JAMES PHILIP ELLIOTT
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James Philip Elliott made important contributions to improve our understanding of the structure of atomic nuclei in the second half of the twentieth century. In 1958 he proposed the SU(3) model, explaining rotational behaviour of nuclei in the context of the shell model. His idea, based on elegant and seminal group-theoretical concepts, reconciled the independent-particle with the liquid-drop model, which until then existed as disconnected views of the nucleus. In the 1960s and 1970s he developed methods to extract properties of the nuclear interaction from the phase shifts of nucleon–nucleon scattering. From 1980 until his death he contributed to the development of the interacting boson model of Arima and Iachello, and its microscopic understanding in terms of symmetries of the shell model. For his outstanding achievements in theoretical physics, in 2002 he and Francesco Iachello were awarded the Lise Meitner prize of the European Physical Society for ‘their innovative applications of group-theoretical methods to the understanding of atomic nuclei’. His achievements were also recognized by the award of the Rutherford Medal and Prize of the Institute of Physics in 1994.

EARLY LIFE AND FAMILY BACKGROUND

James Philip (Phil) Elliott was born on 27 July 1929 in Gosport, Hampshire. He was the son of James Elliott and Dora Kate Elliott, née Smith. He had one elder sister, Doreen Joan Coats, married to George Coats.

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Phil’s father, son of a country labourer who worked as a gardener, was one of eight children and he left school very early, with little formal education, to help earn money for the family. The family lived in Tanyard, Midhurst, Sussex. He started with very simple jobs, such as delivering shoes for the shoe-menders. He then joined the railway, first cleaning the steam engines, and worked his way up to fireman then engine driver. Finally he was the foreman driver at the Gosport train depot, near Portsmouth.

Phil’s mother’s family ran a bakers and grocers business in the small town of Cocking in Sussex, a few miles away from Midhurst. The business was bankrupted in the 1920s when she was a child. She trained in Chichester to be a teacher and became the headmistress of the two-teacher village school in West Lavington on the edge of Midhurst. Not untypical of a rural area, the other teacher later became Phil’s aunt. Phil and his sister benefitted greatly in their early days at school from the help and encouragement of their mother. Phil left home in 1946 to go to university and until then he lived with his family in a house rented from the railway, just outside Gosport station.

**SCHOOLING**

All of Phil’s schooling was within the state system. First he attended an infant school, from 1934 to 1936, very close to home. He is recorded as saying that he had no happy memories from there because of the formidable women teachers. Despite this, he came near the top of the class in reports.

The junior school, Newton Boys, he attended from 1936 to 1939. It was a bit further away from home, about a 15-minute walk into Gosport town. At Newton Boys all the teachers were men. They were just as strict as the awesome ladies in the infant school, but friendlier.

In later life he did not recall being taught any science in junior school but there was plenty of maths and arithmetic, which he enjoyed. He was always at or near the top of the class. In 1939 he was successful in the examination that determined whether one went on to attend a grammar or secondary modern school. This examination became popularly known as the 11+ when it was formally included in the Butler Education Act of 1944. He was only 10 years old at the time of this examination, his birthday being just prior to 1 August, and, as a brighter pupil, he gained entry to Gosport Grammar School.

These were, of course, turbulent and dangerous times, with Britain and France declaring war on Germany on 3 September. Portsmouth and neighbouring Gosport were obvious targets. Not surprisingly, just as Phil joined the grammar school it was evacuated to Eastleigh, which is about 20 miles away. By chance a large new school building had been built at Eastleigh for the local elementary secondary school. It was decided that the two schools would share the building, with one school having a long ‘academic or classroom’ morning followed by an afternoon of games and other outdoor pursuits. The other school did the same things but the other way round. This pattern then alternated week by week. It sounds awkward but, according to Phil, it worked.

**GOSPORT GRAMMAR SCHOOL**

Despite the turmoil of the war years, academic work proceeded quite smoothly. Much of this was due to the newly appointed young headmaster, Alan Walker, and a number of experienced
teachers who had returned from retirement to fill the void created by teachers who joined the armed forces. As we find in Boxall (2001), the headmaster ran the school with a fine blend of discipline and kindness.

At Gosport, mathematics became ever more fascinating for Phil as taught by the main teacher H. F. (Bunny) Dent, a Cambridge graduate. He emphasized the logic and beauty of the subject. The physics teaching left little impression, devoted as it was to remembering rather than understanding things. Chemistry from the enthusiastic and popular E. J. (Sandy) Day was a different matter. He conveyed the fascination of science and, in spite of it being wartime, had managed to build a well-equipped laboratory at the school in Eastleigh.

