Rep. Prog. Phys. 52 (1989) 823-879. Printed in the UK

Nuclear physics in the United Kingdom 1911–1986

W E Burcham

Department of Physics, University of Birmingham, Birmingham B15 2TT, UK

Abstract

After a brief introduction on work in classical radioactivity this article attempts to present the main contributions made in the United Kingdom, up to 1986, to the concept and understanding of the atomic nucleus. Particular phases of the development of nuclear physics in the country have been chosen and in each (if relevant) attention is given to the interaction between the Universities, Government Laboratories and Government and other funding agencies. From the work thus supported some examples of experimental and theoretical advances have been selected.

This review was received in March 1989.

0034-4885/89/070823+57$09.00

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1. Introduction: classical radioactivity and the nuclear atom

When Ernest Rutherford arrived in Cambridge from New Zealand in 1895 the Cavendish Laboratory was directed by J J Thomson. Röntgen's discovery of x-rays in 1895 had provided Thomson and his students with a powerful tool for the study of the gaseous discharge; in 1896 Rutherford joined him in this work. In that same year radioactivity was discovered by Becquerel and it was quickly seen that the radiations from uranium could be used as a new tool for producing ionisation. But Rutherford also saw that the ionisation response could be used to learn something about the radiations themselves. From the years 1896 to 1898, when he moved to McGill University, Montreal, came the recognition of two main types of radiation:

(i) *the α rays*, readily absorbed by thin metal foils and later shown to be helium nuclei;

(ii) *the β rays*, more penetrating than the α rays and now known to be (negative) electrons.

Later, and elsewhere, the γ *radiation* which is part of the electromagnetic spectrum was also identified in radioactive decays. Rutherford's work (1899) on the radiations established the ionisation method for the study of radioactivity; the general programme of research at the Cavendish at the time the work started is described by Rutherford himself (1910).

Rutherford was in Montreal until 1907 and there with Soddy proposed the revolutionary *atomic transformation theory* of radioactive change, which is summarised in a Bakerian lecture to the Royal Society (Rutherford 1905) and in his first book (1906); this work led to the award of the Nobel prize for chemistry to Rutherford in 1908. According to this theory, atoms of a radioactive substance disintegrate spontaneously with the emission of either an α or a β particle and with the formation of a new chemical atom, which itself may further disintegrate. Rutherford and Soddy (1902) illustrated the changes that occur by following the decreasing activity of ThX ($^{224}_{88}$Ra) extracted from thorium and the recovery of ThX in the original sample, as shown in figure 1. Similar results were obtained at about the same time though not in such great quantitative detail by Sir William Crookes (1900) using uranium and UX. The work of Crookes, carried out in his personal laboratory in London, led later to the discovery of the scintillation property of zinc sulphide under α-particle bombardment (Crookes 1903).

Rutherford and Soddy observed that a specific radioactive atom is characterised by a *decay constant* λ in the exponential law $N_t = N_0 e^{-\lambda t}$ relating the number of radioactive atoms present in a sample at time t to that at time zero. From this the familiar half-value period $T_{1/2}$ is readily found to be $T_{1/2} = 0.693/\lambda$. They also noted that disintegration products should be present in radioactive minerals and soon Ramsay and Soddy (1903, 1904) at University College, London demonstrated the direct production of helium from radium emanation. This was beautifully confirmed by Rutherford and Royds (1909) who allowed α particles to pass through a thin glass wall to form helium in a formerly helium-free space. Ramsay worked further on the emanation, determining its atomic weight by direct weighing (Gray and Ramsay 1911), but none

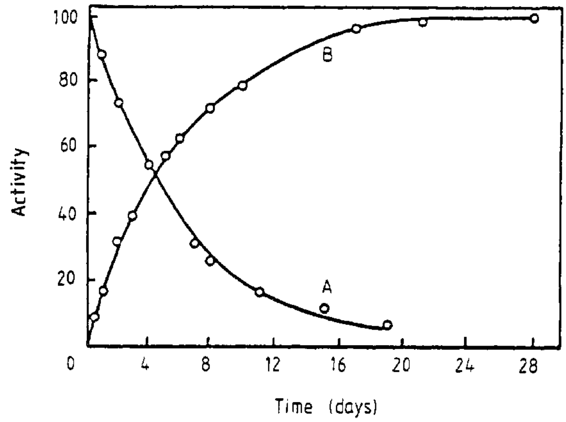


Figure 1. Radioactive decay: curve A, decay of ThX extracted from thorium; curve B, recovery of ThX activity in a thorium sample after a chemical separation of ThX (Rutherford and Soddy 1902).

of this work gave any clue to the origin of the radioactive rays. The time was ripe for a major breakthrough and that came in 1911 in Manchester.

Owens College of Manchester was founded in 1851 and became part of the Victoria University in 1903/4. The city was prosperous and supported a vigorous cultural life in which the new University played a full part. In 1907 Rutherford succeeded Sir Arthur Schuster in the Langworthy chair of physics; it was to be an outstandingly successful appointment (Birks 1962) and probably the happiest period of Rutherford's life. Certainly he lost no time in setting up apparatus to continue his McGill experiments and he was fortunate in obtaining from the Vienna Academy a loan of 450 mg of radium bromide from which radon could be withdrawn for source preparation. At McGill he had noticed a blurring of the photographic image left by a collimated α-particle beam that had traversed a thin absorber. Similar deflections were also observed in β-particle scattering at Cambridge (Crowther 1908) but Rutherford knew that α rays were much harder to deviate than the lighter β particles and he therefore asked Geiger to search for further evidence for the intense electrical forces that must exist in the atom. The first requirement was for an absolute single-particle detection method and this led to the important technical development of the electrical particle counter (Rutherford and Geiger 1908, figure 2*a*). Comparisons between this and the scintillation screen so far used for α detection verified the efficiency and reliability of the latter and in fact scintillation detectors were used almost exclusively for about the next twenty years.

Geiger's scattering experiments (1910) seemingly verified the predictions of Thomson (1910) that the total deflection of an α particle in passing through matter should be the (small) resultant of a large number of small deflections from encounters with individual atoms (figure 3*a*). But there were signs of an anomaly and Marsden (Birks 1962) was asked to look especially for *large-angle* scattering (figure 3*b*). He found it in such measure as to render the Thomson atom structure untenable and Rutherford's interpretation (1911) was to envisage single-scattering from a massive central *nucleus* in the atom. His simple classical calculation of the scattered intensity on the basis of an inverse square law of force was verified and extended by Darwin at Manchester in what is an early example of the cooperation of experiment and theory. Darwin showed that only the inverse square law could account for the experimental results; wave-mechanical verification followed much later (Mott (1928), after Wenzel).

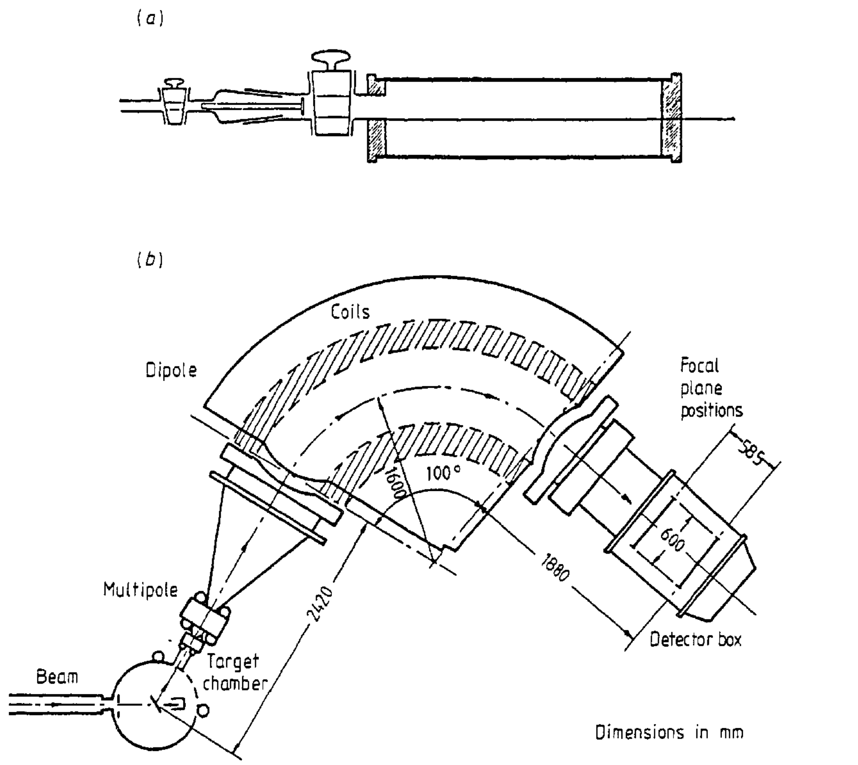


Figure 2. Particle detection. (*a*) Gas (proportional) counter used by Rutherford and Geiger (1908) for counting single α particles. The ionisation pulses were observed with an electrometer. (*b*) A modern spectrometer for heavy particle detection and momentum measurement (Pringle *et al* 1986). The detector box in fact contains proportional counters.

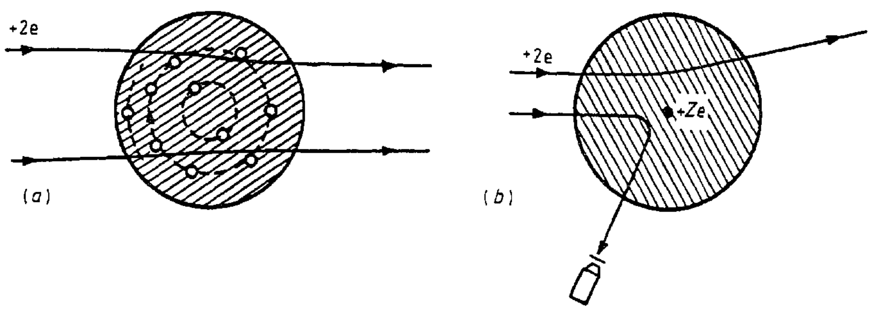


Figure 3. The scattering of α particles by an atom: (*a*) the Thomson model and (*b*) the Rutherford model.

The planetary atom model proposed by Rutherford, in which the electrons filled a sphere of atomic dimensions surrounding the central nucleus, was not immediately recognised as a major advance. But in 1912 Niels Bohr visited Manchester and with first-hand knowledge of the nuclear hypothesis he was able on his return to Copenhagen to introduce the new quantum theory into the atom model with spectacular results. In the next year he sent Rutherford the first of three papers (Bohr 1913) in which the concept of stationary, non-radiating electron orbits appeared and very soon Moseley (1913, 1914) in Manchester had interpreted the characteristic x-ray spectra of many elements in terms of the Rutherford–Bohr atom. His work was a confirmation of the suggestion of van den Broek in Holland that the number of electrons in the neutral atom and hence the nuclear charge in units of the electron charge taken positive should be the *atomic number Z* of the element, i.e. its ordinal number when arranged in a sequence of increasing atomic weights. Bohr worked again in Manchester in 1914-6 and published more papers both on atomic spectra and on the stopping power of matter for charged particles, but by then the seminal work had been done. That work, which launched the Rutherford-Bohr atom into twentieth-century physics, was nurtured in Denmark, but incontrovertibly had its roots in the United Kingdom.

2. The nucleus 1911-1932

2.1. Survey

Rutherford's laboratory in Manchester during the years 1911-4 was a busy, happy and exciting place with many visitors from overseas and a remarkable output of published work. Although tests of the nuclear hypothesis had a high priority the main effort was still in the properties of the radioactive radiations and in the genetic relationships proposed by the transformation theory. Knowledge of the radiations became more quantitative and particular difficulties, such as those enshrouding the origin of the β and γ radiation began to appear. These of course simply stimulated the experimental effort. But interruption was at hand because during the war of 1914-8 most of the laboratory staff left, and the forward thrust of the nascent nuclear physics all but vanished. Only through the devotion of Rutherford himself, in his own meagre time free of war work, was progress maintained. Working alone except for his assistant Kay on the collisions of α particles with light atoms, he was led to the discovery of artificial transmutation (§ 2.2); it was a superb culmination to the years of achievement at Manchester.

Rutherford succeeded J J Thomson as Cavendish Professor of Experimental Physics in Cambridge in 1919. Aston was already at Cambridge but Chadwick came from Manchester and among others in the period under review were Ellis, who had met Chadwick at a prisoner-of-war camp in Germany during the war, Blackett who had served in the Royal Navy, Allibone, Appleton, Cockcroft, Dee, Feather, Kapitza, Lewis, Massey, Oliphant, Sargent, G I Taylor, Walton, C T R Wilson and Wynn-Williams. They were joined year after year by visitors from overseas attracted by the reputation of the laboratory and the eminence of its leader, and of course by research students from Cambridge and other universities. In his Bakerian lecture to the Royal Society in 1920 Rutherford looked forward to the study of the nucleus by the collision method that he had pioneered in Manchester and this became the main research programme of his laboratory although it was accompanied (§ 2.2) by a continued attack on the problems of the radiations themselves. Much of what was achieved is presented in the book *Radiations from Radioactive Substances* by Rutherford, Chadwick and Ellis, whose publication in 1930 marked in a sense the conclusion of the great epoch of classical radioactivity that had begun in 1896. As far as the nucleus was concerned, that was in 1930 simply a structure of protons and electrons.

Under Rutherford the Cavendish was a laboratory for *experimental* physics. Bohr in Copenhagen meanwhile had set up a school of *theoretical* physics but this pattern was not followed in Cambridge, although Dirac's fundamental paper on quantum mechanics appeared in 1925 and the new (wave) mechanics was applied by Fowler and by Mott especially to appropriate problems; results from the theory of barrier penetration even began to appear in Rutherford's own papers. And, in 1928, Hartree published a paper on the self-consistent field of force in the atom that was later to greatly influence nuclear calculations. But the laboratory primarily trained *physicists* and this was to prove highly important for the development of general physics in the country because the effects of the war on university research had been serious. Moreover research was not well funded although the creation of the Department of Scientific and Industrial Research (DSIR) in 1915 and of the University Grants Committee (UGC) in 1919 provided welcome access to public funds. Among the institutions besides the Cavendish Laboratory that sought such support were the Universities of Oxford, where Soddy and Russell continued work on the radioactive series and London (Imperial College) where G P Thomson, after his appointment in 1930, introduced nuclear physics and cosmic ray physics into the research programme. The general study of radioactivity also continued at Manchester after Rutherford's departure and E J Williams, at Manchester and Cambridge, worked on the energy loss of charged particles in matter. Support for equipment and for research staff was also provided by the Royal Society and by Trusts and Foundations such as the Goldsmiths' Company as well as by universities and colleges, but the vital task of supporting research students was primarily that of the DSIR.

2.2. Selected achievements 1911-1932

Rutherford's detailed predictions of the consequences of the nuclear hypothesis for α-particle scattering were verified by Geiger and Marsden (1913). At the same time Soddy and Russell, then in Glasgow, in parallel with Fajans and Hevesy, had formulated the *displacement laws* governing the change in chemical nature of an atom resulting from the emission of an α or β particle. Such evidence, together with the experiments of Moseley on x-ray spectra, was entirely consistent with the role of the atomic number Z of an element as the charge number of the nucleus of the corresponding Rutherford-Bohr atom. Soddy and Russell also established from their radiochemical studies, in parallel with those of Hahn in Germany, that pairs of radioelements with extremely similar chemical properties but different decay constants existed, for example thorium and radiothorium. In 1913 Soddy boldly proposed that such pairs were actually chemically identical because they had the same nuclear charge though different atomic weight. This concept of *isotopes*, together with the displacement laws, established our understanding of the location of the radioelements in the periodic table.

Isotopy was in no way obliged to appear only in the heavy elements. Again in 1913, which was a remarkable year for the nuclear atom, Thomson had seen and Aston had confirmed a 'new gas' of mass 22 whose ions accompanied those of neon of mass 20 in deflection experiments. Immediately after the war Aston (1919) built the first *mass spectrograph* in which separated electric and magnetic deflections provided not only mass resolution but also velocity focusing for a beam of ions. This instrument and its higher precision successor (Aston 1927, 1933) yielded, over the years, an isotopic analysis and hence a physical atomic weight for a large number of elements. From this work came a large and systematic list of accurate masses (relative to an $O = 16$ standard) of neutral isotopic atoms. At the same time, information on the angular momentum and magnetic moment of nuclei began to appear, notably in the work of Jackson at Oxford on optical hyperfine spectra (e.g. for Cs, Jackson 1928, 1934).

Rutherford's personal interest in the α particle continued strongly throughout the period. At Manchester, Geiger and Nuttall (1911) assembled data relating α-particle energy to emitter lifetime which were to lend powerful support to the theory of barrier penetration. Wilson in Cambridge (1912) published pictures of α- and β-ray tracks (figure 4) taken in the expansion chamber which had been under development for several years; some of them showed single scattering events of the sort that Rutherford had postulated.

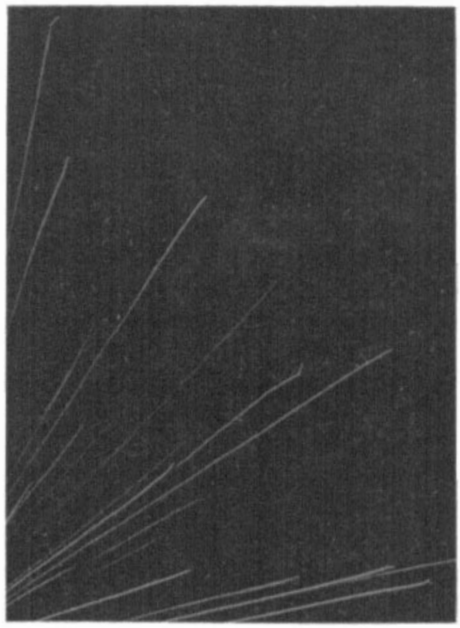
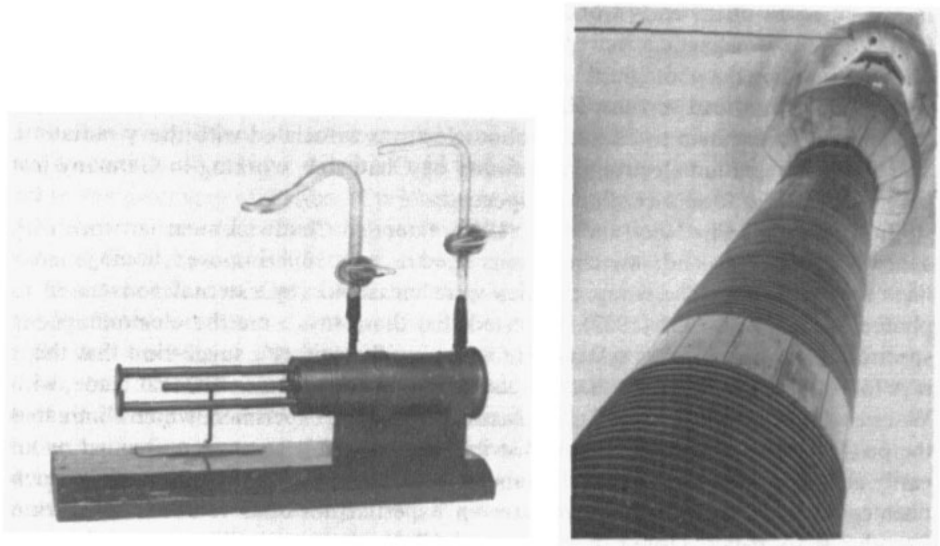


Figure 4. Early α-particle cloud-chamber tracks (Wilson 1912).

