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HIGH ENERGY NUCLEAR PHYSICS

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Preface

This book is based on lectures, given at Birmingham University for the past three years, to first year postgraduate students in nuclear physics. It is intended to be an introduction to the subject; an attempt has been made, therefore, to explain the concepts and principles in some detail. An elementary knowledge of quantum mechanics is assumed; when necessary reference is made to the standard texts by Schiff (*Quantum Mechanics* – McGraw Hill) and Fermi (*Nuclear Physics* – University of Chicago Press). The important topics of high energy electron scattering and of strange particles have been excluded, partly to keep the book of reasonable size and partly because excellent review articles on both these subjects have appeared in the last two years.

I have drawn freely from the standard works on the subject, and these are listed in the Bibliography at the end of each Chapter.

My thanks are due to my colleagues Dr A. P. Batson, Dr C. J. Batty, Dr S. J. Goldsack and Dr D. H. White for permission to use material from lectures given by them; to Dr A. C. L. Barnard, Dr P. J. Duke, Dr P. V. March and Dr H. Muirhead for their comments on a preliminary draft of the manuscript; Mr J. S. Lilley and Dr M. Schneeberger kindly helped with the proof reading, while Dr Batty drew the figures.

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I must also express my thanks to the authors and publishers who have given permission for the use of figures and photographs; acknowledgment is made in the caption to the revelant figure or plate. Lastly, my thanks are due to M M. Appleton for her patient typing and retyping of the manuscript.

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CHAPTER I

Introduction

Since 1932, following the discovery of the neutron by Chadwick, it has been realized that nuclei are composed of neutrons and protons. The central problem of nuclear physics has therefore been the investigation of the nature and origin of the forces which bind the protons and neutrons together to form a nucleus. Already in 1932 it had been realized that there were important limitations on the nature of the nuclear force, implied by certain properties of nuclei. Studies of the mass defects of nuclei, and their variation with atomic number, showed that the binding energy of a nucleon (the generic term covering both a neutron and a proton) in a nucleus is approximately constant throughout the periodic table. This fact indicates that the nuclear forces are saturated.

Secondly, the magnitude of the binding energy is found to be large, and equal to about 8·5 MeV per nucleon. This immediately tells us that the nuclear forces are very strong compared with electromagnetic forces or gravitational forces. Quantitatively, the strength of the electromagnetic interaction may be expressed in terms of a dimensionless coupling constant $e^2/\hbar c \simeq 1/137$ ($\hbar = h/2\pi$), while the gravitational interaction can be characterized by a dimensionless coupling constant $Gm^2/\hbar c \simeq 2 \times 10^{-39}$ where G is the gravitational constant and m is the mass of the proton. The strength of the nuclear forces, which is implied by a binding energy of several MeV per nucleon, is characterized by a coupling constant $g^2/\hbar c \sim 1$.

The range of nuclear forces is known to be rather small, that is, two nucleons only exert a force on each other when they are closer than about 10^{-13} cm. This information comes from a number of sources. For example, Wigner showed that the concept of a short-range force could give an explanation for the relatively low binding energy of the deuteron (2·2 MeV) compared with that of the α-particle

(27·7 MeV). This low binding energy for the deuteron could be due to a neutron–proton force which is strongly attractive and of short range, or to a force which is less strongly attractive but of longer range. More precisely, it is the product of the depth of the potential and of the square of its radius which is roughly determined (for given potential shape) by the low binding energy of the deuteron. The high binding energy observed for the α-particle cannot then be obtained with the relatively weak forces of long range, compatible with the deuteron, but requires the strongly attractive short-range possibility, with the four nucleons packed closely together.

Information on the character of the nuclear forces may be obtained from an analysis of nucleon–nucleon scattering experiments, and this subject is dealt with in more detail in Chapter VII. In particular, neutron–proton scattering experiments at energies above 40 MeV show that there is a high probability for the struck protons, initially at rest, to emerge in the forward direction. This can be readily understood only if the force between neutron and proton has a 'charge exchange' character, so that the incident neutron may go on as a proton after a relatively small momentum transfer.

These characteristics of nuclear forces suggest that a convenient starting point for the theory of nuclear binding is to consider the analogy with chemical binding. In particular the homopolar bond, typified by the hydrogen molecule, is known to be an exchange force. The hydrogen molecule is saturated in the sense that a third hydrogen atom would not be strongly attached to the two atoms which already comprise the molecule, and which are known to be relatively tightly bound. An assembly of many hydrogen atoms has a total binding energy approximately equal to the number of molecules present, and therefore proportional to the number of atoms present. The correct dependence of the nuclear binding energies on the number of particles in the nucleus will be obtained if it is assumed that the forces between nucleons have similar characteristics to the forces of homopolar chemical binding.