At grammar school, the more able pupils missed a year, so that Phil was more than a year younger than his classmates. He was consistently near or at the top of the class. At 14 years old, in 1943, he passed the General School Certificate in eight subjects with five credits and very good in mathematics. Two years later he passed the Higher School Certificate in physics, chemistry, pure maths and applied maths. Because of the evacuation, the school had shrunk in pupil numbers. The small sixth form meant that much of the day was spent in private study. Phil stayed on for a third year in the sixth form to take the County Scholarship exam. Alan Walker, the headmaster, advised him not to try for Oxbridge scholarships. His view was that even if Phil won every possible scholarship, he would have had grave difficulty in maintaining the Oxbridge lifestyle. At the same time he saw that Phil would prosper at the local University College of Southampton, then a university college providing London external degrees. Phil took the advice. He won a Hampshire County Scholarship in Mathematics that covered fees and living expenses for three years. He was the first person in his family to enter university. Looking back later he felt Alan Walker’s advice had been wise. His stay at Southampton was happy and successful.

Phil was very keen on sport, just as his father had been, and was an enthusiastic footballer and cricketer. Indeed he captained the school football and cricket teams in his last two years. Figure 1 shows him in this role in both teams. The passion for sport never deserted him. Phil was also the Head Prefect for his last two years. He was already showing that he could lead and take responsibility.

**University of Southampton**

Phil was admitted to the Honours Mathematics Degree course at Southampton. In the first term students had to take physics as well as mathematics. Those who did not perform well in the subsequent examinations then moved on to a general degree course in physics and maths. Phil dropped physics because he had found the detailed course on electromagnetism too much, although he enjoyed the laboratory work.

Phil had Dr Hamburger, a refugee from the war, as his personal tutor. He was an expert on Hilbert spaces. He lectured to the first year on analysis, which the students found tough, with Dedekind sections and nests of intervals posing a real challenge. For Phil it was the linear algebra—as he was to find, so basic for quantum physics—taught by Nancy Walls (her maiden name) that really made an impact. This was partly the nature of the subject but also because her teaching was inspirational.

The honours maths class was small, only eight students, so the students had the benefit of close contact. The head of department was Professor Janto Davies. He ran a friendly department at a difficult time. The graduating students were awarded London (external) degrees.
Figure 1. Phil Elliott as captain of the school football and cricket teams. In both cases he is seated in the centre of the front row. He maintained a passion for sport throughout his life.
The way forward after graduation was not straightforward for Phil. He was liable to be called up for military service and he was pondering the idea of joining the Inland Revenue. By chance, however, things were changing in the university at Southampton. A new professor, Hermann A. Jahn, had just been appointed as professor of applied mathematics. He moved from the University of Birmingham, where he had worked in the Department of Mathematical Physics under Rudolph Peierls FRS. Jahn was setting up a group and looking for graduate students to work on the structure of atomic nuclei. This appealed to Phil because he was keen to apply his mathematics and not just study it for its own sake. It also meant that his military service was deferred while he was still a student.

Jahn was best known for his work on the application of mathematical methods to atomic shell theory. In particular he was known for the Jahn–Teller theorem (Jahn & Teller 1937), which states that degenerate configurations of non-linear molecules cannot be stable. During the war Jahn had worked at Farnborough on the vibration of aircraft wings. Afterwards he returned to university life at Birmingham, where Peierls encouraged him to turn his attention to nuclear theory and, in particular, look at how group theory, then being applied by Giulio Racah (Racah 1942a,b, 1943, 1949) to the shell theory of atoms, could be used in nuclear theory.

Jahn set Phil to work on the structure of light nuclei, namely $^6$Li and $^{10}$B, including non-central forces such as the tensor and spin–orbit forces. He was also directed to calculate magnetic and quadrupole moments. Jahn introduced him to tensor operators, coefficients of fractional parentage, the group $U(2l + 1)$ and its subgroups. In other words he had to learn about group theory. Jahn was, of course, an expert in applying it to atomic systems, but here there was an added difficulty. Now one is dealing with a system of neutrons and protons, whereas one only has electrons to worry about in atoms. In the nuclear case, isobaric spin is a key feature of the system.

Before launching into all of this, Phil had to repair the holes in his physics. As you will recall, he had left that behind after the first term’s electromagnetism. He had to quickly catch up on quantum mechanics and nuclear physics by reading books by Paul Dirac FRS, Hermann Weyl ForMemRS, van der Waarden and Richard Courant and David Hilbert ForMemRS, as well as a well-known review (Bethe & Bacher 1936) on nuclear physics.

It was a very good time to be introduced to nuclear structure. Experimental facilities and methods were developing fast. Theoretically, the angular momentum techniques developed by Racah in the 1940s were now available, and Jahn was one of the first to appreciate these techniques and the associated group theory. Phil benefitted a lot from Jahn’s work, as we can see in Phil’s tribute to him at the Jahn memorial lecture (22)*.