One of the first experiments in Cambridge under Rutherford was a determination by Chadwick (1920) of the atomic number of gold, platinum and copper to about 1% by a precision scattering experiment. Later α-scattering experiments (Chadwick 1930) showed that with light elements a deviation from pure inverse-square law scattering occurred, giving evidence for finite nuclear size, while for α particles in helium a quantum mechanical interference effect, predicted by Mott (1930), was seen. According to Mott himself (1986) Rutherford was impressed by this successful example of theoretical interpretation of experiment. Mott's work (1929) also included the important calculation of electron-nucleus scattering which is basic in modern nuclear radius determinations.

In the last years of the war Rutherford had sought to test the theories of Bohr and Darwin concerning the collisions of α particles with light atoms. For hydrogen, oxygen and nitrogen the theories seemed to work well except that there appeared to be an anomalous effect in nitrogen, which many might well have shrugged off. But not Rutherford—he pressed his observations of unexpected hydrogen ions (protons) from nitrogen to the inescapable conclusion that 'the nitrogen atom is disintegrated under the forces developed in a close collision with a swift α-particle'. This was the discovery of artificial transmutation (Rutherford 1919); the simple apparatus used is shown in figure 5(a). The process revealed is now described formally as an (α, p) reaction and is written in symbols as

$$^{14}_{7}N + ^{4}_{2}He \rightarrow ^{17}_{8}O + ^{1}_{1}H.$$



(*a*) (*b*)

Figure 5. The old and the new: (*a*) the Rutherford disintegration apparatus, 1919 (reproduced by permission of the Cavendish Laboratory, Cambridge) and (*b*) the column of the Daresbury NSF tandem accelerator in its pressure vessel, 1982 (reproduced by permission of the Daresbury Laboratory).

This process, which was beautifully depicted in the cloud chamber by Blackett (1925) and by Blackett and Lees (1932) was followed up by Chadwick (1926) in Cambridge. Using RaC′ or Po α particles and scintillation detectors he found that all elements in the periodic table up to potassium except He, Li, Be, C and O underwent an (α, p) reaction. Energy releases were measured, for comparison with Aston's masses if possible and evidence for energy levels in residual nuclei and for resonance processes was obtained (Chadwick and Constable 1932). Interpretation was stimulated by the theory of barrier penetration given by Gamow, who visited Cambridge in 1929. By 1932, the traditional scintillation detector was being replaced by the shallow ionisation chamber, whose pulses were amplified externally and recorded photographically or by the scale-of-two thyratron counter invented by Wynn-Williams (1932). The electrical counting method was used extensively by Rutherford and Chadwick and their collaborators in experiments on the rate of emission of α particles by radium and on the fine structure of α-particle groups from RaC, ThC and AcC as well as in the transmutation work.

For a short time Rutherford had entertained the idea that β particles arose from the electronic structure of the atom despite the requirement of the displacement laws that they should be nuclear. He saw a connection between the discrete lines appearing in magnetic spectra of β radiation and the discrete energy levels of the atom. But the data were at first simply not good enough to support conclusions of this sort and the Manchester laboratory therefore embarked on a systematic study of the radiations from Ra(B+C), including the γ radiation which often seemed to accompany the β rays and which was known to be electromagnetic. This study included the major technical achievement of Rutherford and Andrade (1914) in measuring the energy of low-energy x-rays and γ rays from RaB by the crystal diffraction method. The most important result of the early work was probably the observation of Rutherford *et al* (1914) that in a magnetic spectrographic study of the RaB β rays the same discrete lines appeared on the photographic plate both from a bare source and from that source covered by a thin lead screen. The line, then, were certainly extranuclear in origin and we now know them to be due to photoelectrons associated with the γ radiation. The true disintegration electrons were found by Chadwick, working in Germany just before the war, to form a continuous spectrum.

In Cambridge, Chadwick and Ellis (1922) extended Chadwick's earlier work with a new spectrograph, and saw continuous spectra with superimposed homogeneous lines for Ra(B+C). The γ-ray energies were measured (by external conversion to photoelectrons) and Ellis (1922) suggested that these rays were the electromagnetic spectrum of a nuclear level system. He agreed with Meitner's suggestion that the γ rays followed β transitions to these levels from a parent nucleus. He also made, with Wooster (Ellis and Wooster 1927), the classic calorimetric experiment which eliminated the possibility that the continuously distributed β particles were accompanied by an easily absorbed radiation so that the same energy change could be observed for each disintegration. This work provided later an experimental basis for Pauli's neutrino hypothesis. A paper 'Origin of the γ-rays' (Rutherford and Ellis 1931), although mainly concerned with the α-γ connection, does also round off a period of important experimental contributions in the United Kingdom to our understanding of β decay.

Current understanding of nuclear structure in 1932, just at the time of the great discoveries of that year (§ 3.2) was reviewed at a Royal Society discussion meeting (Rutherford 1932).

3. The beginnings of big nuclear science 1932–1939

3.1. Survey

In 1932 the Cavendish Laboratory under Rutherford saw the discovery of the neutron, the transmutation of lithium by hydrogen ions and the observation of electron pair production. These events, each of which contributed to a Nobel prize award, are fully chronicled by Hendry (1984) and the reader of the articles in this book may well wonder how the laboratory came to lose its pre-eminence in the field by the end of the decade. Certainly the death of Rutherford in 1937 was a major factor, although Bragg, who succeeded him in the Cavendish chair in 1938 did everything possible to maintain the prestige of the laboratory. But during Rutherford's last years there had been losses of senior staff which weakened the Cavendish while strengthening other departments of physics in the country. Among these were the moves of Blackett to Birkbeck College, London, Mott to Bristol and Massey to Belfast in 1933, of Walton to Dublin in 1934, of Chadwick to Liverpool in 1935, of Ellis to Kings College, London in 1936 and of Oliphant to Birmingham in 1937. Some added strength, both to Cambridge and other universities began in 1933/4 with the arrival of refugees from Germany. Through the influence of Rutherford and of Lindemann particularly, temporary university places were found for many, including Bethe, Frisch, Fröhlich, Goldhaber, Peierls and Szilard in nuclear physics. Others such as Simon, Mendelssohn, Kuhn and Kurti were soon also to make their mark on the subject and Max Born brought distinction as a theoretical physicist.

The discovery of pair production by Blackett and Occhialini (§ 3.2) was a success for Dirac's theory of negative energy states as well as for experimental technique. It became part of our understanding of the interaction of radiation with matter but did not lead to a continuing research programme. The discovery of the neutron by Chadwick (§ 3.2), however, had a great effect on both theory and experiment. In the former it avoided the need to pack electrons too tightly and offered an explanation of some observed nuclear spin values, for example of ^{14}N. In the latter it opened the way to a study of nuclear reactions and radioactivity throughout the periodic table, and to the discovery of fission. Curiously, however, neutron physics did not become a major programme at Cambridge. Other laboratories, notably that of Thomson at Imperial College, to which Moon had been appointed in 1932, began to take the lead.

The main thrust of Cavendish nuclear physics after 1932 derived from Cockcroft and Walton's success in disintegrating lithium with fast hydrogen ions (§ 3.2). This might well have been anticipated in one of the laboratories in the USA or Germany which were developing accelerators and indeed Lawrence's cyclotron at Berkeley was itself producing observable disintegrations soon after the Cambridge announcement. Rutherford of course was delighted that the intensity limitation imposed by the use of radioactive sources had been removed, and recognising that strong effects could be seen at energies below 200 keV he asked Oliphant to construct a high-current transmutation apparatus to complement the lower intensity but higher voltage equipment of Cockcroft and Walton. He was not so enthusiastic for the upward extension in energy of the latter apparatus, and for some time he resisted Chadwick's suggestion that a cyclotron should be built, but in the end he supported both, though not until Chadwick had left to build his own cyclotron at Liverpool (Chadwick 1938). In 1935 Sir Arthur Eddington wrote a forceful survey of the achievements of the Cavendish, coupled with an appeal for funds, and in 1936 it became known that Sir Herbert Austin was willing to donate a large sum of money for the furtherance of scientific research; this came to Cambridge. The University had meanwhile undertaken an ambitious rebuilding programme which provided accommodation for new high-voltage accelerators and (in consequence) space to build a cyclotron. The Austin benefaction made it possible to purchase the former from the Philips Company of Eindhoven and a 1 MV accelerator was operating in 1937 just before Rutherford's death. A larger accelerator, nominally for 2 MV but never reaching this level, was also purchased and was operating in 1939. The 8 MV cyclotron was built jointly by the Metropolitan Vickers Company and Cavendish staff, under the general direction of Cockcroft, who had given up high-voltage work in 1935; it was operating in 1938.

The lead thus given in Cambridge was followed elsewhere in the United Kingdom. Chadwick's cyclotron at Liverpool was similar to the Cambridge machine and Oliphant, after a visit to Berkeley, began to build an even larger accelerator of this type at Birmingham, with help from the Nuffield Foundation. At Imperial College, Thomson installed a small electrostatic generator of the type pioneered by Van de Graaff in the USA and prepared for a larger (2 MV) pressurised machine; at Oxford a 400 kV Cockcroft–Walton generator was set up and at Bristol, Powell constructed a similar high-voltage machine for 700 kV. Developments such as these also took place rapidly overseas and by 1939 it was clear that the techniques of electrical engineering were contributing vitally to the growth of nuclear science, which would in the future demand larger equipment and larger resources of both money and manpower. That conclusion was dramatically endorsed by the wartime development of the nuclear reactor (§ 4).

Not all nuclear physics in the country in the 1930s was concerned with accelerated particles. In addition to the development of detecting systems (§ 3.2) there was a β-ray spectrometer group at Birkbeck College and general studies of radioactivity in several universities, including Birmingham. At Oxford, Jackson and Kuhn continued high-resolution experiments in optical spectroscopy, with the notable refinement of the Doppler-free conditions offered by an atomic beam (Jackson and Kuhn 1935). Their experiments, together with other hyperfine work under Tolansky at Imperial College, London and at Manchester, provided much data on nuclear moments and isotope shifts (e.g. for Pt, Tolansky and Lee 1937).

Although theoretical nuclear physics was sometimes decried by Rutherford, the calculations of Gamow and of Mott had a detailed relevance to the Cavendish experimental programme. Fowler, who had guided Mott's work, was a member of the Department of Mathematics, but after his appointment in 1932 as John Humphrey Plummer Professor of Mathematical Physics he had a room near that of his father-in-law (Rutherford) in the Cavendish. He found there a copious supply of problems and during the 1930s he directed the work not only of Mott but of others such as Bhabha, Jaeger, Hulme and Taylor who were able to apply Dirac's relativistic quantum mechanics to the problems of the interaction of radiation with matter. Dirac himself was also a member of the Department of Mathematics, but with the exception of Blackett, he did not interact directly with experimentalists. In contrast, others such as Massey at Cambridge and Williams at Manchester were equally at home in both experiment and theory, and there was even sometimes a direct challenge to theory, such as the invitation by Chadwick to Peierls to work out the theory of the deuteron photodisintegration (§ 3.2). The presence in Cambridge at least of so many able theoretical physicists conveyed one great advantage—quantum mechanics was taught at both undergraduate and postgraduate level to physicists as well as to mathematicians. But outstanding work later to be significant for nuclear structure was done elsewhere, particularly at Bristol and at Imperial College, London where Fröhlich *et al* (1938) discussed what is now known as the meson theory of nuclear forces and used the neutral meson (Kemmer 1938) to ensure charge independence. And at Manchester, Hartree (1935) had set up a mechanical differential analyser for numerical calculations which was a forerunner of the electronic digital computer (e.g. EDSAC at Cambridge).

Research support and training of research students (who were often candidates for the PhD degree) in the 1930s continued through the channels that had earlier been established, namely the DSIR for specialised research equipment and for student maintenance grants and the UGC for university general funds. From these funds grants for research and teaching were made at the discretion of university authorities. Private foundations and benefactors also continued support. From the point of view of nuclear physics as a university discipline, the subject may perhaps be said to have come of age during the period, and its increasing maturity was marked not only by specialised conferences such as the International Conference on Nuclear Physics in Cambridge in 1934 but also by the publication of text books (e.g. Feather 1936) and specialised review articles.

3.2. Selected achievements 1932–1939

3.2.1. The positron and the neutron. In 1931 Occhialini joined Blackett in Cambridge. He brought with him from Italy the technique of coincidence counting that was being used by Rossi for cosmic ray studies and Blackett saw at once that this could be used to control a cloud chamber actuating mechanism so that a picture need only be taken when a particle had passed through the chamber. The particles present in cosmic ray showers at sea level are usually energetic enough to traverse a chamber and in 1933

Blackett and Occhialini published shower pictures, taken in 1932. Some of these (figure 6) contain tracks of particles of electronic mass and positive charge, shown by their curvature due to a magnetic field applied to the chamber. Despite the prediction of such particles (positrons) by Dirac's theory (1930), Blackett was extremely cautious in advancing his own photographs as evidence for their existence. While every possible source of confusion in the pictures was being thoroughly checked, Anderson in the USA published a photograph, taken in a cloud chamber randomly expanded, of a single magnetically bent track passing in a known direction through a lead plate. Because of the unambiguous interpretation of his photograph Anderson is generally credited with the positron discovery although Blackett's shower pictures, without a claim for new positive particles, appeared before Anderson's. Since the showers seemed to include a non-ionising stage a search was also made for pair production by γ rays and this was found (Chadwick *et al* 1934). In this work the positron mass was established as 1.02 ± 0.10 times that of the electron, its spin was indicated as equal to that of the electron and the inverse process to pair production, namely positron annihilation, was predicted. It was realised that the annihilation radiation had already been seen, but not understood, in some earlier Cavendish experiments on the absorption of hard gamma radiation.

In Rutherford's Bakerian lecture of 1920 occur the words 'Under some conditions, however, it may be possible for an electron to combine much more closely with the H nucleus forming a kind of neutral doublet . . .'. The search for such an object, which

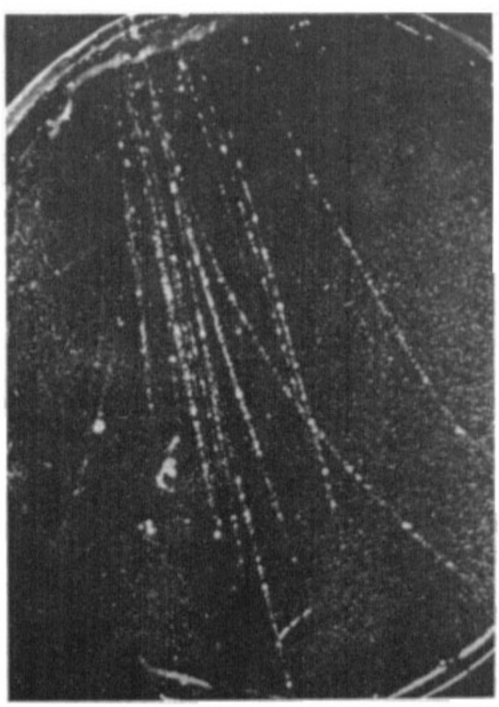


Figure 6. Cloud chamber tracks of particles in a cosmic ray shower, including some with a positive charge (Blackett and Occhialini 1933).

was later called the neutron, had been actively pursued at Cambridge during the years 1920-32, but it was not until 1930 that the first lead was obtained. That was in fact the observation by Bothe and Becker in Germany of a highly penetrating radiation from the α-particle bombardment of beryllium. This was rapidly followed by the discovery by Curie and Joliot in France that this radiation, which they supposed to be electromagnetic, could eject *protons* from hydrogenous material. When Chadwick heard of these results and their tentative interpretation as a Compton effect, he immediately realised that the neutral particle that he and others had been watching for might at last have been produced and that the α-beryllium reaction was in fact the process $^9Be(\alpha, n)^{12}C$ i.e.

$$^9_4Be + ^4_2He \rightarrow ^{12}_6C + ^1_0n.$$

He tested this hypothesis very rapidly and unambiguously by allowing the radiation to produce projected nuclei not only of hydrogen, but also of nitrogen in an ionisation chamber with amplifier and photographic recording. By comparing quantitatively the energy of the hydrogen and nitrogen recoil nuclei he concluded that they had been projected by elastic collision with a fast particle of a mass approximately equal to that of the proton. From similar observations on the reaction $^{11}B(\alpha, n)^{14}N$, for which all the masses except that of the neutron were known from Aston's work, he refined the neutron mass in atomic mass units to $1.005 < M_n < 1.008$. This calculation completed an experiment which by the brilliance of its conception as much as by the force of its conclusion won immediate acceptance. The full paper describing the discovery (Chadwick 1932) was accompanied by reports of observations by Feather (1932) on the neutron-induced reaction $^{14}N(n, \alpha)^{11}B$ and by Dee (1932) on the weakness of the coupling of neutrons to electrons as put in evidence by a failure to produce observable ionisation in a cloud chamber.

Goldhaber had joined the Cavendish Laboratory as a theoretician to work under Fowler in 1933 but he rapidly developed close contacts with experimentalists and in 1934 he suggested to Chadwick that deuterium, the heavy stable isotope of hydrogen discovered in the USA in 1932, might be disintegrated into a proton and neutron by the 2.62 MeV γ rays of ThC′. Chadwick rapidly and successfully tried the experiment and the resulting paper (Chadwick and Goldhaber 1935) presented the binding energy of the deuterium nucleus to within 10% of its current value; the necessary theory was worked out by Bethe and Peierls (1935) in Manchester. Comparison of the $^2H(\gamma, n)^1H$ reaction yield with that of the inverse reaction $^1H(n, \gamma)^2H$, namely the capture of neutrons by protons, revealed a discrepancy which could be understood if the neutrons were slowed down before capture. This moderation effect, antedating its observation by Fermi's group in Rome, was regarded by Chadwick as 'speculation' (see Goldhaber, in Hendry (1984)) and was never published. Once the slowing-down effect was realised, experiments on slow neutrons were undertaken at Cambridge but the next important advance in the United Kingdom was made by Thomson's group at Imperial College using a radon-beryllium neutron source (Moon and Tillman 1935, Tillman and Moon 1935). Moon had noticed that Fermi had not definitely established the existence of *thermalised* neutrons and they therefore looked for increased neutron induced activity in a sample when a surrounding moderator was cooled down. The effect was found, but in addition strong selective absorption effects depending on the nature of the samples and detectors showed up. These finally had to be interpreted as evidence for sharp resonant capture of slow neutrons in moderately heavy nuclei, in contrast with the monotonic variation with neutron energy expected until then. This work and similar observations by Fermi's group became the basis of the compound-nucleus model of a nuclear reaction proposed by Niels Bohr in 1936. The Imperial College workers later used a small high-voltage accelerator to develop a time-of-flight neutron spectrometer with which they demonstrated the Maxwellian velocity distribution of thermal neutrons (Fertel *et al* 1938).

