3 Nuclear Structure and Nuclear Energy

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In 1909 experimental work on the scattering of α (alpha) particles (the nuclei of helium atoms) by matter was done by Geiger and Marsden (a final year undergraduate) under the direction of Ernest Rutherford, a New Zealander then at Manchester University. This work showed that scattering through large angles, more or less in the backward direction, was much more common than was expected. Rutherford's careful analysis of such results showed that the positive charge carried both by the α particles and near the center of the scattering atoms was concentrated in a very small small volume. Furthermore, the positive charge on the atoms was an integer multiple of the electron charge e that corresponded to the position of the element in the periodic table, which we now call the *atomic number* Z. This work, and 1913 X-ray absorption work by Moseley, showed that an atom consists of a very small but massive positive nucleus, whose charge is balanced by Z electrons. Around this time Niels Bohr, from Copenhagen, showed up in Manchester with an explanation of how a quantum theory can explain how the electrons were held in relatively large orbits around the nucleus.

It was already known that the nuclear reactions that occurred in radioactive decay produced an enormous amount of energy per atom. The isolation of radium from a particular uranium ore by Marie Sklodowska Curie and Pierre Curie was successful because after each chemical separation the radium-bearing portion could be identified by its more intensive radiation, and, in later stages, by its emission of heat and light. This was quantified in the twenties and thirties by Rutherford and his collaborators in Cambridge, England. Nuclear fragments could be emitted from excited nuclei with energies of the order of millions of electron volts per particle, rather than the few electron volts per molecule typical of chemical reactions. A key part of the analysis needed to show this was provided by Einstein's identification of the total energy of a particle or system of particles at rest with M_0c^2, where M_0 is the *rest mass* of the particle or system, and c is the speed of light. For example, the mass of a deuterium atom, hydrogen with one extra neutron, is $2.0141M_A$, and of a helium atom is $4.0026M_A$, so the fusing of two deuterium atoms to form a helium atom releases $0.0256M_Ac^2 = 23.8 \times 10^6$ eV of energy, where the atomic mass unit M_A is defined as one twelfth of the mass of a carbon atom. Controlled nuclear fusion of this sort promises to satisfy all the energy needs of the planet. For promise to turn to fulfillment, economical control of such reactions between light elements is necessary, and it is not yet clear that we are any closer to getting such control than we were fifty years ago

Although some of the essential features of nuclear properties were not identified until the early 1930s, most were understood before that, largely by Rutherford and his collaborators. It was recognized that slow radioactive decay in uranium-bearing rocks enabled geological formations to be dated to more than a billion years ago. It was recognized that radioactive decay in rocks could account for the continued net flow of heat out from the earth – temperature goes up as depth below the earth's surface increases in a deep mine. It was recognized that nuclear reactions between light elements could provide the energy needed to power the stars, whereas the energy source known before nuclear physics was developed, the gravitational energy of a star, was not sufficient to keep the sun close to its present temperature over the period in which modern forms of life have existed on earth. It was known there are three types of radiation that are emitted in spontaneous radioactivity, α particles, which are helium nuclei with $Z = 2, N = 2$, β (beta) particles, which are electrons, and γ (gamma) rays, which are photons of very high energy electromagnetic radiation.

In this Chapter I will discuss the physics involved in energy production, in nuclear reactors, in nuclear weapons, and in the stars, and some of the practical issues that prevent nuclear energy from being a simple solution to the problems that have arisen from excessive burning of carbon-rich materials. In the following Chapter I will discuss how the small magnetic moments carried by atomic nuclei can be used as a probe of physical and chemical details of materials, whether artificial or of biological or geological origin.

