. (2)],

$$V = V_0 + Pf(\theta_E/T) + Qf(\theta_D/T) \qquad (2)$$

where V_0 is the volume at 0 K, *P* and *Q* are Einstein and Debye constant mixing coefficients respectively, $f(\theta_E/T)$ is the Einstein function, and $f(\theta_D/T)$ is the Debye function. This analysis mirrors the description of heat capacity data for benzene in terms of lattice and internal intramolecular vibrational components.[14,20] The refined Einstein and Debye temperatures of Equation (2) are shown in Table 1 and correspond to vibrational wavenumbers of 74 cm^{-1} and 1045 cm^{-1} for C_6H_6, and 66 cm^{-1} and 1033 cm^{-1} for C_6D_6, values that could represent in each case a kind of average over lattice (optic) modes and over molecular (acoustic) modes primarily arising from H(D) wagging, respectively.

Table 1: Results of the single-Einstein plus single-Debye model fitting of molecular volume *V*.

	V_{0K} [Å^3]	θ_E [K]	θ_D [K]
C_6H_6	115.886(1)	106.5(3)	1504(1)
C_6D_6	115.366(1)	94.84(1)	1486.5(4)

We have shown that for a suitably chosen system the effective size of deuterated molecules is not necessarily smaller than that of their hydrogen isotopologues: depending on the temperature, it may even be larger, with the corollary that under these conditions deuterium is larger than hydrogen. Could this result form a basis for the explanation of the "inverse" kinetic isotope effect, such as that observed in the racemization of optically active doubly bridged diphenyl compounds where replacement of hydrogen by deuterium in the bridging methylene groups leads to a decrease in the rate of racemization?[21]

Experimental Section

Samples (1 g) of normal and perdeuterated benzene (99 atom % D) obtained from Sigma Aldrich Chemical Ltd. were frozen in a liquid-nitrogen-cooled stainless-steel mortar and ground by hand to a fine powder. A 6*H*-SiC reference material (0.25 g) was mixed with each sample as an internal standard before sealing in a 5 mm diameter vanadium sample can and loading into a standard vanadium-tailed, top-loading, cold-cycle refrigerator. Neutron powder diffraction data were recorded on the high-resolution diffractometer (HRPD) at the ISIS Facility, Rutherford Appleton Laboratory, UK, at backscattering $2\theta = 168°$ over the time-of-flight range 10–110 ms corresponding to a *d*-spacing range of 0.2–2.2 Å. The C_6D_6 sample was cooled to 5 K and data recorded at approximately 10 K steps up to 280 K for a period of 12 μh A (ca. 8 min) for each run. The data collection period for the C_6H_6 sample was increased to 24 μh A (ca. 16 min) because of the high incoherent scattering cross-section of hydrogen for neutrons and, in this case, data sets were recorded in approximately 20 K steps.

The diffraction data were analyzed using the Rietveld method implemented by the program TOPAS-Academic[22] and using a structural model based on reference [13]. Structures were visualized using the program MERCURY.[23] Figures showing the results of the Rietveld fitting at 5 K for C_6H_6 and C_6D_6, comparative fits to the C_6D_6 molecular volume data using "single-Einstein", "single-Debye", and "double-Debye" models, and tabulated unit cell volume data are available in the Supporting Information.

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