Sir Harold Walter Kroto. 7 October 1939 — 30 April 2016

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SIR HAROLD WALTER KROTO

7 October 1939 — 30 April 2016
Harry Kroto received the Nobel Prize for Chemistry in 1996 for his discovery of several new allotropes of carbon and in particular the now-famous C_{60}, whose atoms are arranged in the spheroidal shape of the truncated icosahedron and which he named as buckminsterfullerene after the architect famous for his design of geodesic domes. Earlier in his career he made important discoveries concerned with the production of small, semi-stable molecules by pyrolysis methods and their characterization, mainly by means of microwave rotational spectroscopy. He was proud to have discovered by this means the compound CH_2=PH because it contains the first known example of a carbon–phosphorus double bond. He later also made notable contributions to the field of materials chemistry, especially through his work on carbon nanotubes. Harry used his charismatic personality to very good effect in furthering the public understanding of science and was particularly good with children in this context. He also had strong views about science and religion which led him to become a campaigning atheist. He was a loyal and supportive friend and led a very happy family life with his wife Margaret and their two sons.

EARLY LIFE, SCHOOL AND UNIVERSITY EDUCATION

Harold Walter Kroto was born on 7 October 1939 in Wisbech, Cambridgeshire in the UK. He was always called Harold by his parents and at school (figure 1). It was not until his undergraduate days that he acquired the name Harry, by which he was later universally known. Harry’s parents were Heinz and Edith Krotoschiner (the family name was changed to Kroto in 1955). The story of how these two German nationals ended up in the UK is sadly familiar. Heinz and Edith lived in Berlin, where Heinz had been born in 1900, where he grew up and
where he subsequently ran a business producing toy balloons with graphics printed on them. As a Jew, it was becoming increasingly uncomfortable for him to continue living in Berlin and so he abandoned his business and escaped, via Holland, to England in 1938. His wife joined him shortly afterwards. Initially, they lived in London and he attempted to start in the same line of business again, but at the outbreak of the Second World War Heinz was declared an enemy alien and was interned on the Isle of Man. He was released sometime before the end of the war. Harry’s mother was evacuated to Wisbech in 1939 (where Harry was born), but moved back to London when he was three weeks old. In 1940, Harry’s mother was given the choice of yet another move, to either Peterborough or Bolton. She chose Bolton, where Harry grew up and went to school. Harry has described himself as having ‘a couple of somewhat eccentric parents (in particular an extrovertly gregarious mother)’ (81).* It seems possible that Harry inherited these aspects of her personality.

After the war, Heinz Krotoschiner retrained, through an apprenticeship, and qualified as a toolmaker in a short time. He worked in that capacity for some years until, in 1955, he started yet again his own factory for making balloons and printing on them. Harry has acknowledged in his Nobel biography (81) that his work in many aspects of the family business during the school holidays was valuable training in problem-solving skills.

Harry was fortunate, as were many of his generation, that his schooling coincided with the period, ushered in by the 1944 Education Act, in which a high-quality, academic education was available even to the poorest (his parents had lost everything as a result of their move). Initially, he attended Wolfenden Street School in Bolton, but in 1947 transferred to Bolton School. Although Bolton School was at that time a Direct Grant School, he was able to win a scholarship, which ensured that his parents did not have to pay fees. He enjoyed his time (1947–1958) at Bolton School and developed wide interests, especially in graphic art (enthusiasm for which was a thread that ran throughout his life), geography, gymnastics and woodwork to begin with. As he approached the Sixth Form, however, he started to lean towards the sciences: chemistry, physics and mathematics. He also participated in the dramatic arts, as is illustrated by his appearance as the Duke of York in Shakespeare’s *Henry V*, the title role in which was played by Ian McKellen, who was in the same year at Bolton School and

* Numbers in this form refer to the bibliography at the end of the text.
Figure 2. Harry as the Duke of York (third from left) and Ian McKellen (pointing) in the Bolton School production of *Henry V*.

is now a world-famous and much-honoured actor (see figure 2). Harry also developed as an athlete, played football and cricket and became an accomplished tennis player.

Chemistry was his favourite academic subject. He has written (81): ‘I, like almost all chemists I know, was also attracted by the smells and bangs that endowed chemistry with that slight but charismatic element of danger.’ Harry was inspired by two chemistry teachers he encountered at Bolton School. The first was Dr Wilf Jary, who impressed Harry with his experimental dexterity, and the second was Harry Heaney, later to become Professor of Organic Chemistry at Loughborough University. It was Heaney who advised Harry Kroto to follow a degree course in chemistry at the University of Sheffield, which he considered to be the best chemistry department in the UK at the time.

Harry arrived at the University of Sheffield at the age of 19 in October 1958. Despite having many extracurricular interests (including playing in the university tennis team and acting as art editor of the student magazine *Arrows*, which also required him to design covers and posters), he obtained a first class BSc degree in chemistry in 1961. Originally, he had favoured organic chemistry (partly as a result of Heaney’s influence), but during his undergraduate years his interests gravitated towards spectroscopy and quantum mechanics. He had the good fortune to be taught the former by Richard N. Dixon (FRS 1986), subsequently Professor of Theoretical Chemistry at the University of Bristol, and the latter by John N. Murrell (FRS 1991). Murrell was later to become Harry’s close friend and colleague at the University of Sussex.

Harry began his doctoral research in October 1961, with Richard Dixon as his supervisor. Two publications (1, 2) resulted from this period and both involved the production of small, short-lived molecules by the technique called flash photolysis, as developed by R. G. W. Norrish FRS and G. Porter FRS (Norrish & Porter 1949). In this approach, a highly energetic but short pulse of radiation (the flash) is fired into the vapour of a precursor substance (for
example, bromoform HCBr\textsubscript{3} in (1)). Molecules of the precursor absorb the radiation and rapidly decompose to produce (usually) a short-lived radical (for example, CBr in (1)). After a short delay of $\sim$10 microseconds, lower-powered radiation of an appropriate wavelength range is passed through the vessel containing the nascent radicals, allowing their electronic absorption spectrum to be photographed (in the case of CBr described in (1), the electronic transition is $^2\Delta_2 \leftarrow ^2\Pi_2$). As Harry pointed out in his Nobel biography (81), ‘George Porter was Professor of Physical Chemistry at Sheffield at the time, so there was a lot of flashing going on’. Harry also had other calls on his time while he was carrying out his doctoral research. For example, he was president of the university’s athletics council and he represented the university at tennis. During that period, he met his future wife, Margaret Hunter, who was reading philosophy, politics and economics at the university. They married on 20 July 1963.