The exchange nature of the homopolar bond is associated with the fact that, from the quantum viewpoint, one cannot tell which electron is associated with which atom in the molecule. This is sometimes expressed by saying that the two electrons are continually being exchanged by the two atoms of the molecule. In fact, the molecular exchange force is proportional to the probability for electron exchange taking place. The neutron–proton scattering experiments at 40 MeV could be readily explained in terms of a nuclear exchange force in which charge was transferred from one nucleon to the other in the exchange process.

The hypothesis that nuclear forces had an exchange character was first put forward in 1932 by Heisenberg. However, the origin of these exchange forces was at that time quite unclear. The only interaction then known to change the charge of a nucleon was the beta-decay interaction, an exceedingly weak interaction whose coupling strength may be specified by a dimensionless parameter of order 10^{-14}. To account for a binding energy as much as 8 MeV per nucleon one needs an interaction characterized by a dimensionless coupling constant $g^2/\hbar c$ of the order of unity. No such interaction was known in 1932.

A decisive advance was made by Yukawa in 1935. It is well known that the interaction between two electrically charged particles can be described in quantum mechanical terms by saying that one particle emits a photon (a zero mass quantum) which is subsequently absorbed by the second particle. In an analogous way Yukawa pictured the strong nucleon–nucleon interaction in terms of one nucleon emitting a quantum which is promptly absorbed by the other nucleon. The short-range nature of the nucleon–nucleon force implies that these quanta have a finite mass; in fact their mass may be deduced from a knowledge of the range of the force, the range 10^{-13} cm corresponding to a mass value of $\sim 400\ m_e$ (see p. 5). For this reason the quanta were termed mesons, a generic term for particles of mass intermediate between that of the electron and that of the proton. We now know that there exist in nature several mesons, of different masses and lifetimes. However, only one of these particles appears to be intimately connected with nuclear forces, and this is the pi-meson, or pion. Therefore in this book we shall only be concerned with pions and nucleons.

Suppose we represent a neutron by the letter n, a proton by p, and a pion by π^+, π^- and π^0, depending on its electric charge. We can then write down the interaction between two nucleons via intermediate pions as, for example,

$$n_1 \longrightarrow n_1 + \pi^0 \quad \text{and then} \quad \pi^0 + p_2 \longrightarrow p_2$$

where the subscripts refer to nucleons at positions 1 and 2. In this case a neutron and a proton interact but remain as a neutron and a proton respectively. Similarly

$$p_1 \longrightarrow n_1 + \pi^+ \quad \text{and then} \quad \pi^+ + n_2 \longrightarrow p_2$$

and $$n_1 \longrightarrow p_1 + \pi^- \quad \text{and then} \quad \pi^- + p_2 \longrightarrow n_2$$

In these cases the exchange of a charged pion exchanges the charge of the two nucleons. It is clear that the force associated with the neutral pion does not change the charge of the nucleons. There is evidence that the nuclear forces involves both non-charge exchange and charge exchange forces (Chapter VII), which indicates that any practical meson theory of nuclear forces must involve both charged and neutral particles.

We may therefore regard nucleons as sources of the meson, or pion, field, in the same way that electric charges are sources of the electrostatic field. The force between two nucleons, in terms of this field, as distinct from the particle picture, is due to the action of the field produced by one nucleon on the second nucleon. This is the exact analogue of the description of the electrostatic force between two charges in terms of the action of the electric field, produced by the one charge, on the second charge. The relationship between the range of the force and the mass of the field quantum can be derived by means of the following illustration. The relativistic relation between the total energy, E, the momentum p, and the mass m, of a particle is

$$E^2 - p^2c^2 - m^2c^4 = 0 \tag{1.1}$$

Replace E by $+i\hbar\,\partial/\partial t$ and p by $-i\hbar\nabla$, according to the usual rules of quantum mechanics. This substitution gives

$$-\hbar^2\frac{\partial^2}{\partial t^2} + \hbar^2\nabla^2c^2 - m^2c^4 = 0 \tag{1.2}$$

Let us now introduce a function $\phi(\mathbf{r}, t)$ which has the significance of a potential and which we may regard as the field variable. Thus

