

the cool end of the reaction chamber, one finds a tangled 'felt' in which each strand is a bundle of single-walled nanotubes.

The crucial question is what feature of the nanotubes' structure engenders their monodispersivity. Smalley faced an equivalent puzzle eleven years ago when contemplating a mass spectrum of carbon clusters that showed the 60-atom cluster to be (under the right conditions) overwhelmingly favoured over its neighbours⁴. And as before, it seems to be all a matter of where one places the six- and five-membered rings. Careful consideration of the problem has prompted the confident suggestion that the nanotubes all have an identical helicity: that which is denoted (10,10) (in a notation that characterizes the diameter and pitch in terms of the arrangement of six-ring ribbons). What is special about this configuration?

Most nanotube helicities give steps around the circumference of the open tube end, where, if you like, each helical ribbon terminates. But for the (10,10) tube, the open end has a crenellated rim in which each six-ring has an edge perpendicular to the tube axis. That is a good thing, Smalley suggests, because this arrangement uniquely allows the outermost edges of the 'exposed' six-rings to be capped with carbon-carbon triple bonds, leaving no dangling bonds at the tube end.

True, it means that each of these acetylenic groups will be uncomfortably strained, bent to about 120° rather than the customary 180°. But calculations suggest that the energetic price is not as high as one might imagine; and after all, the benzyne units that are the parent structures of these putative end rings are not unknown to organic chemists, even though they are more than a little reactive.

If the tube is to keep growing rather than closing off into the kind of short nanotubes seen in most previous syntheses, pentagonal rings (which curve the sheets inwards) have to be prevented. This (the story goes) is where the metal catalyst comes in. We are invited to imagine a single nickel atom scooting around the circumference of the open tube, annealing away defects such as five-membered rings as soon as they are formed. And why not?

Meanwhile, there is the need to account for the fact that all the tubes in a rope apparently run from one end to the other, while some must surely become attached to the bundle (in the gas phase) at a later stage than others. That can be explained if one assumes that short tubes deposited on long ones are fed by diffusion of the carbon feedstock (in whatever form that may take) along the surfaces of the long tubes, as well as by deposition from the gas phase, until the open end catches up with those of the other tubes.

Why, though, the magic number of

Ganymede: wrinkled but magnetic



NASA/JPL

ON 27 June, the Galileo spacecraft flew within 7,500 km of the surface of Ganymede, Jupiter's favourite boy (and largest moon). The first pictures taken were released last week, including this view of cratered and mountain-ridged crust, 55 km top to bottom. The high resolution of these images reveals more complicated tectonic processes than had been widely expected, including shearing like that on the San Andreas fault.

Another surprise was that Ganymede has a magnetic field — the first to be firmly detected around any moon. It may be generated by convection in a layer of salty water below the surface; if so, the same layer might also be involved in the surface tectonism.

We will learn a lot more in November, when Galileo meets Callisto, nearly Ganymede's twin in size and composition, if not in looks. Comparing the two worlds should help us to understand each one.

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13.8 Å, given that one can postulate larger tubes that also have the favourable crenellated ends if they have the right helicity? It turns out that 13.8 Å is (near enough) the diameter of a tube built up from a hemispherical cap of half a C₂₄₀ fullerene. The significance of that is that C₂₄₀ is the first fullerene larger than C₆₀ that shares its symmetry, with the 12 pentagons in the same icosahedral arrangement. For an ideal carbon onion built around a central C₆₀, C₂₄₀ is the next layer. The uncanny thing is that a cap of this sort makes the (10,10) nanotube just the right size to drop a C₆₀ molecule down the middle, because when C₆₀ sits symmetrically within C₂₄₀, the distance between the carbon shells is almost an exact match for the inter-layer spacing in graphite. This is a freak of nature. There is no earthly reason why the shell separation between the two polyhedra, which is set (in relation to, say, the hexagon width) by geometry alone, should so nearly coincide with the layer spacing of graphite, set by the strength of the van der Waals interaction. But there it is; the archetypal nanotube turns out to be a perfect pea-shooter for C₆₀.

The (10,10) nanotubes are among the one-third of all possible types whose atomic structure is predicted to predispose them to metallic conductivity. This expectation seems to be borne out: measurements of the conductivity of individual ropes, unravelled from the mass by the bargain-basement method of applying Scotch tape and pulling, suggest along-axis resistivities of less than 1.0 μΩ m (only twice the in-plane resistivity of graphite) (J. E. Fischer, Univ. Pennsylvania). This is probably an upper limit, but measurements on individual tubes will be trickier.

One hesitates to say it, but this could just be the breakthrough that nanotube science has been waiting for. When they were first reported⁵, single-walled nanotubes were hailed as a panacea for the problems of comparing observation and prediction, because their properties — mechanical, electronic and magnetic — would not be the convoluted product of those of several walls. But attempts to study them have been held back by the difficulty of obtaining samples free from other carbon and non-carbon debris (not to mention the range of tube diameters). Now nanotube preparation stands a chance of becoming less a matter of crude materials processing, with products sharing little more than composition, general morphology and inter-layer spacing, and more a case of macromolecular synthesis, yielding identical molecules that happen to be micrometres long. Indeed, the new method bears a startling resemblance to the 'living' polymerization techniques that have revolutionized polymer science: a metal atom chaperones the reactive end of a growing polymerized structure so as to ensure the controlled formation of defect-free chains of uniform length. And just as living polymerization has opened new doors in polymer technology, so these monodisperse nanotubes may become the strands of a nanotechnological materials science. □

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