

fluid acts as if it has zero viscosity. At low temperature, the only elementary excitations that have a non-negligible probability of being thermally excited are those in the linear (phonon) region and around the parabolic (roton) minimum. It should be noted that, despite their different names, it is difficult to picture phonons and rotons as qualitatively different. It is more appropriate to regard them as labels given to excitations in different wavevector Q regions of the same dispersion curve.

The lifetime of a roton can be understood in terms of the four-quasiparticle decay process first introduced by Landau and Khalatnikov [2] and refined by Bedell *et al.* [3]. A roton excited by a neutron decays by combining with a thermally excited roton and then decaying into two other quasiparticles. As the temperature is lowered, the number of thermally excited rotons rapidly decreases, giving rise to a very strong temperature dependence of the roton lifetime and hence the linewidth of the density fluctuation spectrum $S(Q, \omega)$ measured for wavevectors Q and energy transfers ω by neutron scattering.

Until recently, only the neutron spin-echo (NSE) technique has been capable of resolving the anticipated linewidths at temperatures T below about 1.2 K. In a pioneering NSE experiment, Mezei obtained high-resolution measurements of roton widths down to 0.96 K [4]. Recent developments on the neutron backscattering spectrometer IN10 [5] at the Institut Laue-Langevin, Grenoble, have allowed access to the Q, ω range of the roton minimum with very high (<1 meV) energy resolution, thereby extending the range of measured roton parameters to lower temperatures.

Examples of the measured raw spectra from neutron scattering are shown in Fig. 2 [6]. It may be noted that when the intrinsic peak width is small compared to the energy resolution, the peaks are asymmetric with a shoulder on the larger neutron energy loss side. This peak shape was modelled on the premise that it resulted from the finite- Q resolution sampling $S(Q, \omega)$ around the parabolic roton minimum. The intrinsic lineshape was described by a Lorentzian and the extracted roton width and energies are plotted in Fig. 3 as a function of the temperature.

The fitted roton widths in Fig. 3a are seen to be in excellent agreement with the predictions of Bedell *et al.* and the NSE measurements of Mezei. It is clear from the magnitude of the error bars that the present measurements constitute a significant improvement on those of Mezei,

expanding the range of reliable measurement of the roton width by an order of magnitude. However, the temperature dependence of the roton energy clearly disagrees with the predictions of Bedell *et al.* The measured roton energy changes much more slowly with temperature than expected. The rather good agreement between theory and experiment previously shown by the NSE technique [4] is seen to break down at temperatures below 1.2 K, while the theory is expected to work best in the $T \rightarrow 0$ limit.

The origin of this behaviour is not understood at present and will require further study. There may be temperature-dependent mechanisms such as multiphonon effects that play a role in determining

the roton energy but do not directly affect the temperature dependence of the roton lifetime [7]. Alternatively, the roton lineshape may not be Lorentzian, but intrinsically asymmetric [P. Nozières, private communication], which would shift the roton energy away from the centre of gravity of the peak.

References

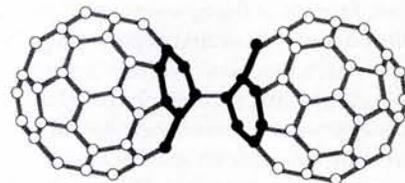
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C₆₀ Discovery Written in Molecules

The 1996 Nobel Prize in Chemistry has been awarded to R.F. Curl, Jr., and R.E. Smalley of Rice University, Houston, USA, and to H.W. Kroto, University of Sussex, UK, for their discovery of fullerenes. Laszlo Forro from the Ecole Polytechnique Fédérale, Lausanne, who chaired the *Fullerenes and Nanotubes* symposium at the EPS-10 General Conference (Sevilla; 9–13 September 1996) reports that the latest developments highlighted at the symposium illustrated perfectly the versatility of these remarkable materials.

Following the discovery of high-temperature superconductivity in doped fullerenes, the latest excitement in fullerene chemistry research is coming from structures based on the intermolecular bonding of the C₆₀ spheres to form C₆₀ dimers, one-dimensional polymers, two-dimensional networks, high-pressure polymerized phases, *etc.* Many of the bonded C₆₀ structures can be produced using a high-temperature, high-pressure treatment. S. Buga (Institute for Superhard Materials, Moscow) showed at the EPS-10 symposium *Fullerenes and Nanotubes* a fascinating pressure-temperature phase diagram of fullerenes, ranging from soft C₆₀ to structures "harder" than diamond. Application of these materials is foreseen.

A second major development is chemical modification of the C₆₀ cage by, for instance, replacing a carbon atom with nitrogen (synthesized by F. Wudl, Santa Barbara, CA). This leads to a new family of compounds, called azafullerenes, which are charged, very reactive and might lie at the origin of a whole class of new fullerene-derivatives. W. Andreoni (IBM, Zurich), who is one of the leading theorists in this field, gave a talk on the electronic structure and the unconventional bonding in azafullerenes. The most interesting molecule is the (C₅₉N)₂ dimer, which seems to have the same structure as the



Local bonding in an azafullerene dimer molecule maps out "96", the year azafullerenes were discovered.

(RbC₆₀)₂ dimer. The structural refinements of this latter compound, which may present a prototype for a whole class of C₆₀ dimers, were illustrated by G. Oszlanyi (Central Research Institute for Physics, Budapest). The local bonding structure in the dimer resembles the number "96" (see figure), prompting Oszlanyi to joke that the date of the discovery of this new type of molecule was inherently written in the molecule itself.

The exceptionally good electron field-emitting characteristics of C₆₀ nanotubes make them potentially very attractive for applications in devices such as displays, for example. W.A. de Heer (EPF, Lausanne) demonstrated how his group has developed a method of purifying and aligning carbon nanotubes in a thin-film form. They have also performed a wide variety of different types of physical measurements (transport, magnetotransport, magnetism, electron spectroscopy, *etc.*).