HIGH ENERGY PHYSICS

Edited by

E. H. S. BURHOP

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PHYSICS DEPARTMENT
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Numbers in parentheses indicate the pages on which the authors' contributions begin.

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PREFACE

The subject of high energy physics is so vast and the rate at which it is developing is so rapid that it is now extremely difficult to envisage a work both comprehensive and up to date, written by a single author.

In the present compilation an attempt is made to cover the most important aspects of the subject in seventeen chapters written by different authors. In this way, at the expense of a certain nonuniformity of style from chapter to chapter and in some cases of a small amount of overlap, it has been possible to provide an account of the subject of considerable scope and topicality.

While this is primarily a reference book, the individual chapters are intended not merely to provide progress reports on a number of different topics, but also to give sufficient basic material to be of value for graduate students entering the field as well as for experienced research workers.

The introductory chapter by V. F. Weisskopf puts the whole subject in perspective in a masterly way. Subsequent chapters deal with the interactions of protons, antiprotons, π mesons, and κ mesons with nucleons; scattering and interaction processes at high energies; electromagnetic properties of the fundamental particles and the question of the limits of validity of quantum electrodynamics; weak interactions and neutrino physics; and hypernuclei and mesonic atoms.

The authors include specialists in both theoretical and experimental physics so that it is inevitable that there should be differences in emphasis among the different chapters. The emphasis is always on the physics however. Details of mathematical formalism as of experimental technique have been for the most part avoided.

It is well known that authors do not all write at the same rate. Since the work is being published in three volumes the content of each volume has been determined by the order in which the articles came to hand rather than by the natural order suggested by the rational development of the subject. It is hoped that readers will bear with the editor in this respect and will feel it a rather small price to pay to ensure that the various chapters contain the most recent material at the time of publication.

E. H. S. Burhop

January 1967

CONTENTS

Pion-Nucleon Interactions

J. Hamilton

Electromagnetic Form Factors

T. A. Griffy and L. I. Schiff

Unitary Symmetry

P. T. Matthews

QUANTUM THEORY AND ELEMENTARY PARTICLES

Victor F. Weisskopf

I. Introduction

> All these things being considered, it seems probable to me that God in the beginning formed Matter in solid, massy, hard, impenetrable, moveable Particles, of such Sizes and Figures, and with such other Properties, and in such Proportion to Space, as most conduced to the End for which he formed them; and that these primitive Particles being Solids, are incomparably harder than any porous Bodies compounded of them; even so very hard, as never to wear or break in pieces; no ordinary Power being able to divide what God himself made in the first Creation. While the particles continue entire, they may compose Bodies of one and the same Nature and Texture in all Ages: But should they wear away, or break in pieces, the Nature of Things depending on them would be changed. Water and Earth, composed of old worn Particles and Fragments of Particles, would not be of the same Nature and Texture now, with Water and Earth composed of entire Particles in the Beginning. And therefore, that Nature may be lasting, the Changes of corporeal Things are to be placed only in the various Separations and new Associations and Motions of these permanent Particles.
>
> —Newton (1952a)

In this well-known and justly famous statement, Newton recognizes the logical necessity of elementary particles in order to explain the existence of materials with well-defined properties, such as "Water" or "Earth," metal or mineral, liquid or gas, and with characteristic and ever-recurring qualities

Matter must be composed of some entities on which those qualities are based, entities which today are called atoms or molecules. Newton faces a problem, however: the elementary constituents of matter must possess specific properties that do not change with time: they should not "wear off in use," they should be immune to any rough treatment. He solves this problem by assuming that they are "incomparably hard" and indestructible by any ordinary power. But today we know that this is not so. Atoms can be broken by a very ordinary power, for example by lighting a match, but still they possess an intrinsic shape. They regenerate themselves whenever the original conditions are reestablished. What Newton ascribes to the "first Creation" happens everywhere and at any time. We find well-defined shapes without permanence of the unit itself.

Today we know what Newton did not know, that this is based upon quantum mechanics; it is based upon a very simple idea, namely that energy is connected with symmetry and shape. Quantum mechanics requires that the states of lowest energy exhibit simple shapes, which are determined by the inherent symmetry of the internal conditions within the system. It is this symmetry which is the shape-giving agent. In the atomic world, there are two symmetries which are decisive. One is the symmetry of space, rotational and translational, and the other is the symmetry of permutation, the identity of electrons.

The space symmetry determines the character and shape of the atomic states. It admits scalar waves with one component, spinor waves with two components, and so on. The shape of the states follows from the spherical symmetry of the nuclear Coulomb field: the states of lowest energy must be simple spherical harmonics.