Bohr's compound nucleus model led Kapur and Peierls (1938) to develop a formula for the discrete resonant scattering of neutrons by a complex nucleus; later (Bohr *et al* 1939), processes occurring in the region of overlapping levels were discussed.

3.2.2. Transmutation by high-velocity positive ions. The story of Cockcroft and Walton's success in transmuting lithium with high-velocity positive ions is told by Allibone, by Walton and by Cockcroft himself in Hendry (1984) and by Hartcup and Allibone (1984). It starts with Cockcroft's arrival in Cambridge in 1922 although the first steps towards an accelerator were taken by Allibone in 1926. He succeeded in building a vacuum tube that would withstand a voltage of 300 kV, but did not use it for positive ions. Walton, who arrived in 1927, attempted to build both a betatron (as it would now be called) for electrons and a linear accelerator for positive ions, but the focusing conditions necessary for the proper operation of such machines were not realised. Fortunately at just this time, towards the end of 1928, Cockcroft saw the manuscript of Gamow's paper on barrier penetration by charged particles which made it clear, contrary to previous belief arising from Rutherford's α particle experiments, that extremely high voltages were not necessary for producing transmutations. He sent a memorandum on the subject to Rutherford, envisaging a 300 keV proton beam and in due course, after some hesitation, received permission to proceed, the cost to be met from university funds. In the next stage, Cockcroft together with Walton became intimately involved with the Metropolitan-Vickers Company who not only supplied a 350 keV transformer, but also, through C R Burch, made available their range of low vapour pressure 'Apiezon' products, which proved vital in the construction and pumping of continuously evacuated rectifiers and accelerating tubes. The first Cockcroft–Walton equipment produced a rectified voltage output up to 280 kV but no disintegrations were seen at this energy because only gamma radiation had been sought before it became necessary to dismantle the apparatus and move to a new location.

The final form of the second apparatus is shown in figure 7 (Cockcroft and Walton 1932a); it was a transformer-rectifier-condenser multiplying circuit similar in design to one used by Schenkel in 1919. The voltage of up to 800 kV that could in principle be developed was applied to a porcelain accelerating tube fed with protons from a discharge tube. When lithium was used as a ground potential target for the ion beam (Cockcroft and Walton 1932b), the emission of α particles in accordance with the (p, α) reaction

$${}^{7}_{3}\mathrm{Li} + {}^{1}_{1}\mathrm{H} \to {}^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He}$$

was seen for proton energies as low as 125 keV. The α particles were detected by the scintillation screen and by the ionisation chamber and had an energy agreeing well with prediction from Aston's masses. Within a year beautiful confirmation of the nature of the reaction was obtained by Dee and Walton (1933) using an expansion chamber. Disintegrations produced by deuterium ions were seen by Cockcroft and Walton in 1934 but the most interesting results with this ion were obtained with the small 200 kV accelerator of Oliphant *et al* (1934a). It was found that deuterons interacted with other deuterons to produce both ^{3}H and ^{3}He particles according to the reactions ^{2}H(d, p)^{3}H and ^{2}H(d, n)^{3}He. The ^{3}He particles had a short range and were

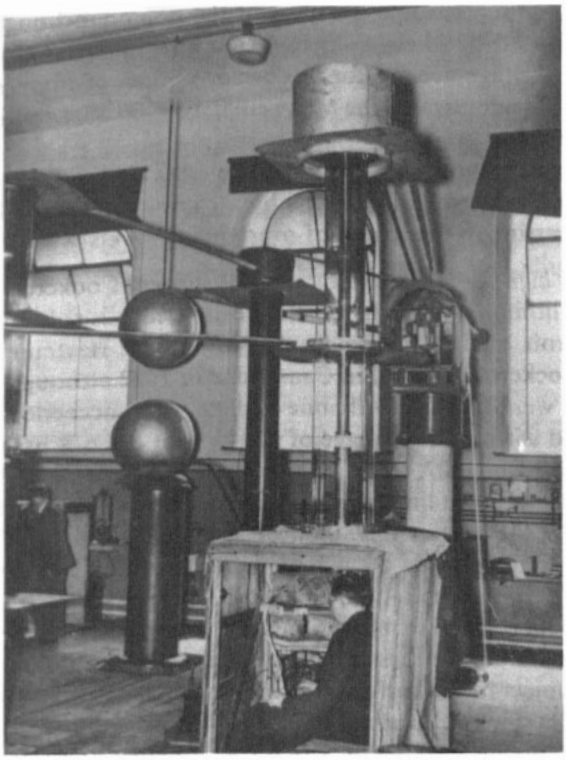


Figure 7. The Cockcroft–Walton disintegration apparatus, 1932, showing Walton (seated) (reproduced by permission of the Cavendish Laboratory, Cambridge).

not seen directly but Dee and Gilbert (1935) were able to observe them by passing a deuteron beam from the Cockcroft–Walton equipment into a deuterium-loaded expansion chamber. Later the same authors (1937) used a high-pressure methane–argon cloud chamber to observe the angular distribution of protons recoiling from 2.4 MeV neutrons produced in the ^{2}H(d, n) reaction. Isotropy in the centre-of-mass system was found and it is interesting to note that this experiment had as its objective the understanding of the *mechanism* of a nuclear interaction as distinct from the energetics. The small Oliphant accelerator was also used in the first transmutation of *separated isotopes* (of lithium) (Oliphant *et al* 1934b). It was also used (unsuccessfully) to look for a reaction produced by tritium nuclei formed in the deuteron–deuteron reaction, as described by Rutherford (1937) in his last paper. The Philips 1 MV generator enabled the work of Cockcroft and Walton to be extended to elements up to fluorine. Formation resonances were seen in the work of Curran *et al* (1939) on the (p, γ) reaction with beryllium, boron, carbon and fluorine and in the experiment of Burcham and Devons (1939) on the ^{19}F(p, $\alpha\gamma$)^{16}O reaction, in which the technique of magnetic analysis of the disintegration particles was used.

The availability of cyclotron beams of energy up to about 9 MeV in the UK in 1938 permitted the non-resonant region of nuclear excitations to be studied. An early test was made by Hurst *et al* (1940) at Cambridge of the Oppenheimer–Phillips theory of deuteron reaction yields as a function of energy.

3.2.3. ***Instruments.*** The study of decay schemes and reaction products during the period 1932–9 led to instrumental advances. Ellis in his later β-spectroscopic work had employed a cobalt-steel permanent magnet whose field could be set by magnetising coils (Cockcroft *et al* 1932). This instrument attracted Rutherford's attention and Cockcroft was asked to provide a similar facility for α spectroscopy. The result was an annular electromagnet with semicircular focusing (Cockcroft 1933) which was used extensively in the measurement of α-particle energies relative to that of the standard group from RaC′. The new technique replaced range measurements in many experiments and is described by Rutherford *et al* (1933) in the first of a series of papers. These established the fine-structure and long-range α-particle patterns of the radium, actinium and thorium α emitters and provided confirmation of the nuclear level schemes deduced by Ellis from observation of γ-ray spectra. Towards the end of these experiments Lewis (1937) developed a fast hard-valve scaling circuit which soon replaced thyratron circuits for pulse counting. The contributions of the United Kingdom to the methods of electrical counting up to this time are summarised by Wynn-Williams (1937). A further important advance was the development under Feather of coincidence counting for resolving complex decay schemes and for determining decay lifetimes (Dunworth 1940). At the end of his paper Dunworth quotes the results of a calculation by Pryce on the angular correlation of successive γ rays which foreshadowed the future development of such studies for the determination of nuclear angular momenta.

The photographic plate technique for the registration of the tracks of charged particles was used both in Vienna and in Cambridge before the war for the examination of radioactive decay chains. Powell at Bristol, however, recognised the inherent power of such a simple and compact technique, with its integrating property, and after consultation between physicists (Taylor and Powell) and the Ilford Company, half-tone emulsions were selected for more extensive trial. They were tested on the Bristol accelerator and later on the Cambridge 1 MV equipment and were found to offer resolution comparable with that of other range-measuring methods both for protons from (d,p) reactions and for recoil protons produced by incident neutrons (Powell and Fertel 1939, Powell 1940). In 1940 the half-tone plates were used in a collaborative inelastic scattering experiment with protons from the Liverpool cyclotron (Powell *et al* 1940). At about the same time more extensive observations of the elastic scattering of protons and deuterons from light nuclei were made but the results of these studies were not published until after the war. In due course, Powell's insight and skill in developing and using the photographic plate detector led to the discovery of the charged pions (Lattes *et al* 1947) and to the award of a Nobel prize. The neutral pion was discovered some years later in the USA.

4. Wartime developments 1939–1946

The interpretation of the experiments of Hahn and Strassmann on the activities resulting from the bombardment of uranium by slow neutrons was given by Meitner and Frisch in the issue of *Nature* dated 11 February 1939. They made the simple suggestion that a liquid-drop type of nucleus might fragment when disturbed into smaller drops of approximately equal size, as would a real liquid drop with reduced surface tension. In the next week's issue of the journal Frisch described the detection of these fragments in an ionisation chamber; he christened the new phenomenon *fission*. The classical paper of Bohr and Wheeler developing the theory of the slow-neutron fission of ^{235}U

was published in the Physical Review two days before the United Kingdom declared war in September 1939. The events just mentioned and their consequences for the country are fully documented by Gowing (1964); the discovery of fission itself is readably described by Frisch (1979).

At the time of Meitner and Frisch's *Nature* letter, the Cavendish Laboratory was still the main centre of nuclear physics in the country but the Liverpool laboratory under Chadwick was growing rapidly and smaller activities in the field, including cosmic ray work, were to be found at Birmingham, Bristol, Manchester, London (Imperial, King's and Birkbeck Colleges) and Oxford. The Cambridge and Liverpool cyclotrons were in early stages of operation and the Cavendish 1 MV accelerator was able to provide neutron sources of the order of 1kg RaBe equivalent strength. Because of the chemical interest of Fermi's early neutron activation experiments particularly in respect of transuranic element production, the Cavendish had been joined in 1935/6 by Egon Bretscher, a chemist from ETH Zurich. After 1937 he used the strong neutron sources at Cambridge, and must have been close more than once to the discovery of fission. When the discovery was actually made, the Cavendish was busy with its new accelerators and although Dee announced the new phenomenon on the radio in February 1939 only Feather and Bretscher (1939) immediately undertook experiments in the field. Together they applied the critical absorption method of x-ray spectroscopy to determine the atomic number of a fission fragment and later Feather himself (1939) used a recoil method to show that *fast* neutron fission took place in a time of less than about 10^{-13} s. Others felt perhaps that although fission would certainly open up an enormous area of experiment, yet it did not address the central problem of nuclear physics—the nature of nuclear forces. In the upshot, the main investigations in the Cavendish, many of them associated with visitors, or with research students completing their theses, continued undisturbed up to and even beyond the outbreak of war. Elsewhere however, fission attracted considerable attention; at Imperial College an important measurement of the neutron yield in the process was made (Michiels *et al* 1939).

In the spring and early summer of 1939 senior staff in universities began to be called upon to learn about defence measures and even before September a large proportion of the country's nuclear physicists were attached 'for a few weeks' to Government establishments. The 'few weeks' became, for most, about five years, during which the new science of radar was nurtured, and it led to an almost complete cessation of general (other than mission-oriented) nuclear research in the country. Some, however, did continue, in parallel with classified work, notably a study of the reactions of deuterons with heavy elements using the Cambridge cyclotron; fission induced by deuterons in uranium and thorium was observed (Gant and Krishnan 1941) and the Oppenheimer–Phillips theory of deuteron excitation functions was further tested (Krishnan and Nahum 1942). At Liverpool, in addition to the cyclotron scattering work already mentioned (§ 3.2), decay-scheme experiments took place, for example those of Walke *et al* (1940) on ^{51}Cr. Theoretical nuclear physics also almost disappeared during the period, except for classified work, but some aspects of the meson theory of nuclear forces were discussed, for example the photodisintegration of the deuteron (Fröhlich *et al* 1940).

In the growth of effort on neutron-induced fission itself and its possible applications, the key discovery was that of von Halban, Joliot and Kowarski in France that prompt neutrons were emitted in the fission process and that these might be numerous enough to generate a chain reaction. In the summer of 1939 Peierls in Birmingham showed the way to calculate the critical parameters of a reacting system, but even before this, other papers on the same subject had inspired Thomson to bring the possibilities before Tizard, the chairman of the Committee on the Scientific Survey of Air Defence. It was agreed that a research effort was necessary but before it could be started war broke out and physicists moved to other tasks. The matter came up at the War Cabinet and Appleton, then head of the DSIR, was asked to make enquiries. He was for a time unaware of the interest of Thomson and of Tizard and he consulted Chadwick; this led to a period of overlap of responsibility between the DSIR and the Air Ministry. A crucial scientific point at the time was the fact that although the Imperial College group had failed to produce a multiplying system using natural uranium oxide and simple moderators they had noted that success might be achieved with uranium enriched in ^{235}U. This same point had occurred to Frisch, who had come to Birmingham from Copenhagen at the outbreak of war to work with Peierls. Together they speculated on the possibilities of a 'superbomb' and they concluded that if pure ^{235}U were used, as little as 1 kg of metal would suffice. They wrote a short report on the matter (Gowing 1964, Appendix I) which reached Tizard and led to the formation of the MAUD Committee which was responsible to the Ministry of Aircraft Production for uranium work over the critical years 1940/1.

The story of the MAUD Committee and its Technical Sub-Committee is told fully by Gowing (1964) in whose judgment it proved to be one of the most effective scientific committees ever to have existed. It produced two reports in July 1941, written it would seem mainly by Thomson and Chadwick. The first dealt with the use of uranium for a bomb and the second examined the role of uranium as a source of power; together they summarised the work, under Chadwick's general direction, of teams at Birmingham, Cambridge, Liverpool, London (King's and Imperial Colleges) and Oxford, and at Imperial Chemical Industries, over some 15 months. In brief summary it had been shown by Halban and Kowarski at Cambridge (after their escape from France bringing with them essentially the total world stock of heavy water) that it was almost certain that in a system composed of uranium oxide or uranium metal, with heavy water as the slowing down medium, a divergent slow-neutron chain reaction would be realised if the system were of sufficient size. Bretscher and Feather had predicted that such a system would produce ^{239}Pu and that this should be thermally fissile like ^{235}U. But the prospect of a plutonium bomb was only dimly perceived and the possible military application, which ensured Government support, was still based on the fast-fission of a critical mass of ^{235}U, as envisaged by Frisch and Peierls. The bomb project of course demanded accurate nuclear cross-section information and this was obtained using the Liverpool cyclotron. It also vitally needed a means of separating the uranium isotopes (^{235}U is only 1/140 part of natural uranium) and a pilot gaseous diffusion plant was designed by Simon at Oxford. Birmingham and ICI chemists were preparing uranium metal and hexafluoride of the required purity for the diffusion plant.

The MAUD report reached the Government's Scientific Advisory Committee in August 1941, and it was soon recognised that while effort could not be spared under wartime conditions for the development of a power source, the bomb project was of the highest importance. The Tizard mission to the USA in the autumn of 1940 had already opened a door to collaboration and it was agreed that the power source should be pursued as a joint UK-USA-Canada undertaking but that the main UK effort should be devoted to the bomb programme. The whole project was withdrawn from the Ministry of Aircraft Production and placed in a Special Directorate (code-named 'Tube Alloys') under the DSIR.

The complex history of Tube Alloys from 1941 until the end of the war is carefully and critically set out by Gowing (1964). An early decision was to place an embargo on the publication in British journals of material that might relate to the project and much useful nuclear physics from British universities therefore did not appear in the open literature until well after the war and after a declassification process. Typical examples are the work of the Cambridge group on neutron detectors and neutron flux measurements (e.g. Allen and Wilkinson 1948) and on α particles emitted in the fission process (Cassels *et al* 1947). A list of British papers declassified by 1947 will be found in *Nature* **159** 411-2.

From the point of view of the progress of nuclear science in the country, the Tube Alloys project was enormously important. After the Quebec Agreement of August 1943 (Gowing 1964) it gathered together many nuclear physicists who had been working in other fields since 1939/40 and sent them to help, under the general direction of Chadwick in Washington, in the great laboratories at Berkeley, Oak Ridge and Los Alamos. Others went to the nascent British-Canadian power project in Montreal. From the contacts then made stemmed major technical and theoretical advances, such as the scintillation plus photomultiplier counter (Curran and Baker 1948) and the phase-stable accelerator, that were to reach fruition in post-war years. And, from the teams in the United States and Canada, with their parent Directorate in London, grew the United Kingdom Atomic Energy Establishments (which were initially part of the Ministry of Supply).

By the end of the war, university staffs had reached a low level and approaches were made to secure the return of many who had worked in radar and Tube Alloys. At the same time the war-time Government laboratories began to think of their own future and to resist the loss of staff who had served them well. What they could not resist was the emergence of a wholly new and vital field of Government science—atomic energy—and this proved an attraction powerful enough to compete with universities. From the point of view of the development of nuclear physics in this country the most significant senior appointments were those of Cockcroft to be Director of the proposed Atomic Energy Research Establishment at Harwell (November 1945), of Dee to the chair of Natural Philosophy in Glasgow (from 1945) and of Feather to the similar chair in Edinburgh (October 1945). These moves, allied to that of Blackett from Birkbeck to Manchester in 1937, in a sense completed the dispersion of Rutherford's staff from the Cavendish that began in 1933. Their new task was to help to establish and to consolidate a national effort in nuclear science and in this undertaking the guiding influence of Cockcroft, even above that of Chadwick, was to prove crucial.

5. Post-war expansion: the making of a community 1946–1957

5.1. Survey

In the years between the opening of the AERE Harwell in 1946 and the creation of the National Institute for Research in Nuclear Science (NIRNS) in 1957 nuclear structure research in the United Kingdom expanded and diversified. By 1939 some of the main problems of the subject had been perceived but not solved but by 1946, although most of those problems still remained, the promise of atomic energy appeared likely to lead to unprecedented support for the necessary basic research. Moreover the technical developments of the war years had provided new tools for the work and the resumption of degree courses by many students ensured a plentiful supply of postgraduates interested in training in research. Rarely can the conditions for the evolution of a subject have been so favourable.

The Telecommunications Research Establishment (TRE) at Malvern was, at the end of the war, a highly efficient organisation with much experience in high-frequency transmitters and pulse circuits. Such techniques were just those required for accelerator construction and in due course many TRE staff were transferred to AERE to form part of the electronics group, with a mandate to develop new accelerating techniques. The electron synchrotron principle was quickly shown to work at Malvern by Goward and Barnes (1946) and a number of 30 MeV accelerators of this type, including one for the University of Glasgow, were built (Fry *et al* 1948). At about the same time others were developing electron linear accelerators (Fry *et al* 1947). The experience acquired in these years was of great service to later developments in the universities and in the National Institute.

