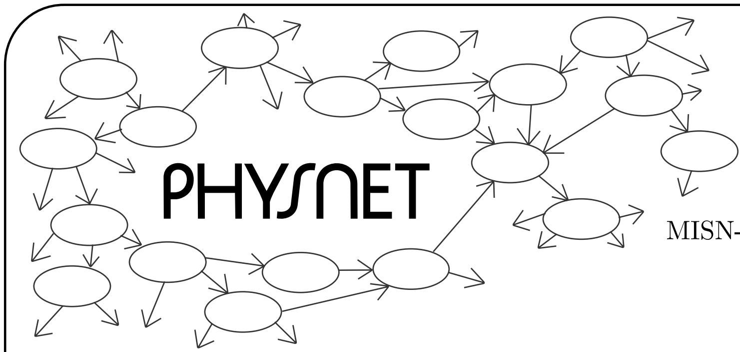
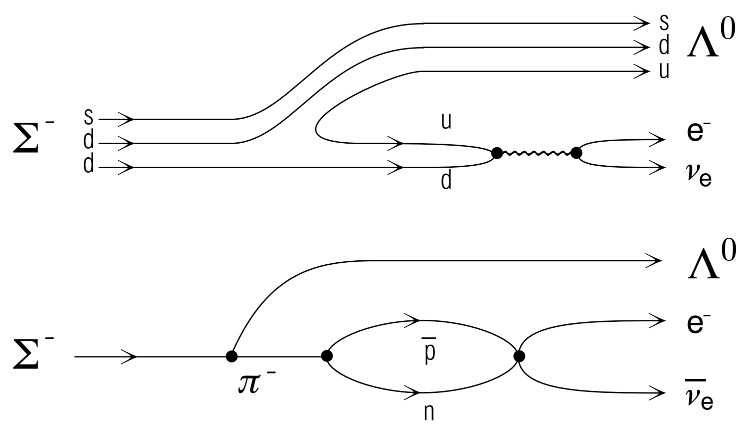


MISN-0-280

THE STRONG INTERACTION



Project PHYSNET Physics Bldg. Michigan State University East Lansing, MI

THE STRONG INTERACTION

by

J. R. Christman

1. Abstract 1

2. Readings 1

3. Description
- a. General Effects, Range, Lifetimes, Conserved Quantities . 1
- b. Hadron Exchange: Exchanged Mass & Interaction Time . 1
- c. Charge Exchange 2

4. Hadron States
- a. Virtual Particles: Necessity, Examples 3
- b. Open- and Closed-Channel States 3
- c. Comparison of Virtual and Real Decays 4

5. Resonance Particles
- a. Particles as Resonances 4
- b. Overview of Resonance Particles 5
- c. Resonance-Particle Symbols 6

6. Particle Names
- a. Baryon Names; T, Y 6
- b. Meson Names; G-Parity, T, Y 6
- c. Evolution of Names 7
- d. The Berkeley Particle Data Group Hadron Tables 7

7. Hadron Structure
- a. All Hadrons: Possible Exchange Particles 8
- b. The Excited State Hypothesis 8
- c. Quarks as Hadron Constituents 8

Acknowledgments 8

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Input Skills:

1. Explain how isospin is applied to strong interactions (MISN-0-278).
2. Apply the uncertainty principle to energy conservation violation by intermediate states (MISN-0-279).
3. Interpret Particle Diagrams and give the associated coupling constants (MISN-0-279).
4. Define "virtual particle" (MISN-0-279).

Output Skills (Knowledge):

K1. Relate the strong interaction to the exchange of hadrons.

K2. Explain what is required to produce real, observable (not virtual) particles.

K3. Describe how resonance particles are placed into four meson and six baryon categories.

K4. Discuss how particles in the same category can differ.

K5. Explain how categorization arises from differences in internal parts (quarks) and motion of quarks.

Output Skills (Rule Application):

R1. Given the mass of an exchanged particle, estimate the range of the corresponding interaction.

R2. Estimate the mass and lifetime of a resonance particle from a plot of cross-section vs. energy.

R3. Given a scattering process and a single exchanged hadron, draw the corresponding Particle Diagram.