The permutation symmetry admits two alternatives: the quantum state may be symmetric or antisymmetric with respect to an exchange of particles. Nature chose the second alternative for electrons, which gives rise to the Pauli principle. We know today that the spinor character of electron waves is a necessary consequence of this. This is where the large variety of atomic shapes comes from, since electrons are forced into higher and different forms when the lower ones are occupied. In many ways, the Pauli principle replaces the classical concept of impenetrability or hardness. Two identical particles, obeying the principle, can never be brought to the same place. It is therefore reasonable to reserve the term "particle" for the entities which obey the Pauli principle.

The spectrum of atomic energy levels reflects the basic symmetries. They produce characteristic groups of levels—the multiplets—whose multiplicity, wave form, and other properties are determined by the symmetry. We arrive in that way at a classification scheme of atomic levels by means of the spin and angular-momentum quantum numbers.

It is important to keep in mind that these symmetries do not determine all properties of the quantum states. They determine the general shape and many other features, such as the structure of the level spectrum and details regarding transition probabilities. They do *not* give the size or the energies of the quantum states. These properties are determined by the strength and nature of the forces with which the particles are bound within the system. The symmetries alone are not sufficient for a complete description of a system; a knowledge of the dynamic conditions is required.

II. Quantum Mechanics and "Permanent Particles"

Let us now return to Newton's remarks. Does quantum mechanics of atomic structure fully remove the difficulty which Newton brought forward? It leads to an essential insight into the origin of fundamental shapes in nature: intrinsic shape and ever-recurring properties of atoms are possible without the atoms' being incomparably hard. But Newton would not have been completely satisfied with this answer, because our conclusions are based upon the existence of other particles, electrons and nuclei, which themselves possess intrinsic properties, such as mass, charge, spin, and magnetic moment. So the question obviously is raised again on a new level. Are the atomic constituents incomparably hard? Is there an ordinary power that can take them apart?

As far as the nuclei are concerned, the answer is known. Nuclei can be taken apart by ordinary power; they consist of protons and neutrons. The intrinsic shapes and forms of nuclei are determined by the same symmetries as the atomic shapes. This is why nuclear physics is similar in so many ways to atomic physics, for instance with respect to shell structure and multiplet structure of the spectra. But nuclear quantum states are dominated by an additional symmetry: nuclear forces are independent of the nature of the nucleon, whether it is a neutron or a proton. This dichotomy is analogous to the dichotomy of the two spin directions and, therefore, this additional symmetry takes the form of an invariance with regard to rotations of a symbolic spin, the isotopic spin. Hence nuclear quantum states have one more characteristic quantum number, which makes it possible to group nuclear levels into super multiplets reflecting this new symmetry.

The isotopic symmetry brings in a new feature: the multiplets contain states of different charge—isobaric nuclei of different charge belong to the same spectrum and can be considered as states of the same system. Another new feature should be mentioned here. In the atom, transitions between states of the spectrum are accompanied by the emission or absorption of light quanta, at least in solated systems. In the nucleus we find a new way of going from an excited state to a lower state, namely by the emission of a lepton pair, consisting of an electron and a neutrino. Such transitions occur, of course, between states of different charge. Apart from this and the additional symmetry, nuclear structure and dynamics resemble closely the structure and dynamics of atoms.

Here again we must keep in mind that symmetries determine only the shape of the quantum states and their groupings into multiplets. The actual size of the states and the characteristic energies are determined by the relevant forces. It is, therefore, of interest to compare atomic with nuclear sizes and energies. The atom is held together by an electric force whose potential is given by e^2/r with $e^2/hc = 1/137$, e being the electronic charge, r the distance from the center of the field, h Planck's constant, and c the velocity of light. From this it follows that atomic sizes are of the order of a Bohr radius $a = h^2/me^2$ and atomic energies of the order of the Rydberg $R_y = me^4/h^2$, with m being the electron mass. The nucleus is held together by a nuclear force whose potential is somewhat more complicated, but whose most relevant contribution has the Yukawa form

$$(g^2/r)[\exp(-r/r_0)]$$

where $g^2/hc = 0.08$ and r_0 is the range of nuclear forces. If, for a moment, we set the exponential factor equal to unity, we get the same kind of potential as in atoms and would expect the size of nuclei to be of the order of a "nuclear Bohr radius" $a_N = h^2/Mg^2 = 2.5 \times 10^{-13}$ cm where M is the nucleon mass, and nuclear energies to be of the order of a "nuclear Rydberg" $R_N = Mg^4/h^2 = 6$ MeV. These values do indeed give a good orientation as to the sizes and energies of nuclear phenomena. The fact that a_N is of the same order as the range of nuclear forces is a justification for the omission of the exponential factor in the Yukawa force.