The AERE had the obvious duties of trying to understand neutron-induced reactions, including fission, and of studying reactor design. It moved quickly in early 1946, under Skinner as Cockcroft's deputy at first, to prepare for a large cyclotron (which became actually a 170 MeV synchrocyclotron and operated in 1949), a 5 MV Van de Graaff accelerator (which also operated in 1949), an electromagnetic isotope separator (Allen 1951) and an experimental reactor. The reactor (BEPO, 1948) and its successors (DIDO, 1956; PLUTO, 1957; HERALD, 1960 at AWRE) provided a copious source of thermal and epithermal neutrons; for higher energies, up to 10 keV, a small pulsed electron linear accelerator acting as a photoneutron source was used (Merrison and Wiblin 1951). After some years of successful operation of the synchrocyclotron as a neutron source, AERE designed a 600 MeV proton linear accelerator to extend the energy range upwards. This was stopped when it was found at Liverpool by Le Couteur (1955) and Crewe and Gregory (1955) that a satisfactory proton beam could be extracted from a synchrocyclotron. The nearly-completed 50 MeV first section was transferred to the books of the National Institute in 1959.

In the universities things moved more slowly, but the DSIR was sympathetic with proposals to build three machines capable of producing the mesons that were expected to mediate nuclear forces and which were actually discovered in 1947. As a result, Chadwick at Liverpool started to build a 400 MeV synchrocyclotron, which was completed by Skinner after he succeeded Chadwick in 1949, Oliphant at Birmingham planned a 1000 MeV proton synchrotron, completed by Moon after Oliphant's departure for Canberra in 1950 and Dee at Glasgow erected a 340 MeV electron synchrotron. Although these machines contributed mainly to the field of particle physics, which rapidly became differentiated from nuclear structure research, there was cross fertilisation and each of the laboratories concerned developed a strong nuclear structure group. Each of these universities, and the AERE as well, supported a theoretical physics group with interests in nuclear structure, notably that of Peierls at Birmingham; similar groups were to develop at Manchester, University College, London, Oxford and Cambridge. They all became intimately involved with calculations on nuclear models or the nuclear force.

In 1946 only Cambridge and Liverpool were able to continue nuclear reaction research without too much delay. Installations similar to the Cambridge 1 MV equipment were procured by Liverpool, Oxford, Glasgow and Edinburgh universities with the object of continuing or commencing studies of the light nuclei. At Cambridge the pre-war 2 MV Philips generator was rehabilitated and used by Devons and by Wilkinson (§ 5.2) but it was already clear that neither the beam spread nor the maximum energy available from cascade generators was likely to meet experimental requirements for long. Cambridge therefore initiated the construction of a small pressure-insulated electrostatic generator, with the support of the English Electric Company, and made ambitious plans for a major nuclear research development on a new site. This would have included an electron linear accelerator. Unfortunately, although Cockcroft gave general encouragement to the plans, he himself had resigned the Jacksonian Chair and Frisch, who succeeded him in 1947, developed different interests. In the end the timescale for the development lengthened and when Mott succeeded Bragg as Cavendish Professor in 1954, an end was effectively made to Cambridge nuclear, as distinct from particle, physics. The electrostatic generator had in fact been built and operated under the direction of Shire, but this and the two cascade generators were soon to disappear. Members of the post-war group left the Cavendish one by one and when it became known that Wilkinson was to move to Oxford (in 1957) it was clear that an era had concluded.

Electrostatic generators were in use during the 1950s not only in the Nuclear Physics Division at AERE, then headed by Bretscher, but also at AWRE Aldermaston and at the Associated Electrical Industries laboratory under Allibone at Aldermaston Court. The 2 MV machine started in 1939/40 at Imperial College was used there by Devons after his move from Cambridge in 1950; it was to be succeeded by a 6 MV CN generator built by the High Voltage Engineering Corporation (HVEC) of the USA; in the end both the 2 MV and 6 MV machines were installed at Manchester after Devons' appointment there in 1955. A similar machine went to AWRE in 1956. By the end of the period under review it was quite obvious that the future of high-resolution work lay with accelerators of this type and proposals were made in 1956 for two or even three generators operating on the tandem principle which incorporates an ingenious voltage doubling method. Such generators were either to be constructed or bought from HVEC, which had started to build its first EN tandem for a terminal voltage of 6 MV (proton beam energy 12 MeV) in 1956. In the end (§ 6.1) the AEA, together with Messrs Metropolitan Vickers, built tandems for AERE and AWRE and an EN machine was provided for Liverpool University through the DSIR.

At Liverpool, Cambridge and Birmingham cyclotrons existed and provided deuteron beams of energy up to 20 MeV (and other particles at corresponding energies) but with poor resolution. This was adequate, however, for the study of what became known as direct, as distinct from compound, nuclear reactions. The Cambridge and Liverpool cyclotrons were phased out in 1957 and 1960, respectively, but the magnet of the former was moved to Birmingham where it was used in the construction of a small azimuthally varying field (AVF) cyclotron (§ 6.1). At University College, London, a small electron microtron was built (Henderson *et al* 1953) and at Manchester the first stage of a heavy ion linear accelerator (HILAC, Nassibian *et al* 1961) was completed with DSIR support.

As a result of the installations and appointments mentioned so far the years 1946–57 saw the growth of a flourishing nuclear structure community in the United Kingdom. By 1957 it numbered probably about 350 PhD or equivalent staff and pre-doctoral students, and it comprehended the Universities of Birmingham, Glasgow, Liverpool, Manchester and Oxford as major centres and several other institutions all supported partly by UGC but mainly by DSIR research funds. To these should be added the groups at AERE, AWRE and AEI (Aldermaston) whose facilities were often made available under appropriate arrangements to university members of the community, and particularly in practice to Oxford staff who were near at hand. Some of the major university centres recognised the growth of nuclear science by establishing senior posts, often at professorial level. The community communicated with itself by personal travel, national and international conferences and through the general open literature as well as by laboratory reports. An important development was the establishment under the auspices of the Physical Society of London (whose Proceedings carried many nuclear structure papers) of a regular national conference series, organised by the Society's Nuclear Physics Sub-Committee. These six-monthly meetings enabled research students to hear invited papers of high quality and to participate themselves at the level of 'Shorter Communications'. Universities soon came to take these conferences very seriously as an essential complement to the high-power international meetings and as a useful part of the training of a candidate for the PhD degree. That degree too, later to be much criticised both by industry and by Research Councils for 'specialisation' or 'irrelevance', played a significant part not only in advancing the subject of nuclear physics but in helping to identify a community—of those who had achieved a measure of independence in research through advanced study.

The support of the nuclear structure community in the universities through the UGC and the DSIR in the 1950s was not ungenerous, but it was not easy for academic institutions to match the levels of resource available in AEA laboratories. That these levels should obtain in commissioned or applied research was conceded, but in fact they obtained also in the underlying basic research programme to which the universities were also hoping to contribute. The misgivings of senior university staff on this situation gradually became more and more articulate and in the end, and largely through Cockcroft's influence, NIRNS was set up to ensure that universities had access in Institute laboratories to the powerful facilities that were required by the developing research programme. This pioneer scientific development took place at a time when science budgets disbursed through Government agencies were still increasing and it recognised both the merit and the potential of the total community of particle and nuclear physicists that had grown up in the universities of the country since 1946. And, just at the time of the creation of NIRNS, as if to confirm the wisdom of that decision, an announcement came of the discovery in the USA of the non-conservation of parity in weak processes, emphasising how it had been possible for decades to remain in ignorance of a fundamental facet of the behaviour of elementary particles.

In 1954 the Conseil Européen pour la Récherche Nucléaire (CERN) came formally into being but its impact on nuclear structure research in the United Kingdom was small during the period under review. In the same year Government effort in nuclear research was formally placed under the control of the newly created United Kingdom Atomic Energy Authority (UKAEA).

5.2. Selected achievements 1946–1957

5.2.1. Nuclear reactions. Neutron physics had acquired considerable momentum during the war, mainly for its relevance to fission and to the nuclear properties of materials, but by 1946 interests had widened and included studies of the two-body problem. Powell and Occhialini (1947) using the Cambridge 1 MV accelerator as a source, reported on the scattering of 9 MeV and 13 MeV neutrons by protons in the new Ilford Nuclear Research emulsion (Powell *et al* 1946) in which the concentration of silver halide had been largely increased. Deviations of the angular distribution from isotropy were seen at 13 MeV and these were compared with the predictions of a meson theory of nuclear forces by Ramsey (1947) working with Fröhlich at Bristol. The neutron energy was not high enough to give a good determination of p-wave phase shifts but after the commissioning of the AERE synchrocyclotron (Pickavance *et al* 1950) data at much higher energies began to appear and to contribute to a growing understanding of the problem. At Cambridge (and later at Harwell) neutron velocity spectrometers of the time-of-flight type were built and with the former an important determination of the capture cross section of ortho- and para-hydrogen for thermal neutrons was made (Squires and Stewart 1955).

A variable energy source of neutrons in the MeV range was provided at AERE by use of the endoergic reaction ^{7}Li (p, n) on the 5 MV electrostatic generator. Inelastic scattering of neutrons by light elements with excitation of bound states was studied by Freeman (1955a, b) using this source and detecting the de-excitation γ radiation. Her work on ^{19}F was especially significant in view of the calculations of the energy levels of this nucleus then being made using at least two different nuclear models. Universities such as Oxford and Glasgow carried out similar work, but using the ^{2}H(d, n) reaction as the neutron source.

The experiments of 1946–57 that directly stemmed from the pre-war programme of the Cavendish Laboratory were on the reactions of protons with light nuclei. The development of the radiofrequency ion source (Thonemann 1946) later made α-particle beams as easily available as those of protons. At Cambridge there was a continuation of the determination of energy releases in reactions, which soon showed up the need for magnetic analysis (Freeman and Baxter 1948, Burcham and Freeman 1949). This method was used at Birmingham with an annular magnet of the Cockcroft (1933) type to obtain energy releases in the lithium and boron plus proton reactions to an accuracy of about 0.1% (Collins *et al* 1953). Resonance experiments also continued at Cambridge and some of the most informative were those of Devons and Hine (1949) which showed how the *angular distribution* of gamma radiation in proton-capture reactions could be analysed to yield spin-parity information for nuclear levels; a particularly elegant study of interference in the ^{7}Li(p, γ)^{8}Be reaction was made. Similar work soon began to appear from Glasgow and Liverpool and at Cambridge the observations were extended to α-particle reactions (Shire *et al* 1953) and to resonantly scattered protons (Dearnaley 1956). In reactions of the type (p, $\alpha\gamma$) or (α, pγ) in which radiation is observed following the excitation by particle emission of a low-lying state of a residual nucleus, the *angular correlation* between the direction of the emitted particle and the radiation is informative. This was shown for the process ^{19}F(p, $\alpha\gamma$)^{16}O by Barnes *et al* (1950) in an experiment that became the model for much subsequent work. The general theory of the angular correlation of successive radiations was reviewed in a definitive article by Devons and Goldfarb (1957).

The determination of level spins and parities (I^π) by correlation methods was usefully complemented by direct measurement of the multipolarity of electromagnetic transitions by internal conversion methods. Devons, after his move to Imperial College, London, continued to test this method for pair conversion of high-energy transitions in the light elements (Devons *et al* 1954). An even more important property of a radiative transition is its mean life (since this measures the squared matrix element of a multipole operator between initial and final nuclear states), and in the early 1950s, following a measurement of 7×10^{-11} s for ^{16}O* at Cambridge (Devons *et al* 1949), the Imperial College group developed and tested several powerful methods covering the range 10^{-9}–10^{-15} s (Devons *et al* 1955). The recoil-distance (RDM) and Doppler shift attenuation (DSAM) methods have found extended and continued application.

In addition to spin and parity, isobaric spin T provides a good quantum number for many nuclear levels. Because of the existence of symmetry-destroying Coulomb forces in nuclei, this was not expected until Radicati (1952, 1953, 1954) in Birmingham made explicit calculations. Experimental evidence for the validity of the isobaric spin concept in nuclear structure and in a wide range of light nuclear processes was obtained over the years 1953–7 by Wilkinson and his collaborators using accelerators at Cambridge and at Brookhaven and is reviewed by Wilkinson himself (1969); the work included the conclusion that in the two-body system the nuclear force in the nn charge state is weaker than that in the equivalent np state. At the same time Wilkinson (1956a) assembled a detailed review of radiative transition strengths in the light nuclei.

Most of the experiments so far mentioned were made at beam energies less than about 2 MeV and with beam widths appropriate to discrete levels of the compound nuclei involved. In another class of experiments, appropriate to cyclotrons, energies of 10–20 MeV were used and attention was concentrated both on the reaction mechanism and on the spin/parity of low-lying levels of residual nuclei. This type of work had been pioneered during the war with photographic plate detectors (§ 3.2) and in the post-war years sophisticated nuclear emulsion cameras were built that were used with gaseous targets at Liverpool (Burrows *et al* 1951) and at Birmingham (Freemantle *et al* 1953) with both hydrogen and helium ions. Similar work took place at Birmingham, Cambridge and Liverpool using counter techniques (Greenlees 1955), which are more appropriate for solid targets.

A significant discovery made at Liverpool (Burrows *et al* 1950, Holt and Young 1950) was that the protons emitted from (d, p) reactions with light nuclei using deuterons of energy about 8 MeV showed strong forward peaks, quite uncharacteristic of reactions proceeding through a Bohr compound nucleus. It was soon realised that this was a first example of the general behaviour of *stripping* or transfer reactions at the energy used and the observations were rapidly extended to a wide range of nuclei, using both counter and emulsion techniques; figure 8 shows one of the first stripping peaks to have been seen. The results of Burrows *et al* were quickly interpreted by Butler (1950), working under Peierls in Birmingham, and his full theory of the stripping process was given in 1951. An alternative approach using the Born approximation was given, following a conference presentation in 1950, by Bhatia *et al* (1952) at Liverpool. As a result of their analysis it was shown that stripping (and generally nucleon-transfer) reactions could provide spectroscopic information on the states of the residual nucleus excited in the reaction, and this type of reaction has been very widely used. Further developments, particularly at Liverpool, were to apply magnetic analysis to the outgoing protons, to study the (d, n) stripping reactions and to examine the correlation between reaction particles and subsequent gamma radiation.

The period under review also saw the earliest experiments in the country on *heavy-ion induced reactions*, which had been observed with the 60″ cyclotron at Berkeley. Using the similar accelerator at Birmingham, Walker and Fremlin (1953) studied the way in which carbon ions could be pre-accelerated in a low charge state in the cyclotron, stripped of electrons and finally accelerated in a high charge state to an energy of about 10 MeV per nucleon. A substantial radiochemical programme was undertaken (Chackett *et al* 1954), partly in the hope of producing new transuranic elements, and the promise of the new field was amply demonstrated, but the real expansion of heavy-ion physics had to await the deployment of the linear accelerator and the tandem electrostatic generator (§ 6.1).

5.2.2. Decay schemes, orientation and photoprocesses. The post-war period saw the availability of strong sources of neutron-rich isotopes from nuclear reactors and this stimulated the development of instruments such as magnetic beta spectrometers (e.g.

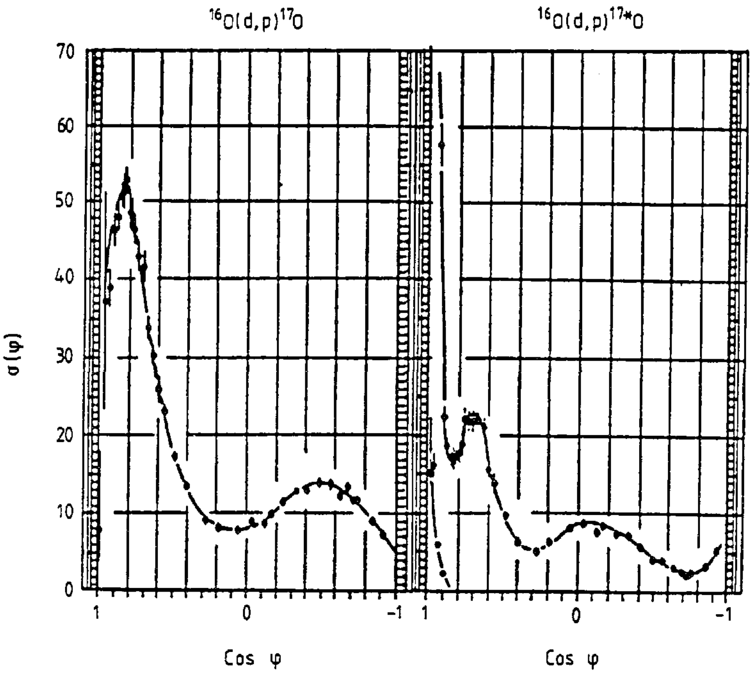


Figure 8. Angular distribution of protons arising in a (d, p) stripping reaction (Burrows *et al* 1950). The ordinate gives the relative yield of protons as a function of centre of mass angle for the reaction.

by Feather at Edinburgh) for the study of *decay schemes.* For low energy radiations the proportional counter with field tubes was shown by Curran *et al* (1949a) to have manifest advantages. It was applied by these authors (1949b) in an important determination of the end-point of the β spectrum of tritium which set an upper limit of 1/500 of the electron mass for the mass of the (electron) antineutrino emitted in accordance with the scheme

$$^3_1H \rightarrow ^3_2He + e^- + \bar{\nu}_e.$$

The proportional counter technique was also developed extensively at AERE by West (1953). Radioactivity, apart from its intrinsic interest, also provides a method of detecting small samples, and it was used (as well as the mass spectrometer and electron multiplier) in nuclear spin and magnetic moment determinations by Bellamy and Smith (1953) working under Frisch in Cambridge. They applied the atomic beam magnetic resonance method to a number of radioactive isotopes of the alkali metals. At about the same time an atomic beam was being used by Kuhn and Woodgate (1951) in Oxford in optical absorption experiments to determine spins and moments of stable nuclei. But at Oxford, the main effort of the period in nuclear physics, at first under Lindemann (then Lord Cherwell) and after 1956 under Bleaney, was to enlist the expert knowledge of Simon and Kurti to obtain the low temperatures necessary for *nuclear orientation experiments.* This was achieved, using a method suggested by Bleaney (Daniels *et al* 1951, Bleaney *et al* 1954), in a crystal containing radioactive nuclei and was sensed by observation of an anisotropic angular distribution of gamma radiation from the daughter nucleus. Such angular distributions had been earlier calculated by Spiers (1948) in one of the first papers in this field. Figure 9 shows the

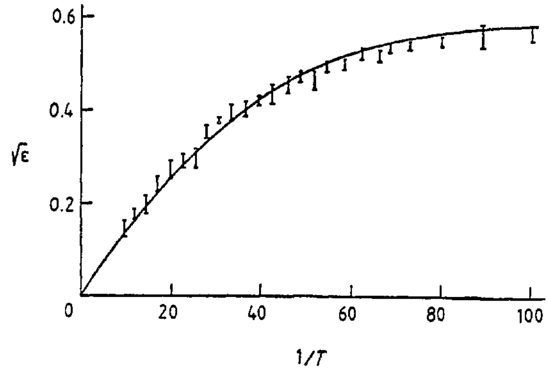


Figure 9. Alignment of Co nuclei: the square root of the gamma-ray anisotropy for the decay, labelled $\sqrt{\varepsilon}$, is plotted against the inverse temperature in K. The full curve is predicted for a nuclear magnetic moment of 3.5 nuclear magnetons (Bleaney *et al* 1954).

dependence of anisotropy on temperature for ^{60}Co, which yielded spin and magnetic moment information. In nuclear orientation experiments, reviewed in 1957 by Blin-Stoyle and Grace, anisotropy of angular distributions of radiation results from a non-uniform population of magnetic substates in the radiating nuclei. It is also non-uniform population of substates which leads to a non-isotropic correlation between the directions of emission of two gamma rays in a nuclear cascade. If the intermediate state in such a case has a magnetic moment and a long enough mean life, it will be possible by application of an external magnetic field to perturb the angular correlation (PAC) and to determine the magnetic moment. In 1956 Phillips and Jones in Cambridge were able to measure the magnetic moment of the 0.197 MeV state of ^{19}F by this method, which now has very wide application.