Phil remembered some highlights from his time as a student with Jahn. At one point Jahn presented him with some of his calculations that led to conflicting results. Phil was able to see the flaw in his arguments and remove the conflict. No doubt that must have been a big boost to his confidence. Phil also discovered a new mathematical relationship for angular momentum coupling that later became known as the Elliott–Biedenharn theorem, since Biedenharn had also discovered it independently at about the same time. In his thesis, Phil used two-body coefficients of fractional parentage to compute the matrix elements for non-central forces for

* Numbers in this form refer to the bibliography at the end of the text.
The calculations were carried out in $LS$ coupling. This was the accepted basis of what was then known as the quasi-atomic model, later known as the nuclear shell model. Phil’s work showed that if one wanted to reproduce the properties of the p-shell nuclei then non-central forces were essential. One also needed one-body spin–orbit splitting because of the interaction of the valence nucleons with the nucleons in the $^4$He core. Together with Jahn he published a brief letter in *Nature* (1). The full paper, with all the mathematical details, was published later (2).

All of this was carried out in just two years at Southampton, and these were not the days of high speed computers. Most of the work was done on hand-operated calculators such as the Facit or later the electrically powered Marchant. The work was completed in the two years, but it took another year before it was all written up. The oral examination for Phil’s PhD was carried out by Sir Harrie S. W. Massey FRS and C. A. Coulson FRS. The degree was finally awarded by London University in 1953.

One considerable bonus of his time as a graduate student was that Phil met his future wife, Mavis Rosetta Avery. She was also a student at Southampton and was training to be a teacher.

**AERE Harwell 1951–1959**

After the two years of intense effort on his postgraduate studies Phil was anxious to begin to earn some money, even although he had not yet completed the writing of his thesis. He joined the Theoretical Physics Division of the Atomic Energy Research Establishment (AERE) at Harwell. He was fortunate that Jahn had maintained contact with Peierls at Birmingham. Peierls, together with M. H. L. Pryce (FRS 1951), had just taken over the leadership of the Theory group at Harwell, following the dramatic and highly publicized arrest of the previous head, Klaus Fuchs, in 1950. Jahn had learned that there was a vacancy in the Theory group at the lowest level of scientific officer. The position was intended to support work on neutron-transport problems. Jahn recommended Phil, who was interviewed by Peierls and offered the job. Again, the nature of the job meant that his military service was further deferred. The move to Harwell almost came to naught because of a dispute with the Civil Service about salary. Salaries were subject to additional annual increments for the postgraduate years, but only after the age of 21 and Phil had been 20 in his first postgraduate year.

Given the great fuss about the arrest of Fuchs it came as a surprise to Phil that his new boss was Boris Davison, another Russian, but he was an émigré who had fled from communist Russia. No surprise: Phil found that he had a lot to learn. To devise approximate solutions for neutron-transport equations he needed integral transforms and complex variable theory. This was necessary to look at neutron transport in various geometrical situations of interest to reactor designers and possibly to weapons specialists. Davison turned out to be very helpful in this regard; he gave a series of lectures on a wide variety of integral transforms. Later Davison moved to Canada and wrote a definitive book on the topic (Davison & Sykes 1958). Most of what Phil did in this period was written up as Harwell internal reports, but one more lasting piece of work on Milne’s problem with a point source was published later (4).

He might have continued in this line of work but for the appointment of B. H. (Brian) Flowers (FRS 1961), later Lord Flowers, to be head of the Theoretical Division in 1954. Flowers had worked on the wartime nuclear project at Chalk River in Canada. On his return, he completed a DSc under Peierls at Birmingham on nuclear structure. Flowers was at that
time interested in extending the group-theoretical methods of Racah and Jahn from $LS$ to $jj$
coupling (Flowers 1952). Following the work of Mayer (1949) and of Haxel et al. (1949), who
provided a simple explanation of the magic numbers observed in nuclei, it became necessary
to develop the classifications and the fractional-parentage methods for the nuclear $j$ shells. He
was keen to encourage more basic physics at Harwell and he was aware of Phil’s thesis work
on nuclear structure. So Phil was encouraged to return to nuclear structure studies; half time
at first, but when Neutron Transport moved to AEE Winfrith, it became full time.

Brian Flowers was very active in nuclear structure theory, as was A. M. (Tony) Lane (FRS
1975). The theory division was an intellectually stimulating place with a very productive group
led by Tony Skyrme. Besides Phil, it included John Bell (FRS 1972), Tony Lane, John Perring,
Roger Phillips and John Soper. Skyrme organized regular informal meetings of the group in his
office. One of the group was charged with selecting an important paper in the latest journals
and presenting it to the group. Lively discussion followed, often in the form of a dialogue
between the speaker and Skyrme. For this reason the meetings were known as ‘Skyrmishes’.
The group also interacted with the neighbouring Oxford group that included Roger Blin-Stoyle
(FRS 1976), David Brink (FRS 1981) and M. H. L. Pryce. Members of the group attended
Oxford seminars. Blin-Stoyle invited Phil to give lectures at Oxford on group theory and
angular momentum. There was also an experimental group at Harwell, with a Van de Graaff
accelerator, who were interested in measuring energy levels, moments and transition rates in
nuclei. Joan Freeman and George Morrison were members of this group part of the time. This
was Phil’s introduction to direct interaction with experimenters, although at this time Flowers
took the lead in the interactions during their collaboration on the spectrum of $^{19}$F and the
odd-parity states in $^{16}$O.

