SOCIETÀ ITALIANA DI FISICA

RENDICONTI
DELLA
SCUOLA INTERNAZIONALE DI FISICA «ENRICO FERMI»

XXVI CORSO

Argomenti scelti sulla fisica delle particelle elementari

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a cura di M. CONVERSI
Direttore del Corso

VARENNA SUL LAGO DI COMO
VILLA MONASTERO
23 LUGLIO - 4 AGOSTO 1962

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edited by M. Conversi
Director of the Course

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Selected Topics on Elementary Particle Physics

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Introduction.

M. Conversi

Director of the Course

The present book contains the lectures and some of the seminars delivered at the XXVI Course of the « Enrico Fermi » International School of Physics at Varenna (Lake Como) during the summer 1962. This is not the first and will certainly not be the last Varenna Course concerned with the physics of elementary particles. This field is indeed growing so rapidly that it appears now adequate to have each year one course on some selected topics where significant steps have recently been accomplished.

It is perhaps worth recalling that the Varenna International School of Physics was born just a few years after the artificial production of some elementary unstable particles had become a reality. The first course dealt with elementary particles as observed in the natural source of cosmic radiation. The second course, in 1954, was mainly dedicated to elementary particles as artificially produced at the large accelerators. In the few years which have elapsed since then, a great amount of work has been carried out both on experimental and theoretical grounds. However, our understanding of the field is still far from being satisfactory; our information appears much too scanty (or pehaps our intelligence much too inadequate) to achieve such an understanding; and in accordance with a sort of general law of Science, every problem for which occasionally we thought we had found a solution dragged in its wake new questions to be answered. The present overall picture of the field is extremely complex and the old naive idea of a few fundamental particles as the ingredients of which nature is made up, appears today definitely obsolete. In spite of this unsatisfactory situation regarding our deep understanding of the field, we should not underestimate, however, the considerable progress which has been made, nor should we forget that the description of the elementary particles and of their interactions represents a formidable challenge and is probably the most crucial problem of contemporary physics.

The selection of the topics for the present Course aimed not only to present some of the most interesting results recently obtained, but also to fill certain gaps with respect to the arguments chosen for previous Courses on elementary particles. Thus, lectures on strongly interacting particles and the new resonant states, as well as on the form factors of the elementary particles, appeared highly desirable for this Course.

The existence of resonant states for the pion-nucleon system has been known since the discovery of the isobar state in 1953; but only in the past two years has it been shown that the occurrence of similar resonances is a somewhat general characteristic of the strong interactions. Most of these resonant states have been established in bubble chamber experiments partly carried out at the « E. O. Lawrence » Radiation Laboratory in Berkeley. Professor A. H. ROSENFELD, from this Laboratory, presents in a first group of lectures the phenomenological aspects of the strongly interacting particles and resonances. The theoretical counterpart of the subject is developed in a second group of lectures by Professor J. J. SAKURAI, of the « Enrico Fermi » Institute for Nuclear Studies in Chicago.

It is not only a matter of historical interest to point out the existence of a link between this first and the third part of the Course (form factors of elementary particles) through the suggestion by NAMBU, in 1957, that excited states might exist for pionic systems, yielding a possible explanation for the nucleon form factors in the electron scattering experiments at Stanford. The series of lectures on the form factors of elementary particles, by Professor S. D. DRELL of the University of Stanford, yields, in the third part of this book, a self-consistent presentation of this important subject.

The second part of the Course is made up of two distinct groups of lectures, both of a phenomenological character, on the physics of the strange particles. The « weak » decays of these particles are discussed in the lectures delivered by Professor F. S. CRAWFORD, of the Radiation Laboratory at Berkeley. The other group of lectures, by Professor H. K. TICHO, of the University of California at Los Angeles, are devoted to the strange particle resonances.

In addition to the groups of lectures quoted above, which aimed to give a more or less self-consistent account of the corresponding topics, it was felt worthwhile presenting in isolated seminars by various speakers (or exceptionally in a group of seminars by the same speaker) other arguments of miscellaneous nature related to the field of elementary particles. Subjects of great present interest, such as the existence of two types of neutrinos and the Regge poles, where among those discussed in these seminars. However, only seminars containing unpublished material have been included in this book (and collected in the last part of it). Titles and speakers names of the remaining seminars are listed at the end of the book together with references to the corresponding relevant literature.

