question of going beyond the limit that Nature has imposed for the maximum size of nuclei. The relative occurrence of prolate versus oblate shapes is a non-trivial issue that has been discussed a good deal in nuclear physics. Semi-classical theory offers a rather transparent model description of this in terms of the response of triangular and other closed classical orbits to deformation, but the problem is that one needs larger Fermi droplets than nuclear physics can provide to test the theory.

Fission

The break-up of a drop of quantum liquid under the influence of its electric charge, *i.e.*, fission, can be studied from a new angle by examining the fission of multiply charged metallic clusters. In all cases the fission process depends on the competition between the cohesive surface force and the repulsive electrical force. The relevant parameter is therefore the ratio of the Coulomb energy to (two times) the surface energy of a sphere, *i.e.*,

$$E_c/2E_{\text{surf}} = (Q^2/N)/(Q^2/N)_{\text{crit}}$$

where Q is the charge. Inserting typical material constants into the equation one realizes that while 200 nucleons can hold 90 elementary charges together, the same number of metal atoms can hold at most 9 excess charges without immediately fissioning. This reflects the difference between nuclear cohesion, which is due to the strong force, and metallic cohesion which is of electromagnetic origin.

A new stage is set for fission studies thanks to this difference. Quantum effects are likely to be much more pronounced in metallic clusters than in nuclei (modifications of the smooth liquid-drop picture owing

to quantum effects at the fission-like saddle-point shape makes fission interesting already in nuclei). There are some intriguing experimental results for the fission of doubly charged silver and potassium clusters [13] with sizes up to $N = 30$. The division into different fragment pairs seems indeed to be dominated by quantum effects for symmetric mass splits. For clusters in this size range one expects the saddle shapes to be (nearly) two spheres in contact, so the quantum effects are those relating to spherical shapes. Since these shapes can be studied by other means, it would be even more interesting to investigate, using new experiments, the fission of larger clusters with charges greater than 2 since they can have saddle shapes that do not resemble two spheres in contact.

Atypical Molecules: A Bridge to Chemistry

The cooling of a hot metallic droplet through evaporation of (neutral) atoms has much in common with neutron evaporation from the compound nucleus. In both cases the process is described by transition-state theory. The difference lies in the level-density laws. For nuclei, the level-density law of a fermion system alone applies, while for a metal cluster the level density is a product of the ionic, *i.e.*, the oscillator level density, and the fermionic electron level densities. It is the latter that is strongly modulated by the cluster's shell structure, so the fermionic structure plays an important rôle in evaporation processes involving clusters, and in describing how shell structure becomes washed out with increasing temperature. There exists here a bridge to transition-state theory in chemistry, where the emphasis lies

on the oscillator level density, while the electrons are assumed not to contribute because they presumably remain in their adiabatic ground state during typical molecular dissociation processes. In this sense, metal clusters are atypical molecules. Once again we see how a marriage between the young science of cluster physics and a more mature partner can be rich in mutual inspiration.

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1994 HEWLETT-PACKARD EUROPHYSICS PRIZE

New Molecular Forms of Carbon

The 1994 Hewlett-Packard Europhysics Prize of EPS for outstanding achievements in condensed matter physics has been awarded for "the discovery of new molecular forms of carbon and their production in the solid state" to **D.R. Huffman** (The University of Arizona, Tucson, USA), **W. Krätschmer** (Max-Planck Institut für Kernphysik, Heidelberg, Germany), **H. Kroto** (University of Sussex, UK), and **R.E. Smalley** (Rice University, Houston, USA).

Donald Huffman was honoured last year for the discovery of C_{60} by being appointed the Regents' Professor of Physics in the Department of Physics, The University of Arizona, Tucson, Arizona, USA. He studied at Texas A&M University and at Rice University before receiving his Ph.D. from the University of California, Riverside, in 1966. After working as a National Science Foundation postdoc at the University of Frankfurt, he joined The University of Arizona as an Assistant Professor in 1968, becoming Professor in 1975. Professor Huffman, whose research focuses on the optical properties of small particles, has visited Europe regularly, first as a Visiting Scholar to the University College, Cardiff, and then on a sabbatical to the European Space Agency operations in Noordwijk and as

Clockwise from the upper left: D.R. Huffman, W. Krätschmer, R.E. Smalley, and H. Kroto.

a Humboldt Senior US Scientist to the Max Planck Institute in Stuttgart and Heidelberg. After filing a patent application on the C_{60} production process, which is handled by Research Corporation Technologies, he set up the first commercial operation to manufacture and market the material, and was appointed in 1991 to be the first Director of the newly formed Arizona Fullerene Corporation, which aims to bring together fullerene research carried out at The University of Arizona and Arizona State University. Professor Huffman won the Materials Research Society's 1993 MRS Medal for his work on fullerenes.