3.1 Structure and properties of nuclei

Nuclei are composed of protons, which are just the nuclei of ordinary hydrogen atoms, with an electric charge $+e$, and neutrons, which are similar to protons, but have zero electric charge. These two particles are both called *nucleons*. Neutrons were not identified until 1932, when James Chadwick's group in Cambridge, following a lead given by Irène Joliot Curie and Fréderic Joliot, found that some nuclear reactions gave a particle that knocked protons out of materials containing hydrogen. This discovery was very important, because earlier people had often thought of the neutral component of nuclei as a tight combination of a proton and an electron, which obscured the actual similarities between neutrons and protons. The mass of a proton is $1836.2 m_e$, where m_e is the electron mass, and the mass of the proton is $1838.7 m_e$, so a free neutron can decay into a proton and an electron, releasing energy $1.5 m_e c^2$. This occurs quite slowly, taking about 11 minutes, and is an example of β decay. Both the proton and the neutron, like the electron, are fermions, and have an intrinsic *spin* angular momentum of $\hbar/2 = h/4\pi$. With this intrinsic angular momentum is associated a magnetic moment, which for the electron has a value close to minus the Bohr magneton

$$\mu_B = \frac{eh}{4\pi m_e}\,, \tag{1}$$

with the value 9.27×10^{-24} joules per tesla, but the proton and neutron, with their much larger mass, have much smaller magnetic moments, $+1.52 \times 10^{-3} \mu_B$ for protons and $-1.04 \times 10^{-3} \mu_B$ for neutrons.

Clusters of nucleons go to build up larger nuclei in much the same way that clusters of molecules form liquid drops. There is a negative contribution proportional to the number of nucleons, and a positive contribution proportional to the surface area, analogous to the surface tension of a liquid. Since the nucleons are fermions, it is energetically favorable for the number of protons and neutrons to be equal, so that they can go into the lowest levels for each type of nucleon, just as it is favorable for electrons in an atom to occupy the lowest available energy levels. However, the Coulomb repulsion between the protons favors neutrons over protons, so that for all but the lightest stable nuclei the neutron number N is greater than the proton number Z. It is also generally true that nuclei with even numbers of protons and neutrons, such as the α particle, or the $A = 16$ isotope of oxygen, ^{16}O, have more binding energy than their odd-numbered neighbors. Also the the ground states of such even Z, even N, nuclei have zero angular momentum and zero magnetic moment, whereas nuclei with odd proton number Z or odd neutron number N have angular momentum and magnetic moments nonzero in their ground states.

The binding energy per nucleon of a nucleus increases from 1.1 MeV for deuterium to about 7 MeV for helium, and grows slowly to a maximum of 8.8 MeV around iron, with $Z = 20, N = 26$. Because of the increasing effect of the repulsion between protons in heavy nuclei, the binding energy per nucleon decreases beyond iron, so that most of the elements beyond lead, which has $Z = 82$, are radioactive, and decay to lower values of Z and A.

3.2 Radioactivity, fission, and other nuclear reactions

Most of the radioactivity which is found naturally on earth is due to the effects of decays of the long-lived isotopes of uranium, ^{238}U with 92 protons and 146 neutrons, and ^{235}U with 143 neutrons. The first of these has a half-life of 4.5 billion years, and emits an α particle, which gives the thorium isotope ^{234}Th with 90 protons and 144 neutrons. Over the course of a few weeks the nucleus loses an electron by β decay, which turns one neutron into a proton, and then there is a second, rather faster, β decay that takes the atomic number back to 92, and gives ^{234}U. This isotope of uranium has an alpha decay, with a half life more than 10^5 years to ^{230}Th, and this has a slightly quicker alpha decay to radium, ^{226}Ra. This has a half-life of 1600 years, it gives out much more energy per decay than the original ^{238}U; it was the substance isolated by the Curies, chemically similar to barium. The alpha decay of radium leads to a Group VIII inert gas, radon. If your basement has an unusually high concentration of radium in the building materials or in the ground, the radon emission is bad news, because it is a gas with a half-life of a few days, and you may breathe it when you are in the basement. Eventually, without many more long delays, this chain reaches the unstable isotope of lead, ^{210}Pb, and then a stable isotope, ^{206}Pb. There are two similar chains of naturally occurring radioactive materials, one based on ^{232}Th, which has a long half-life of 1.4×10^{10} years, and decays to the short-lived (6.7 years) ^{228}Ra and then on down to ^{208}Pb, the commonest lead isotope. The third is based on ^{235}U, which has a lifetime of 7.1×10^8 years, whose decay product, ^{231}Th, emits an electron in beta decay to form the long-lived (32,000 years) protoactinium isotope ^{231}Pa, which eventually follows a chain down to ^{207}Pb, another common lead isotope. While Rutherford was still at McGill University, he and Soddy used the ratio of the uranium or thorium isotopes to the lead isotopes in naturally occurring ores to determine the age of the rocks in which they were found. He also realized that the heat produced by these reactions would explain the amount of heating escaping upwards to the earth's surface. Both these discoveries put physics firmly on the side of the billion-year old solid earth favored by biologists and geologists, rather than the less than 100 million years that had been argued for by an earlier generation of physics.