It was a fortunate coincidence that the President of the Italian Physical Society, Professor GILBERTO BERNARDINI, is also an expert in the field of elementary particles. I am deeply indebted to him for profitable discussions and suggestions in the early stage of preparation of the programme.

I also wish to express my sincere thanks to the lecturers and speakers who contributed to make the Course pleasant and successful.

Dr. ANTONIO ZICHICHI acted as a Scientific Secreary at the Course. I gratefully acknowledge his close co-operation in preparaing the programme and his continuous efforts during this Course to make it alive by stimulating and contributing to the discussions.

INDICE

Miscellaneous Subjects

Strongly Interacting Particles and Resonances.

A. H. Rosenfeld

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Introduction.

I want to start with a few words about terminology. I will use the word « particle » to include both stable particles and « resonant states » which can decay rapidly via the strong interaction into other particles. Hence a precise but less conventional title for this course would be « Strongly Interacting Particles: Bound and Unbound ». Notice that I have altogether avoided the word « elementary ».

The most familiar example of an unbound state is the $I=\frac{3}{2}$, $J=\frac{3}{2}$ pion-nucleon *resonance*. In this case there is only one decay channel, and we can show that the pion-nucleon scattering phase shift goes through 90° at the resonance; if there were more than one channel we could still show that the scattering amplitude becomes pure imaginary at the resonance.

An example of a *slightly bound* system is the deuteron. Precisely because it is slightly bound its properties tend to be those of the sum of its constituents, and we tend to think of it as a « composite » system.

An example of a *tightly bound* system is the pion, considered as a bound state of a nucleon and an antinucleon. Its binding energy is so great ($m_\pi \ll 2m_{\mathcal{N}}$) that the new system has properties completely different from its constituents. Since at this moment in history we cannot calculate these properties, we tend to think of the pion as an « elementary » particle.

It is best to classify a particle by properties other than its decay via any particular channel; thus it would be an incomplete statement to say that the Y^0_* of mass 1520 MeV is a $\Sigma\pi$ state, because this neglects all other possible final states. In fact, the Y^*_0 (1520) decays into $\Sigma\pi$ (about 60 %), $\overline{K}\mathcal{N}$ (about 30 %), and $\Lambda\pi\pi$ (about 10 %).

I. - The Four Basic Interactions and Their Quantum Numbers.

Since there are many particles and only four interactions it is better to discuss first the interactions. Anyway I feel that eventually the interactions will explain the particles rather than vice versa.

In nature only four fundamental interactions exist: gravitational, weak, electromagnetic, and strong. It is generally assumed that all four interactions obey the following symmetries and conservations laws [1], even if they are not experimentally tested for all the interactions:

a) Conservation of four-momentum and angular momentum.

b) Conservation of electric charge.

c) Conservation of baryon number B and lepton number L.

d) invariance under CPT.

The operator C when applied to a single particle in its own rest frame transforms the particle into the corresponding antiparticle. (Thus we assume that every particle has an antiparticle which may or may not be distinct.) For some purposes it is convenient to think of an antiparticle as a hole in a negative-energy particle sea. The C concept is useful mainly for a system of nonstrange neutral mesons, discussed more fully later.

e) Invariance under T (or CP, because of *d*)).

The notion of a moving picture offers a simple physical model of the time-reversal operation. The time-inverted situation is obtained by running the movie backward. Time-reversal invariance requires that to an observer who does not know the initial conditions the inverted situation makes sense.

The time-reversal operation is meaningful only for microscopic systems, not for the large ensembles that are governed by statistical as well as microscopic mechanics.

Additional conservation laws are obeyed by some but not all of the four interactions. These we take up next.

1. - Strong interaction.