The photons emitted in radioactive decay or in nuclear reactions can themselves be used to induce nuclear processes. The conditions under which the Doppler broadened and recoil-shifted radiation emitted from a nuclear level could be resonantly absorbed in that same level in the nuclei of a stable sample were discussed by Moon (1951). He was able to restore recoil loss by mounting a source on the tip of a high-speed rotor and, by observing a resonance effect in back (elastically) scattered radiation, to deduce the radiative width of the level concerned ($\Gamma = 2.1 \pm 0.4 \times 10^{-5}$ eV for ^{198}Hg 412 keV). This work made a significant contribution to the discovery of recoil-free scattering by Mössbauer in Germany in 1958 and to the measurement of the helicity of the neutrino, also in 1958, after the discovery of parity non-conservation in 1956. The most studied inelastic process with photons is the photodisintegration of the deuteron (§ 3.2) which was pursued at Oxford (Wilson *et al* 1949) using radioactive sources and at Cambridge (Barnes *et al* 1952, Wilkinson 1952) using proton-capture radiation. At higher energies still the bremsstrahlung radiation available from electron synchrotron targets was used by AERE workers to study photodisintegration and photofission processes in nuclear emulsion (Goward and Wilkins 1955, Goward *et al* 1949). Similar work with gases took place at Glasgow (Wright *et al* 1956) using both expansion chamber and counter detectors and was analysed assuming suitable wavefunctions for the target nuclei (Gunn and Irving 1951, Flowers and Mandl 1951). The spectacular giant electric dipole resonance of photodisintegration, first observed in the USA, can be understood as a collective oscillation of neutron and proton fluids in the nucleus against each other, but as pointed out by Wilkinson (1956b, following a conference presentation in 1954) it may also be interpreted as a superposition of many intershell transitions in a microscopic model. This confrontation of collective and single-particle models became a recurring theme in subsequent years.

5.2.3. Instrumentation and theory. In many of the experiments so far mentioned energy-sensitive detectors, such as sodium iodide crystals (for γ radiation) were used. Efficient data accumulation then required pulse height analysers but the various cumbersome electronic devices which had been used during wartime work in Cambridge for α-particle spectroscopy suffered seriously from channel drift. Soon after his arrival in Cambridge Frisch built an amusing (but non-trivial) mechanical pulse sorter (Frank *et al* 1951) but the real breakthrough was made, also in Cambridge, by Wilkinson (1950a) and by Hutchinson and Scarrott (1951). In these instruments the innovations of analog to digital conversion, data storage and visual display that are now routine practice in the electronics industry, were introduced. At this time British firms were beginning to market some of the simple nuclear electronic units such as scalers and amplifiers, under the general design authority of AERE Harwell. The circuits of some of these units are described by Kandiah and Chaplin (1956). A definitive text on gaseous detectors, which was to influence the development of ionisation and proportional counters, appeared during the period (Wilkinson 1950b).

The status of nuclear structure theory during the post-war decade is summarised by Devons (1949) who also describes experimental methods, and by Elton (1959); Elton himself (1950) made an early analysis of the information on nuclear sizes that might become available through elastic electron scattering. Work was proceeding at AERE and at University College, London (e.g. Buckingham *et al* 1952) on the nuclear force, but stood in need of data that were only just beginning to appear. Field-theoretic corrections to the electromagnetic interaction were a front-line topic and were discussed at a Physical Society meeting in Birmingham (Peierls 1955). For nuclear structure in a narrow sense however the most important advances were in shell-model theory, starting in Peierls' group in Birmingham and continuing under Jahn at Southampton and under Flowers and Skyrme at AERE. The model, which seeks for a Rutherford–Bohr type of description of the nucleus, is reviewed in the comprehensive article of Elliott and Lane (1957). Some of the calculations for specific nuclei had a particular interest, especially those for mass 18 and 19 (Elliott and Flowers 1955). For ^{19}F an excellent account of the experimental level system for even parity states was given, but this was followed in 1957 by a paper by Paul at Harwell showing that a good account could also be given by the collective model. The connection between these two models continued to attract the attention of many groups (Peierls and Yoccoz (1957), see also Perring and Skyrme (1956) for the special case of $A = 4n$ nuclei) and stimulated attempts to understand the moment of inertia of deformed nuclei (Yoccoz 1957). For nuclear *magnetic* moments the single-particle shell-model predictions clearly stood in need of improvement and an important advance was made by Blin-Stoyle in 1953 when he invoked interaction between different nucleon configurations. For reactions, the historical compound-nucleus model, and the more recently identified direct processes, were thoroughly examined by Lane and Thomas (1958) within a dispersion theory framework. A prescription for the level density of a Fermi gas at an excitation energy appropriate to compound nucleus reactions was given by Lang and Le Couteur (1954). Increasingly during these years it was seen to be both necessary and possible to bring all aspects of nuclear reaction behaviour into one theoretical formalism, from which the characteristics of particular types of behaviour could be extracted. Some work was also carried out during the period on β-decay theory, but the main advances came after the discovery of parity non-conservation, or lack of mirror symmetry, in the weak interaction and these will be referred to in the next section.

6. The nuclear structure community: consolidation, work and support 1957–1974

6.1. Survey

By the end of 1957 the main centres of nuclear structure in the United Kingdom had been defined. On the one hand was the AEA, which was about to strengthen its laboratories at AERE Harwell and AWRE Aldermaston by the completion (1959) of vertical tandem accelerators with a terminal voltage of about 7 MV and a proton beam energy of nearly double this (Allen *et al* 1959). On the other were the universities, whose nuclear interests derived from key appointments dating back to the mid 1930s. As in earlier years, universities were funded generally through the UGC and specifically by the DSIR after scrutiny of applications by its Research Grants Committee. For nuclear physics a Sub-Committee had been set up as early as 1951 and recommendations of this body provided not only several major installations, but also (after 1962) 'consolidated' grants to ensure adequate exploitation of the new facilities. In this way Liverpool received the EN tandem giving 12 MeV protons (1961) and Oxford (after discussions with the Minister of Science) a similar machine (1963) together with an 8 MV injector designed under NIRNS auspices to provide 20 MV protons in the coupled mode (acceptance 1967). Grants were also made to Manchester for completion of the heavy ion linear accelerator (HILAC, § 5.1), to Glasgow for an electron linear accelerator for about 100 MeV (acceptance 1967, see Hogg *et al* 1972) and to Birmingham for construction of the small AVF cyclotron for 12 MeV deuterons (Cox *et al* 1962). These facilities not only strengthened the major university nuclear structure centres already defined, but also established the level of support that a university might optimistically expect to enjoy (but not to exceed). The overall situation in the UK for nuclear structure accelerators in 1962 is shown in table 1.

The creation of NIRNS in 1957 and the opening under its auspices of the Rutherford High Energy Laboratory (RHEL) (1957) and the Daresbury Nuclear Physics Laboratory (DNPL) (1962) provided universities with access to facilities that were too large to be operated by a single institution alone. Both laboratories were planned with high-energy machines in view but the first accelerator to operate at RHEL was the 50 MeV proton linear accelerator (PLA) and at Daresbury, the Nuclear Structure Facility (NSF) has survived the demise of the particle physics programme. The Royal Charter of NIRNS (23 June 1958) included among the Institute's objects the encouragement of the use of central facilities by scientists in the universities, the AEA and industry, and delivered a comprehensive mandate for general education, training and research in nuclear science. Under the benevolent chairmanship of Lord Bridges and with the active guidance of Pickavance, the first laboratory Director, the Institute, with initially much help from the AEA, became a model central support system over its eight years of existence. Many of the detailed procedures were worked out for the users of the PLA, among whom were found not only teams from major centres but also collaborations involving several of the smaller universities with staff members trained in nuclear structure research. Through working at RHEL, sometimes in collaboration with the in-house laboratory group under W D Allen (or later Stafford or Hanna), such staff felt part of a community in a way that had not so far been open to them and the whole

Table 1. Main nuclear structure accelerators in the UK or projected in 1962/3.

Accelerator	Energy (MeV) (protons)	Location	Closure date
Van de Graaff	2–6	AERE (2) AWRE (2)	—
(one-stage)		AEI	1963
		Manchester	1986
Tandem Van de Graaff	12	AERE	—
(two-stage)		AWRE	1967
		Liverpool	1979
Tandem Van de Graaff	20	Oxford	—
+injector (three-stage)			(FT, see § 7.1)
Cyclotron	50	AERE (VEC)	—
	6–10 per nucleon	Birmingham (2)	—
Synchrocyclotron	170	AERE	1979
	400	Liverpool	1968
Heavy ion linac (HILAC)	10 per nucleon	Manchester	1980
Proton linac (PLA)	50	RHEL	1969
Electron linac	30 (55)	AERE	1976
	100	Glasgow	1982

community was much strengthened. The PLA began producing useful data in 1960 and was enhanced to provide a polarised proton beam in 1961; it was highly reliable because of the excellent technical services of the laboratory, but as an accelerator it was somewhat inflexible since the output energy was not smoothly variable and the macroscopic duty cycle made coincidence experiments difficult. As interest in heavy ion work grew worldwide it became clear that a different accelerator would be needed for the future nuclear structure programme, and this scientific requirement, allied to budgetary problems, led to the closure of the PLA in 1969, at a time when it was supporting the research of at least nine universities as well as part of that of the Nuclear Physics Division of AERE. Savings from the closure were not earmarked for any specific new development.

The interests of the DSIR Nuclear Physics Sub-Committee and NIRNS had a close connection, despite a fairly clear division of responsibilities. For this reason the Physics Committee of NIRNS, which advised the NIRNS Board on new projects, became in due course a Joint Consultative Panel for Nuclear Research chaired by Cockcroft and serving both bodies. It was perhaps inevitable that in 1965, only a year after the formal inauguration of the Rutherford High Energy Laboratory, the two parent organisations were merged under the provisions of the Science and Technology Act to form the Science Research Council (SRC), chaired by Melville. The SRC charter made no specific reference to nuclear physics but it was clear from the outset that the financing of nuclear research in national laboratories such as RHEL and in universities would henceforth be one coordinated operation, to be viewed in the light of the claims of all other branches of science and technology. Nuclear physics had lost for ever the privileged position that it had enjoyed under the protective umbrella of NIRNS. The SRC on the other hand had acquired many responsibilities from the amalgamation, not least among which were the continuance of cooperation with both the UGC and the UKAEA, and the payment of the subscription to the CERN organisation. With the UGC an important understanding concerned takeover of DSIR-funded research equipment and staff posts. This had happened at the end of the 1957 and 1962 UGC planning quinquennia and further transfers took place in 1967 but not in 1972 because of the unwelcome effect of such arrangements on the SRC budget. With the AEA, university use of AERE and AWRE accelerators continued during the period at a cost specified by the Authority. Regrettably the AWRE tandem was closed in 1967, but some equipment was transferred to Harwell, where facilities were also enhanced by the operation of the pulsed neutron source IBIS (1962), of a 30 MeV electron linac (1959), and of the 'chemist's' variable energy cyclotron (VEC) which was designed by NIRNS and operated at its full energy of 50 MeV for protons in 1966. The (4 MV) pressurised electrostatic generator at the AEI laboratory, together with that laboratory's research reactor, both ceased operation in 1963 because of economic pressures.

The SRC conducted its business through a small number of Boards, with membership mainly drawn from user universities and this article is concerned almost exclusively with the Nuclear Physics Board, first chaired by Powell, and with its variously entitled Committees for Nuclear Structure which maintained detailed and intimate contact with the discipline. In the first year of its existence the Council could do little but accept the financial provisions handed on by its predecessor bodies and nuclear and particle physics jointly absorbed 46.1% of the total budget. The reduction of this percentage to 21.5 over the next two decades was accompanied by difficulties, for both communities, of the most serious kind. At the beginning, however, the fortunes of nuclear structure were in the ascendant. The Oxford and Glasgow projects, scientifically and geographically distinct, were in hand and enlisted the support necessary to bring them to completion, after which they were monitored by Boards of Visitors. Smaller university accelerators were improved, for example by the funding of a polarised deuteron source at Birmingham and by the support of the development of complex gamma ray spectrometers at Liverpool and Manchester. There was also generous provision of computer installations and each major centre received an annual exploitation grant, together with machine maintenance funds if necessary. These university grants, amounting for nuclear structure only to a few per cent of the total Nuclear Physics Board budget, were vital to the well-being of the community throughout the period and enabled much work of the highest quality to be completed (§ 6.2).

The major task confronting the community during the years 1957–74 was to convince the SRC and the higher official bodies to which it reported (and from which it received guidance often amounting to instruction) of the need for at least one new nuclear structure accelerator. In the early years, even as late as 1965, when budgets for nuclear physics expenditure were increasing at something like 10% per annum, it seemed possible that two new centres could be created, one near Oxford to replace the PLA and one in the north to serve the Liverpool–Manchester groups. The two-centre policy unfortunately did not survive firstly because of the Board's high priority for joining the '300 GeV' programme at CERN and secondly because of the escalating costs of the CERN subscription as a result of devaluation of the pound in 1967 and of the country's worsening economic situation. It then became necessary to think of just one machine and to decide on its location and each of these questions proved contentious. A series of working parties, starting under the DSIR in 1962, considered and rejected a cyclotron proposal but recommended in 1967 the purchase of an XTU horizontal tandem generator from HVEC. By 1968, however, in the light of cost increases due to devaluation, Willmott as chairman of the current working party promoted discussion of a home-built machine. The shape of what finally became the present Nuclear Structure Facility was first seen in the 1968 papers of the working party and was a vertical tandem for 20-30 MV terminal voltage as advocated by K W Allen. The Nuclear Physics Board received this proposal sympathetically and asked Willmott to chair a small study group to advance the project. Some eighteen months later, in January 1970, the Board under Wilkinson agreed to recommend to Council, then chaired by Flowers, that on educational and scientific grounds a National Tandem Laboratory should be sited at the Daresbury Laboratory, as it was then called. In April, Voss at Daresbury undertook the preparation of a detailed design study and Ashmore, as Director from July, gave this work every encouragement. The design study came to the Board in October 1972 and was transmitted with a firm recommendation for approval to Council, who accepted it in November. This approval was conditional on a site investigation, which fortunately went well, but because of the unusual nature of the buildings, with their 70 m tower, a public enquiry was called for, and was completed by July 1973. At last, in December 1973, planning permission for the development was received from the Department of the Environment and the last impediment in the way of a start was removed. It was only just in time, for within a few weeks, severe cuts in public expenditure were announced by the Government but the NSF was by then secure and funding was approved by the Department of Education and Science in 1974. It had been a hard struggle since 1962 and the country, through the many delays, had lost one generation of accelerators in comparison with the rest of the world, while the endurance of the community had been sorely tried. More trials were indeed to come during construction (§ 7.1) but at least a future programme could then always be foreseen (§ 7.2).

6.2. *Selected achievements 1957-1974*

6.2.1. Fundamental interactions. By 1958 many laboratories throughout the world had studied the consequences of the discovery of parity violation in the weak interaction which governs β decay. In that year, work on the topic in the UK was summarised in a Royal Society Discussion (*Proc. Roy. Soc.* A **246** 441-94); notable among the results were the confirmation at Oxford of the β-decay asymmetry for polarised ^{60}Co nuclei (Grace *et al* 1957) and the demonstration by Cavanagh and his collaborators at AERE (1957) of a longitudinal polarisation of electrons in the same decay. Wilkinson (1958) was the first to classify the types of experiment that might reveal parity-violating effects in the strong and electromagnetic interactions. Much theoretical work on the magnitude of such effects in low-energy processes (impurities of perhaps 1 part in 10^7 in wavefunctions) was carried out by Blin-Stoyle and his collaborators at Sussex over the next few years. This is summarised, together with experimental results on asymmetries or circular polarisation in γ transitions, by Blin-Stoyle himself (1973). Attention was also given during the period to the possibility that interactions might violate invariance with respect to time-reversal (Blin-Stoyle 1973); an experiment at Sussex on electromagnetic transitions in ^{192}Pt is described by Holmes *et al* (1971).

Also of interest to fundamental theory, as foreseen by Wilkinson (1962), were the accurate measurements of comparative half-lives for Fermi-type β decay of mirror nuclei of mass number 4n+2 by an AERE-Birmingham-Oxford collaboration under Joan Freeman (Clark *et al* 1973). When the results of such measurements were fully corrected (Blin-Stoyle and Nair 1967, Wilkinson 1970a) and analysed along the lines indicated by Blin-Stoyle and Freeman (1970), it was possible to deduce the (vector) strength constant G_V for nuclear beta decay, and by comparison with the constant for muon decay to obtain a value for the difference between the small but important model-dependent corrections to the two constants. Blin-Stoyle and Freeman used this information to set limits on the mass of the intermediate boson that conveys the weak interaction according to the unified weak-electromagnetic theory of Salam and Ward (1964). Wilkinson, however, (1975) used similar data, with an assumed boson mass and a theoretical relationship given by Sirlin, to deduce the charges of the 'up' and 'down' quarks which are supposed to form a nucleon sub-structure. In further and extensive studies of the β-decay interaction (Wilkinson 1974a) he established that the *axial* strength constant is quenched by nearly 10% in finite nuclei. He also made careful and important studies (Wilkinson 1970b, 1974b; see also § 7.2.1) of a possible lack of symmetry between another class of β decays of mirror nuclei. Some of the small corrections that are necessary to the theory of β decay if such effects are to be established must arise, in part, from the meson exchange effects first discussed by Bell and Blin-Stoyle (1957). The phase space factor that enters vitally into most β-decay calculations was parametrised and tabulated by Wilkinson and Macefield (1974).