III. The Baryon

Would Newton have been satisfied at this point? Not completely; the number of elementary particles is essentially reduced to three: proton, neutron, electron. (We do not count the light quantum among particles, since it is the quantum of the electromagnetic field and obeys Bose statistics. The neutrino is excluded because it never appears as a constituent of matter.) But the existence of these particles still remains an assumption: they have "God-given" properties and may have to be "incomparably hard" so as not to change their properties when in use.

Let us first look at the situation regarding the proton and the neutron. So far nobody has taken a nucleon apart. The Rutherford of this stage is not yet known. It seems probable, however, that the nucleon is not "incomparably hard" either. Indications of an internal structure are clearly present; there exists a spectrum of excited states of the nucleon. These are not usually called excited states, but the observed phenomena can hardly be interpreted differently. What do we observe? When the nucleon is exposed to any kind of high-energy beams, it is transformed into short-lived states of higher energy, which are known under various names, such as *hyperons* or *resonances.* The name *baryon* will be used for the entity which appears in the form of proton or neutron, or in the form of its excited states. In the spectrum of baryon states (see Fig. 1), the proton and the neutron figure as the ground

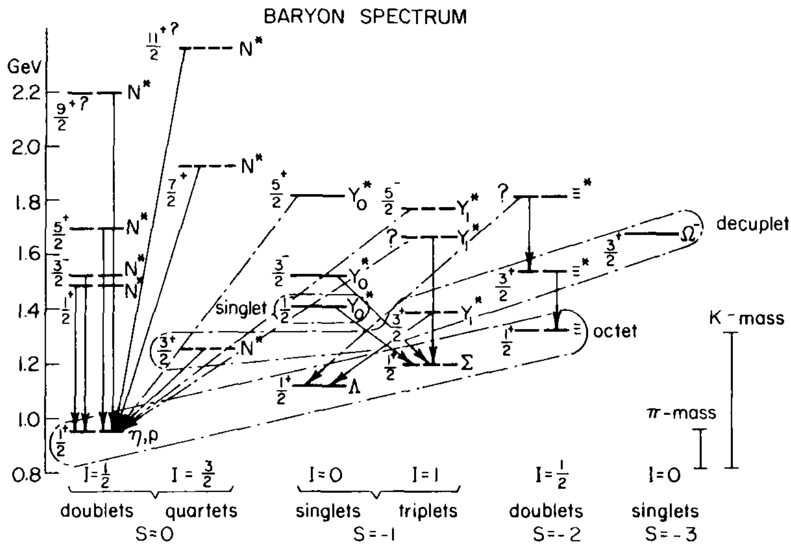

Fig. 1. Spectrum of the energy states of the baryon. The isotopic spin I and the strangeness S are given at the bottom, the angular spin and parity are given at the left of the level, the symbol at the right. The isotopic multiplicity, the transitions by meson emission, and some SU(3) multiplets are indicated; solid lines indicate π emission, broken lines K emission.

states—they form a ground-state doublet. Speaking exactly, the neutron also is an excited state of the proton. All other states can be reached by supplying the nucleon in the ground state with the necessary excitation energy in one form or another. Some of the excited states have different charges from the ground state; some have different strangeness or hypercharge—a new property which turns up for the first time in these phenomena. The excited states return to the ground state in one or several steps, with the emission of π mesons, K mesons, light quanta, or electron-neutrino (lepton) pairs.

The charged mesons and the lepton pairs are charge carriers and therefore are emitted when there is a charge difference between excited and ground states; the K mesons are also strangeness carriers and are emitted when the strangeness changes. The K meson carries a positive unit of strangeness, the anti-K meson (K) carries a negative unit.

In atoms, transitions between quantum states take place mostly by light emission or absorption; that is, by coupling with the electromagnetic field. In atomic nuclei we find, in addition, lepton-pair emissions (electron-neutrino pairs), which are produced by weak interaction coupling with the lepton field. In the baryon spectrum we find also a third kind of emission, transitions with meson emission, which is transacted by the strong interaction of nucleons with a meson field. All three couplings are active in any of the three cases. But the energy differences between atomic states are too small to allow the emission of lepton pairs, for which an energy of at least 0.51 MeV is needed because one of the leptons must be an electron; the differences between nuclear states are large enough for lepton-pair emission (β radioactivity) but too small for the emission of mesons, the smallest of which has a mass of about 140 Mev. In the spectrum of the baryon, however, the transitions are paid for in a new currency—the mesons—although the ordinary currency—light quanta and lepton pairs—is not excluded.