Towards the end of his PhD research in 1964, Harry was attracted by the prospect of post-doctoral work in North America. With the help of Richard Dixon, he won a prestigious National Research Council of Canada post-doctoral fellowship in the world-famous molecular spectroscopy laboratory, headed by Alex E. Douglas (FRS 1970) and housed within the Division of Pure Physics of the National Research Council (NRC) in Ottawa (see figure 3), which had Gerhard Herzberg FRS at the helm. Herzberg’s contributions to molecular spectroscopy won him the Nobel Prize for Chemistry in 1971. Collected in the NRC, Ottawa, at that time was a glittering array of talent, including Donald A. Ramsay (FRS 1978), Cecil C. Costain, James K. G. Watson (FRS 1987), Takeshi Oka (FRS 1984) and Jon Hougen. Harry enjoyed the freedom given to him by Herzberg and Douglas to pursue whatever interested him. Initially, he worked in Don Ramsay’s laboratory on the NCN radical (3, 4) produced by the flash photolysis of cyanogen azide NCN\textsubscript{3}. Takeshi Oka, who had befriended and helped Harry and Margaret when they first arrived in Ottawa, was a member of Ramsay’s laboratory at that time and Harry’s close scientific interaction with him cemented a lifelong friendship between them. Harry later became interested in the microwave spectroscopy being conducted in Cecil
Costain’s laboratory, and at the end of his first year in Ottawa he transferred to Costain’s group. There he worked on the microwave spectrum of cyanogen azide (5). Harry learned much about quantum mechanics and spectroscopy from Jim Watson and Jon Hougen. The people he got to know at NRC had a strong influence on his intellectual development and his friendship with them lasted for the rest of his life. His admiration for Herzberg shines through the obituary he contributed to The Guardian newspaper (30 March 1999).

At the end of two years in Ottawa, in 1966, Harry moved to the USA to a post-doctoral position at Bell Telephone Laboratories, Murray Hill, New Jersey, where he worked on investigations of liquid phase interactions by laser Raman spectroscopy. After a year, it was time to return to the UK and begin his independent academic career at the recently-founded University of Sussex.

University of Sussex 1967–1985

At the invitation of John Murrell, who had moved from Sheffield to Sussex in 1965 as professor of chemistry, Harry accepted a tutorial fellowship in chemistry at the University of Sussex at a salary greatly reduced from that he had received at Murray Hill. With one child already (Stephen, born in Ottawa in 1966) and another on the way (David, born in Brighton in 1968; see figure 4), the Krotos considered returning to the USA, but the conversion of the Sussex post to a lectureship convinced them to stay. Harry remained at Sussex until 2004, first as lecturer from 1968 to 1977, then as reader from 1977 to 1985, as professor from 1985 to 1991, and finally as Royal Society research professor from 1991 to 2004.

Harry’s publications in the period from 1967 until the discovery of C₆₀ in 1985 reveal how his interests developed. The first papers published from the University of Sussex were essentially a continuation of his interests from his time in Ottawa and Bell Labs. The period between 1972 and 1985 was particularly productive, resulting in about 80 publications concerned with the synthesis and spectroscopy (mainly rotational and photoelectron spectroscopy) of small ‘semi-stable’ reactive molecules.

First, he became attracted by the possibility of producing small, short-lived molecules by techniques such as pyrolysis and then characterizing them spectroscopically. Photoelectron spectroscopy provides detailed information about the electronic structure of a molecule, while microwave (rotational) spectroscopy can yield the order of the atoms (by isotopic substitution), precise molecular geometries, electric dipole moments, details of any internal rotational motion and, in suitable cases, vibrational separations in the lowest energy modes of molecules. Initially, he concentrated on generating, from a range of precursors, unstable sulfur analogues of well-known oxygen-containing molecules such as carbon monoxide CO, acetaldehyde CH₃CHO, acetone (CH₃)₂O, formaldehyde H₂CO and ketene CH₂=CHO. Thus, for example, CS (6), H₂C=S (7) CH₂CHS and (CH₃)₂CS (8), and CH₂=CS (9) were produced and characterized spectroscopically. Other hitherto unknown molecules were also identified by the pyrolysis technique and characterized spectroscopically. To give one example, the new linear molecule chloro-sulfido-boron, ClBS, was generated by passing S₂Cl₂ over boron heated to 1000°C and was characterized in detail by the two spectroscopic methods (21).

An excellent, full account of Harry’s research strategy in connection with the many molecules he produced by pyrolysis is given in his Tilden Lecture in 1982 entitled
‘Semi-stable molecules in the laboratory and in space’ (26). During the early 1970s he wrote a well-received monograph on rotational spectroscopy, entitled *Molecular rotation spectra*, published by Wiley in 1975 (10), which meant that he was on top of the theory of the subject.*

The superb Hewlett-Packard 8460A microwave spectrometer, available in Sussex from the mid 1970s, had the novelty of semi-automatic frequency scanning of backward wave oscillators. This freed the operator from the fiddly task of manually adjusting klystron dimensions, reflector voltage, etc., to generate radiation over a tiny frequency range and allowed him/her to concentrate on the difficult matter of getting the ‘semi-stable’ molecules into the waveguide cell. So, he was well equipped theoretically and experimentally to make rapid progress with the detection and analysis of small, unstable molecules.

From the sulfur (and selenium) analogues of familiar oxygen-containing organic compounds, Harry next turned his attention to phosphorus counterparts of simple nitrogen-containing compounds. These, too, were often generated by the pyrolysis of suitable precursors. In this project, he teamed up with his Sussex colleague John Nixon (FRS 1994), an expert in the synthesis and chemistry of phosphorus compounds. As a result of this collaboration, they produced a large number of P analogues of simple, familiar N-containing organic molecules and in the process discovered simple, general methods. Thus, CH$_3$C≡P, the analogue of methyl cyanide, was produced (11, 18) by flow pyrolysis of the precursor

* *Molecular rotation spectra* is a compact, but rigorously argued, monograph, written for spectroscopists from the viewpoint of modern quantum mechanical methods (including angular momentum operators, derivation of selection rules and vibration–rotation interaction theory), as learned from Jon Hougen and James K. G. Watson while at NRC in Ottawa some ten years earlier. Harry was delighted when, in 1992, it was republished by Dover, an honour reserved for classic texts. The preface of the Dover edition includes numerous rotational spectra of small (and some very long) molecules, all recorded with a Hewlett-Packard 8460A microwave spectrometer. These spectra (all from his own research) illustrate the beauty and elegance of the subject.
Figure 5. The $J = 4 \leftarrow 3$ transition of CH$_3$C≡P recorded with a Hewlett-Packard 8460A microwave spectrometer. CH$_3$C≡P was produced by pyrolysis of CH$_3$CH$_2$PCl$_2$, which loses two units of HCl to give the product. G.S. signifies the rotational transition in the vibrational ground state. Transitions marked as $v_8 = n$ are the same rotational transition in a vibrational state with $n$ quanta of the lowest frequency bending mode excited. Upward-pointing transitions are at zero-applied electric field strength and downward-pointing lobes are the Stark effect (see text). The $J = 1 \leftarrow 0$ transition of HC≡P (with just one Stark component) is also present. (Reproduced from (26) with permission of the Royal Society of Chemistry.)

CH$_3$CH$_2$PCl$_2$ from which HCl is eliminated.

$$\text{CH}_3\text{CH}_2\text{PCl}_2 \to \text{CH}_3\text{C≡P} + 2\text{HCl}$$

This approach proved to be generally applicable (26), so that, by the pyrolysis of the appropriate precursor CH$_3$CX$_2$PY$_2$, it was possible to generate and fully characterize (by rotational and photoelectron spectroscopy) the family of phospha-alkynes CH$_3$C≡P (11, 18), FC≡P (17, 20), CH$_2$=CH–C≡P (24) and others. Precursors of the type R–C≡C–CH$_3$ allowed, for example, each of H–C≡C–C≡P (25) and N≡C–C≡C–C≡P (28) to be formed by the general pyrolysis route R–C≡C–CH$_3$ + Cl$_3$P $\to$ R–C≡C–C≡P + 3HCl, with R = H or CN. The corresponding reaction of methyl cyanide with phosphorus trichloride, namely N≡C–CH$_3$ + Cl$_3$P $\to$ N≡C–C≡C≡P, leads to cyano-phospha-ethyne (19), a P analogue of cyanogen. All three of these linear molecules were detected by means of their microwave rotational spectra.