1·1. *Orders of magnitude.* – The strong (nuclear) interaction has the following characteristics:

a) The range is short. Its order of magnitude is given by the pion Compton wavelength,

$$\lambda\!\!\!^{-}_\pi = \frac{\hbar}{m_\pi c} = 1.4\cdot 10^{-13}\text{cm} \equiv 1.4 \text{ fermi}\,. \tag{1}$$

b) The energy is large. For example, nuclear bindings run in tens of MeV and the production of mesons in hundreds of MeV.

c) The natural unit of time for strong interactions is given by the time it takes for a light signal to cross a distance equal to the range of nuclear forces:

$$\tau = \frac{\hbar}{m_\pi c^2} \approx \frac{1}{2}\cdot 10^{-23}\,\text{s}\,. \tag{2}$$

d) If a reaction takes place in a time τ the corresponding full width at half-maximum Γ of its Fourier transform is

$$\Gamma = \frac{\hbar}{\tau} = \frac{\frac{2}{3}\cdot 10^{-21}\,\text{MeV s}}{\tau}\,.$$

A more useful form is

$$\Gamma = \frac{\hbar c}{\tau c} = \frac{197\ \text{MeV fermi}}{\tau c}\,. \tag{3}$$

If we take, for example, $c\tau = 1$ fermi, we get $\Gamma = 200$ MeV. (Notice that if the particle has mass m and is produced with momentum $p \equiv \eta mc$, then it actually goes an average distance $\eta c\tau$ from its point of production. If η is large, this factor can help the resonance get out of the range of nuclear forces before it decays.) The $\frac{3}{2}$, $\frac{3}{2}$ pion-nucleon resonance Δ has $\Gamma_\Delta \approx 100$ MeV (*i.e.*, $c\tau \sim 2$ fermi). Similarly the ρ-meson has $\Gamma_\rho \approx 100$ MeV. But the ω-meson has $\Gamma_\omega \leqslant 15$ MeV and probably $\Gamma_\omega \approx 1$ MeV. This means a corresponding $c\tau \simeq 200$ fermi, which is « outer space » in comparison with the dimensions involved in nuclear interactions.

1.2. *Additional conservation laws for the strong interactions.* – The student who needs further basic information on these conservation laws will find a helpful exposition in a review article by Wick [2].

1.2.1. Conservation of isotopic spin I (both $|I|$ and I_z). Figure 1 shows the particles that are stable against decay via the strong interaction. Most of them have been known for many years, although the η-meson was not discovered until 1961, and its quantum numbers were sorted out only in 1962. The particles without any strong interaction (photons and leptons) are shown as thin bars; thick bars represent the strongly interacting particles (mesons and baryons), whose grouping into multiplets is evident. This grouping suggested that all members of the multiplet shared a new quantum number I, called isotopic spin. For the rest of this text we refer to it for short as isospin, a conserved vector in « ispace ». The projection of I along the « charge axis » was called I_z, and gave the electric charge in units of $|e|$.

$$Q = \frac{Y}{2} + I_z \,. \tag{4}$$

The constant Y is called the « hypercharge », since it measures the « center of charge » of a multiplet. For mesons the hypercharge and the « strangeness » are the same thing. For the nucleon doublet, though, we have

$$Q = \tfrac{1}{2} + I_z \,,$$

i.e., $Y=1$. However, since nucleons are familiar, we like to say they have zero strangeness, *i.e.*, we invent the relation

$$Y = S + B \,,$$

where S is the strangeness and B the baryon number.