In almost all these naturally occurring radioactive processes, gamma rays are emitted as well as alpha and beta rays. The gamma rays are high energy photons emitted when the transition emitting the helium nucleus or electron does not lead directly to the ground state of the product nucleus, but to an excited state. Gamma rays are then emitted as the product nucleus sheds it extra energy and goes into its ground state.

An unexpected feature of beta decay is that in the simplest examples, when a nucleus emits an electron and goes to the ground state of an adjoining nucleus, the energy of the electron has a continuous spectrum, with an energy that varies between zero and a maximum that corresponds to the mass difference between the initial nucleus and the sum of the masses of the final nucleus and electron. Momentum conservation dictates that a particle at rest that decomposes into two components should have the speeds of the final particles inversely proportional to the masses of the two particles, and they should be in opposite directions. If energy is also conserved in the reaction the speeds should be unique. Pauli suggested a resolution of this paradox by postulating the emission of a third particle with no electric charge, which carried off the missing momentum and energy, but could not be observed. This unseen particle was called a *neutrino* in a detailed theory constructed by Fermi. No direct observations of the neutrino were made until 1953, when Reines and Cowan (Phys. Rev. **90**, 492, 1953) used the absorption of neutrinos from a nuclear reactor by protons, to reform neutrons, as a detection method for neutrinos.

The discovery of the neutron, which more or less coincided with the development of powerful accelerators such as E. O. Lawrence's cyclotron at Berkeley, provided a powerful new tool for nuclear physicists, because neutrons could penetrate nuclei without having to overcome the Coulomb force that repels one nucleus from another. Hahn, Strassmann and Meitner in Berlin began to find strange effects when uranium was bombarded with neutrons, as Fermi's group in Rome had done a few years earlier. They did a more careful chemical analysis than Fermi had done, and where Fermi thought he had a new isotope of radium, Hahn's group identified an element similar to barium, although they were expecting a transuranic element.. Meanwhile Lise Meitner, an Austrian Jew, had had to move to Sweden in a hurry after the German absorption of Austria. In spite of her hurried departure, Hahn and Meitner continued in regular correspondence, and she, with her nephew Otto Frisch, decided the decay product must be barium, produced by fission into barium and krypton. They coined the name *nuclear fission*, by which the process has been known ever since. Hahn and Meitner met briefly in Copenhagen, where she told Hahn of their interpretation of his results in terms of fission. She did not get to share Hahn's Nobel Prize for the discovery, but she lived another thirty years.

The identification of barium as one of the products of the violent reaction that occurs when uranium is bombarded by neutrons suggested to Meitner and Frisch that the increase in size destabilizes the heavy nuclei, so that they split into two parts, which are likely to have too many neutrons in relation to the number of protons, and so they will need to convert many of the neutrons to protons by beta emission. This discovery, revealed just nine months before the beginning of the war in Europe, spurred immediate activity on the feasibility of a chain reaction induced by neutrons in uranium, particularly in the USA, in the UK, where Frisch and Peierls were living, and in France.

For a long time it was thought that such a chain reaction was entirely man-made, but in 1972 the remains of a geological nuclear reactor from more than a billion years ago were found in Oklo, in the West African country Gabon.