The Theory group at Harwell made some of the major advances in nuclear theory, and
Phil was at the heart of some of them. For example, together with Lane, he showed how a
constant two-body spin–orbit force induces a variable one-body spin–orbit term in the nuclear
mean field, consistent with the data known at that time (3). This helped to clarify the nature
of the nucleon–nucleon force. A beautiful contribution, made together with Skyrme, was the
analysis of the separation of centre-of-mass motion from the internal motion of the nucleons
in the context of shell-model calculations (6). Their proposed solution is elegant and simple
and is used to this day.

Shell-model calculations with configuration mixing (requiring the diagonalization of
matrices of modest size with a few hundreds of matrix elements) were becoming possible and,
together with Flowers, Phil started a programme to explore the feasibility of this approach to
nuclei at the beginning of the $sd$ shell, just beyond $^{16}$O. The isotopes $^{18}$F and $^{19}$F could be
described with a Gaussian central force with a single parameter and a one-body spin–orbit
term taken from $^{17}$O (5). The energy spectrum and other properties of the nucleus $^{20}$Ne,
with two valence neutrons and two valence protons in the $sd$ shell, could be calculated,
following ideas by Wigner (1937), in a favoured-supermultiplet approximation; that is, in
a basis restricted to states that are totally symmetric in space and totally anti-symmetric
in spin and isospin. When mixing with other supermultiplets was included, as a result of
spin-dependent interactions and in particular the spin–orbit interaction, the dimensions of the
matrices became prohibitively large. These and similar numerical calculations for other $sd$-
shell nuclei consistently showed that a single-$j$ shell would have been an inadequate basis and
that $s$ and $d$ orbits were inextricably mixed. It was an important lesson that was to be brilliantly
exploited by Phil.
In his lectures at Oxford he described how Racah applied group theory to classifying the allowed anti-symmetric states for many particles in a particular shell and also analysing the interactions by its group-theoretical properties. He had seen from the shell model study of $^{19}\text{F}$ that in nuclei the shells were inextricably mixed. It was this that made him ask himself whether Racah’s ideas could be extended to mixed shells and led him to his best-known work that brought together the shell and collective models. During this time he wrote several review articles on the shell model. Of particular note was a long article in *Handbuch der Physik* with Tony Lane (7).

SU(3)

To appreciate the full extent of his subsequent achievement, we need to take a step back and consider the landscape of atomic nuclei as they were understood in the middle of the twentieth century. On the one hand there was the recent achievement of Mayer (1949) and of Haxel et al. (1949), who made a substantial breakthrough in our understanding of nuclei by recognizing the importance of the spin–orbit coupling. Until then, the interpretation of nuclei took place in an $LS$-coupling basis, in analogy with what was found in atoms, and it was assumed that the total orbital angular momentum $L$, associated with the orbital motion of all nucleons, and their total spin $S$ are conserved quantities during the nucleonic motion, giving rise to several glaring discrepancies with observed nuclear properties, not least the failure to explain the ‘magic numbers’ as found in all but the lightest nuclei. A strong coupling between the orbital motion and the spin of each nucleon destroys the $LS$ classification and leads to a $jj$-coupling basis, where each nucleon has a well-defined angular momentum $j$ that arises from the coupling of its orbital angular momentum to its spin. The hypothesis of a strong spin–orbit coupling lacked theoretical foundation but was nevertheless immediately adopted because of its empirical success. The ensuing model, now commonly referred to as the (spherical) nuclear shell model, became the standard way of interpreting nuclei and soon a wealth of mathematical techniques was developed, allowing adaption to nuclear $j$ shells; reviewed, for example, by de-Shalit & Talmi (1963). The starting point of the nuclear shell model is the independent motion of the individual nucleons in a $j$ shell, giving rise to excitations that involve specific nucleons; in other words, to so-called single particle excitations. A departure from this first-order image is only possible through interactions between the nucleons and the mixing of single particle configurations.

Around the same time, alongside this independent-particle picture, a very different model of the nucleus was being developed by Bohr & Mottelson (1953). Their starting point was to consider the nucleus as a dense, charged liquid drop, which was known since the 1930s to provide a remarkably accurate description of nuclear masses. There was no reference to the individual motion of the nucleons, but excitations of a nucleus were associated with vibrations of the droplet’s surface or with its rotations in the case of a non-spherical shape. The collective model, as it became known, was vindicated by many observations, especially in heavy nuclei where rotational bands were found to be ubiquitous.

So, the middle of the twentieth century saw the rise of two successful nuclear models based on two different, seemingly contradictory, views of the nucleus—single particle versus collective. This situation would still have been acceptable if the models were to describe different nuclei or different nuclear states, but it became increasingly clear that this was not the case: $sd$-shell nuclei such as $^{20}\text{Ne}$ and $^{24}\text{Mg}$ were found to display collective characteristics.
(rotational bands with energies that follow a $J(J+1)$ pattern, with band members that are connected by strong electric quadrupole transitions), but could also be described with the spherical nuclear shell model. How could this be?