Wolfgang Krätschmer has been with the research staff of the Max Planck Institute for Nuclear Physics, Heidelberg, since 1976, and has acted since 1987 as a Co-investigator for the development of a photospectrometer for the European Space Agency's orbiting infrared observatory ISO. He studied physics at the TU Berlin and received his doctorate from the University of Heidelberg in 1971 for research on radiation damage carried out at the Max Planck. Dr. Krätschmer's research from 1971 to 1977 mainly concerned heavy-ion astrophysics and after working for a year on interstellar silicate materials with D.R. Huffman at the University of Arizona and with R.F. Knacke at Stony Brook, he began studying astrophysically important dust materials. In recognition of the discovery of fullerenes, he was awarded the German Physical Society's 1992 Stern Gerlach Prize for Physics, the Deutschen Forschungsgemeinschaft's 1993 Leibniz Prize, and the 1993 Alexander von Humboldt Prize.

Harold Kroto has been the Royal Society Research Professor in the School of Chemistry and Molecular Sciences, The University of Sussex, Brighton, since 1991. He studied chemistry at the University of Sheffield where he stayed on to complete his Ph.D. in 1964 before working as a postdoc with the National Research Council in Ottawa, Canada, and as a member of the technical staff of the Bell Telephone Laboratories, Murray Hill, USA, for one year. In 1967, he joined the University of Sussex as a Tutorial Fellow, becoming Professor in 1985. Professor Kroto, whose research interests mainly involve interstellar molecules and circumstellar dust and the spectroscopy of unstable chemical species, has spent time as a visiting scientist or professor in Vancouver, Ottawa, Berkeley, Zagreb, Paris, and Los Angeles. He became a Fellow of the Royal Society in 1990 and for work on fullerenes, was awarded the American Physical Society's International Prize for New Materials (jointly with R.F. Curl and R.E. Smalley), the 1992 Italgas Prize for Chemistry, and the Royal Society of Chemistry's 1993 Longstaff Medal. Aside from serving on committees belonging to the UK's Science Research Council, the Science and Engineering Research Council, the International Astronomical Union, and the Max Born Institute, he has been a member of the Editorial Board of *Chem. Soc. Reviews* since 1986, of *Z. Physik D* since 1992, and of *J. Chem. Soc. Chem. Comm.* since 1993.

Richard Smalley has been the Gene and Norman Hackerman Professor of Chemistry at Rice University, Houston, Texas, USA, since 1982 and Professor of Physics since 1992. Educated at Hope College and The

CALL FOR NOMINATIONS

1995 Hewlett-Packard Europhysics Prize

The Selection Committee for the Hewlett-Packard Europhysics Prize invites nominations for the 1995 award. The Prize is given for an outstanding contribution to condensed matter physics within the previous five years, with the potential for leading advances in electronic, electrical or materials engineering. Nominations may be submitted by EPS members as individuals or as representatives of a Division, Section or Group.

Previous winners have been B.L. Altshuler, A.G. Aronov, D.E. Khmel'nitskii, A.L. Larkin, and B.Z. Spivak (1993) and H. Ibach, G. Ertl and J.P. Toennies (1992). To maintain the extremely high standard, it is necessary that the Committee receives proposals which represent the breadth and strength of European condensed matter physics. Proposals should indicate the motivation for the award and include, if possible, a brief *curriculum vitae* of each of the nominees and a short list of major publications. Letters of support from authorities in the field which outline the importance of the work are also very helpful.

All information will be treated as strictly confidential, and although proposals are acknowledged, there will be no further correspondence. Nominations should be submitted before **30 June 1994** to the Selection Committee, H-P. Europhysics Prize, EPS, P.O. Box 69, CH-1213 Petit-Lancy 2.

University of Michigan, he worked as a research chemist with Shell for four years before taking a M.A. and a Ph.D. in chemical physics (in 1973) from Princeton University. After spending four years as a postdoc at The University of Chicago where he pioneered supersonic jet laser-beam spectroscopy, he returned to Princeton as an Assistant Professor in chemistry in 1976, becoming Professor in 1981. Professor Smalley, whose research interests mainly involve spectroscopic studies of gases, molecules, radicals, ions, and simple clusters, has won several prizes for C_{60} research including the 1991

Irving Langmuir Prize in Chemical Physics, the 1991 *Popular Science Magazine* Grand Award, the 1992 Robert A. Welch Award in Chemistry, the 1992 American Physical Society's International Prize for New Materials (jointly with R.F. Curl and H. Kroto), the US Department of Energy's 1992 E.O. Lawrence Award, the 1993 John Scott Award, and the 1993 William H. Nichols Medal. He is a member of the APS and the American Chemical Society and has been on the Editorial Boards of *Chem. Phys. Lett.* since 1982, of *J. Cluster Sci.* since 1988, and of *Molecular Phys.* since 1991.