3.3 Nuclear reactions in the stars

Stars like the sun are mostly composed of hydrogen and other light elements, and the energy that is radiated out from such stars is largely supplied by the release of energy in the process of fusion of protons to form alpha particles, with a release of energy of 7 MeV per proton. This is the energy, radiated largely as visible light, and as infrared and ultraviolet close to the visible spectrum, that keeps the earth's surface at a comfortable temperature close to 300 K and supplies light for photosynthesis in green plants. To a large extent animal and bacterial life depends ultimately on plants, growing, dead, or fossilized, to supply its energy needs. The only other major sources of energy available are geothermal sources, from volcanic action powered by residual heat in the earth's interior, and from radioactive decay of heavy elements.

The hydrogen and other light elements in stars are held there by gravity. If the temperature is low, as it must have been when stars were forming, no nuclear fusion will occur, because the nuclei are not traveling fast enough for them to overcome the repulsive forces due to their positive charges. At this stage any heat radiated out from the surface must be replaced by further contraction of the gas, which makes the gravitational potential energy of the star more negative. Roughly half of this released potential energy goes to replace the energy radiated out, and half goes to increase the kinetic energy of the atoms, and so increase the temperature of the star. Eventually, as this process goes on, the temperature rises to a few million degrees, and some of the protons are going fast enough to react with one another to form a deuteron, a positron (the positively charged antiparticle of the electron), and the neutrino that always accompanies beta decay of a neutron or proton. We can write this reaction as

$$p + p \to d + e^+ + \nu \,. \tag{2}$$

This is one of the slow steps in the synthesis of helium, as it involves simultaneous collision of two protons and beta decay of one of them. The deuterons can then react directly with one another to form an alpha particle, or one deuteron can react with a proton to form ^{3}He, and this can then pick up another neutron in a collision with a deuteron to form an alpha particle.

The temperature of the center of the sun, where most of the nuclear fusion occurs, is around 19×10^6 K (34 million Fahrenheit), and at that temperature it is generally agreed that another process is important, in which carbon and nitrogen act as catalysts. This was analyzed in a 1939 paper by Hans Bethe (Phys. Rev. **55**, 434), who was awarded the 1967 Nobel Prize for the work. The reactions in this cycle leave the number of carbon and nitrogen nuclei unchanged, and it involves the six reactions

$$^{12}C + H \to ^{13} N + \gamma \,, \quad ^{13}N \to ^{13} C + e^+ + \nu \,, \quad ^{13}C + H \to ^{14} N + \gamma \,,$$

$$^{14}N + H \to ^{15} O + \gamma \,, \quad ^{15}O \to ^{15} N + e^+ + \nu \,, \quad ^{15}N + H \to ^{12} C + ^4 He + \gamma \,. \tag{3}$$

When the supply of protons begins to be inadequate the star must shrink in order to release more gravitational potential energy and raise the temperature enough for alpha particles to come close enough to combine. Here there is a major problem that two alpha particles cannot be combined, since the ^{8}Be nucleus disintegrates immediately into two alpha particles. Various different things can happen to a star beyond this point. Its surface can cool while its core gets hotter, to form a *red giant.* It can collapse to form a *white dwarf,* which has a very high density, so that the atoms are completely ionized, and the nuclei move around in a more or less uniform background of electrons. It can collapse even further, by way of a supernova explosion, such as the one observed in 1054, which ultimately formed the Crab *pulsar.* Pulsars were first observed in 1967 by Jocelyn Bell (Burnell) and Tony Hewish; Hewish got the Nobel Prize in 1974, but his graduate student did not. Pulsars have a rapidly varying and very regular light output – in the case of the Crab pulsar the frequency is about 30 Hz (oscillations per second). They appear to be *neutron stars*, in which the the density is so high that the protons capture electrons to form neutrons, leaving the electrons and protons restricted to the surface region of the star, whose radius is a few kilometers. Higher mass stars are not stable as neutron stars, but collapse further to form black holes, as Chandrasekhar argued, to the disbelief of his mentor, Eddington, in the early 1930s.