Figure 5 shows a portion of the spectrum of CH$_3$C≡P (26) recorded by means of the Hewlett-Packard 8460A microwave spectrometer. This instrument relied for its high sensitivity on the Stark effect; that is, the effect of a uniform, static electric field of strength $E$ on the rotational energy levels (and therefore transitions) of a molecule which, as a result, split into several components. Rapid switching of the electric field strength between 0 and $E$ allows both the zero-field transition (upward-pointing in figure 5) and the Stark components into which it splits at field strength $E$ (downward-pointing lobes) to be displayed. The detailed pattern of Stark components (intensities and shifts) of a given rotational transition is determined by the quantum numbers involved and often allows their relatively straight-forward assignment. The electric dipole moment of the molecule can be determined
Figure 5 is a good example of why Harry derived much aesthetic pleasure from such spectra. It was also possible to produce a whole family of phospha-alkenes \( R-CX=PY \) by means of the pyrolysis of various types of precursor. A general method that was discovered \( 26 \) utilizes the precursor \( RCX_2PY_2 \), from which, on heating to a sufficient temperature, \( XY \) is eliminated to leave the phospha-alkene, according to

\[
RCX_2PY_2 \rightarrow R-CX=PY + XY
\]

By using this route the phospha-alkenes \( CH_2=PH \) \( 12, 23 \) and \( CH_2=PCl \) \( 12, 27 \) were generated and then detected through their rotational spectra, to mention just two examples. \( CH_2=PH \) was the first molecule carrying a carbon–phosphorus double bond to be synthesized (Harry said he got more intellectual satisfaction from this than from the discovery of \( C_60 \)). The methods of production of all the phospha-alkynes and phospha-alkenes mentioned here, and of various other \( R-CX=PY \) not mentioned here, are fully described in the Tilden Lecture \( 26 \).

Harry also began a collaboration with his Sussex colleague, David Walton, in the mid-1970s, the aim of which was to synthesize linear molecules in the series of cyano-polyynes \( H(C\equiv C)_n-C\equiv N \) and to examine their rotational spectra. David Walton had great expertise in the (potentially dangerous) field of polyynes synthesis and his contribution was very important. Long, linear molecules of this type have several low-energy bending modes of vibrations, excited states of which are well-populated at room temperature. Such molecules therefore exhibit in their rotational spectra rich vibrational satellite patterns (i.e. rotational transitions in vibrationally excited states of the bending modes). The main reason for the research initially appears to have been to provide a severe experimental test of the theory of vibration–rotation interaction in such linear molecules, with which Harry was familiar from the preparation of his monograph *Molecular rotation spectra* \( 10 \). The first molecule in the series to be prepared and its rotational spectrum observed was cyanobutadiyne, \( H(C\equiv C)_2-C\equiv N \) \( 13 \) (sometimes called cyanodiacetylene), and it does indeed exhibit a beautiful pattern of bending vibrational satellites (see figures 1 and 2 in \( 13 \)). Interestingly, an undergraduate, Andrew Alexander, reading for the BSc by Thesis degree, was the student involved in the project. Harry was always a strong advocate of this type of degree.

Almost simultaneously, a search (suggested by Harry to Takeshi Oka, who enthusiastically took up the suggestion) was carried out with the Algonquin Park radio-telescope in Canada for the \( J=4 \rightarrow 3 \) rotational transition of cyanobutadiyne in emission in the interstellar medium. Although this transition had not been observed directly in the laboratory, an accurate frequency was available from the ground-state rotational and centrifugal distortion constants reported in \( 13 \). The transition was quickly detected \( 14 \) in the interstellar cloud that lies in the direction of Sgr B2. This led Harry to speculate that, since cyanobutadiyne has two carbon atoms more than any molecule that had hitherto been detected in interstellar space, the molecular clouds in the direction of Sgr B2 must be rich in carbon-containing molecules. David Walton experienced more difficulty with the synthesis of the next member of the series \( H(C\equiv C)_n-C\equiv N \), that having \( n=3 \), but was eventually successful \( 22 \). Although the terrestrial rotational spectrum of \( HC_7N \) was detected, the date booked for making observations on the Algonquin telescope arrived just as the spectroscopic constants of this species were being measured in the laboratory. After some drama, involving a chain of telephone calls—(a) from Colin Kirby, the research student working on \( HC_7N \) at Sussex, to Margaret Kroto, (b) from Margaret to a friend, Fokke Cruetzberg, of Ottawa days and, finally, (c) from Fokke...
to Harry at the telescope—the experimental results arrived just in time to allow the detection of HC₇N in the interstellar medium (15). Synthesis of the cyanopoly-yne having \( n = 4 \) proved to be experimentally challenging, but Takeshi Oka was able to extrapolate along the series H(C≡C)\(_n\)–C≡N (\( n = 1, 2 \) and 3) to predict with remarkable accuracy the spectroscopic constants for \( n = 4 \) and thereby to observe a rotational transition of HC\(_9\)N in space (16). This molecule was later observed in the laboratory.

In his Tilden Lecture (26), Harry speculated that chains of carbon atoms such as HC\(_n\) (i.e. without the cyano group) should also be detectable in the interstellar medium. So it was that, as 1985 approached, not only had Harry and his Sussex colleagues synthesized a large number of small, reactive or unstable molecules containing B, S, P or Se and characterized them spectroscopically, but also, stimulated by his work with David Walton on cyanopolyynes, Harry had turned his thoughts to the possibility of detecting long chains of carbon atoms in the interstellar medium as a way of trying to understand interstellar chemistry. He speculated in particular about the role of red-giant carbon stars in producing such carbon atom chains.


Louis Pasteur ForMemRS remarked that (Pasteur 1854), ‘Dans les champs de l’observation le hasard ne favorise que les esprits préparés’, often translated as ‘In the field of observation, fortune favours only the prepared mind’. Readers may judge from the following account whether this statement is appropriate to the discovery of buckminsterfullerene, C\(_{60}\). Harry published in 1992 an excellent, discursive, personal account in *Angewandte Chemie* (47) from which the intensity and excitement surrounding the discovery is almost tangible. Inevitably, the description set out below relies for its facts on the *Angewandte Chemie* article and also on a similar account given in Harry’s Nobel Prize lecture (61), although some of the detail of the discovery has necessarily been omitted.