Fullerenes: The Classical Profile of a Major Scientific Breakthrough

Until recently, the only known forms of pure crystalline carbon were diamond and graphite. In diamond, each carbon atom is tied to four others in a three-dimensional tetrahedral arrangement by strong sp^3 bonds. The result is a transparent insulator of unique hardness. In graphite the atoms lie in two-dimensional sheets of hexagons, like chicken-wire, with each atom tied to three others by strong sp^2 bonds. The fourth electron occupies a π bond formed from the perpendicular p-orbitals and this lies at the origin of the black colour and electrical conductivity. The sheets sit in stacks which makes graphite a good lubricant.

The prizewinners discovered a third form of carbon in which graphite-like sheets are wrapped into cage-like molecules, so-called fullerenes named after the American engineer Buckminster Fuller who constructed

geodesic domes according to similar principles. The way in which chicken wire may be given curvature is by mixing pentagons between the hexagons and, as shown by Euler, with 12 pentagons the cage closes; the number of hexagons determines the size of the cage. Finally, three-dimensional packings of cage molecules yield solids, the so-called fullerenites.

The archetype molecule and the first one discovered is C_{60} , the "buckyball", which has the shape of a football and a diameter of 0.7 nm (a real football usually has its 12 pentagons painted black and its 20 hexagons white). C_{60} is the smallest fullerene in which the 12 pentagons are kept apart by hexagons. The edge between a pentagon and a hexagon in C_{60} is a sp^2 bond, and the edge between two hexagons carries an additional π bond, that is, the former edge is a single

Basic structures of carbon crystals: from the left, the tetrahedral network of diamond, the hexagonal layers of graphite, and the buckyballs of fullerite.

bond and the latter a double bond. These features give the C_{60} molecule great strength and make the solid a yellowish semiconductor. In solid C_{60} , the molecules are positioned on a face-centered cubic lattice with a closest approach between balls nearly the same as the distance between the sheets in graphite. At normal pressures, the solid is therefore soft, like graphite, but becomes extremely hard at high pressures. Thrown against steel walls at speeds of about twenty thousand miles per hour, solid C_{60} just bounces back.

The C_{60} molecule has the shape of a truncated icosahedron as constructed by Archimedes; its point symmetry is the highest possible, after that of a perfect sphere. With the addition of 5 more hexagons, a belt of hexagons forms around the molecule, which then attains the shape of an American football. This C_{70} was the second fullerene discovered by the prizewinners.

Interstellar Matter Suggested New Form

What led to the discovery of the fullerenes and fullerenes was not the search for new lightweight materials with superb mechanical, electrical, magnetic, or optical properties, nor was it the search for new catalysts, batteries or pharmaceuticals, but the search for the composition and structure of interstellar matter. Huffman and Krätschmer had been trying for years in their respective laboratories to produce a carbon dust which had the same absorption spectra as observed for interstellar dust. Together in Heidelberg in 1983 they evaporated graphite rods by resistive heating in a helium atmosphere and noted that a double hump in the ultraviolet absorp-

tion spectrum of the soot which they had never encountered before appeared at a particular helium pressure.

H. Kroto and D. Walton in Brighton had been interested for over 10 years in certain interstellar molecules containing long, straight carbon chains and, together with radioastronomers, had succeeded in verifying the presence of such chains with up to nine atoms. However, they believed that much longer chains might be formed in the outer atmosphere of red giants. In 1984, Kroto heard from his friend R.F. Curl about an apparatus designed by R.E. Smalley and his students in Houston whereby laser evaporation combined with a supersonic jet of inert gas produced a beam of atom clusters, whose sizes were analyzed by mass spectroscopy. Kroto and Curl succeeded in talking Smalley into trying out carbon. The chains being sought for were found, but the attention of Smalley, Kroto, Curl, and of their students J.R. Heath and S.C. O'Brien, was drawn to

Absorption of carbon particles in the infrared. At elevated helium quenching gas pressure, there are four stronger lines emerging out of the continuum. Theory predicts precisely four ir-active fundamentals for a football structured C_{60} molecule and they should occur close to the measured positions. Such spectra gave the first strong hint that C_{60} had been produced in macroscopic quantities. Some of the tiny line features originate from the less abundant fullerene C_{70} .

larger clusters, notably to C_{60} which under particular conditions turned out to be much more abundant than all the others. Smalley and Kroto, who apparently knew more about Buckminster Fuller's domes than the shape of a football, were able to guess the structure, as well as the structural principles of other fullerenes. During the next years they gathered considerable circumstantial evidence to support their hypothesis. Also carried out were theoretical calculations of the physical properties of this icosahedral molecule, such as the ultraviolet absorption and the infrared vibration spectra, but for five years nobody was able to produce C_{60} in the quantities needed for a structural determination.