External Resources (Required):

1. M. J. Longo, *Fundamentals of Elementary Particle Physics*, McGraw-Hill (1973); and *Scientific American*: R. E. Marshak, "Pions," (Jan. 1957); R. D. Hill, "Resonance Particles," (Jan. 1963).

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Our publications are designed: (i) to be updated quickly in response to field tests and new scientific developments; (ii) to be used in both classroom and professional settings; (iii) to show the prerequisite dependencies existing among the various chunks of physics knowledge and skill, as a guide both to mental organization and to use of the materials; and (iv) to be adapted quickly to specific user needs ranging from single-skill instruction to complete custom textbooks.

New authors, reviewers and field testers are welcome.

Views expressed in a module are those of the module author(s) and are not necessarily those of other project participants.

THE STRONG INTERACTION

by

J. R. Christman

1. Abstract

Ater a review of properties of the strong interaction, this module introduces two new ideas: (a) the cloud of virtual hadrons around each hadron; and (b) the resonance particles.

2. Readings

1. Longo, Chapter 3.
2. R. E. Marshak, "Pions," *Scientific American* (January, 1957).
3. R. D. Hill, "Resonance Particles," *Scientific American* (January, 1963).

3. Description

3a. General Effects, Range, Lifetimes, Conserved Quantities. Only hadrons interact via the strong interaction. Hadrons scatter from other hadrons, producing changes in their motion, and/or other particles, via this interaction mechanism. It is sufficiently strong to bind low energy hadrons together and this binding is responsible for the binding of neutrons and protons in the nucleus. It is of short range (10^{-15} m). Particles which decay via the strong interaction have lifetimes typically on the order of 10^{-24} sec. This is also roughly the time two particles travelling near the speed of light are within 10^{-15} m of each other. The strong interaction is charge independent: for example, it is the same for neutrons as for protons.

Strong-interaction scatterings and decays conserve energy, momentum, charge, baryon number, electron number, muon number, strangeness, and isotopic spin. The interaction is invariant under parity, charge conjugation and time reversal.

3b. Hadron Exchange: Exchanged Mass & Interaction Time. The nature of the interaction itself is believed to be associated with the exchange of hadrons between the interacting particles. The lightest hadron

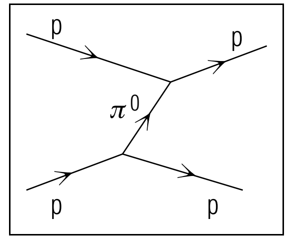

Figure 1.

is the pion with a mass of about 140 MeV, so one possibility for strong nucleon-nucleon scattering is shown in Fig. 1.

For some time Δt, the system is in violation of the law of energy conservation by at least 140 MeV. The maximum length of time this can occur is:

$$\Delta t \simeq \frac{\hbar}{\Delta E} = \frac{1.05 \times 10^{-34}}{140 \times 10^{6} \times 1.6 \times 10^{-19}} = 4.7 \times 10^{-24}\,\mathrm{sec}$$

which is roughly the time of a typical strong interaction. An estimate for the range of the interaction can be obtained by assuming the pion moves at a speed close to the speed of light. It then will move about

$$4.7 \times 10^{-24} \times 3 \times 10^{8} = 1.4 \times 10^{-15}\,\mathrm{m}$$

in time Δt. This is indeed the range of the strong interaction.

Hadrons with greater mass than the pion can be exchanged but the exchange must take place in shorter times and over smaller distances. The short range part of the strong interaction is thus complicated by the possibility of multiple pion exchange as well as kaon, eta and baryon exchange.

3c. Charge Exchange. The various charge states of the pion have roles to play, as the diagrams in Fig. 2 show.

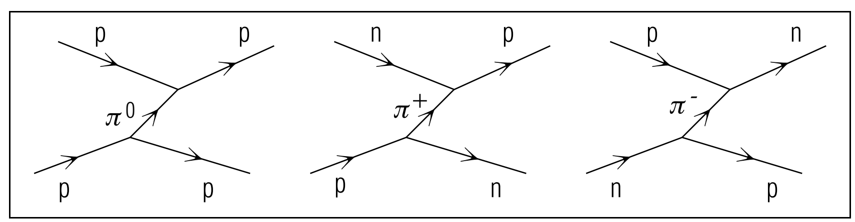

Figure 2.