The solution to this conundrum was given by Phil. He was, first of all, familiar with the work of Racah, who had analysed the substructure of the unitary algebra $U(2l+1)$ that appears in the problem of many electrons placed in a single-$l$ shell. The study of the subalgebras of $U(2l+1)$ must have seemed an esoteric topic to many at that time, but Phil realized that some profound physical ideas were hidden behind it. For example, Racah (1943) had identified the orthogonal subalgebra $SO(2l+1)$ of $U(2l+1)$ and had associated it with the ‘seniority number’—the number of electrons not in pairs coupled to orbital angular momentum $L=0$.

Secondly, Phil was aware that Wigner’s supermultiplet classification of $p$-shell nuclei leads to an orbital $SU(3)$ algebra and of the suspicion that this was at the origin of the rotational behaviour of nuclei such as $^8$Be. It was thus natural (but, as it usually goes, also remarkably insightful) to study the algebraic substructure of $U(6)$, which is the relevant algebra for the $sd$ shell of the harmonic oscillator. It turned out that $U(6)$ contained, besides a trivial $U(1) \times U(5)$, corresponding to a separate treatment of $s$ and $d$ shells (ruled out on the basis of numerical shell-model calculations), the orthogonal subalgebra $SO(6)$ and, more importantly, also the subalgebra $SU(3)$. In fact, Phil proved (8) that the algebra of any entire harmonic oscillator shell $p, sd, pf, sdg, \ldots$ contains $SU(3)$ as a subalgebra and hence that valence nucleons, even if confined to such a shell, may display rotational behaviour. Furthermore, he was able to show (9), this time through an analysis of the algebraic substructure of $SU(3)$ itself, that a single one of its irreducible representations corresponds to one (or several) intrinsic state(s) out of which all states of one (or several) band(s) can be projected. After the derivation of these results, it remained to establish the physical origin of the reduction from $U(6)$ to $SU(3)$. This, according to the recollections of Phil himself (26), became clear during a discussion with Ben Mottelson in Copenhagen in 1957. It can indeed be shown that the isoscalar quadrupole interaction between nucleons is responsible for the lowering of symmetry (8, 9).

All of this took place at Harwell—where he lived at Ridgway House, the guest house at Harwell, for the first few years. The communal life was good, although he felt isolated at times. He could indulge his passion for football by playing for AERE in various local leagues. He also sang in the AERE choir, although he says he sang rather feebly. He had taught himself to play the violin from about 16 and played in the second violins of the Abingdon Orchestra and later recalled that he had practised late at night in the AERE squash court because of the acoustics there. Then, on 10 September 1955, he married Mavis Avery at the Congregational church in West Wickham, Kent. They went on to have a son, Michael, and two daughters, Jacqueline and Catherine. They had a long and happy marriage. In figure 2 we see them on honeymoon in Guernsey; family walks in the hills were long a feature of their family life.

**University of Rochester 1957–1958**

Although he was happy with his work at Harwell, Phil felt that it was time to look for a university post, where teaching and research could be combined. Now, together with Mavis and their first child Michael, he took a first step in this direction when he was given leave of absence to take up a visiting associate professorship at the University of Rochester in New York State. He had hesitated because Michael was so young, but he was persuaded by Franz
Mandl among others; Mandl had made a similar visit the previous year. The family crossed the Atlantic on the *Queen Mary*. It cost about the same as the airfare, but with the great merit of being able to carry much more luggage. The trip was supported in part by a Fulbright scholarship.

The year was a profitable one. R. E. Marshak was the head of department at the time. He had worked on the Manhattan Project during the war. At Rochester he had moved from nuclear physics to its bourgeoning offshoot, particle physics. Bruce French was the head of the nuclear structure group and was known for his work on reactions as well as structure. Both of these men made Phil very welcome. He and Mavis were lucky enough to be able to rent the house of a Rochester academic who was in Europe for a year. Bruce French also taught Phil to drive. This was, of course, essential in the US.

During the year he taught two graduate courses. One was on nuclear structure theory and the other was on nuclear reactor theory, which for Phil required more preparation. The latter was usually given by Marshak, but he was happy to have a year off. It was customary in Rochester at that time that a graduate student would write up the notes of a visiting lecturer. Malcolm Macfarlane made a first-class job of the notes under the title ‘Collective motion in nuclei’ (10). Marshak wanted to publish them as a small book in a series he was editing. Phil delayed because he wanted to add to it. Unfortunately he was very busy and, as a result, it was never published. Marshak chided him, in a friendly way, that his department had to cover the costs for supplying the many copies of the notes that were requested.