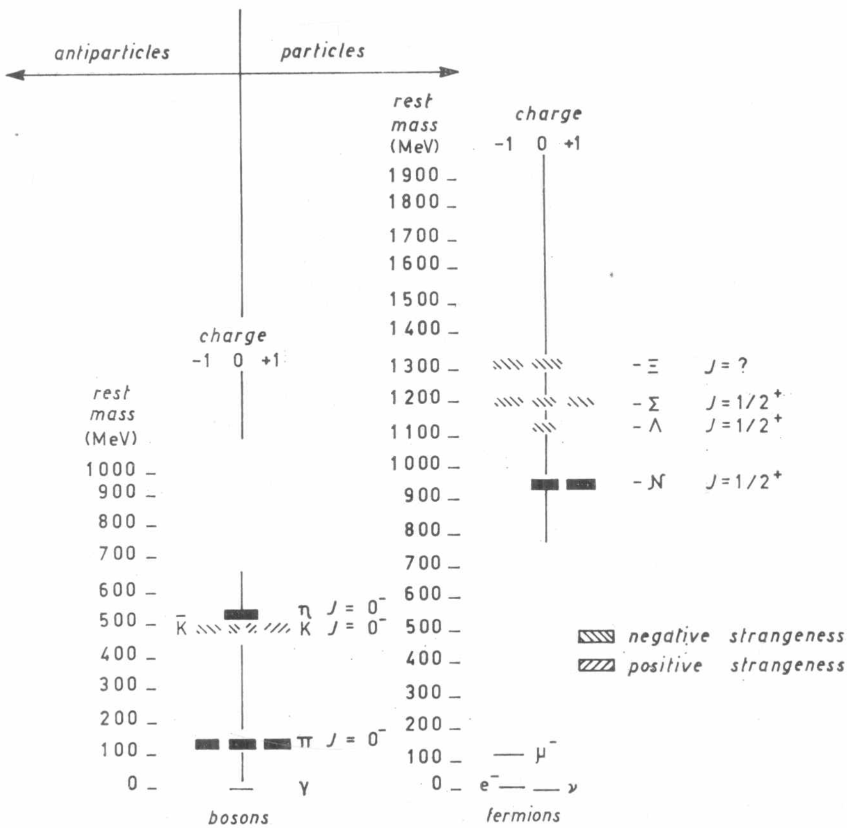

Fig. 1. – Particles stable against strong decay.

In summary, both Y and S are used to describe the position of the center of a multiplet, but Y is used to relate its displacement from zero charge, and S is used to relate its displacement from the center of charge of the « nonstrange » particles.

1.2.2. Separate invariance under C and P; G parity. We define *parity* P as the operation that reflects space co-ordinates. Then the parity of a wave function of orbital angular momentum l is $(-1)^l$. As discussed in any text on particle physics each particle has also an « intrinsic » parity, which for both the π-meson and the K-meson has been determined experimentally to be odd [1*b*]:

(5*a*) $$P|\pi\rangle = -|\pi\rangle ,$$

(5*b*) $$P|K\rangle = -|K\rangle .$$

We discuss the parity of fermion-antifermion pairs in connection with eq. (18). We define *charge conjugation*, C, as the operation that transforms particles into antiparticles and vice versa; thus electrons e^- transform into positrons e^+, while π^+ transforms into π^-, and π^0 into itself. As W. S. C. WILLIAMS has pointed out [1*a*] a more satisfactory name for this operation would be particle-antiparticle conjugation, as there is not always a change in electric charge.

We want the photon to have the same behavior under C as electric or magnetic fields and currents, namely

(6) $$C|\gamma\rangle = -|\gamma\rangle .$$

Since π^0-decays electromagnetically into two identical particles (two γ-rays) and since C is conserved by the electromagnetic (em) interaction as well as by the strong interaction, we have

(6*a*) $$C|\pi^0\rangle = +|\pi^0\rangle .$$

Since charged particles are not in eigenstates of C, we can get no selection rules by applying C alone (although we can get other useful relations). Therefore for most charged particles we do not bother with C except to note that $C^2 = +1$, and that $[C, H] = 0$, where H is the strong or electromagnetic Hamiltonian. But in the case of charged pions we want to adopt the convention

(6*b*) $$C|\pi^{\pm}\rangle = +|\pi^{\mp}\rangle ,$$

in analogy with (6*a*). This choice is arbitary; we could have chosen

$$C|\pi^{\pm}\rangle = \exp[\pm i\delta]|\pi^{\mp}\rangle ,$$

but (6*b*) is simpler. We will use (6*b*) in defining G, which we take up next.