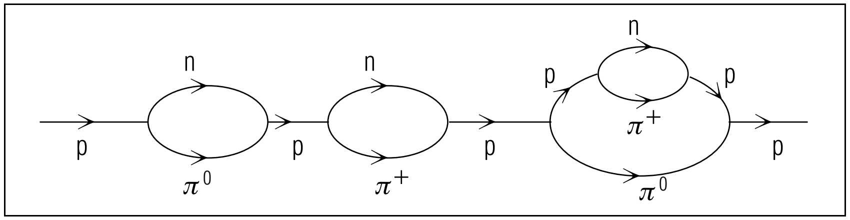

Figure 3.

Note that the proton and neutron can exchange their identities during the course of the interaction.

4. Hadron States

4a. Virtual Particles: Necessity, Examples. It is unreasonable to assume that a proton, for example, emits a pion only in the presence of another hadron for, in that event, there would be a mechanism which signals the presence of the second particle. It must be that the "proton" sometimes exists in a state which consists of a proton and a pion. In fact the trail of a proton may look as shown in Fig. 3 and any of a large number of diagrams.

Since the coupling constant $g_s \approx 1$, the vertices $\mathrm{p} \to \mathrm{p}+\pi$, $\mathrm{p} \to \mathrm{p}+2\pi$, ..., $\mathrm{p} \to \mathrm{p} + n\pi$ all compete with each other. Of course the larger the number of pions, the greater is the violation of energy conservation and the shorter the time the particle can be in such a state.

The virtual particles accompanying the hadrons are not limited to pions: any hadron can be created. The only requirements are that the appropriate conservation laws for the strong interaction, except conservation of energy, hold at each vertex. Examples for the pion are shown in Fig. 4.

4b. Open- and Closed-Channel States. The proton has been used as an example above. The same statements are true for all hadrons. Given any hadron, there is a non-zero probability that the hadron will be in a state with any combination of other hadrons consistent with the conservation laws. These various possibilities are called channels. An open channel is any state which conserves all quantities, including energy, appropriate for the strong interaction. A closed channel is any state which conserves all quantities, except energy, appropriate for the strong interaction. Final, observed states must be open channels with respect to the initial state. Intermediate states can be open or closed channels.

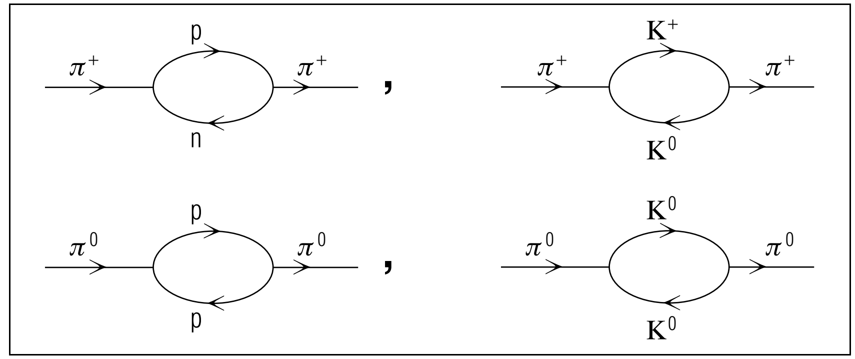

Figure 4.

4c. Comparison of Virtual and Real Decays. Our picture of the hadron system is a collection of particles, each one of which continually produces the others. If the energy (mass) of a single particle is greater than the sum of the masses of the particles in another state, the particle decays to that state. Otherwise the particles when in the other state are virtual and unobservable, and the state is short lived. The interaction between two hadrons takes place via the exchange of such virtual particles. When the total energy is great enough for the virtual particles to become real, they do, and the interaction produces other hadrons as the final product.

5. Resonance Particles

5a. Particles as Resonances. Total cross sections for hadron-hadron scattering as functions of energy show a great deal of structure. The cross section is a measure of the probability that a particle will be scattered out of the original beam; that is, it measures the probability that an interaction takes place. As an example, the cross section of π^- incident on p as a function of center of mass total energy is shown in Fig. 5.