During this year, which he enjoyed very much, Phil visited a number of other universities to give seminars and he attended the annual American Physical Society meeting in Washington. He visited Chicago and had an interesting discussion with Wigner on the relation between Wigner’s SU(4) and Phil’s SU(3). The full group is, of course, SU(4) × SU(3).
UNIVERSITY OF SOUTHAMPTON 1959–1962

With his work on SU(3), Phil’s reputation in the world of nuclear physics was firmly established. Shortly after he returned to Harwell from Rochester, Brian Flowers moved to a chair in physics at the University of Manchester. Phil might have joined him, but because all of their family connections were near the south coast he was reluctant to move permanently north. In career terms this did not look like a good decision. There was a rapid increase in the growth of nuclear physics activity in the Manchester region, Daresbury Laboratory and also Liverpool. However, he was now keen to move to a university.

A position became available in the Department of Applied Mathematics at his alma mater, the University of Southampton. The university had become independent of London in 1952 with the granting of its charter. He applied and was successful in obtaining a lectureship under his former supervisor Hermann Jahn, who was still head of applied mathematics. Apart from Jahn’s students, there was little other nuclear physics.

There were new challenges for Phil with teaching and a growing family. He also acquired several research students, notably Malcolm Harvey, to continue the development of the SU(3) methods. One thing he missed at Southampton was close interaction with nuclear structure experimentalists. However, that was to change.

UNIVERSITY OF SUSSEX 1962–1994

In September 1961 Phil received a letter from Roger Blin-Stoyle, whom he had known and interacted with when he was at Harwell. The letter told him that Blin-Stoyle had just been appointed to the chair of theoretical physics at the new University of Sussex in Brighton. The university was to admit its first science students in September 1962. The letter invited him to apply for a position as senior lecturer in theoretical physics. Again, this was not a simple decision. He was teaching in a mathematics department where he felt at home. The staff at Southampton had been very helpful and he felt a commitment to Southampton. There were, however, strong attractions of the Sussex offer. First, he would be part of a much larger group of nuclear physicists than in Southampton. Second, it would take him back to his family roots in Sussex. Third, it would be exciting to be part of something new. It had apparently been agreed that a large part of the teaching of maths to science students would be done by theoretical physicists, and he would be involved in the planning of that. All of this won the day and he moved to Sussex. He was to stay there until he retired formally in 1994.

Phil’s first year, 1962, turned out to be a very busy year. He taught at two international summer schools. The first was in Mexico City at the invitation of Marcos Moshinsky, with whom he had links. The second was in Prague, where most of the students were from the east side of the Iron Curtain.

The University of Sussex had research as a main priority from its beginning. Phil was soon joined by E. A. (Eric) Sanderson and later, in 1967, by J. A. (Tony) Evans; both of them had been students of Gerry Brown from his days in Birmingham. In his time at Sussex Phil published about 80 papers. Vital contributions to these papers were made by a succession of research fellows, including Harry Mavromatis (Lebanon), Andy Jackson (USA), Ram Tripathi (India), Nabil Kassis (Palestine), Ernesto Maqueda (Argentina), Stan Szpikowski (Poland), Peter Park (Canada), Piet Van Isacker (Belgium), Giu Lu Long (China) and Vi Sieu Lac (Australia). The group suffered a heavy blow when Eric Sanderson died prematurely in 1985.
The group held regular meetings, sometimes with the experimental group of Dennis Hamilton, that were steered by Phil. Everybody was expected at some point to contribute to the discussion and explain his or her latest research. The atmosphere was never aggressive but somehow Phil succeeded in voicing his critical opinion in a clear but gentleman-like manner, guiding his interlocutor towards a correct solution of the problem at hand. His standards were high. Above anything else, he tried to instil in those he mentored respect for experimental observation: no model, however algebraically elegant, would get his approval if it was disconnected from experiment. There was close collaboration with the experimental group of Dennis Hamilton, who was always very keen for his graduate students to understand as much about nuclear theory as possible. A good example was David Warner, an experimenter who showed an excellent grasp of theory (e.g. Casten & Warner 1988). In joint meetings of the group it was a case of ‘standing room only’ because of the large number of students in the experimental group.

Quite apart from his research, Phil’s career flourished at Sussex. He was promoted in 1964/65 to reader and a few years later to professor. He went on to be head of physics, and from 1979 to 1984 he was dean of mathematics and physics. In the latter role he provided great support to Sir Denys Wilkinson FRS, then the vice-chancellor, in a period of considerable student unrest. Wilkinson paid him tribute for this in the eulogy he delivered at Phil’s memorial service.

By the time of his retirement Phil was unhappy with how universities had developed. In his youth they were ‘communities of scholars’, but, in his words, they had become more like a ‘factory’ with ‘products’ (students) being turned out by a ‘workforce’ (academics) under the direction of a ‘management’ (administration). The great expansion in student numbers had led to this situation, but it was far from clear that it was in the best interests of students or our society.