The basic nucleon-nucleon interaction itself, of which the parity-violating potential is a very small constituent, was further studied through proton-proton and neutron-proton scattering experiments on the Harwell synchrocyclotron at energies up to about 150 MeV. Cross sections, polarisations and the Wolfenstein parameters which characterise the polarisation after scattering of an initially polarised beam were determined. The paper of Jarvis *et al* (1964) describes the measurement of the R' parameter at 140 MeV and gives references to the determination of the other quantities. Excellent data became available also from the PLA for 20 to 50 MeV cross sections (Batty *et al* 1964) and the Harwell-Rutherford results were incorporated in a phase-shift analysis by Perring (1968). In a much lower energy domain an important measurement of the cross section for the capture of thermal neutrons by protons was made at Oxford by Cox *et al* (1965); their result deviated by +10% from theory and was later explained by the operation of pion exchange in the nuclear force. Significant also was a determination of the neutron-neutron scattering length by Butler *et al* (1968) using pi-mesons from the Liverpool cyclotron and observing the $^2H(\pi^-, \gamma)2n$ process. All these measurements contributed to knowledge of the real nucleon-nucleon force, but did not lead to its specific form. For nuclear structure calculations it was therefore still necessary to use a semi-phenomenological form of the potential consistent with nucleon-nucleon data, but reasonably simple in analytic form. One form of potential, which has been much used in recent years, was suggested by Skyrme (1959) at Harwell.

6.2.2. Nuclear reactions and properties (high-resolution experiments). The period under review was marked by the introduction of high-resolution semiconductor detectors both for charged particle and γ-ray studies; the history of these detectors and their construction at AERE is reported by Dearnaley (1966). In addition there was extensive development of fast organic scintillators such as those manufactured by the Nuclear Enterprises Company (Birks and Pringle 1972). Detector techniques for nuclear structure were comprehensively reviewed by England (1974). The period also saw the appearance of large digital computers in all major laboratories, adapted for both on-line and off-line processing of nuclear data. Each institution developed its own system; that at Oxford is described by Murray and Macefield (1967). The improved instrumentation greatly facilitated most experiments in nuclear structure physics, and particularly the rapidly expanding study of nuclear states produced through heavy ion reactions. But, even before the new detectors were available, there had been progress in on-line gamma-ray spectroscopy with large sodium iodide crystals (e.g. for ^{14}N, Broude *et al* 1957) and the angular correlation method for finding spin and sometimes parity values from the (p, γ) reaction was being exploited (e.g. for ^{31}P, Broude *et al* 1958). Gamma-ray widths and level sequences were obtained and evidence for collective features was sought. Similar work took place with the 6 MV Van de Graaff accelerators at AWRE and at Manchester, using ^{3}He as well as hydrogen ions. At AWRE a time-of-flight system installed on the accelerator enabled precision measurements of the neutron spectrum from (^{3}He, n) and (d, n) reactions to be obtained (Macefield and Towle 1960). Accelerator calibrations were aided by accurate measurements of (p, γ) resonance energies at AEI Aldermaston (Hunt *et al* 1960). Analysis of experiments on gamma-ray sequences was aided by an authoritative review of electromagnetic matrix elements by Rose and Brink (1967).

The commissioning of the tandem generators at AERE, AWRE and Liverpool permitted high-resolution work on level properties to be extended to elements of higher atomic number. Twin and Willmott (1964) characterised states of ^{50}Cr by use of the proton inelastic scattering reaction (p, p$'\gamma$) with detection of protons and gamma-rays in coincidence. Kaye and Willmott (1965) obtained angular correlation data for the ^{52}Cr(p, p$'\gamma$) reaction and Andrews *et al* (1964) studied the nucleus ^{53}Cr using the ^{52}Cr(d, p) reaction with 6.5–8 MeV deuterons. The use of the DWBA formalism for the analysis of such experiments stimulated a number of theoretical studies, mainly at Liverpool and Manchester, of transfer processes, including stripping to unbound states (Goldfarb 1965, Huby 1970) and heavy ion reactions (Buttle and Goldfarb 1966). The value of measurements at energies just below the Coulomb barrier was pointed out. The AERE tandem was used by Oxford workers (Macdonald and Grace 1967) to study the level scheme of ^{56}Fe and together with the AWRE machine (which had a tritium beam facility), was employed by Bradford workers to extend spectroscopic observations into the near statistical region of overlapping levels (McGregor and Brown 1966). The energy-variability of the tandem accelerators was also exploited in experiments on the fluctuations and correlations of yields in reactions such as ^{27}Al(p, α)^{24}Mg and the relevant theory was tested (Brink *et al* 1964). The broader general features of proton capture reactions (p, γ) were shown (Tanner *et al* 1964) to correlate inversely with the giant dipole resonance of photodisintegration (γ, p). In the early 1960s it was realised that isobaric spin was a valid, model-independent concept over a wide range of nuclear excitation energies and studies of isobaric analogue states (Jones *et al* 1964) and of the mass formula for isobaric multiplets (Wilkinson 1964) were made.

In the later 1960s angular correlation experiments with high-resolution detectors often exploited a method described by Litherland and Ferguson in which the number of populated magnetic substates of a final nuclear state can be limited (Lewis *et al* 1968). The detection of gamma radiation by the germanium counter soon led to the development at Liverpool, following Chalk River, of 'suppressed' spectrometers in which Compton electron background was much reduced by veto signals from a large sodium iodide counter surrounding the active detector. These spectrometers adapted excellently to the determination of radiative lifetimes by the DSAM (Sharpey-Schafer *et al* 1971). Later, facilities for measuring gamma-ray polarisation were added to the spectrometers (Butler *et al* 1973). With this instrumentation, Liverpool groups in particular examined level structures of many nuclei in the (sd) and $f_{7/2}$ shells (e.g. ^{25}Mg, Butler *et al* 1975); I^{π} values and multipole mixing ratios for particular levels were derived. In such experiments, level lifetimes were usually determined using the

DSAM technique; a typical example is the work of Macdonald *et al* (1968) on the levels of ^{40}Ca using the Oxford accelerator system. A few lifetimes shorter than those accessible to the DSAM were measured at AERE by the ingenious crystal 'blocking' method in which the result of an excited nucleus recoiling out of the shadow of a line of crystal centres is sensed (Clark *et al* 1971). For the level spectra, increased resolution with wide angular coverage in charged particle studies was provided by the multichannel spectrographs at AWRE (after 1970 at AERE) and at Oxford. These instruments employed nuclear emulsion detectors and could therefore record a complete angular distribution for many groups of particles on one exposure; an automatic scanner for the tracks recorded was developed at Bradford (Stephenson and Dale 1971). A typical experiment is that of Jeans *et al* (1969) on the reaction $^{208}Pb(d, p)^{209}Pb$ and of Darcey *et al* (1971) on the states of nickel isotopes surveyed by the (t, p) reaction. A particular feature of many of the experiments in the latter part of this period, notably those of the Manchester group using the Liverpool tandem, was the identification of the level sequences of the collective model in deformed nuclei.

Most of the accelerators available in the period could be used to produce new radioactive nuclei, and there were decay scheme studies of proton-rich nuclei formed in HILAC bombardments at Manchester (e.g. ^{73}Br, Murray *et al* 1970). At Harwell, the decay of an isomeric excited state of ^{53}Co produced at the VEC was found by an Oxford group to exhibit true proton activity (Jackson *et al* 1970).

Determination of nuclear moments continued at Oxford (Grace *et al* 1962) using the nuclear orientation method and at Sussex (Rochester and Smith 1964) by atomic beam magnetic resonance, while at the NPL a precision determination of the proton magnetic moment in nuclear magnetons was made (Petley and Morris 1969). A method was devised to determine the electric quadrupole moment of an excited state using Coulomb excitation (Harper *et al* 1971) and the ratio of multipoles in γ transitions was studied in γ-γ correlations at Sussex (Hamilton 1969). The interpretation of experiments on nuclear moments and on multipole mixing ratios in electromagnetic transitions is simplified if a spin-oriented initial state can be produced and during the period low temperature techniques were used for this purpose both at Oxford (Kaplan *et al* 1972) and Sussex (Fox *et al* 1972). At Oxford, Grace and his collaborators (Randolph *et al* 1973) showed how to determine the g factor of an excited nuclear state by sensing the alteration of an associated radiation distribution by precession of the nuclear moment in the calculable magnetic field of a hydrogen-like ion, e.g. $^{16}O^{7+}$. Figure 10 shows curves taken during this experiment.

The spectroscopic information assembled by the programmes mentioned was precise and extensive and invited detailed comparison with theory. This was above all the theory of the shell model, which was elaborated and applied to specific cases by groups at AERE, Birmingham, Glasgow, Manchester, Oxford, Southampton and Sussex. The connection of shell-model states with collective features of nuclear behaviour had been examined by Peierls and Yoccoz (§ 5.2) and by Brink but a major advance was made by Elliott (1958). This was the demonstration that degenerate states of particles moving in a spherical simple harmonic oscillator potential, if classified in terms of representations of the group SU_3, would cluster into a rotational band. This work, and its application to the calculation of level schemes with an assumed internucleon potential (Elliott and Harvey 1963) has greatly clarified the microscopic theory of nuclear rotations. Some years later (Elliott *et al* 1968) it was shown at Sussex that arbitrariness in specifying internucleon potentials could be avoided by direct calculation of useful matrix elements from experimental nucleon-nucleon scattering data. The Sussex work

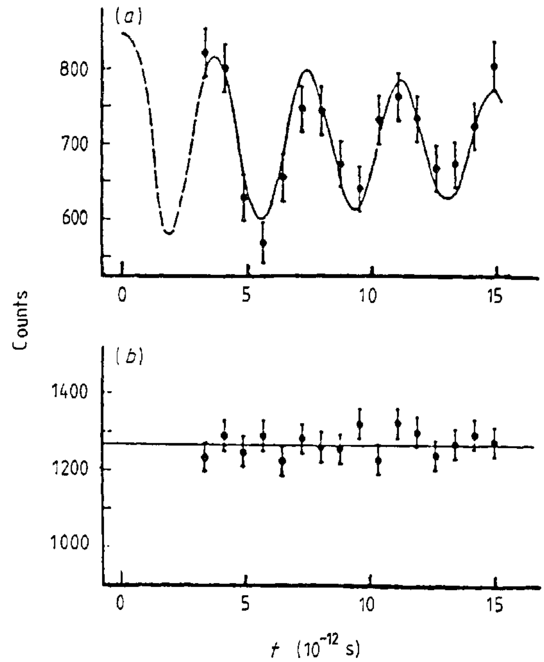


Figure 10. The magnetic *g* factor of excited nuclear states: (*a*) the variation of gamma-ray intensity from the 6.13 MeV level of ^{16}O due to precession in the internal magnetic field of an oxygen ion. The timescale is determined by the distance travelled by the ion before the precession terminates in a stopping foil; and (*b*) the lack of variation for the 7.12 MeV level (Randolph *et al* 1973).

was used at Glasgow (Cole *et al* 1974) in an untruncated treatment of nuclei of the (sd) shell. Guidance on the question of nuclear sizes was given by Elton (1961) who later, with Swift (Elton and Swift 1967), derived single-particle potentials appropriate to the nuclear p and (sd) shells from nucleon separation energies and electron scattering results. Wilkinson (1966) used a typical potential to calculate E2 radiative widths for levels in the p shell. The general problem of nuclear structure calculations was reviewed by Elliott in 1971; he emphasised that for most purposes the two-body matrix elements must be treated as adjustable parameters.

6.2.3. Nuclear reactions and properties (low-resolution experiments). In parallel with the high-resolution work there were experiments with light ions which examined nuclear interactions not necessarily involving compound nucleus formation. These direct interactions were discussed for neutron capture by Lane and Lynn (1959). More generally, at incident energies of about 10 MeV per nucleon, interactions were considered to average over the underlying fine structure levels. The 'optical' model which described such scattering in a simple way was reviewed by Brown (1959) and its conventional form was revised by Lane (1962) to include a potential depending on neutron to proton ratio (isospin-dependent). The number of free parameters of the model was reduced in the 'folding' reformulation due to Greenlees *et al* (1968) which, although completed in the USA, has its origin in the scattering experiments in the UK in the early 1960s. Later, many versions of the folding model were evolved, for example by the King's College, London group (Sinha and Duggan 1974). Some of the relevant scattering work was carried out on the Birmingham cyclotrons and on the PLA at the Rutherford Laboratory and had already received conventional analysis, especially by the theoretical group established by Wilkinson under Hodgson in the Oxford Nuclear Physics Laboratory (1958) and by the King's College group. A representative set of experiments carried out at the PLA with 30 MeV protons and a range of nuclei comprehended elastic scattering (Ridley and Turner 1964), reaction cross section (Turner *et al* 1964), polarisation (Craig *et al* 1964) and analysis (Barrett *et al* 1965). At Birmingham, polarised deuteron work analysed partly in collaboration with the University of Surrey revealed the *j*-value dependence of vector analysing power (Basak *et al* 1974) and the influences of the deuteron D state admixture on both vector and tensor analysing power (Johnson *et al* 1973). In 1974 this group commissioned a polarised helium-3 ion source for a cyclotron (Burcham *et al*) which enabled spin-dependent effects in ^{3}He-nucleus scattering to be studied accurately. The isospin dependence of the optical potential was very clearly verified by the observation at the PLA of an augmented yield of neutrons in the (p, n) reaction to isobaric analogue states (Batty *et al* 1963).

In 1962 Wilkinson, in his Rutherford lecture to the Physical Society, pointed out that mesonic probes could yield much important information on nuclear structure. After the operation of the NIMROD proton synchrotron at the Rutherford Laboratory in 1963, beams of pions and kaons could be used for this purpose and during the next decade these were exploited by a Birmingham, Rutherford, Surrey collaboration (Clough *et al* 1974). Proton beams of energy 385 MeV were used at Liverpool to verify the fundamental shell structure of nuclei through the (p, 2p) reaction (James *et al* 1969); figure 11 shows the evidence from this work for bound shells of particles in ^{12}C. At Harwell the lower energy protons from the synchrocyclotron were used by an Oxford group to excite radiative transitions in nuclei of A up to about 40; it was found that the inelastic scattering picked out states with strong ground state transitions. The use of probes of a few hundred MeV energy in nuclear structure physics was reviewed by Jackson (1968).

Selectivity in nuclear process was demonstrated in a quite different field when Scott *et al* (1972) from Oxford, using the VEC at Harwell, showed how heavy ion transfer

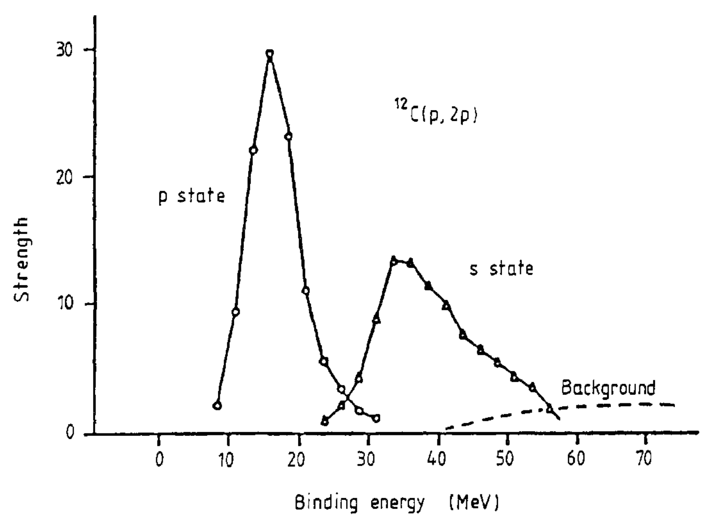


Figure 11. Evidence for the nuclear shell model. The peaks show the yield of protons from the (p, 2p) reaction in ^{12}C and give evidence for the binding of s-state and p-state particles in the nuclear structure (James *et al* 1969).

reactions could pick out states with dominant 1-, 2- or 3-nucleon configurations. Heavy ion physics in general expanded largely during the period under review because of the availability of beams from the tandem accelerators, with which Coulomb excitation was used for the determination of radiative matrix elements (Eccleshall *et al* 1962): Manchester workers were able to use beams of Fe and Kr from the HILAC in a pioneer study of the lifetimes of high spin states in rotational bands in deformed rare-earth nuclei (Kearns *et al* 1974).

In some heavy ion reactions a compound nucleus may be formed by fusion as a preliminary to evaporation of particles, and study of the process inverse to this, namely fission, was a major programme at AERE. This included a full theoretical study of the place of fission in nuclear reaction theory with consideration of double-humped potential barriers (Lynn 1973). The AERE 30 MeV electron linac, later upgraded to 55 MeV, was devoted largely to this work, although neutron time-of-flight and general photodisintegration experiments were also undertaken (Firk *et al* 1963). The special role of the giant dipole resonance in such processes was studied during this work (Medicus *et al* 1970). The role of angular momentum and excitation energy in the fission of ^{239}Pu was examined at the VEC Harwell by Cuninghame and Goodall (1975). With the availability of high-energy electron beams from the Glasgow linac, data on nuclear charge and transition densities soon began to appear (Singhal *et al* 1971).

7. A national facility 1974–1986

7.1. Survey

In 1974 some 300 physicists, including about 100 research students supported by the SRC, were engaged on nuclear structure research in the country. The experimentalists were mainly using six university accelerators and a number of AERE machines on the programmes outlined in § 6.2. Work had started on the NSF at the Daresbury Laboratory (Aitken *et al* 1974) and commissioning was expected in 1978. Altogether, prospects for the subject might have been judged good, but such a conclusion would have been ill-founded. The next twelve years, to which this section is confined, were to see the closure or impending closure of several accelerators, escalating costs and mounting delays in the NSF construction and severe restriction of funds available for university grants. The approval of the NSF in 1972 had of course implied the closure of the Liverpool and Manchester machines, but what had not been foreseen were the severe effects of inflation and of deteriorating foreign exchange rates on SRC uncommitted funds. These external factors were not under Council control, but internally there were policy decisions to enhance support for engineering and applied science at the expense of 'big science' both in grants and in the allocation of research studentships and fellowships. In consequence the fraction of the SRC budget that went to nuclear and particle physics nearly halved between 1974 and 1986. It is hardly surprising that by the early 1980s, and before the NSF was operating, a decline in community numbers had set in.

In approving the NSF, the SRC had accepted the desirability of improvements to the major facilities at Glasgow and at Oxford, and proposals were made for each in 1974. At Glasgow a small 30 MeV electron accelerator was to be built to take over photoneutron and weak interaction physics from the main 100 MeV machine, which would then be improved for electron scattering work. At Oxford there had been misgivings about the performance of the coupled system and it was proposed to convert the generously designed injector into a folded tandem machine with emphasis on its heavy ion capability. The terminal voltage of 10-12 MV would put it into the class of the HVEC Emperor tandems and would permit the EN tandem to be discontinued. Both these proposals were funded in 1974/5; the small electron accelerator was used for photonuclear work from 1977 and the Oxford folded tandem operated in 1979 (Barratt *et al* 1981). Other groups, while waiting for the NSF, were using either their own domestic accelerator or the machines at Harwell, of which the VEC proved a convenient successor to the PLA and to the AERE synchrocyclotron, which was closed in 1979. Groups funded for AERE experiments in May 1975 included King's College and Queen Mary College, London, Manchester, Edinburgh, Oxford, Birmingham and Bradford.