**Visits to Rice University 1984 and 1985**

We have seen that Harry Kroto was already thinking about the possible role of long chains of linked carbon atoms in connection with the chemistry in the interstellar medium. On a visit to his friend and colleague, Robert Curl, at Rice University, Houston, Texas, in 1984, Harry learned that Richard Smalley (also at Rice) had developed a laser-ablation source attached to a mass spectrometer by means of which it was possible to observe spectra of refractory materials. For example, Smalley had used this instrument to entrain in a pulse of helium gas the plasma produced when a laser impinges on solid silicon dicarbide SiC\(_2\), sweep the pulse of gas (after ionization) into the time-of-flight mass spectrometer and record the visible spectrum of SiC\(_2\) (Michalopoulos et al. 1984). Harry saw immediately that by using this technique it should be possible to vaporize graphite and examine the products to see whether long chains of carbon atoms were produced. It took 18 months to persuade Smalley to provide enough time on the instrument to try the experiment and Harry was determined to be there when it was carried out. He travelled to Houston in late August 1985, using money borrowed from Margaret to pay his air fare. Only a few days were scheduled for the experiments, which began on 1 September, with Smalley’s students, Jim Heath and Sean O’Brien, operating the instrument.
By varying the helium pressure and the distance the helium-entrained pulse travels to the mass spectrometer, they manipulated the clustering conditions, and thereby found that the peak in the spectrum corresponding in mass to 60 carbon atoms was more intense than other \( C_n \) peaks and could be further enhanced (see figure 6 for a print of an early mass spectrum annotated by Harry).

Such an interesting result brought an extension to the time allowed for the graphite experiments and this was used to refine the conditions to optimize the intensity of the \( C_{60} \) signal. The result was astounding, as may be seen by the spectrum in figure 6, which shows that not only was the \( C_{60} \) peak many times stronger than those adjacent to it, but that \( C_{70} \) was also special in that respect. Evidently, \( C_{60} \) must be more stable and/or formed more readily than other \( C_n \). There followed a period of intense speculation among Curl, Kroto, Smalley and the students about what endows \( C_{60} \) with its special properties. What could be its geometry? A consensus grew in favour of a closed, spheroidal structure, which thereby avoided the need for dangling (unsatisfied and therefore reactive) bonds. Harry had vivid memories of the linked hexagons from which Buckminster Fuller’s geodesic domes at EXPO 67 in Montreal were constructed. He also recalled the polyhedral star-dome he had constructed for his children years before, now languishing in a cupboard at home in Sussex. He discussed this at lunch with Curl on Monday 9 September and recalled cutting out pentagons as well as hexagons when making the star-dome. Should he call his wife to get her to count the vertices (he suspected there might be 60)? Eventually, for reasons of time difference he decided not to, and Smalley obtained a book about Buckminster Fuller’s geodesic domes from the Rice University library.

At a dinner for the team in a Mexican restaurant on the evening of 9 September, all the evidence was reviewed again. Everyone agreed with a spheroidal geometry. Geodesic domes were discussed. Harry recounted once more the properties of the star-dome: its spheroidal shape and his recollection of hexagonal and pentagonal faces. The next morning, Smalley
appeared with a paper model, made during the night, based on the star-dome characteristics and constructed from 20 hexagonal and 16 pentagonal faces. It had 60 identical vertices, each occupied by a carbon atom. It was so beautiful and so simple that they knew it must be correct. It transpired that its shape was known to mathematicians as a truncated icosahedron and was familiar to most people as the shape of a soccer ball, with its pattern of hexagons and pentagons (see figure 7). Harry suggested the name buckminsterfullerene for C₆₀ and, after some resistance and discussion, it was accepted. Strangely, but unknown to Harry at that time, the experimental discovery of C₆₀ had been preceded by the remarkable speculation of David Jones, a scientific journalist writing as ‘Daedalus’ in the New Scientist in 1966 (Jones 1966), that balloons composed of linked carbon atoms might exist. Moreover, in 1970, Osawa had proposed that a molecule C₆₀ having a truncated icosahedral geometry could exist (Osawa 1970).

Harry delayed departure from Houston for a further day to participate in the writing of the now-famous, short paper submitted to Nature (29) (received only 13 days after the first experiment on 1 September). According to Web of Science, as of 31 December 2016, this paper had been cited about 10 000 times.

As beautiful and simple as their explanation might be, it was an uncomfortable fact that the experimental identification of C₆₀ relied on the enhanced intensity of a single peak at 720 u in the mass spectrum of ablated graphite. Moreover, the enhanced intensity of the C₇₀ mass peak also required explanation. Smalley proposed that this cage could be constructed from two hemispherical C₃₀ halves of C₆₀ by inserting a ring of 10 additional C atoms between them (see figure 7). Many papers followed in the next few years, discussing especially other possible closed Cₙ structures. One notable piece of experimental evidence was the successful encapsulation of a lanthanum atom within C₆₀ (30). In 1987 Harry published an important paper (32) in which he enunciated a set of empirical geodesic and chemical rules for predicting which clusters Cₙ would exhibit closed, hollow carbon cages of enhanced stability relative to near-neighbours. Prominent among these rules were: (a) that according to Euler’s Law
(learned from the Daedalus article (Jones 1966)), a sheet composed only of hexagons cannot close, the insertion of 12 pentagons being necessary for closure; and (b) that structures in which each pentagonal ring is completely surrounded by hexagonal rings (i.e. the pentagons are isolated from each other—the celebrated Isolated Pentagon Rule) are of special stability. All 12 pentagonal rings in C_{60} are completely isolated from each other and C_{60} satisfies the other rules enunciated in (32). Therefore, C_{60} was assigned the optimum stability. The next cluster to satisfy the Isolated Pentagon Rule and to exhibit the necessary 12 pentagons was C_{70}, thus neatly explaining the dominance of the C_{60} and C_{70} mass spectral peaks in the products of laser-ablation of graphite. Harry also predicted, on the basis of his rules, closed-cage structures and enhanced stability relative to near-neighbours for those C_n for which n = 24, 28, 32, 36 and 50, but these necessarily have some contiguous pentagons and are therefore predicted to be of lower stability.

So, the circumstantial evidence grew, and the more it grew, the greater became Harry’s confidence that he and his Rice colleagues were correct. But chemists like to have a macroscopic sample of a substance in their hands and characterize it spectroscopically (usually by the NMR and infrared techniques—the mass spectrum was already available) and Harry was no exception. The infrared spectrum was readily predicted to consist of four fundamental vibrational bands and, since all carbon atoms were equivalent, the $^{13}\text{C}$ NMR spectrum should consist of a single line, so spectroscopic characterization of C_{60} should be straightforward. The problem was how to produce a macroscopic sample. This was not achieved until September 1990 and the five years between the discovery of C_{60} in 1985 and its characterization via a macroscopic quantity were stressful and, in some respects, lonely.

**A macroscopic sample of C_{60} in 1990**

Harry was convinced that it was impracticable to produce a macroscopic sample of C_{60} by the laser-ablation approach. An interest that he and the group at Rice had developed in the possible role of C_{60} in soot formation (31) led, eventually and indirectly, to a way of producing much larger quantities of C_{60}. An electron micrograph of carbon micro-particles published in 1980 (Iijima 1980) appeared to show a set of concentric, quasi-icosahedral, giant fullerene-like shells, very similar in appearance to models of giant fullerenes, such as C_{540}, constructed by Harry’s research student Ken McKay. This stimulated Harry to initiate an electron microscopy project to examine the relationship between C_{60} and soot formation. The approach was to strike a carbon arc in helium gas inside a bell-jar evaporator and examine whether C_{60} accompanied the production of the round carbon micro-particles as the helium pressure was increased. They did indeed detect carbon micro-particles by electron microscopy, but the project soon foundered because Harry had assumed that only a very small quantity of C_{60} would result, the detection of which would require a very sensitive quadrupole mass spectrometer. The money for the quadrupole mass spectrometer was not forthcoming, C_{60} was not detected and the project was placed in abeyance.