**SU(3) continued**

Phil’s research at Sussex fell, by and large, into three phases. In the first phase there was a continuation and development of his work on SU(3) until about 1968. Malcolm Harvey completed his thesis and moved to a position at Chalk River in Canada. New students joined: Colin Wilsdon from Oxford and Marie Claire Bouten from Belgium. Bouten developed an interpolation method between SU(3) and $jj$ coupling that could be applied to the whole $sd$ shell (15). For practical calculations it was necessary to extend the techniques of Racah to the algebra of SU(3) and to calculate matrix elements in this basis (12). Another extension was to implement a departure from an exact $LS$ coupling in the SU(3) scheme. This could be achieved by noting that the one-body spin–orbit term in the SU(3) basis, which is mostly responsible for the breaking of $LS$ coupling, approximately leads to a new intrinsic quantum number $K = K_L + K_S$, the sum of the spin and orbital angular momentum projections on the $z$ axis. The inclusion of this breaking turned out to be essential for a correct description of odd-mass $sd$-shell nuclei (18).

**The Sussex interaction**

The second phase of Phil’s work at Sussex began when he lectured in 1965 and 1966 at summer schools in Varenna (13) and Herzeg-Nov (14) on rather more general questions of
nuclear forces and structure. This took him away from soluble models with simple forces like pairing and quadrupole to the search for more realistic forces, consistent with detailed nucleon–nucleon scattering results. A course of lectures on many-body theory by Brian Easlea, another of Gerry Brown’s students, caught his attention particularly. So, in parallel with the work on SU(3), Phil and his colleagues embarked upon a programme to deduce nuclear interaction matrix elements from experimental nucleon–nucleon phase shifts. The main objective was to transport the information contained in the phase shifts over into the nuclear many-body problem. Until then, this was usually done by assuming some parameterized form of the nucleon–nucleon interaction and deducing its parameters from a least-squares fit to the phase shifts. Phil and his collaborators showed that, provided the two-body matrix elements are expressed in an oscillator basis, brackets due to Talmi (1952) and Moshinsky (1959) can be used that transform two-particle wave functions to centre-of-mass and relative coordinates. This method was first applied in a Born approximation to the entire nuclear potential (16), and later, in its definitive form, by introducing an auxiliary potential in a distorted-wave Born approximation (17). As a by-product, the method established an unambiguous relation between the matrix elements in an oscillator basis and the decomposition of a two-body interaction into its central, symmetric and anti-symmetric spin–orbit and tensor parts—a connection that is used to this day in shell-model calculations.

During the 1970s Phil worked, together with P. G. Dawber, on a major project, the writing of a monograph on the use of symmetry in physics (19); it was translated into Russian in 1983 and into Chinese in 1986. The book captures the essence of Phil’s approach to physics, which is to put the powerful and abstract techniques of group theory at the service of theories and models of physics. It has become one of the standards in the field of group theory which is still used today by physicists in all areas. He was also in demand as a speaker at conferences and international schools of nuclear physics; figure 3 shows him speaking at the International Symposium on Capture Gamma Ray Spectroscopy in Grenoble, France, in 1981.

**THE INTERACTING BOSON MODEL**

The third phase of Phil’s work at Sussex began in the mid 1970s. Virtually all our understanding of nuclear structure is based on the idea of an assembly of neutrons and protons. Even the rotational model of Bohr & Mottelson (1953) has microscopic roots in the Nilsson potential for individual nucleons in a deformed field. In the early days of nuclear physics there was also some success with the alpha particle model, but it was limited to a few light nuclei.

The middle of the 1970s saw the rise of a new collective model of the nucleus, the interacting boson model (IBM) of Arima & Iachello (1975). Although Phil had some reservations he saw that it was clearly of interest and it occupied his attention from about 1980 until he retired and beyond. It is assumed in the IBM that low-energy collective states in a nucleus can be described in terms of s and d bosons with angular momenta 0 and 2. There was a lot of interest in the model worldwide because: (a) it had links with both the shell model and the collective model, and (b) it was simple to apply although it had a number of free parameters. The latter feature made it very popular with experimenters since they could readily apply it to their results.