Bulk Production Led to Confirmation

At about this time, Huffman started wondering whether the double hump he and Krätschmer had seen might have been caused by C_{60} . In 1989, Krätschmer and his students B. Wagner and K. Fostiropoulos reproduced the results of the 1983 carbon-arc experiment and furthermore measured the mass spectrum and the infrared vibrational spectrum (see figure), which was predicted to exhibit only four peaks due to the icosahedral symmetry of the molecule. Surprisingly, these were the vibrations of the soot samples produced under double-hump conditions; C_{60} thus seemed to be present in abundance. Substitution of ^{12}C by the heavier isotope ^{13}C produced the shift of the vibrational spectrum expected for an all-carbon molecule. Finally, the Heidelberg group did what a chemist would have done right away: they tried to dissolve the sample in benzene, which should work if the soot really did contain "spherical benzene". When they saw the solvent turn red, the group knew that it had produced the first concentrated solution of fullerenes. The solvent was evaporated and it was found that tiny crystals remained, which readily redissolved. The crystals could be sublimed and condensed to form smooth films which later turned out to contain about 80% C_{60} and 20% C_{70} . Huffman and his collaborator L. Lamb in Tucson could immediately verify Krätschmer's findings and were able to study the crystal structure of C_{60} using X-ray and electron diffraction. Kroto in Brighton had tried the Krätschmer-Huffman method two years earlier, but ran out of funding. He and his students now returned to the technique and succeeded in producing a C_{60} - C_{70} solution, in separating the two molecules, and in proving their structures by ^{13}C nuclear magnetic resonance.

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Potential Applications Abound

Research on applications of fullerenes has spread like wildfire since the discovery in 1990 by Krätschmer and Huffman of a simple way to produce these novel molecules. Within months, many groups could make their own fullerenes. One group looked with the electron microscope not at the carbon soot but at the burned ends of the graphite rods used in the evaporation process and found "chicken wire" rolled up like tobacco leaves in a cigar. Another found shells of successively larger fullerenes resembling onion rings. It has been possible to make from the rolls "buckytubes" several nm in diameter and up to 1000 times longer. The hexagons spiral their way along the tube until reaching the end, where the presence of 6 pentagons ensures a proper capping with no bonds left dangling. It has even been possible to open the tubes and through some kind of capillary effect to fill them with lead atoms. The buckytubes could be the strongest fibers known and may even find use as microscopic wires.

It has been found that semiconducting solid C_{60} can be doped with alkali atoms entering between the buckyballs and one of the first surprises in fullerene research was that K_3C_{60} becomes superconducting below 19 K (the highest transition temperature obtained in a fullerene is presently 33 K). Another surprise was that intercalation of an organic agent (TDAE) in solid C_{60} produces a soft ferromagnet. Highly ordered C_{60} films can be grown on crystalline substrates such as gallium arsenide and this property may make such films suitable for microelectronic fabrication. Researchers have claimed that putting a thin layer of C_{70} on a silicon surface can speed up the growth of diamond films by ten orders of magnitude. Such films could harden tool surfaces, or be used to insulate microelectronic circuits. Films containing C_{60} and C_{70} have the interesting property that they become more opaque in bright light and might therefore find use as optical limiters. Adding C_{60} and C_{70} to certain polymers yields excellent photoconductors. Hexagons in some of the larger fullerenes form a spiral instead of a belt resulting in non-linear optical properties. Such materials might find applications in the higher-harmonic generation of light.

Fullerenes were originally thought to be so stable that they should not react with other materials. But chemists have learnt how to slip an extra carbon or nitrogen atom into a fullerene as a hitching post for new ingredients, thus creating the "bunnyball". This opens the way for making complex compounds based on fullerenes, called fulleroids. Decorating fullerenes with transition metal complexes may result in excellent catalysts, while "Teflon balls" ($C_{60}F_{60}$) have been produced in macroscopic quantities and might turn out to be an excellent lubricant. Such tiny ball bearings would also fit nicely into the new world of "micro-machines". Finally, fullerene cages have been used to trap various atoms. In this form, the fullerenes could perhaps find application in molecular batteries and in drug-delivery systems.