In September 1989, Harry learned from a friend of a conference paper (Krätschmer et al. 1990a) which reported the infrared spectrum of a film of arc-deposited carbon. The spectrum showed four absorption bands at wavenumbers consistent with those predicted for C_{60}. Their apparatus was similar to the bell-jar arrangement used by McKay. Harry immediately removed the McKay apparatus from storage and asked research student Jonathan Hare and undergraduate project student Amit Sarkar to repeat the experiment. They eventually (after various equipment problems and generous advice from Krätschmer) found conditions under
which the infrared spectrum could be consistently observed. The implication was that the deposit must contain about 1% of $C_{60}$, although Harry found this difficult to believe. A mass spectrum of the soot taken on 27 July 1990 showed a decent $C_{60}$ signal, but equipment failure precluded repetition of the experiment. On Friday 3 August 1990, Jonathan Hare optimistically added benzene to a sample of bell-jar soot and left it to stand for the weekend. On Monday morning, he noted a reddish solution above the solid. During that week, he prepared more extract and evaporated the solution down to a few drops, but could detect no $C_{60}$ signal in a mass spectrum that was run on the evaporated solution on Thursday 9 August.

The next morning (Friday 10 August) Harry received a telephone call from the journal Nature asking him to referee a paper submitted by the Krätschmer/Huffman group. He agreed and the manuscript was faxed to him immediately. It described the sublimation of $C_{60}$ from arc-deposited carbon, the dissolution of the sublimate in benzene to give a red solution and formation of crystals from the solution. The properties of the crystals, established by X-ray and electron diffraction, were just as expected for $C_{60}$.

To his great credit, Harry submitted his report to Nature the same day, congratulating the authors and recommending publication without delay (Krätschmer et al. 1990b). The fact that Harry did not isolate the first macroscopic sample of $C_{60}$, even though he had Jonathan Hare’s red solution on his desk, was an enormous disappointment, but all was not lost. The Krätschmer/Huffman paper for Nature reported neither of the two methods of characterization beloved of organic chemists, namely, the mass spectrum and NMR spectrum. Clearly, to record these spectra was a matter of urgency. At this point, Harry sought the help of a colleague at Sussex, the organic chemist Roger Taylor, whose input was crucial in two respects. First, he advised how to vaporize the red extract from a fast-atom bombardment matrix and thereby obtain its mass spectrum. This spectrum showed the presence of not only $C_{60}$, but also $C_{70}$ and indeed other fullerenes $C_n$, where $n$ is an even number. Secondly, Taylor isolated pure samples of $C_{60}$ and $C_{70}$ by preparative gas chromatography. The solutions of pure $C_{60}$ and pure $C_{70}$ in benzene were magenta and an intense red, respectively (see figure 8). The $^{13}$C NMR spectra of pure samples of $C_{60}$ and $C_{70}$ dissolved in benzene were then obtained (34).
As predicted, C\textsubscript{60} exhibited just a single transition, while C\textsubscript{70} showed four peaks having the intensity ratio of 2:1:2:1 in order of increasing chemical shift, a confirmatory signature.

Thus, the two fullerenes were fully characterized, no one could possibly doubt the discovery and all remaining anxiety vanished. Harry was knighted for services to chemistry in January 1996. Curl, Kroto and Smalley were awarded the 1996 Nobel Prize for Chemistry (see figure 9) ‘for their discovery of the fullerenes’.

Fullerene chemistry in the 1990–1996 period

Following the publication of (34) in 1990, there was an explosive growth in both experimental and theoretical studies of the chemistry and physics of the fullerenes. For example, Harry published about 100 articles between 1990 and the award of the Nobel Prize in 1996. Some reported the infrared (35), Raman (36) and ultra-violet spectra (37) of C\textsubscript{60} and C\textsubscript{70}, while others investigated the circular dichroism (38) and neutron scattering characteristics (39) of C\textsubscript{60} fullerene. Many articles were concerned with the chemistry of C\textsubscript{60}, including its fluorination (40), bromination (41), hydrogenation (42) and chlorination (49). Other chemistry involved the formation of C\textsubscript{60}Ph\textsubscript{12} by aromatic substitution (43), the preparation of C\textsubscript{60}(ferrocene)\textsubscript{2} (48), the hydroboration of C\textsubscript{60} (53), the intercalation of P\textsubscript{4} into C\textsubscript{60} (54), the reaction of C\textsubscript{70} with benzyne (55), the preparation of cyclopentadienyl derivatives of C\textsubscript{60} (51) and so on. The chemistry was conducted almost entirely in collaboration with Sussex colleagues Roger Taylor and David Walton, with significant input from Jonathan Hare. Of the approximately 100 papers that emerged from the Kroto group from 1990 to 1996, Taylor and Walton were co-authors of the majority. Other articles published in that period describe the search for, and characterization of, other C\textsubscript{n} (n ≠ 60 or 70) closed-cage fullerenes, including the isomers of C\textsubscript{78} (46), the ground-state geometry of C\textsubscript{84} (44) and the \textsuperscript{13}C NMR spectra of C\textsubscript{76}, C\textsubscript{78} and C\textsubscript{84} (50). An investigation of the hydrogenation of C\textsubscript{76}, C\textsubscript{78} and C\textsubscript{84} with zinc/hydrochloric acid yielded hydrogenated clusters, but with some evidence of
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cage degradation (59). The concepts of stability domains and strain relief originally invoked
in connection with C_{28} were refined and applied to other small members of the fullerene
family in an attempt to predict stability among their derivatives (52). The role of smaller
clusters in space was also considered (56). There was speculation (45) about the existence
of circumstellar and interstellar fullerenes and their role as carriers for the diffuse interstellar
bands (DIBs), as first suggested in the original Nature paper of 1985 (29). Papers published
towards the end of the 1990–1996 period heralded a change of direction in the Sussex
research. For example, two articles published in Carbon in 1995 entitled ‘Hemi-toroidal
networks in pyrolytic carbon nanotubes’ (57) and ‘Nanotubes from vapor-grown carbon fibers’
(58), and one entitled ‘Nanoscale encapsulation of molybdenum carbide in carbon clusters’
in Chemistry of Materials in 1996 (60), indicate a move into materials aspects of carbon
nanotube/fullerene research.

The growth of activity in research involving the fullerenes in the period 1990–1996 was
not restricted to the Sussex group. Smalley and colleagues at Rice University also carried
out much research in the area, for example, metals interacting with smaller fullerenes (Guo
et al. 1993), but with the main focus shifting later to the recently-discovered, single-walled
carbon nanotubes (Lou et al. 1995). There were also contributions from theoreticians. Many
consisted of high-level calculations on single isomers, but the more ambitious often involved
the discovery of rules for making predictions of stability among closed-cage fullerenes. As
early as 1986, the Stone–Wales transformation was proposed as a hypothetical mechanism
for the interconversion of fullerene isomers (Stone & Wales 1986). The Leapfrog Principle
(Fowler & Steer 1987) predicts pseudo-spherical carbon clusters C_n, with n = 60 + 6k and
k equal either to zero or to any integer greater than one and having closed electronic shells.
The Principle predicts the symmetries of the bonding orbitals of these ‘leapfrog’ clusters.
The Spiral Conjecture (Manolopoulos et al. 1991) for fullerenes states that the surface of
every fullerene may be unwound in at least one continuous spiral strip sharing five-
and six-membered rings. Assignment of higher fullerenes (Diederich and Whetten 1992) used
predicted 13C NMR spectra from the spiral algorithm, which also gave clues to formation
mechanisms (44). These are but a few of the contributions of theoreticians.