The bosons are interpreted as correlated (or Cooper) pairs formed by two nucleons in the valence shell coupled to the angular momentum 0 or 2. Consequently, a nucleus is
characterized by a constant total number of bosons $N$, which equals half the number of valence nucleons (particles or holes, whichever is smaller). Since a single boson can exist in six different states (one $s$ and five $d$ states), the relevant algebra of the model is $U(6)$, and this must have caught the attention of Phil. In fact, the three dynamical symmetries of the IBM, $U(5)$, $SU(3)$ and $SO(6)$ (see Iachello & Arima 1987), were known to Phil from his earlier shell-model work on $sd$-shell nuclei. He realized, however, that while both algebras are $U(6)$, the physics behind them is different. In the IBM-1, the original and simplest version of the model, where no distinction is made between neutron and proton bosons, all states are necessarily in a symmetric representation of $U(6)$. This is not the case in the nuclear shell model when fermions are considered in the $sd$ shell. Owing to the short-range attractive nature of the nuclear force, nucleons occupy a maximally symmetric spatial configuration, but can only do so consistent with the Pauli exclusion principle. As a result, in the $sd$ shell, the relevant $U(6)$ representations are not necessarily symmetric, and this renders a straightforward connection between the IBM-1 and the nuclear shell model difficult. A microscopic interpretation of the IBM, namely its justification in terms of the nuclear shell model, is more naturally obtained by distinguishing between neutron and proton bosons, leading to the second version of the model, the IBM-2 (Arima et al. 1977). The connection can be established by associating, for neutrons and protons separately, the seniority quantum number $v$ in fermion space with $2N_d$, twice the number of $d$ bosons. This is the essential idea behind the OAI mapping (Otsuka et al. 1978), which is limited to spherical or weakly deformed nuclei.
Phil realized that the underlying principle of the OAI mapping was the identification of corresponding symmetries and quantum numbers in fermion and boson spaces. For a better microscopic understanding of the IBM it was thus necessary to develop versions of the model where shell-model symmetries were naturally built in. Together with A. P. White, this led him to propose another version of the model (20), known as IBM-3, which includes a neutron–proton boson (i.e. a fermion pair made up of one neutron and one proton). Since the IBM-3 includes a complete $T = 1$ triplet, with neutron–neutron, neutron–proton and proton–proton bosons, states with good isospin can be constructed and associated with the corresponding shell-model states. Soon afterwards, together with Tony Evans, he proposed the most elaborate version of the model (21), IBM-4, in which the bosons were also assigned an intrinsic spin $S$. It included the IBM-3 bosons with $S = 0$ and $T = 1$ and an additional set of bosons with $S = 1$ and $T = 0$.

The problem that interested Phil most was the microscopic justification of the IBM in terms of the nuclear shell model, and, while the first IBM-3 and IBM-4 papers (20, 21) outlined a programme in this direction, much remained to be done to achieve this goal. In later work, he applied the IBM-4 to nuclei in the $sd$ shell (23), but most of Phil’s research in the 1980s and 1990s was devoted to the problem of the relation of the isospin-invariant IBM-3 to the nuclear shell model. It led to a series of papers in which sometimes intricate group-theoretical methods were used to arrive at this goal, as described in his review articles (24, 25).

In one of his last papers, co-authored with Tony Evans, Phil applied his by now famous SU(3) model to further the microscopic understanding of the IBM (27). The starting observation was another implicit assumption in the mappings considered so far; namely, they are all based on a seniority scheme, either SU(2) or SO(5). But it is known that seniority is mixed in deformed nuclei, hence putting any known mapping on a questionable basis in such nuclei. Phil and Evans proposed, therefore, to use SU(3) as the connecting symmetry between fermion and boson spaces. As in the earlier first papers on IBM-3 and IBM-4 (20, 21), an outline is given for how this deformed mapping can be achieved by listing the relevant representations in both spaces (27). It is a programme of research that surely is worth pursuing.

Phil’s SU(3) model has been one of the most important breakthroughs in nuclear physics, since it bridged the gap between the two contrasting views of the nucleus that were developed in parallel in the 1950s and it did so by introducing the elegant and seminal concept of spectrum generating algebras or dynamical symmetries. The pioneering character of this work is self-evident when one realizes that it occurred several years before similar ideas developed in high-energy physics in the context of the eightfold way. Phil’s work is widely cited by nuclear physicists, but arguably is still not recognized at its true value by other physics communities. His achievements were, however, recognized by the award of the Rutherford Medal and Prize of the Institute of Physics in 1994; figure 4 shows him being awarded the prize by Clive Foxell, president of the Institute of Physics. In addition, for his outstanding achievements in theoretical physics, he and Francesco Iachello were awarded the Lise Meitner prize of the European Physical Society in 2002 for ‘their innovative applications of group-theoretical methods to the understanding of atomic nuclei’.

**Family life at Sussex**

The background to all of Phil’s work at Sussex was a happy and fulfilling family life. He was a busy man, but he had time for his children. He often worked in his study with the door
closed or in the sitting room marking exam papers, but he was always interested in what they were doing. He greatly enjoyed working in the garden at their house in Lewes as well. He found it an ideal way to relax, and he was good at it; he kept the family supplied with fruit and vegetables all year round. He encouraged the children in the garden too, and ensured they each had a bit to call their own. They also helped him some of the time, especially at harvesting. They topped and tailed gooseberries, popped runner beans or shucked broad beans and peas, encouraged by the promise that they could watch television if they did it.

Phil maintained his passion for football and cricket. His daughter Jacky recalls that, before she left home, she sometimes went with him to watch Brighton football club play and he was a very vocal spectator—he made sure the players knew what they should be doing. If the game was worth it, he also watched it on television or listened on the radio.

He retained an enjoyment of classical music and opera and occasionally country music. His taste in comedy lay with The Goons, Spike Milligan and Monty Python. As we see from figure 2, he liked the outdoors life. Holidays often involved walking on the moors and the mountains of Great Britain. He was also good at mending things, a trait inherited perhaps from his father and now passed on to his son. If something was broken, he could often mend it with bits and pieces from his ‘culch pile’.
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