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \frac{m^2c^2}{\hbar^2}\right)\phi = 0$$

and for convenience we may put $K = mc/\hbar$ so that

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} - K^2\right)\phi = 0 \tag{1.3}$$

The time independent form of this equation is

$$(\nabla^2 - K^2)\phi = 0 \tag{1.4}$$

which may be compared with that of a static electric field which is

$$\nabla^2\phi = 0 \tag{1.5}$$

and whose solution is

$$\phi = e/r \tag{1.6}$$

for a point charge at the origin. The solution of (1.4) is readily shown to be

$$\phi = g\frac{e^{-Kr}}{r} \tag{1.7}$$

where g is a constant which has the dimensions of an electric charge, and which can be referred to as the nucleon strength, or as the coupling constant appropriate to the interaction. ϕ may be regarded as the potential associated with the nuclear force field, with the form $\phi = g\dfrac{\exp(-Kr)}{r}$ to be compared with the electrostatic potential e/r. The energy of a second nucleon due to this potential field is given by $g\phi$, so that the interaction energy between two nucleons separated by a distance r has the form $g^2 \exp(-Kr)/r$. The exponential character of this interaction energy corresponds to a characteristic range $r_0 = 1/K = \hbar/mc$. Now from a study of the deuteron by Wigner, and from the analysis of n–p scattering data at low energies, it has been deduced that the range of the nuclear force is of the order of 10^{-13} cm. If r_0 is taken to be 10^{-13} cm, then $m \sim 400m_e$; this value gives the order of magnitude of the mass necessary for the quanta of the meson field, that is, of the pions. Further, with this value of the range of the force, the coupling parameter $g^2/\hbar c$ is required to have a value of order unity in order to fit the known strength of nuclear forces.

It has already been noted that the line of thought followed by Yukawa runs closely parallel to the quantum-mechanical treatment of the electromagnetic field. However, the quanta of the meson field can also carry charge, whereas the quanta of the electromagnetic field are of zero mass and zero charge. Quantum electrodynamics is known to give an excellent description of almost all electromagnetic phenomena. The quantum mechanics of the nuclear field has turned out to be much more difficult to handle than quantum electrodynamics.

Mesons

A single stationary nucleon cannot emit or absorb a meson with conservation of energy and momentum. However, the uncertainty principle allows energy conservation to be violated over short time intervals, a violation of energy conservation by an amount ΔE being permitted for a time Δt, provided that $\Delta E . \Delta t \sim \hbar$. For the emission of a pion by a nucleon the magnitude of the violation of energy conservation ΔE is about 140 MeV, that is, the energy equivalent of the rest mass of the pion; Δt is then $\leqslant 4 \times 10^{-24}$ sec. In this time the meson may travel a distance at most of order $c \times \hbar/m_\pi c^2 = \hbar/m_\pi c$. Thus a stationary nucleon will be surrounded by a cloud of virtual mesons, continually being emitted and re-absorbed. The mesons of this cloud are referred to as virtual because they can be present only over the exceedingly short time intervals ($\leqslant \hbar/m_\pi c^2$) permitted by the uncertainty principle, and are bound to the nucleon, extending at most to distances of order $\hbar/m_\pi c$ from the centre of the nucleon. The presence of this cloud of virtual charged and neutral mesons extends the charge of the proton to a finite extent; it gives the proton charge distribution a finite size of order $\hbar/m_\pi c$ and this has been verified by direct observations on the scattering of 600 MeV electrons from protons at Stanford. Also associated with this cloud of mesons are currents which contribute to the magnetic moment of the proton, bringing this to the value of $+2{\cdot}79$ nuclear magnetons from the value $+1$ expected for a simple Dirac particle of spin $\frac{1}{2}$. Similarly for the neutron, the meson cloud gives rise to the magnetic moment of $-1{\cdot}91$ nuclear magnetons observed.

When two nucleons collide, the momentum that is transferred from the one to the other may be visualized as being carried by the exchange of a virtual meson. If the available energy in the C-system is greater than the meson rest mass then a free meson may be created, which can be detected by conventional means at large distances from the point of collision. Yukawa pointed out that it would not be surprising if the free meson were unstable since there are lighter particles known, the electron, the neutrino and the photon, to which the meson might transform with a release of energy. Further, the meson is strongly coupled to nucleons, which are known to undergo the beta-decay process, and Yukawa suggested a specific model for meson decay on this basis, according to which the free meson would have a lifetime $\sim 10^{-8}$ sec in its rest system.