In 1975/6 the Nuclear Physics Board, conscious of an ever-increasing need for detailed scrutiny and control of the application of resources, placed its whole nuclear structure programme under the supervision of a newly constituted Nuclear Structure Committee (NSC) chaired at first by Bishop and then by Willmott. The Committee would be served in respect of the NSF by a Programme Panel chaired by Morrison. These arrangements and the funding prospects were reported to a community meeting in London on 17th February 1976 which was attended by about 140 people. The meeting expressed its support for the original proposals of the Board to maintain a high standard of excellence at Oxford and Glasgow, and to see that the NSF when ready for operation should be properly provided with experimental equipment, in particular a magnetic spectrometer. There was concern at the low number of research studentships allowed to the Board and some feeling that the Board might not have urged its case strongly enough in Council. In order that the community should be kept fully informed, the Board decided during 1976 to circulate an informal newsletter to user universities. This unfortunately has proved all too often to be the bearer of ill tidings, as in 1977 when the Board's Forward Look for the coming five years had to include sacrifices of the sort that the community meeting had urged should be avoided. They were however very carefully planned, within Council guidelines, and the fact that the damage inflicted was minimised owed much to the foresight of the NSC and its chairman.

By 1978 the NSF had been subjected to the scrutiny of a number of working parties asked to assess its current and long term needs in money and manpower but, owing to uncontrollable delays in civil engineering work, it was far from complete. Much valuable work had been done under Voss towards finalising the charging system (laddertron) developed by W D Allen and the stack structure originally tested at Aldermaston in line with Willmott's early recommendations. A 7 MV pilot machine had been built for full-scale trials and charge-state separators had been tested. The machine tower had dominated the surrounding countryside since the end of 1976, but the total building complex was not handed over until early 1979. Fortunately it had been possible to assemble the whole stack (see figure 5(*b*)) within the pressure vessel by that time and rapid progress was then made, leading to the successful application of 23 MV to the stack (without accelerating tube) in September 1980. Other technical troubles were experienced but the titanium-ceramic tube was installed in the last few weeks of 1981. It was tested at 16.3 MV with carbon-ion beams in June 1982 and by September of that year conditions were sufficiently stable for continuous operation on behalf of the eagerly anticipated experimental programme. Ashmore retired from the post of Laboratory Director in 1981 after seeing the NSF nearly to completion and was replaced by Green from Liverpool. The machine was finally commissioned by the NSF Division under Voss and was officially inaugurated by Sir Keith Joseph on 27 September 1983. In 1983 Voss moved to the SERC Central Office and was succeeded by Twin, on leave of absence from Liverpool. This appointment recognised the change in emphasis in the Division from construction to exploitation and since commissioning the machine has admirably fulfilled the role of a national facility planned for it in 1974.

Since 1976 the Programme Panel has exercised detailed assessment of experimental proposals and installations and a Users' Committee has maintained contact with the community. Much was learned from the administrative procedures worked out long before at the PLA and as at that machine a key element in the NSF success has been the existence of a strong in-house group of nuclear physicists in the NSF Division. Through collaboration between this group, the Nuclear Structure Committee and the users, the high-quality experimental facilities for the NSF evolved while the machine was being built and in 1986 occupied the areas shown in figure 12; an account of the main installations is given by Gelletly (1983). As may be seen these include a magnetic spectrometer (Chapman, Lilley), an isotope separator (Gelletly, Grant), a recoil-product separator (James) and on-line γ-ray detection arrays (Twin, Sharpey-Schafer). The performance of the machine itself in its first two years of operation is described by Aitken *et al* (1986); in 1985/6 the NSF provided 40 different species of accelerated beams for 56 experiments. Some of the results achieved up to 1986 are mentioned in § 7.2.

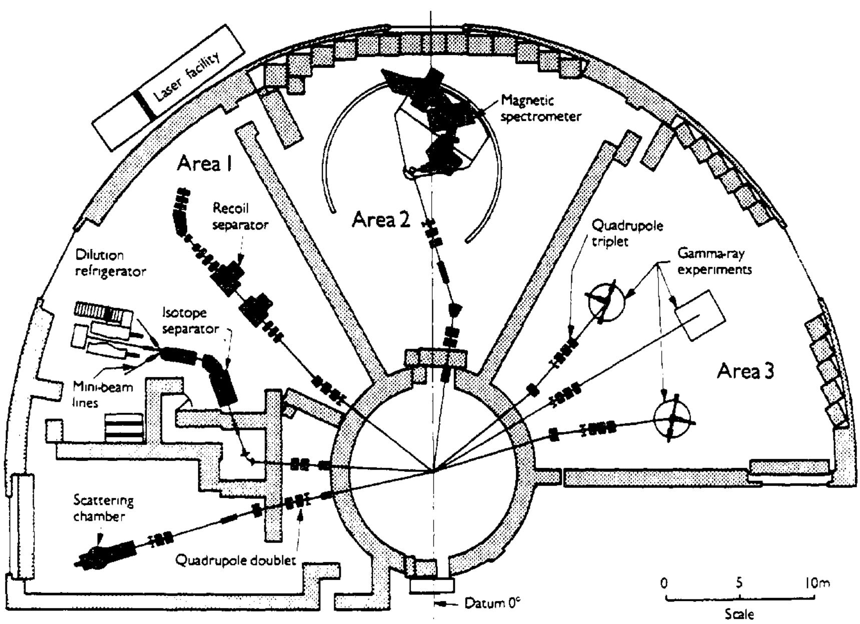


Figure 12. Experimental areas for the Nuclear Structure Facility at the Daresbury Laboratory, 1982. The vertical beam of accelerated particles is deflected through 90° to enter the chosen area (reproduced by permission of the Daresbury Laboratory).

Part of the price for the building of the NSF was paid in 1979 when the Liverpool tandem ceased operation and in 1980 when the Manchester HILAC was closed. At about the same time usage of AEA accelerators for the SRC nuclear structure programme was sharply reduced. But, the Oxford folded tandem (FT) was completed by 1978, and money was found to provide a magnetic spectrometer (MDM/2) for that installation (Pringle *et al* 1986; see figure 2(*b*)). At Glasgow improvements were also made but these were largely fruitless in the long term because already in 1978, the budgetary pressures had made it clear that proper utilisation of the NSF must imply closure, as distinct from a reduced level of operation, of a further accelerator. Towards the end of 1979 the Nuclear Physics Board had reluctantly to recommend to the Council of the SRC (soon to become SERC, the Science and Engineering Research Council) that the high-energy electron linear accelerator work at the Kelvin Laboratory of the University of Glasgow should be terminated; it was only 20 years since the original proposal for the machine had reached the DSIR. Ironically the year of the Glasgow decision (1979) saw the *opening* of the 136 MeV pulsed electron linear accelerator HELIOS at AERE (Lynn 1980) but although this machine, with its neutron booster, offered useful facilities for basic research it was felt that the future for the Glasgow group lay rather in collaboration with the electron microtron group at the University of Mainz. Use of this 180 MeV continuous-beam machine, after the Glasgow accelerator ceased nuclear physics work in 1982, has proved much more successful than might have been feared and UK groups have contributed a photon-tagging system to the accelerator (Kellie *et al* 1985). At the same time, in partial mitigation of the Glasgow decision, it was decided to regard the Oxford FT as a quasi-national accelerator and to encourage increased usage by groups other than those based at Oxford. At Manchester and Birmingham work continued on small accelerators funded by the university concerned. And, because of the delay in commissioning the NSF as well as of the domestic closures, the community as a whole strengthened its SRC-supported collaborative links, both by groups and individuals, with overseas accelerator laboratories. The more important of these throughout the period were CERN at Geneva, the Niels Bohr Institute (NBI) in Denmark, the Brookhaven National Laboratory (BNL), the Lawrence Berkeley Laboratory (LBL) and the Los Alamos Scientific Laboratory (LASL) in the USA, the Institute Laue–Langevin (ILL) at Grenoble, the TRIUMF Laboratory at Vancouver, the Australian National Laboratory (ANU) and the heavy-ion facilities UNILAC at Darmstadt and GANIL at Caen. Partly because of these collaborations but also because of the increasing sophistication of nuclear structure work and the limited accelerator time available to any one group, the number of authors per experimental paper began to increase markedly.

Altogether, in 1981, as preparation for the NSF programme built up, it seemed that at considerable sacrifice the nuclear structure effort of the country had been rationalised and that some semblance of stability for the next few years had been created. It was therefore proper for the Board to consider the longer-term plans that had so far figured only sketchily in Forward Looks, and a working group chaired by Morrison was set up by the Nuclear Structure Committee to identify the next accelerator that would be required by the nuclear structure community. The group ultimately recommended a move away from the traditional nuclear structure experiment and towards the intermediate energy electron probe that would be provided by a 600 MeV continuous beam accelerator, for example a microtron. But before this could really be considered, Council had at last become alarmed at the damage that was being done to big science by a continual run-down of funding in real terms and had appointed in 1982 a Review Committee under E W J Mitchell 'to review the state of nuclear structure physics in the United Kingdom and the significance of the subject in terms of the long-term health of British science'. It had also by 1983 relaxed its restrictions on the number of research studentships that might be funded (though partly at Board expense) in big science.

In 1983, in the highly propitious climate engendered by the discovery of the W and Z bosons at CERN and by the operation of the NSF at a world-record terminal voltage, the Mitchell Committee reported. It gave general support to the study of nuclear structure physics in the United Kingdom and made specific recommendations that the NSF should operate intensively for about four years with no attempt to raise the terminal voltage above about 20 MV. It also endorsed the usage of the Oxford machine by the whole community and it even supported the proposal to upgrade it by the provision of three superconducting linac post-accelerator modules. The Board of course welcomed this report and has adhered to its recommendations. But, despite the good intentions of Council, the budgetary problems remained, and were aggravated once more in 1984 as on earlier occasions by incomplete compensation for international exchange rate fluctuations. It is not the intention here even to outline the perceived consequences for fundamental particle physics of decisions taken with perhaps less than due regard for scientific achievement and promise. It seemed at one time that little less than an orderly withdrawal from participation in the CERN programme would suffice and the Board registered its consternation by all legitimate means at its disposal. Nuclear structure did not escape the new pressures, because the Advisory Board for the Research Councils had indicated to SERC that although new money would be available in 1984/5, none of this should go to nuclear or particle physics. The Nuclear Physics Board therefore undertook a major review of what could be properly supported and concluded that support should be withdrawn from the Oxford FT and concentrated on the NSF. It was recommended that the superconducting modules intended as boosters for the FT should be transferred to the NSF. SERC support for the Oxford machine effectively ceased early in 1988 despite vigorous opposition to closure, not only by Oxford workers but also by other groups whose programmes were not fully or easily accommodated at Daresbury. Whether a means will be found to continue to exploit this valuable national asset in some form is a matter that lies beyond the scope of this survey.

The nuclear structure appendix to the Daresbury Laboratory Annual Report for 1986/7 records 78 experimental or theoretical investigations that took place during the year, involving not only at least 10 universities of the United Kingdom but also nearly 20 overseas institutions. Although not all requests for experimental time could be met, it is clear that the NSF has responded well to the call of the Mitchell Committee in 1983 for vigorous exploitation. Nor has the future been forgotten; a source of polarised sodium ions was installed (1987) and the superconducting modules are being assembled (1988).

The conclusion of this review must be that in 1986 the NSF, the Oxford FT, some overseas laboratories and the AERE jointly provided accelerator or other time for a community of some 250 nuclear physicists including research students, the inheritors of a tradition extending back over 75 years to Rutherford at Manchester. It is a community which after many delays and tribulations still holds, through the enthusiasm and ability of its members, an internationally competitive role in its subject.

7.2. Selected achievements 1974–1986

The nuclear physics programme of this period in the United Kingdom was until 1983 a continuation of that of earlier years (§ 6.2) but with a decreasing number of domestic facilities and an increasing number of international collaborations. By 1983, however, (Nolan *et al* 1983) the first results from the NSF at Daresbury were appearing and the volume of work from that laboratory rapidly increased until at the time of writing (1988) it forms the mainstream of research in the country in experimental nuclear structure physics.

7.2.1. Fundamental interactions. Direct nucleon–nucleon scattering experiments of the sort undertaken earlier at the AERE synchrocyclotron continued at TRIUMF (Clough *et al* 1980). At ILL a collaborative group of the University of Sussex and the Rutherford Laboratory made a new measurement of the neutron lifetime (Byrne *et al* 1980). Their value was included in an exhaustive analysis by Wilkinson (1982) of the details of the neutron β decay, a paper published in the jubilee year of the neutron discovery. Other collaborations, sometimes using the ILL cold neutron facility (Smith 1980), sought evidence for an electric dipole moment of the neutron and looked for other manifestations of the breakdown of conservation laws in the fundamental interactions. Closely related, in the sense of concern for the nature of these interactions, was the final conclusion of the series of papers (§ 6.2) on the comparative half-lives for β^+ or β^- Gamow–Teller decay of mirror nuclei (Wilkinson 1977). Limits were set on the contribution of 'second-class currents' to these decays. Also relevant was the completion at AERE, by 1978, of the series of accurate measurements of comparative half-lives for a number of superallowed transitions, which as indicated earlier (§ 6.2), gave some indication of the mass of the intermediate W boson of the weak interaction, later discovered at CERN. The same superallowed transitions were also examined by Alburger and Wilkinson (1977). At Glasgow (Fitzpatrick *et al* 1976) the accepted theory of the β-decay weak interaction was checked by measurements of the electron capture to positron decay ratio in a number of unstable nuclei produced by photoprocesses at the electron linac. Some experiments which well illustrate the use of complex nuclei to study the properties of the fundamental interactions were carried out at Oxford by Fifield *et al* (1977, 1983). From measurements on the radiative widths of unbound states of ^{20}Ne they were able to test the predictions of the Conserved Vector Current hypothesis for the weak interaction. And, from the very small α-decay width of a $I = 1^+$, $T = 1$ level, they established parity mixing that is consistent with the operation of a weak neutral current in the internucleon force.

The use of pions and kaons as nuclear probes that had taken place at the Rutherford Laboratory was continued at CERN after the closure of NIMROD in 1978. The work developed to include the study of exotic atoms produced not only by kaons from the CERN proton synchrotron (Bird *et al* 1983) but also by sigma hyperons and antiprotons, the latter obtained from the low-energy accumulator ring (LEAR) (Gorringe *et al* 1985). The results on the x-rays from antiprotonic hydrogen and deuterium, in which the normal atomic electron was replaced by $\bar{p}$, were used to extract the strong interaction effects responsible for the shift and width of the 1s 'x-ray' level.

7.2.2. Nuclear reactions and properties. The Liverpool and Oxford groups working with their own accelerators, with AEA facilities or at overseas collaborating institutions continued high-resolution spectroscopic work on nuclei of the (sd) and (fp) shells. Most of this work employed light bombarding particles, the $(\alpha, n\gamma)$ and $(\alpha, p\gamma)$ reactions being found particularly useful, as illustrated by the work of Behbehani *et al* (1979) on ^{43}Ca among many similar studies. Later, however, heavy ions were used in similar work (Nolan *et al* 1981). Some heavier nuclei were also studied, as in earlier years, by the Bradford group using nuclear emulsions exposed at the Oxford, AERE or Liverpool tandem and scanned automatically. In some of this work the Oxford multichannel spectrograph was used (Slater and Booth 1976). Oxford workers themselves used this instrument for conventional spectrographic studies (Roaf *et al* 1979) and in addition the tandem generator was used for accurate measurements of certain interesting lifetimes in light nuclei (Dixon *et al* 1977). An Oxford group developed the powerful particle-particle correlation technique (Smith *et al* 1985) as a new spectroscopic method. In both these undertakings it was often convenient to use heavy ions as the bombarding particle and a light nucleus as target, because of the increased momentum then available for emergent particles.

Heavy ion physics, defined somewhat arbitrarily as the study of collisions between two particles each of mass number above 4, rapidly overtook light ion work in concentration of effort in most of the major centres in the 1970s. Before the NSF and the Oxford folded tandem, with their specially designed heavy ion facilities, came into operation, heavy ion beams could be used at Liverpool, Manchester, Oxford, AWRE and AERE (tandem and VEC) as well as at several overseas laboratories. From work at these centres during the 1960s and 1970s, the main problems and opportunities of heavy ion physics had been identified and extensively explored. In a field of such extent and complexity only a few achievements can be noted here and attention will be concentrated on work which has led on naturally to continuation at Daresbury or has started there. As with light ions, there are two major areas of interest, namely the properties of the nuclei produced in heavy ion reactions and the mechanics of those reactions themselves. The recent use of relativistic ^{16}O beams at CERN to produce nuclear matter at extreme density and temperature will not be considered.