An important postscript to the Nobel Prize: C_{60} and the diffuse interstellar bands

The DIBs have been a challenge to astronomers, physicists and chemists ever since their first
observation (Heber 1922). Mary Lea Heber observed a set of absorption lines produced when
starlight from reddened stars passes through interstellar molecular clouds. Harry suggested
in 1987 (very soon after the discovery of C_{60} in 1985) that C_{60}^+ could be the origin of at
least some of the DIBs (33). His arguments were based on the remarkable stability of the C_{60}
molecule, which was known to be formed in, and to survive in, the plasma produced when
graphite is ablated by a laser. Harry’s reasoning was that in starlight the C_{60} molecule would
become ionized to give the cation C_{60}^+. There the matter rested for some years until 1993
when John Maier (FRS 1999) and co-workers investigated (at Harry’s suggestion) the spectra
of C_{60}^+ molecules in isolation in solid neon or argon matrices (Fulara et al. 1993).

It was later suggested by Foing & Ehrenfreund (1994) that two new DIBs, recently
observed at 9577 Å and 9632 Å, might arise from C_{60}^+, based on their proximity to those of
similar wavelength observed by Fulara et al. (1993) in the solid matrices. The suggestion could
not be confirmed, however, because of uncertainty introduced by matrix-induced wavelength
shifts. Gas-phase measurements were required. Eventually, these were supplied in 2015, also
by the Maier group, via an experiment in which C$_{60}^+$ was confined in a cryogenic trap cooled by helium gas and its spectrum recorded at a temperature of 5.8 K, not far from that of the interstellar medium (Campbell et al. 2015). The two new DIBs at 9577 Å and 9632 Å were thereby positively identified, with an almost exact match in wavelength and linewidth with two absorption bands of gaseous C$_{60}^+$. The authors also tentatively suggested that two much weaker DIBs at 9366 Å and 9429 Å also arose from C$_{60}^+$. 

Harry was of course delighted that his friend John Maier had been successful, especially in view of an interview (https://www.youtube.com/watch?v=TV2NzD16vv0) on the BBC television programme Horizon in which the interviewer said (in connection with Harry’s prediction about C$_{60}^+$ and the DIBs): ‘But others have said that they are nothing like a match for the Diffuse Interstellar Bands.’ Harry smiled and replied: ‘They’re wrong!’ This exchange illustrates very well Harry’s self-belief and scientific courage.


As already noted, there were signs in his research output in 1995/6 that Harry Kroto’s research focus was changing to include the study of materials and in particular the opportunities offered by the discovery of carbon nanotubes. From 1997 until 2016 Harry published approximately 160 articles. Although some of these continued with investigations of the chemical and physical properties of the fullerenes, there is an increasing emphasis on carbon nanotubes, nanowires and metal–organic frameworks, the last being the most recent.

Carbon nanotubes appear to have been discovered independently by several groups over a long period of time. They can be found in the soot produced by the discharge of a carbon arc, while Smalley and co-workers (Guo et al. 1995) used a laser-ablation method to generate them. There are now many methods of macroscopic scale production. Carbon nanotubes are fullerenes in the sense that they are composed of carbon atoms linked together in hexagons and appear like a rolled-up hexagonal mesh. The tubes have diameters $\sim 10^{-9}$ m (hence the name nanotubes) and can have lengths many millions of times their diameter. They can be single-walled or multi-walled. They have many remarkable properties, including high electrical and thermal conductivity along the tube axis, high tensile strength and, as a further example, the ability to encapsulate metals.

During the period 1995 to 2004, the Kroto research group at the University of Sussex, in collaboration with others, published about 100 research articles concerned with carbon nanotubes, nanotubes composed of other materials, and various related nanostructures. David Walton, Jonathan Hare and Nicole Grobert were co-authors of many of these. Only a relatively small number of the most-cited examples will be mentioned here. The group synthesized carbon nanotubes via the catalytic pyrolysis of acetylene (62) and reported a method for the controlled production of aligned carbon nanotube bundles (63). They also synthesized and measured the properties of nanowires composed of Fe (64) or Sn-Pb (65) sheathed in carbon nanotubes. They synthesized carbon nanotubes coated with WS$_2$ (72), but also produced nanotubes composed only of WS$_2$ (67) and measured their shockwave resistance (73). The Sussex group additionally showed how to promote the growth of niobium disulfide
(NbS$_2$) nanotubes by means of a carbon nanotube template (70). The electronic field emission characteristics of NbS$_2$ nanotubes were tested after discovering a method of making large scale samples (74). Routes to molybdenum disulphide (MoS$_2$) nanotubes were devised (68), as well as methods to generate mixed-phase W$_x$Mo$_y$C$_z$S$_2$ nanotubes (69) and silicon-based nanostructures (66). Alloy nanowires, composed of Invar metal inside carbon nanotubes, were an interesting development (71). Research into the chemistry and photophysics of the fullerenes also continued during the period, although the number of published articles decreased significantly compared with the period 1990–1996.

The move to Florida State University at Tallahassee

In 2004, Harry became 65 years old, retired from his position at the University of Sussex and accepted an offer from the Florida State University (FSU), Tallahassee, to take up the Francis Eppes Chair of Chemistry. One reason for the move was to ensure the continued funding of his research, but he was also interested because FSU was keen to explore new ways of using the Internet for educational outreach. This led to GEOSET (Global Educational Outreach for Science Engineering and Technology; see the next section). Another advantage of the move was that Margaret Kroto gave up her job and became the full-time organizer of Harry’s extensive travel plans, and frequently accompanied him. The translation to FSU led to only a short hiatus in research output. His research on nanotubes continued to flourish, with important discoveries such as the in situ nucleation of carbon nanotubes by injection of carbon atoms into metal particles (76), the production of a flexible, cross-linked, multi-walled carbon nanotube paper capable of sensing hydrogen at low concentration (79), and polyurea-functionalized multi-walled carbon nanotubes (75). There was a resurgence of fundamental work on the fullerenes in collaboration with FSU colleagues Paul Dunk and Alan Marshall, including seminal papers on the closed network growth of fullerenes (80), the bottom-up formation of mono-metallofullerenes as directed by charge transfer (82) (both in *Nature Communications*), and formation of the smallest stable fullerene M@C$_{28}$ (M = Ti, Zr or U) grown from carbon vapour (83). He also made contributions in the area of metal–organic framework systems (MOFs) in collaboration with Anthony Cheetham FRS and with FSU colleagues Naresh Dalal and Prashant Jain (77, 78). One article on MOFs has the intriguing title, ‘Electric control of magnetization and interplay between orbital ordering and ferroelectricity in a multiferroic metal–organic framework’ (77).