Examples of Transition between Nucleon States

The simplest example is the emission of a π meson in the transition from the first excited baryon state, a multiplet with the isotopic and ordinary spin of $\frac{3}{2}$. This state has the same strangeness as the ground state; the transition is therefore accompanied by the emission of a π meson. The charge of the emitted π meson depends on the charge difference between the two combining states (see Fig. 2).

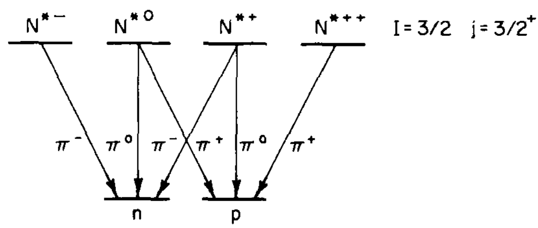

Fig. 2. Transitions between the (3/2,3/2) state and the ground state of the baryon. *I*, isotopic spin; *j*, ordinary spin.

Another example would be the transition from a highly excited state of strangeness different from that of the ground state: there a K meson would be emitted, in order to carry away the difference in strangeness. An odd situation occurs with the lower excited states of different strangeness such as the ones designated by the symbols Σ, Λ, and Ξ. They cannot deexcite by K emission into the ground state, because the mass of the K meson is higher than the energy difference. These states, therefore, would be stable if the conservation of strangeness were an exact law (as the conservation of ordinary charge is). In fact, however, strangeness is conserved in all interactions except the weak interaction. Therefore, there exist very slow transitions from those states to the ground state with emission of π mesons or lepton pairs, mediated by weak interactions, and the lowest states with strangeness different from zero are metastable and decay slowly into the only really stable state, which is the proton.

The excitation of these metastable states takes place mostly in a two-step process: first the nucleon is excited into one of the higher states, without change of strangeness, by proton collision or pion absorption; then a transition to a state of different hypercharge takes place, with the emission of a K meson. This is called associated production, since the end product consists of two entities of opposite strangeness: an excited baryon and a K meson.

IV. The Boson Spectrum

Experiments with high-energy accelerators have revealed not only a spectrum of excited states of the nucleon, but also a second spectrum: the spectrum of mesons, or boson spectrum (see Fig. 3). A careful analysis of the mesons produced by high-energy collisions has revealed that the π and the K mesons are not the only forms in which mesons appear. There exists a

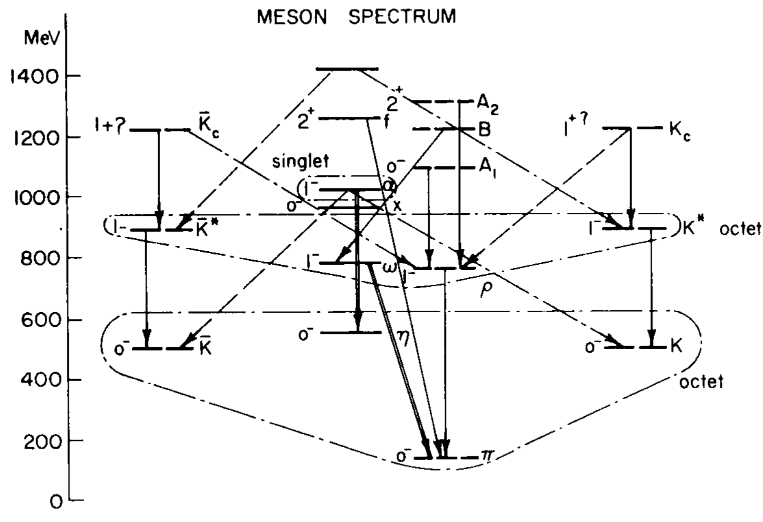

Fig. 3. Spectrum of the energy states of the meson. Isotopic spin I and strangeness S are given at the bottom, angular spin and parity at the left of the level, the symbol at the right. The isotopic multiplicity, the transitions by meson emission, and some SU(3) multiplets are indicated. ——, π emission; — — —, K emission; ═══, 2π emission; — · —, $\bar{K}$ emission.

series of excited states referred to by various letters: ρ meson, ω meson, η meson, and so on, of which the π^- and the K meson are the lowest states. In fact, neither the π^- nor the K meson itself is really stable. Both decay by weak interactions into leptons. Hence they should be considered as true ground states of the meson spectrum only if the weak interactions are neglected.