3.4 Controlled fusion

The main difficulty in obtaining controlled fusion on earth is that the kind of energies associated with the interior of the sun is required to get charged nuclei within range of one another's nuclear forces, even if the charge has its minimal value of one electron charge. The method which has generally been favored has been to confine the charged nuclei by powerful and cleverly designed magnetic fields, and to accelerate the nuclei until the have the energies of many keV which are needed for them to get close enough to one another to fuse. Research in this direction over sixty years or so has let to a lot of knowledge of the instabilities of such a confining system. Alternative approaches such as trapping by lasers, compensating for the positive charge of the nucleus by trapping a μ meson on it (unfortunately the muon only lives for about a microsecond), or imploding bubbles has yielded little in the way of promising results. The announcement in 1989 by Pons and Fleischmann of evidence of nuclear fusion from helium dissolved in platinum or palladium seemed particularly implausible to me, and the experiments seem to be hard to reproduce.

3.5 Nuclear reactors and nuclear weapons

The discovery of nuclear fission in 1938 gave an immediate promise of the availability of a new source of power whose fuel would be much less massive and produce a much smaller mass of waste products than coal or oil. Two key features of nuclear fission were that it could be produced by capture of low energy neutrons in the $A = 235$ isotope of uranium, and that the electrically neutral neutrons could penetrate a target heavy nucleus however low their energy was. The nuclear fission was known to produce further free neutrons, and the big question was whether more neutrons were produced in the fission process than are needed to trigger the fission. If this condition was satisfied it would be possible to produce a self-sustaining chain reaction. If not enough neutrons were produce, one fission would produce some more, but the chain would soon come to an end.

It was soon discovered, by McMillan, Seaborg and others in Berkeley, and by Feather and Dee in Cambridge, that neutron bombardment of ^{238}U forms another fissile element with $A = 239, Z = 94$, which was, and is, called plutonium. This provided an alternative fissile material, whose supply could be built up once a copious source of neutrons was available. In the same way, and to some extent by the same people, many more transuranium elements wee later obtained by further neutron bombardment, or by bombardment of heavy elements with high energy nuclei.

The neutrons emitted by fission of uranium or plutonium are more readily captured by other fissile nuclei if they are slowed down to the speeds characteristic of thermal motion at a moderate temperature. This is achieved by inserting rods of a it moderator into the fissile material. This moderator has to be clear of impurities, including isotopes of the moderating material, that absorb neutrons rather than just scattering them. One of the first choices of moderator was *heavy water*, deuterium oxide, and this was chosen by Heisenberg's group in Germany. The choice made in the USA was high purity graphite. To control the rate of the chain reaction, neutron absorbers can also be inserted to cut down the reaction, or removed to enable it to proceed.

The first successful reactor was set up on the University of Chicago campus in December 1942, and industrial scale reactors, for the production of fissile materials, were set up at Oak Ridge, Tennessee, on the Snake River in Idaho, and on the Columbia River in Washington. Nuclear reactors have been used to power ships, particularly for submarines, which do not have to surface to discharge waste gases, and for aircraft carriers, which have a cruising range limited primarily by food supplies and aircraft fuel supplies. Nuclear reactors are also long-lived power sources for long-range space craft. Nuclear reactors are also long-lived power sources for long-range space craft. Nuclear reactors are an important component of electrical power supplies in many countries, particularly in those that do not have good local supplies of fossil fuels or of water power, but costs are generally much higher than was initially estimated, for a number of reasons. The problems of disposing of radioactive waste, particularly when a nuclear power plant is decommissioned, were seriously underestimated. Safety in uranium mining was neglected in the early days. Structural damage due to radiation causes unexpected maintenance problems. There is a lot of local political pressure against building nuclear plants in populated neighborhoods, even when the same neighborhoods will welcome industries with a much worse safety record than the nuclear industry (at least if you discount the Chernobyl disaster as something that could only have happened in a very poorly managed country).