Harry and Margaret (see figure 10) were forced to return permanently to their home in Lewes, East Sussex, in the autumn of 2015, somewhat earlier than they had planned owing to the onset of motor neurone disease (also known in the USA as either amyotrophic lateral sclerosis or Lou Gehrig’s disease) which progressed rapidly and from the complications of which Harry died on 30 April 2016.

**Other science-based activities: outreach, the Vega Trust and GEOSET**

Harry was undoubtedly charismatic. He was relaxed in the company of children and was certainly not pompous or diffident, as some scientists can be. He was also blessed with a voice/accent that was easy to listen to, but at the same time commanded attention. He was therefore well equipped to pursue successfully his long-standing interest in educational outreach. In 2004, Harry became 65 years old, retired from his position at the University of Sussex and accepted an offer from the Florida State University (FSU), Tallahassee, to take up the Francis Eppes Chair of Chemistry. One reason for the move was to ensure the continued funding of his research, but he was also interested because FSU was keen to explore new ways of using the Internet for educational outreach. This led to GEOSET (Global Educational Outreach for Science Engineering and Technology; see the next section). Another advantage of the move was that Margaret Kroto gave up her job and became the full-time organizer of Harry’s extensive travel plans, and frequently accompanied him. The translation to FSU led to only a short hiatus in research output. His research on nanotubes continued to flourish, with important discoveries such as the in situ nucleation of carbon nanotubes by injection of carbon atoms into metal particles (76), the production of a flexible, cross-linked, multi-walled carbon nanotube paper capable of sensing hydrogen at low concentration (79), and polyurea-functionalized multi-walled carbon nanotubes (75). There was a resurgence of fundamental work on the fullerenes in collaboration with FSU colleagues Paul Dunk and Alan Marshall, including seminal papers on the closed network growth of fullerenes (80), the bottom-up formation of mono-metallofullerenes as directed by charge transfer (82) (both in *Nature Communications*), and formation of the smallest stable fullerene M@C$_{28}$ (M = Ti, Zr or U) grown from carbon vapour (83). He also made contributions in the area of metal–organic framework systems (MOFs) in collaboration with Anthony Cheetham FRS and with FSU colleagues Naresh Dalal and Prashant Jain (77, 78). One article on MOFs has the intriguing title, ‘Electric control of magnetization and interplay between orbital ordering and ferroelectricity in a multiferroic metal–organic framework’ (77).

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outreach. Harry enjoyed giving talks to school children from early in his career. No doubt demand for his talks increased after the discovery of $\text{C}_{60}$, and the fame endowed by a Nobel Prize does no harm when it comes to attracting an audience. His famous $\text{C}_{60}$ ‘Buckyball’ workshops were popular not only because of their hands-on, model-making content, but also because of his gift for engaging children’s attention. They were as successful with primary school children as they were with secondary school pupils. The mutual enjoyment felt during these kinds of interactions is evident from the photograph in figure 11 taken at a ‘Buckyball’ workshop in Malaysia.

Harry felt that the Nobel Prize heightened his long-held sense of responsibility to promote the public understanding of science, especially among children and young adults. In his later years he was in very great demand to give research lectures, and travelled extensively for that purpose—he once told me that he received about one invitation per day involving international travel. He adapted the conference travel to suit his outreach interests, however. He would certainly attend a conference and give a research lecture, but he would also fit in one or
more children’s workshops during the same trip. His ‘Buckyball’ workshops are well-known throughout the world, and have been held in many countries including Australia, Japan, Italy, Malaysia, Germany, Mexico, Sweden, Colombia, Chile, Spain, USA and India. After moving to Florida State University, he used to invite groups of children from elementary schools into the chemistry department for the same purpose. He also did many children’s workshops via the Internet, some of which are available here: http://vega.org.uk/video/subseries/29 (accessed February 2017). One of the ‘Buckyball’ workshops took place at Manchester United Football Club, where two first team players at the time, Diego Forlan and John O’Shea, were recruited to help. This workshop was recorded and is available as a video on the website.

As a result of his special relationship with the University of Sheffield and Bolton School, he participated in regular workshops in both cities, those in Sheffield being organized by the university’s outreach team and its Kroto Research Institute, and he always responded positively (his hectic schedule permitting) to requests from wherever they came.

Others aspects of the public understanding of science were also important to him. In 1994, together with ex-BBC producer Patrick Reams, he created the Vega Science Trust which provided a broadcast platform for the science, technology, engineering and mathematics (STEM) communities, so enabling them to communicate on all aspects of their fields of expertise using exciting Internet opportunities. The Vega Science Trust website http://www.vega.org.uk/ (accessed February 2017) is an amazing and priceless resource that will appeal to anyone with even a passing interest in science. Not only is it already of great historical significance, but it also communicates very effectively the excitement engendered by all aspects of contemporary science. It makes accessible, for example, video recordings of famous scientists discussing their research. Included in these are lectures by Richard Feynman ForMemRS, the outstanding science communicator of his era, interviews with Max Perutz FRS, John Walker (FRS, 1995), Walter Kohn (ForMemRS, 1998), Fred Sanger FRS, Sherwood Rowland (ForMemRS, 2004) and Harry himself (all Nobel Prize winners) and many more. Also available from the Vega Science Trust website are videos of the following types: BBC documentaries, master classes in science, some devoted to art and science, those provided as an educational resource, those intended to help with science careers and, of course, recordings of Harry’s ‘Buckyball’ workshops. The Vega website ceased to be updated in 2012, but it remains an important resource.

Harry’s presidency of the Royal Society of Chemistry from 2002 to 2004 was a role which provided him with an appropriate platform, and many further opportunities, to contribute to the public understanding of chemistry.

Two years after the move to Florida State University at Tallahassee in 2004, Harry set up GEOSET, for which he raised the funds himself. He was helped on the technical aspects by Steve Acquah, who later became the director of the project. GEOSET is a web-based organization, introduced to provide a free resource of educational material. The main website provides a database gateway that links the many institutions that contribute to GEOSET with the local GEOSET site at FSU. The purpose of GEOSET is best described in Harry’s own words http://www.kroto.info/geoset/ (accessed February 2017):

Whereas almost all educational programmes focus on a particular student cohort, the GEOSET initiative’s paradigm shifting strategy is to turn the focus of the educational process round by 180 degrees to target our best teachers and capture Specific Educational Objects or Concept Modules which they have devised to infuse real enthusiasm and passion for intellectual knowledge in
students. Although the GEOSET site streams many outstanding lectures and courses, as indicated above, the primary aim is the creation of an easily accessed cache of specific Teaching Tricks Of The Trade i.e. TTOTTs which outstanding educators have found by experience work. Until now the educational genius of a teacher is in general lost when he or she retires unless a student who also becomes an educator remembers it and uses it in class. GEOSET (and its more inclusive sister GEOSTEAM encompassing the arts and mathematics now in preparation) gives our teachers a measure of immortality previously unavailable.

**OTHER NON-SCIENCE-BASED INTERESTS**

Outside science and education, Harry’s main intellectual passion was for graphic art. As a graduate student at Sheffield, he entered the *Sunday Times* book-jacket design competition and won first prize in the amateur section. The winning design is shown in *figure 12*, which also displays his design for the dust jacket of the first edition of his monograph *Molecular rotation spectra* published in 1975. Other examples of his graphic art can be seen on his website [http://www.kroto.info/graphics/](http://www.kroto.info/graphics/) (accessed February 2017). His sporting passion was tennis, a game that he played with colleagues at Sussex until he was relatively old.