In transitions from an excited state to a lower one, also, the energy difference is emitted mostly in forms of mesons. For example, the so-called ρ meson decays into two π mesons. We can interpret this as a transition from the ρ to the lower π meson state, with the emission of another π meson. Figure 3 shows the most important meson quantum states known today and indicates their quantum numbers. Here, as in the baryon spectrum, we find the same quantum numbers as in nuclear spectra—ordinary and isotopic spin and parity—and also the new strangeness quantum number.

The existence of such excited meson states is perhaps not so surprising as one might think. Let us consider the situation from the point of view of the analogy between light quanta and mesons. Both entities are quanta of a field; the quantum of the electromagnetic field with its source (the charge) is determined by the small constant $e^2/hc=1/137$; it is a weak coupling. The coupling of the nuclear field to its source (the nucleons) is very much stronger. The corresponding magnitude G^2/hc is about 15. This is much larger than the magnitude $g^2/hc \approx 0.08$ which was used in estimating the strength of nuclear forces within nuclei; the nuclear forces have the peculiar property of being quite weak between nucleons whose relative momentum is nonrelativistic, as it is in the case of motion within nuclei. For that special situation the relevant coupling is reduced by a factor $g^2/G^2=(m_\pi/2M)$, where m_π is the pion mass and M is the nucleon mass. It has its large value, however, under general conditions such as those for fields acting between particles of high relative momentum or between particles and anti-particles.

It is because of this circumstance that we can have a theory of nuclear structure based upon relatively weakly interacting proton-neutron systems without recurrence to the higher baryon states. If the relevant interaction constant in nuclear structure were as large as G, the nuclear excitations would be of the order of the baryon excitations; nuclear physics and elementary particle physics would be as closely related as meson physics and baryon physics.

A very strong coupling between field and source would have a number of consequences, some of which can be understood by extrapolation from electrodynamics. It is known, for example, that two light quanta interact weakly with each other. If the coupling constant were larger than unity, however, the interaction would become large and would be comparable with energy of the quanta. It would not be surprising, then, to find states in which several field quanta are bundled together. Such bundles are perhaps an appropriate description of the nature of excited meson states. There remains a question why no meson with rest mass zero exists in analogy to the light quantum. Is this also a consequence of strong interaction, or is there an essential difference between electromagnetic and mesonic fields? This is a most interesting problem which at present is left in complete darkness.

The above-mentioned interaction of light quanta comes from the fact that the two quanta can form virtual electron-positron pairs. Since the coupling constant between nucleons and mesons is large, the virtual pair states would play a much more important role in meson states. In fact, it would not be unreasonable to consider the meson states as states of the baryon-antibaryon system. There cannot be an essential difference between a bundle of field quanta and a state of the baryon-antibaryon system, since the former can produce the latter and vice versa. Because of the strong interaction, any such bundle will contain a considerable fraction of baryon-antibaryon pairs of equal spin and symmetry.

V. Baryons Guarantee Stability

Not only mesons but also baryons should really be considered as surrounded by virtual baryon-antibaryon pairs. After all, the strong meson field in the neighborhood of the baryon must also give rise to virtual pairs. The physical baryon and the physical meson are in fact extremely complicated systems which can be described as mixtures of many different states: they contain any number of baryon pairs and meson bundles, compatible with the quantum numbers. The basic difference between the baryon and the boson states lies in the total number B of baryons present. The baryon spectrum contains all states of matter in which this number is unity (the antibaryons are counted negative), the boson spectrum contains the states with $B = 0$.

The spectrum of states with $B > 1$ would contain the spectra of nuclei with a nucleon number $A = B$ and also the spectra of the isobaric hypernuclei. Such a spectrum would have a coarse and a fine structure. The fine structures are the ordinary nuclear and hypernuclear spectra which are built upon a coarse structure resulting from one or more nucleons' being in an excited state.

Here we recognize the reason why, in the meson spectrum, even the lowest states are metastable and decay by weak interaction into lepton pairs, whereas the ground state of the baryon spectrum—the proton—is really stable, and so are the ground states of all spectra with $B > 1$. The baryon number B is a quantity which is conserved in all interactions; therefore, only mesons can disappear by disintegrating into leptons; baryons must remain forever, a guarantee for the stability of our world.