G parity. Next we wish to take advantage of simultaneous conservation of C and I to derive a new conserved quantity G, first introduced by LEE and YANG [3] and MICHEL [4]. They defined G as $C\exp[i\pi I_y]$, *i.e.*, a charge conjugation and a 180° rotation in ispace around I_y. Actually, with C defined as it is above, we must redefine G as

$$G = C\exp[i\pi I_x] . \tag{7}$$

The reason for introducing G is readily seen. Given a multiplet with $B=S=0$, only the neutral component can be in an eigenstate of C, since C reverses charges. However, the rotation about I_x or I_y again reverses charges, so that the whole multiplet can be an eigenstate of G. Notice that C performs a reflection in ispace, and $\exp[i\pi I_x]$ is a rotation. Hence G has the properties of a parity operation in ispace—and WICK calls it «isotopic parity» [2].

Next we wish to prove eq. (8), *i.e.*, that for any system of n_π pions, $G=(-1)^{n_\pi}$:

To do this it is convenient to represent the pion (which has unit angular momentum in ispace) by the spherical harmonics in ispace, *i.e.*,

$$|\pi^0\rangle = Y_1^0 \propto \cos\theta = z ,$$
$$|\pi^+\rangle = Y_1^1 \propto -\sin\theta\exp[i\varphi] = -x-iy .$$
$$|\pi^-\rangle = Y_1^{-1} \propto +\sin\theta\exp[-i\varphi] = +x-iy .$$

Using the C parity of π from (6*a*) and (6*b*), we then have

$$G|\pi^0\rangle = C\exp[i\pi I_x]|z\rangle = C|-z\rangle = C|-\pi^0\rangle = -|\pi^0\rangle ,$$

and

$$G|\pi^{\pm}\rangle = C\exp[i\pi I_x]|\mp x-iy\rangle = C|\mp x+iy\rangle = C|-\pi^{\mp}\rangle = -|\pi^{\pm}\rangle ;$$

thus G changes the sign of each pion, and consequently

$$G = (-1)^{n_\pi} . \tag{8}$$ q.e.d.

Since C and I are conserved in strong interactions, so is G; consequently an even number of pions cannot transform into an odd number (and vice versa), therefore pion vertices in Feynman diagrams must consist of an even number of pions. We can now repeat the above discussion of the effect of operating with $\exp[i\pi I_x]$ on $Y_I(z)$ to obtain a different result for *any* particle in an eigenstate of C (*i.e.*, any nonstrange neutral meson with arbitrary isospin I). The symmetry of $Y_I^0(z)$ is $(-1)^I$, *i.e.*, $\exp[i\pi I_x]\, Y_I^0 = (-1)^I\, Y_I^0$; thus we have the result

$$G = C(-1)^I \tag{9}$$

for neutral nonstrange mesons. Once established for the neutral member of a multiplet, G applies for the whole multiplet.

1·2.3. Particle-antiparticle systems: the rule « $CPX_s = +1$ ».

(i) *Case* I. *Boson-antiboson pairs.* For two identical spinless bosons such as $2\pi^0$ we all know that the wave function $\psi(r)$ must by symmetric under the operator X, which exchanges these two particles; *i.e.*,

$$X = +1\,. \tag{10}$$

If the bosons are charged, with charge Q, and have spins, we can write a generalized wave function of three variables

$$\psi = \psi(r)\,\psi(Q)\,\psi(S)\,, \tag{11}$$

where the diparticle spin S is given by the vector sum $\boldsymbol{S} = \boldsymbol{S}_1 + \boldsymbol{S}_2$.

$$X\psi = X_r\psi(r)\,X_Q\psi(Q)\,X_S\psi(S) = P\psi(r)\,C\psi(Q)\,X_S\psi(S)\,,$$

i.e.,

$$X = PCX_S\,.$$

This generalized ψ must again be symmetric under X, since boson field operators commute. Therefore

$$X = PCX_S = +1\,. \tag{12}$$

If $\psi(r)$ is an l wave,

$$P = (-1)^l\,. \tag{13}$$

Questions of intrinsic parity and C do not arise, since we have *two* bosons, and $P^2 = C^2 = +1$.

The symmetry of $\psi(S)$ is $(-1)^{S_1+S_2-S} = (-1)^S$, so

$$X_S = (-1)^S; \tag{14}$$