At the time at which Yukawa wrote, such unstable intermediate mass particles had not been observed, but in the years immediately before the war much cosmic ray evidence accumulated for their existence. In particular the cloud chamber work of Anderson and Neddermeyer (1937, 1938) and of Street and Stevenson (1937) suggested that at mountain altitudes there was a considerable flux of penetrating particles of mass around $200m_e$. The instability of these penetrating particles was at first deduced from the so-called 'absorption anomaly'. It was found that the absorption of the particles in a given mass of solid absorber was less than that in the same mass of air, and this difference was interpreted as the extra contribution arising from the particles decaying while traversing the long air path.

The decay of one of these particles was first observed directly in a cloud chamber photograph in 1940, when it was found that the charged decay product was an electron. This appeared to be in accord with the model suggested by Yukawa. However, the lifetime of these particles was directly determined by a counter experiment in the same year and was found to be $2{\cdot}15 \times 10^{-6}$ sec. Despite the disagreement with Yukawa's predicted lifetime, the correspondence between the observed and calculated masses led to the tentative identification of these cosmic ray particles with the mesons postulated in Yukawa's theory.

The classic experiments of Conversi, Pancini and Piccioni in 1945–7 threw considerable doubt on this assumption. These workers showed that the negative cosmic ray mesons had a very weak nuclear interaction with matter; in fact, when the particles were brought to rest in a solid material of low atomic number some of them decayed instead of interacting with the nearest positive nucleus. On the Yukawa hypothesis the combined effects of Coulomb and nuclear attraction should always have resulted in absorption of the negative meson. No absorption is expected of course, for the positive meson, for the Coulomb repulsion will prevent it from getting close enough to a nucleus for the attractive nuclear force to become important.

This result, together with other cosmic ray data, led Sakata and Inoue (1946) and, independently, Bethe and Marshak (1947) to suggest that there were two mesons, one the parent of the other. The nuclear force meson, or Yukawa particle, was postulated to be the parent meson, which subsequently decayed to the meson observed by the cosmic ray workers. This prediction was strikingly confirmed by the photographic emulsion work of Lattes, Muirhead, Occhialini and Powell (1947). These authors observed events in emulsions exposed at high altitudes which they interpreted as the decay at rest of a positive heavy meson ($m \sim 300m_e$) into a light meson ($m \sim 200m_e$). The energy of the secondary meson was found to be a constant, implying a two body decay process; it was subsequently shown that the associated neutral particle was a neutrino. In the more sensitive emulsions that became available later, the lighter meson was seen to decay, at rest, into a positive electron which, on the average, took one third of the available energy. This suggested that the decay process involved three particles; the two neutral particles have been shown to be neutrinos. The heavier meson was designated pi (π) and the lighter particle mu (μ). In this book we shall employ the term pion for the pi-meson and muon for the mu-meson. The two decay sequences can be written

$$\pi^{\pm} \longrightarrow \mu^{\pm} + \nu$$
$$\mu^{\pm} \longrightarrow e^{\pm} + \nu + \nu$$

where ν represents a neutrino. On the basis of Yukawa's ideas one would expect a $\pi \longrightarrow e$ decay process, but recent experiments give a value of greater than 10^4 for the ratio of the decays $(\pi \longrightarrow \mu)/(\pi \longrightarrow e)$. The place of the mu-meson amongst the elementary particles, and the significance of the pi–mu decay, is not yet understood.

Events were also seen by Lattes *et al.* which were interpreted as the capture at rest of negative pions by nuclei, leading to the partial or complete, disruption of the nucleus. In fact, an event of this type was observed by Perkins before the positive pi–mu decay was seen. It was clear from these observations that the pion had a strong interaction with nuclei; the positive pions decay when they come to rest in emulsion for the Coulomb repulsion keeps them away from any nearby nucleus. Both positive and negative pions decay to muons if they decay in flight. An early cosmic ray experiment showed that the lifetime of the pion was of the order of 10^{-8} sec. This was confirmed when pions were first created under laboratory conditions in 1948, using the 380 MeV α-particle beam of the Berkeley synchro-cyclotron.

Prior to the operation of the large accelerators, much cosmic ray evidence pointed to the existence of a neutral meson, which decayed to two or more gamma-rays. Its existence was not finally proved until experiments were carried out at Berkeley on the production of photons from targets bombarded by high energy protons and gamma-rays. The most convincing evidence was afforded by the work of Steinberger *et al.* (1950), who were able to count photons, in coincidence, which were emitted from a beryllium target bombarded by 330 MeV gamma-rays. A series of experiments showed that the observations could only be interpreted in terms of the production of a neutral pion, which decayed, with a half life of less than 10^{-14} sec, to two gamma-rays. It should be remarked here that there is no evidence at the present time for the existence of a neutral muon.