Heavy ion collisions can produce residual nuclei in states of high excitation and high angular momentum and a study of the regularities and specific properties of these high-spin states using the (HI, $xn\gamma$) reaction is a major success at the NSF, through the work of Twin and his collaborators. The observed γ-decaying sequences, especially in deformed nuclei (e.g. in ^{172}Hf, Paul *et al* 1985), manifest a striking behaviour which arises from the variation of coupling between single-particle and collective behaviour as spin increases. The observed 'crossing' of band sequences is connected with partial alignment of nucleon angular momenta (Simpson *et al* 1985) and seems to lead to a rigid-body moment of inertia of nuclei at high excitation (e.g. in ^{84}Zr, Price *et al* 1983). And, in other nuclei, the co-existence of prolate and oblate deformation has been established (e.g. in ^{152}Dy, Nyako *et al* 1986). In γ-spectroscopic experiments such as these the escape-suppressed spectrometer arrays (TESSAS) installed in Area 3 (figure 12) have provided a powerful facility; these instruments (figure 13) were pioneered by an NBI-Liverpool collaboration and are described by Twin *et al* (1983) and Nolan *et al* (1985). It was a particular distinction for the collaboration (Nyako *et al* 1984, Twin *et al* 1986) when a series of regularly spaced γ rays was seen in about 2% of decays of the excited nucleus ^{152}Dy with clear confirmation of earlier suggestions of a 'superdeformation' of that nucleus. The occurrence of an ellipsoidal axis ratio of 2:1 had been indicated by Russian work on fission, but the Daresbury experiment was the first to reveal the relatively low excitation of superdeformed states in a system with a spin as high as 60 $\hbar$. Figure 14 shows the spectrum obtained in this work, which employed the ^{108}Pd (^{48}Ca, 4n) ^{152}Dy reaction at 205 MeV. In reactions such as this the product nuclei have a high recoil velocity, which is useful in lifetime determinations for excited states by the Doppler-shift method and for the implantation of nuclei into metal foils for orientation experiments. Lifetimes of high-spin states in rare-earth

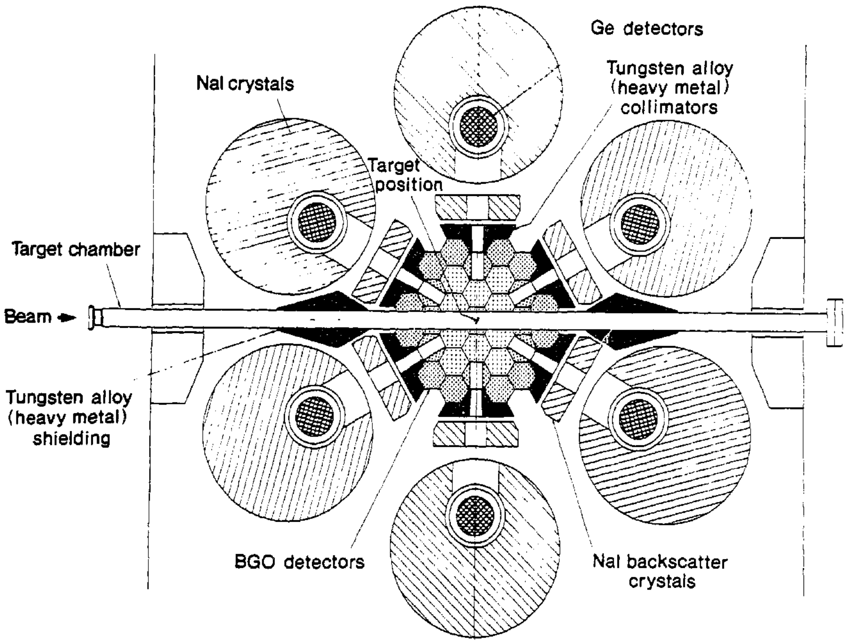


Figure 13. On-line gamma-ray detection at Daresbury, 1986. The highly versatile total energy suppression shield array (TESSA) provides not only a total energy signal for a nuclear cascade from the bismuth germanate (BGO) γ-ray detectors, but also high resolution spectra with background reduction from the germanium/sodium iodide (Ge/NaI) modules (courtesy of P J Twin and the Daresbury Laboratory).

nuclei were measured at the Manchester HILAC using Kr beams (Kearns *et al* 1977) and later at the NSF by the Liverpool-Daresbury group using TESSA (e.g. for super-deformed ^{132}Ce, Kirwan *et al* 1987).

Reactions of the type (HI, xn) at the NSF can lead to the formation of a large number of isotopes of a given element, according to the number x of neutrons evaporated. The on-line electromagnetic isotope separator installed in Area 1 (figure 12) has proved highly successful in analysing such products which are brought to thermal energy in its ion source and thus normally have nuclei in their ground state. After analysis a mass-separated beam of ions or neutral atoms can be obtained and in a major development a Birmingham-Daresbury-Manchester collaboration has observed resonant scattering of dye-laser light from these beams. Resonance is achieved by varying the velocity of the beam or the frequency of the light and for each isotope a given atomic or ionic spectral line will in general show a shift in frequency due to nuclear size and mass effects or a splitting due to hyperfine coupling or both. If the shift is measured for a *pair* of isotopes the change in mean square charge radius $\delta\langle r^2\rangle$ is obtainable and this will sometimes exhibit the onset of nuclear deformation as neutron number changes in an isotope sequence. Figure 15 shows some of the first results (for Sm, Eastham *et al* 1984); because of the high atomic cross sections involved the method is highly sensitive as well as selective and the sensitivity has been considerably improved by coincidence detection of photons and the emitting atoms (Eastham

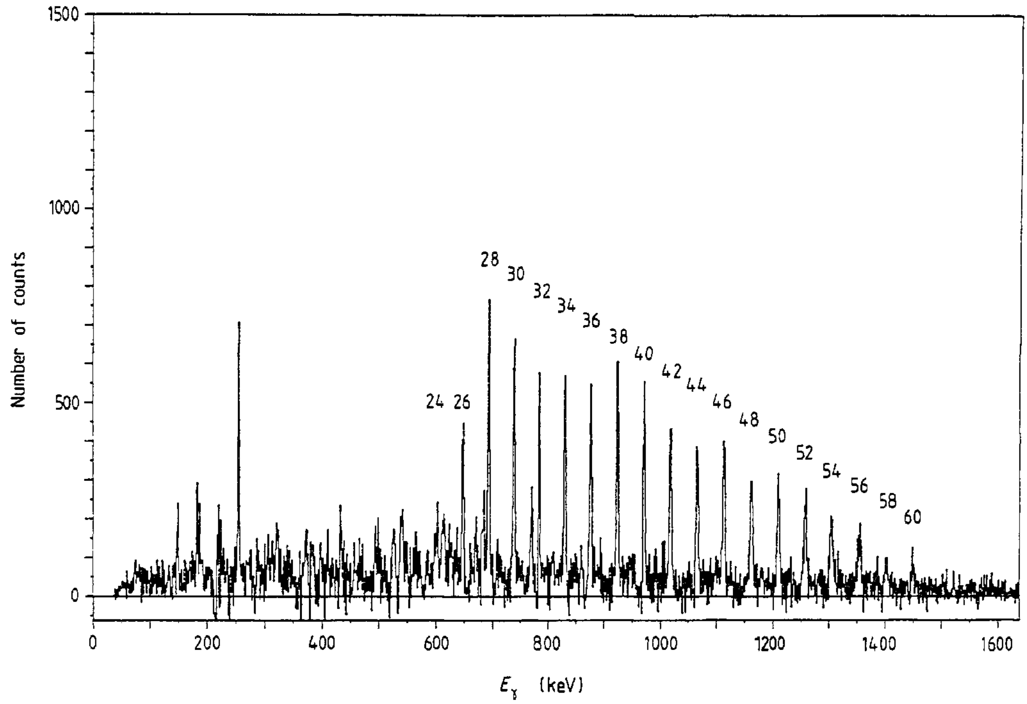


Figure 14. Superdeformation in ^{152}Dy. The gamma-ray lines, obtained with TESSA, have an energy spacing corresponding to a 2/1 ellipsoidal deformation of the radiating nucleus (courtesy of P J Twin and the Daresbury Laboratory).

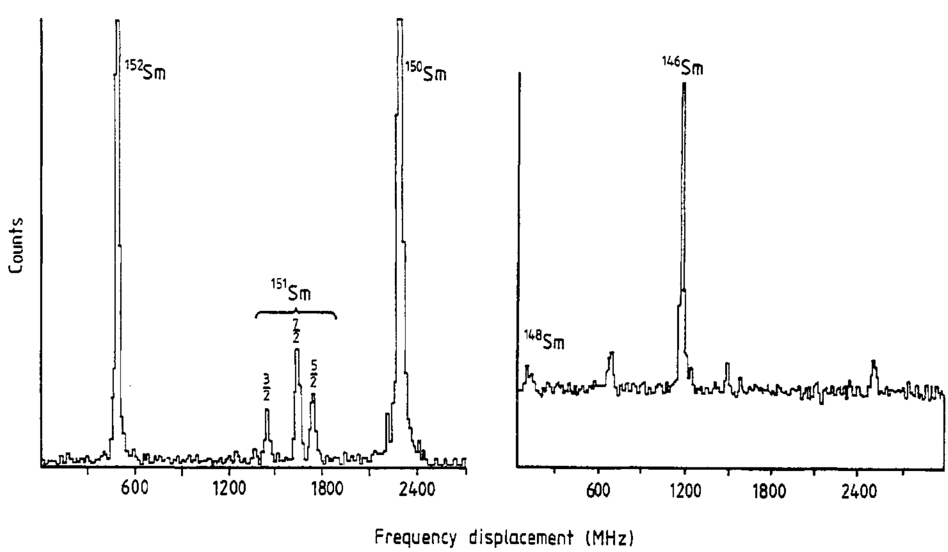


Figure 15. Resonance fluorescence (scattering) spectrum for the 570.68 nm transition in atoms of a beam containing unstable ^{146}Sm and ^{151}Sm as well as stable samarium isotopes. The total angular momentum quantum numbers F of the states of the ^{151}Sm atom ($I = \frac{5}{2}$) are shown (Eastham *et al* 1984).

et al 1986). The mean square charge radius $\langle r^2 \rangle$ relates to the spatial distribution of all nuclear protons but individual valence orbit sizes, for neutrons as well as protons, can be studied by a reaction technique pioneered by Manchester workers (Chapman *et al* 1976, Warwick *et al* 1979). In this, the excitation function for a transfer reaction such as (t, d) or (t, α) is studied in the sub-Coulomb (barrier) energy range.

Because of the trend of neutron to proton ratio in the natural sequence of elements, the fusion of two heavy ions will produce a proton-rich compound system and the evaporation of neutrons in a (HI, xn) reaction will move the residual nucleus even further from the main valley of stability. Other reaction mechanisms involving cluster transfers can lead to neutron-rich nuclei, so that heavy ions have become effective agents for the production of 'exotic' nuclei, in which new manifestations of deformation or shell closure may be seen. Although such phenomena can sometimes be established by the optical scattering technique it is more generally important to examine the γ-ray spectra of such nuclei. At the Oxford folded tandem the nucleus $^{64}_{32}$Ge, with equal proton and neutron numbers, was produced by the $^{12}_{6}$C($^{54}_{26}$Fe, 2n)$^{64}_{32}$Ge reaction and γ radiation from its first excited state was detected by requiring coincidence with neutron counts from a liquid scintillator (Ooi *et al* 1986). At Daresbury, the nucleus $^{80}_{40}$Zr, also with equal nucleon numbers and expected to be stable, was produced by the reaction $^{58}_{28}$Ni($^{24}_{12}$Mg, 2n)$^{80}_{40}$Zr and identified by the recoil separator in Area 1 (figure 12); its radiations were detected on-line in coincidence with the recoil signal (Lister *et al* 1987). Exotic nuclei are generally produced in low abundance, but if the yield is sufficient their mass may be measured using a high-resolution spectrometer. This was done for a number of nuclides with the QMG/2 analyser installed in Area 2 (figure 12) (e.g. ^{33}Al, Woods *et al* 1986).

Experiments on heavy ion reaction mechanisms have established the crucial role played by the Coulomb barrier in many phenomena. Elastic scattering, observed at all energies, shows anomalies at energies near that of the barrier and such effects are ascribed to coupling to inelastic processes (Lilley *et al* 1983, 1985, 1987). Below barrier energy, Coulomb excitation dominates in the excitation of collective nuclear states, but transfer reactions also take place, and such reactions can be used to determine the root mean square radii of the valence nucleon distributions in nuclei (Jones *et al* 1974). It has been established that the simpler types of transfer reaction (e.g. $^{48}_{20}$Ca($^{28}_{14}$Si,$^{27}_{13}$Al)$^{49}_{21}$Sc, Hoath *et al* 1985) may be described by the approximation methods used for light bombarding particles. A special feature of heavy ion processes is of course the selectivity for particular cluster transfers, already noted in § 6.2. Such work is significant since it may reveal the cluster structure of the nuclei concerned and such experiments continued at Oxford during the period under review (Godwin *et al* 1979). An extreme form of clustering which has attracted much attention in heavy ion laboratories is that in which a ^{24}Mg nucleus formed in the ^{12}C + ^{12}C reaction behaves as if one carbon cluster is orbiting about the other; the break-up of excited states of ^{24}Mg into two equal parts was observed by Fulton *et al* (1986). Such systems can also be produced by the inverse process of electrofission, which was studied for heavy elements by the Glasgow-Edinburgh collaboration at the Kelvin Laboratory with electron beams of energy up to 120 MeV (Shotter *et al* 1976). Also inverse to heavy ion reactions is the radioactive emission of heavy particles from heavy elements as an alternative to the more familiar α decay. In 1984 Rose and Jones at Oxford discovered the emission of ^{14}C nuclei at a level of 1 in 10^9 of the normal decay of the radium isotope ^{223}Ra; other similar decays have been seen.

At heavy ion energies just above the barrier, fusion of target and heavy projectile may take place forming a highly excited compound system whose subsequent de-excitation presents some unexpected features when compared with similar systems which in the past have been successfully described by statistical evaporation theories. Neutron emission is certainly favoured when energetically possible but high energy gamma radiation also competes in the initial stages of de-excitation and this has been shown at Oxford (Garman *et al* 1983) to be probably due to the involvement of a giant dipole resonance built on an excited state, as suggested by Brink. Both the particle evaporation and the lower energy photons which arise later in the de-excitation process occur somewhat less frequently than expected (Love *et al* 1985, 1986) and this is ascribed to the influence of high angular momentum in the heavy ion reaction. For energies well above the Coulomb barrier a new mechanism called deep inelastic scattering is found to transfer surprisingly large amounts of energy and angular momentum between colliding nuclei and features of this process were studied particularly by a Birmingham group at the VEC Harwell (Bhowmik *et al* 1979).

Theoretical support for much of the previously mentioned experimental work was forthcoming from the strong groups that were already active in 1974 at AERE, Glasgow, Manchester, Sussex and Oxford. To these was soon added a group at Daresbury and work also continued at Birmingham and Liverpool. The Glasgow untruncated shell-model calculations for nuclei of the (sd) shell (e.g. $A=23$, Cole *et al* (1975); see also the summary paper, Whitehead *et al* (1977)) were much used for comparison with spectroscopic data, and Hartree-Fock calculations were made for ^{16}O by Sussex workers (Halkia *et al* 1982). This last work showed some evidence for clustering of nucleons in the nucleus in agreement with the cluster theories already developed at Oxford (e.g. for $A=18$, Buck *et al* 1979). The Oxford work was particularly relevant to the heavy ion programme, which also received clarification from the barrier penetration models discussed, for example, by Brink and Takegawa (1977) and by Nagarajan and Satchler (1986).

Unfortunately neither the shell model nor the unified model of Nilsson, with a deformed potential, could satisfactorily deal with a whole range of nuclei whose nucleon numbers fell between closed shells and which were readily accessible through heavy ion reactions. For these nuclei the interacting boson model (IBM) of Arima and Iachello, in which nucleons are grouped together into pairs to form bosons with relative orbital momenta $0\hbar$ and $2\hbar$, which then interact, provides a welcome simplification of the many-body problem. The model has been discussed at Manchester, Oxford and Sussex (Tian and Irvine 1983, Zirnbauer and Brink 1982, Elliott and Evans 1981). The history and relevance of the model were reviewed by Elliott (1985) to whom many of the recent advances are due.

The determination of nuclear moments, nuclear spins and multipole mixing ratios continued vigorously by the techniques already developed before 1974, especially those of angular correlation of γ rays and of angular distributions of radiation from oriented nuclei. The latter work was carried out both by Oxford workers (Lattimer *et al* 1981) and by the Sussex group who collaborated in some experiments with the Dubna laboratory in the USSR (Warner *et al* 1979). The same group in collaboration with French and German workers also made correlation experiments on mass-separated fission products at the ILL reactor at Grenoble (Alquist *et al* 1980). Both groups were soon able to use the refrigeration-orientation facility for separated isotopes provided at the NSF, which was designed particularly with implantation work in prospect. This is described in Gelletly's article (1983) and is installed in Area 1 of the NSF (figure

12); typical results are those of Shaw *et al* (1985) on ^{118}I. At the same time the hyperfine interaction techniques developed under Grace at Oxford were further applied to measurements of the *g* factors of excited states of light nuclei (e.g. ^{19}F*, Billowes *et al* 1983) and for heavier nuclei use was made of the strong transient magnetic field which arises when a nucleus enters and slows down in polarised iron foil (e.g. for Ge isotopes, Pakou *et al* 1984).

Although optical isotope shifts and sub-Coulomb transfer reactions give important information on nuclear charge distributions, particularly for rare isotopes and unstable nuclei, the charge radius of a stable nucleus is normally best obtained from elastic electron scattering experiments. During the period under review, results continued to appear from the Glasgow Kelvin Laboratory linear accelerator (e.g. for Mg by Lees *et al* 1976a) and many of these were compared with the predictions of the Glasgow shell-model programme (e.g. for Na, Mg, Al by Singhal *et al* 1982). Electron inelastic scattering data, usually obtained at the same time, yielded radiative matrix elements and transition charge densities (Lees *et al* 1976b). Towards the end of the period, when the end of operations at the accelerator was in sight, the apparatus was adapted to the measurement of elastic scattering at 180° which gave information difficult to get by other means on the magnetisation distribution and hence neutron density in the nucleus. The linac was also used by Glasgow and Edinburgh workers to study electro- and photo-disintegration processes (Sené *et al* 1985), including the fission work already noted. The accuracy of the electron scattering data worldwide was high enough to permit derivation of realistic nuclear proton and neutron density distributions (Brown *et al* 1979).

Experiments of the sort just mentioned, revealing gross properties of nuclei through the well understood electromagnetic interaction, were complemented by low-resolution 'optical' type experiments with light ions. At Birmingham, 25 MeV α-particle elastic scattering was used to reveal neutron shell effects for nuclei with A between 50 and 93 (England *et al* 1982). In the same laboratory the optical potential for ^{3}He particles was explored using a 33 MeV beam of polarised ^{3}He ions (Burcham *et al* 1975), while in subsequent experiments a Birmingham-King's College, London collaboration examined in particular the scattering by Ca nuclei (Hanspal *et al* 1984). The same collaboration was able to conduct similar experiments with an unpolarised triton beam at the NSF (Pearce *et al* 1986) and with cooperation of LASL, to extend the work to polarised triton scattering (Hanspal *et al* 1986). The contribution of D-state admixtures in the ^{3}H and ^{3}He structures to scattering amplitudes was examined at Birmingham by Entezami *et al* (1983) using the (d, ^{3}He) and (d, t) reactions with polarised deuterons and a similar admixture in the α particle was sought by Tostevin *et al* (1984) using the ^{40}Ca(dα) reaction. The extended experimental study of the optical model and of transfer mechanisms made possible by the existence of polarised particle beams at Birmingham underlined the need for a polarised heavy ion source at the NSF. The theory of the nucleon optical potential was examined both at King's College (Sinha 1975) and at Oxford (Brieva and Rook 1978); composite projectiles were considered by Perkin *et al* (1975) and by Sinha. Related to the gross structure work, although studied with a high-resolution system, was the Birmingham-Manchester-Oxford demonstration of a giant resonance built on excited states of ^{16}O (Chew *et al* 1977).

Acknowledgments

The author thanks the Science and Engineering Research Council for permission to refer to decisions in respect of nuclear physics support and acknowledges that the report represents his personal views and not necessarily those of Council. He is grateful, for the supply of information, to K W Allen, T E Allibone, J R Atkinson, S Devons, J M Freeman, P E Hodgson, J R Holt, H R McK Hyder, R O Owens, J M Reid and G H Stafford and to the Nuclear Physics Division, SERC.

He also wishes to thank J M Freeman, B R Fulton, M M Gowing, P B Moon, G C Morrison and J C Willmott for reading the report in whole or in part and for valuable suggestions. He is indebted to M Pendleton and P N Burcham for preparing the typescript and to D M Baggott for help with figures.

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