Not surprisingly, in view of the treatment of his parents in Germany and the UK between 1937 and the end of the Second World War, Harry was a passionate member of Amnesty
International. In fact, for many years the only tie I ever saw him wear carried the familiar ‘candle wrapped in barbed wire’ logo of that organization. He was opposed to all religion, for which he said he had never seen any reason. He spent a considerable amount of time when in Florida opposing the teaching of creationism in high schools as an alternative to teaching of the theory of evolution. In his autobiographical piece on the Nobel Prize website (81), he sets out in detail his reasons for being an atheist and a humanist. On his website http://www.kroto.info/where-i-stand/ (accessed February 2017) may be found his views on scientific, political and religious topics, set down in a forthright manner.

**APPOINTMENTS, PRIZES, HONOURS**

**Appointments**


2004–2015 Florida State University, Francis Eppes Professor of Chemistry

**Membership of societies/national academies**

1990 Fellow of the Royal Society
1993 Mexican Academy of Science; Member Academia Europaea
1997 Hon. Foreign Member Korean Academy of Science and Technology
1998 Hon. Fellow of the Royal Microscopical Society
1998 Hon. Fellow of the Royal Society of Edinburgh
2000 Hon. Fellow of the Royal Society of Chemistry
2002–2004 President of the Royal Society of Chemistry
2003 Foreign Member of the Finnish Academy of Science and Letters
2005 Academy of Sciences (Torino)
2007 Foreign Associate of the National Academy of Sciences (USA)

**Medals and prizes**

1982 Tilden Lectureship and Medal (Royal Society of Chemistry)
1992 Italgas Prize for Innovation in Chemistry 1992
1993 Longstaff Medal (Royal Society of Chemistry)
1994 Hewlett Packard Europhysics Prize (shared with Wolfgang Krätschmer, Don Huffman and Richard Smalley)
1994 Moet Hennessy Louis Vuitton LVMH, Science pour l’Art
1996 Knighthood
1996 Nobel Prize for Chemistry (shared with Robert Curl and Richard Smalley)
1998 Dalton Medal (Manchester Lit and Phil)
1999 Blackett Lectureship (Royal Society)
2000 Ioannes Marcus Marci Medal for Spectroscopy (Prague)
2001  Faraday Award and Lecture (Royal Society)
2002  Erasmus Medal of Academia Europaea
2002  Copley Medal (Royal Society)
2005  Order of Cherubini (Torino)
2008  Kavli Lecturer (Royal Society)

Honorary doctorates

Université Libre de Bruxelles (Belgium)
University of Stockholm (Sweden)
University of Limburg (Belgium)
University of Sheffield (UK)
University of Kingston (UK)
University of Sussex (UK)
University of Helsinki (Finland)
University of Nottingham (UK)
Yokohama City University (Japan)
University of Sheffield-Hallam (UK)
University of Aberdeen (Scotland)
University of Leicester (UK)
University of Aveiro (Portugal)
University of Bielefeld (Germany)
University of Hull (UK)
Manchester Metropolitan University (UK)
Hong Kong City University (Hong Kong, P. R. China)
Gustavus Adolphus College (Minnesota, USA)
University College London (UK)
University of Patras (Greece)
University of Dalhousie (Halifax, Nova Scotia, Canada)
University of Strathclyde (Scotland)
University of Manchester (UK)
Kraków Mining University (Poland)
University of Durham (UK)
Queens University Belfast (NI)
University of Surrey (UK)
Politecnico di Torino (Italy)
University of Chemical Technology Beijing (China)
University of Liverpool (UK)
Florida Southern College (USA)
Keio University (Japan)
University of Chiba (Japan)
University of Bolton (UK)
University of Hartford (USA)
University of Tel Aviv (Israel)
University of Poitiers (France)
Universidad Complutense de Madrid (Spain)
Naresuan University (Thailand)
Harold Walter Kroto

Vietnam National University (Hanoi)
University of Edinburgh (UK)
University of Primorska (Slovenia)

Honorary degrees returned in protest after closure of chemistry departments or courses
Hertfordshire University (UK)
University of Exeter (UK)

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Author profile

Anthony Legon

Anthony Legon was educated at the Coopers’ Company School in Mile End, London, from where he went to University College London to study for the BSc (Special) degree in chemistry from 1960 to 1963. He subsequently conducted his doctoral research at UCL with Professor D. James Millen. He continued at UCL for some years as a lecturer and then reader in chemistry, but spent the whole calendar year 1980 on sabbatical leave working in Willis Flygare’s laboratory at the University of Illinois, Champaign-Urbana. He later held the chair of physical chemistry at the University of Exeter from 1984 to 1989 and from 1990 to 2005, was Thomas Graham Professor of Chemistry at UCL in 1989/90, and finally Professor of Physical Chemistry at the University of Bristol from 2005 to 2008. He is currently Professor Emeritus and Senior Research Fellow in Bristol. Legon’s main research interest is in the understanding of non-covalent interactions (especially those involving hydrogen bonds and halogen bonds) of small molecules in the gas phase. His contributions to this field have been recognized by his election as a Fellow of the Royal Society in 2000 and the awards of the Tilden (1989) and Liversidge (2012) Lectureships and Medals of the Royal Society of Chemistry.

References to other authors

Campbell, E. K., Holz, M., Gerlich, D. & Maier, J. P. 2015 Laboratory confirmation of C_{60}^{+} as the carrier of two diffuse interstellar bands. Nature 523, 322–323. (doi:10.1038/nature14566)


Guo, T., Smalley, R. E. & Scuseria, G. E. 1993 *Ab initio* theoretical predictions of C\(_{28}\), C\(_{28}H_4\), C\(_{28}F_4\), (Ti@C\(_{28}\))H\(_4\) and M@C\(_{28}\) (M = Mg, Al, Si, Ca, Sc, Ti, Ge, Zr and Sn). *J. Chem. Phys.* **99**, 352–359. (doi:10.1063/1.465758)


**Bibliography**

The following publications are those referred to directly in the text. A full bibliography is available as electronic supplementary material via [http://dx.doi.org/10.1098/rsbm.2017.0003](http://dx.doi.org/10.1098/rsbm.2017.0003) or via [https://doi.org/10.6084/m9.figshare.c.3705754](https://doi.org/10.6084/m9.figshare.c.3705754).


(10) 1975 Molecular rotation spectra. London: John Wiley and Sons.


(50) 1993 (With R. Taylor, G. J. Langley, A. G. Avent, T. J. Dennis & D. R. M. Walton) $^{13}$C NMR spectroscopy of C$_{76}$, C$_{78}$, C$_{84}$ and mixtures of C$_{86}$–C$_{102}$: anomalous chromatographic behaviour of C$_{82}$ and evidence for C$_{70}$H$_2$. J. Chem. Soc. Perkin Trans. 2 1029–1036. (doi:10.1039/P29930001029)


(60) 1997 Symmetry, space, stars and C$_{60}$: Nobel Prize lectures in chemistry. Rev. Mod. Phys. 69, 703–722. (doi:10.1103/RevModPhys.69.703)


Biographical Memoirs