It is now known that the pion is certainly the meson that is largely responsible for nuclear forces, although it does not have all the characteristics predicted for it by Yukawa. During the past ten years extensive studies have been made of the production, properties and interactions of pions. In Chapter II the determination of the intrinsic properties of the pion will be described. Chapter III is concerned with outlining some theoretical ideas which will be needed for a full appreciation of some of the later chapters. Chapters IV and V discuss the main pion interactions that are susceptible to theoretical investigation, that is, pion–nucleon scattering and the photoproduction of pions from nucleons. The construction of the large accelerators to produce pion beams has meant that high energy proton and neutron beams have been available for experiments. Many studies of nucleon–nucleus and nucleon–nucleon scattering have been carried out, but the intermediate meson link between the nucleons makes the theoretical approach to the subject very difficult. In fact, the data at present can only be analysed in general phenomenological terms. Chapter VI is concerned with nucleon–complex nucleus elastic scattering, while Chapters VII and VIII consider elastic and inelastic nucleon–nucleon scattering respectively. In the remainder of this chapter, a brief survey will be given of present particle accelerators and experimental techniques. An extensive bibliography on these subjects is given on pp. 18–19.

Accelerators

The main types of accelerator used to obtain nuclear particles with energies above 100 MeV are the synchro-cyclotron and synchrotron for protons and the betatron, synchrotron and linear accelerator for electrons. A full description of the principles of these machines is given in the book by Livingston (1954). Table 1 gives a list of those machines now operating, or under construction, which yield particles with a kinetic energy of more than 100 MeV.

A synchro-cyclotron accelerates 10^{10} to 10^{11} protons per pulse with a repetition rate of 60 to 250 pulses per second. The internal beam current is therefore of the order of a microampere, and this is sufficient to give a large flux of pions for experimental work. The Carnegie accelerator, for example, gives 500 π^- – particles/cm^2.sec focused 20 feet from the target. The exact figures depend on the sign of the pion and on its energy; in any beam there is also a contamination of muons of between 5 and 10%. The magnitude of the external proton beam from a synchro-cyclotron depends upon the details of the extraction system but may be as high as 2% of the internal beam ($\sim 4 \times 10^{10}$ particles/cm^2.sec, as at Liverpool). The extracted beam is sometimes used to produce a relatively clean meson beam, as is done at the Dubna Laboratory near Moscow (see Fig. 8). The highest energy synchro-cyclotron is now the Berkeley 184″ machine, which has been modified to give protons of 720 MeV.

To obtain protons with energy above several hundred MeV it is more economical to build a proton synchrotron. Again some

TABLE 1

Accelerator and location		*MeV*	*Date of first operation*
Proton synchro-cyclotrons			
McGill, Canada		100	1949
Harvard, U.S.A.		160	1949
Orsay, France		165	1958
Harwell, U.K.		175	1949
Uppsala, Sweden		192	1951
Rochester, U.S.A.		240	1948
Berkeley, U.S.A.		190 (d) 380 (α)	1946
		350 (p)	1949
	to	720 (p)	1957
Columbia, U.S.A.		400	1950
Liverpool, U.K.		410	1954
Dubna, U.S.S.R.		280 (d) 560 (α)	1949
	to	680 (p)	1953
Carnegie Institute of Technology, U.S.A.		450	1951
Chicago, U.S.A.		460	1951
CERN, Geneva		600	1958
Proton synchrotrons			
Birmingham, U.K.		1000	1953
Brookhaven, U.S.A.		1000	1952
	to	3000	1954
Delft, Holland*		1000	1960
Saclay, France		3000	1958
Princeton, U.S.A.*		3000	1960–1
Berkeley, U.S.A.		6300	1954
Harwell, U.K.*		7000	1961–2
Moscow, U.S.S.R.*		7000	—
Dubna, U.S.S.R.		10000	1957
Canberra, Australia*		10600	1960–
Argonne, U.S.A.*		12500	1960–
Brookhaven, U.S.A.*		30000	1960
CERN, Geneva		28000	1959
Electron betatrons			
Electric Steel Foundry Co., U.S.A.		100	—
G.E.C., U.S.A.		100	1943
Chicago, U.S.A.		100	1950

* Under construction; therefore the date of operation is the expected date.