Fission weapons were built simultaneously by two different paths. One was by enriching the $A = 235$ isotope of uranium, by the differential diffusion rates of gases containing different isotopes, by electromagnetic separation in the biggest Berkeley cyclotron, and so on. The other way was by building up ^{239}Pu in a reactor or other source of neutrons. In either case, but particularly for plutonium, which has a measurable rate of spontaneous fission, it is vital to assemble the fissile material fast enough that no chain reaction starts before it is fully assembled. Premature ignition would lead to disintegration of the device rather than explosion. Equally, it is necessary for there to be neutrons around to trigger the device as soon as it is assembled. The fast assembly was achieved by shooting two hemispheres of fissile uranium together to form a sphere of critical mass for the bomb that destroyed Hiroshima and a large proportion of its population, while the one that destroyed Nagasaki was fired by the implosion of a hollow sphere of ^{239}Pu. Those who were closest to the explosion were killed by direct effects of the light and other thermal radiation from the explosion, those further away by the shock wave through the air (blast), by falling buildings.. Of those who survived the effects of initial blast, many were killed within a week or so as a result of fast-growing cells (such as those lining the gut) destroyed by the very high flux of gamma rays. there were also many long-term health problems from radiation (mostly gamma ray) damage. The effects of the bomb on six Hiroshima survivors were described in *Hiroshima*, by John Hersey, published by Knopf in 1946. This is a classic book, which has had 92 editions, and the UW library system appears to have one copy, held in the Special Collections.

3.6 Other applications of nuclear reactors

The initial development of nuclear reactors was, because of wartime priorities, sharply focused on the production of fissile materials suitable for the manufacture of bombs. Since it was necessary to keep the reactors cool by running hot water out into the adjacent rivers, it was obvious that reactors were a major source of power, and the design of reactors to produce power economically rather than to produce fissile materials was an obvious step in the immediate postwar period.

The production of radioactive isotopes in reactors was a major problem, particularly as it complicated waste disposal, but the production of tailor-made isotopes was also an opportunity, opened up by the high flux of neutrons inside reactors. Naturally occurring radium and polonium, separated with great trouble from natural uranium decay products, had been used for medical purposes since the first world war, but less dangerous isotopes of more familiar chemical elements could be made by putting the commonest isotope, or isotopes of neighboring elements in the reactor. Isotopes such as ^{3}H (known as *tritium*), ^{14}C, ^{32}P, or ^{35}S can be substituted can be substituted for the usual isotopes ^{1}H, ^{12}C, ^{31}P, or ^{32}S in chemicals that are used in metabolic processes, and their progress followed by the location of their radioactive decays. A technique which was very important at one time is the Radioimmune assay (RIA), developed by Solomon Berson and Rosalyn Yalow, for which Yalow, trained as a physicist, received the 1977 Nobel Prize in Physiology or Medicine; Berman had died before the award was made. They had started by radioactive labelling of insulin given to diabetics, and showing that there was an unexpected immune response to that, but they developed or more flexible method in which the antibodies were labeled, so that the antigens they reacted with could be identified.

Radioactive tracing could also be used in more mundane matters such as tracing leaks in pipes. An alternative method is to put a dye in the liquid flowing through the pipe, but that only works if the leak is visible from the outside.

Neutron also be used to study the properties of solids. A beam of thermal neutrons can be diffracted from the regular array of atoms is a crystalline solid, in much the same way as electrons can be used To some extent this method complements X-ray diffraction. For example, the proton with its single nuclear charge scatters electrons very little, while a neutron scatters quite strongly. Also, neutrons, carrying their own magnetic moments, are quite sensitive to magnetic fields, and can be used to study the magnetic structure of ferromagnets and other magnetic solids, such as antiferromagnets. On the other hand, other materials are difficult to study with neutrons, because they absorb neutrons too strongly. Clifford Shull, from MIT, received the 1994 Nobel Prize for developing the neutron diffraction technique for studies of condensed matter.

Because the energy of a thermal neutron is much less than the energy of the X-rays used to study solids, perhaps 0.04 eV rather than many keV, the energy losses or gains that a neutron has when it collides with a phonon (sound wave) in the solid are much easier to see than the corresponding energy changes in X-rays, so neutron scattering was used in the early days of nuclear reactors to study the energy spectrum of phonons and other excitations in solids. For this development Bertram Brockhouse, of AECL, Chalk River, and McMaster University, both in Ontario, also received the 1994 Nobel Prize, for the development of neutron spectroscopy for studies of condensed matter.