Fairly narrow, well defined peaks are interpreted as particles (called resonance particles). The interpretation is justified as follows. Certain interactions involving intermediate particles give rise to cross sections with peaks. An example of such an interaction is shown in the Fig. 6, where X is an intermediate particle. Energy need not be conserved at vertices but the peak in the cross section occurs at an incident energy

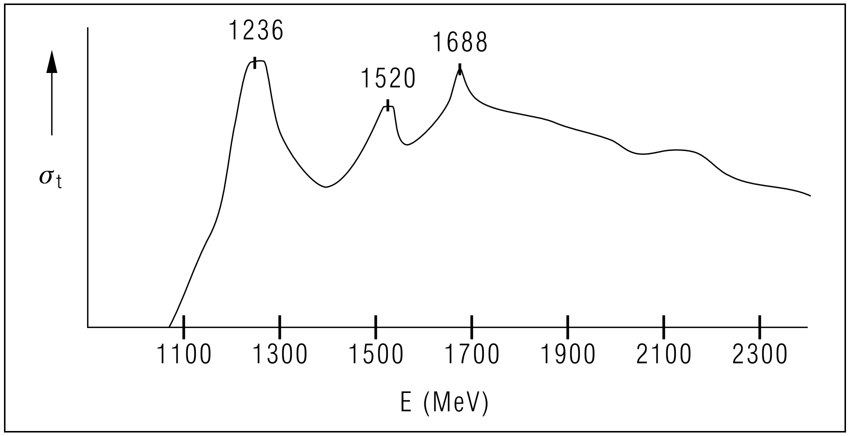

Figure 5.

where energy is in fact conserved. Since the energy plotted is the center of mass energy (i.e. in a frame for which the momentum of the X is zero) the total center of mass energy is just the mass (times c^2) of the X particle. Furthermore the width of the peak is related to the time of the interaction by $\Delta E \Delta t \simeq \hbar$. Here ΔE is the width of the peak and Δt is the lifetime of the X particle.

In addition, by appropriate analysis of data and application of conservation laws, the resonance particle X can be assigned other particle attributes: charge, spin, isotopic spin, strangeness, and baryon number. Confidence in the idea that a resonance is the signal for the appearance of a particle is increased when it is observed that the same resonance particles with the same particle properties appear in a variety of scattering processes. For example, the resonance at 1236 MeV occurs not only in π^--p scattering but also in γ-p scattering etc.

5b. Overview of Resonance Particles. Analysis of peaks in cross-section vs. energy curves has lead to the discovery of hundreds of res-

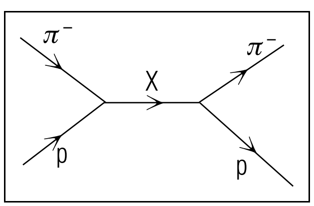

Figure 6.

onance particles, all of them hadrons and all of them decaying via the strong interaction. The resonance particles, according to accepted ideas, must be produced virtually by all hadrons. However, it is only when the interaction takes place at energies near the resonance particle mass that the influence of the resonance particle on the cross-section is seen.

5c. Resonance-Particle Symbols. With the proliferation of resonance particles, the same symbol has come to be used for several particles having similar properties, with the mass written in parentheses after the symbol. The π^--p resonances are denoted Δ(1236), N*(1520), N*(1688), etc. Sometimes the spin of the particle is also given inside the parenthesis: Δ(1236,3/2), N*(1520,3/2), N*(1688,5/2).

6. Particle Names

6a. Baryon Names; T, Y. Particle groups' names differentiate between the groups' hypercharge and isotopic spin. For baryons the group names are:

T	Y	Name
0	0	Λ
0	-2	Ω
1/2	+1	N
1/2	-1	Ξ
1	0	Σ
3/2	+1	Δ

For a particular member of a group, charge is indicated by superscript while the mass in MeV and the spin in units of $\hbar$ are placed in parenthesis after the name. For example, the proton is N$^+$(940,1/2).

6b. Meson Names; G-Parity, T, Y. For some mesons, an additional number is needed. This need arises because, for the non-strange mesons, both particle and antiparticle are in the same isospin multiplet. For example, the pion triplet contains both the π^+ and π^-. We state without proof that the operator

$$e^{+i\pi T_2},$$

where T_2 is the 2-component of isospin, changes one member of the multiplet into another. In fact, it just reverses the change caused by the charge conjugation operator. We define the new operator $\mathcal{G}$ by

$$\mathcal{G} = Ce^{-i\pi T_2},$$

which does not change the particle. G does however change some wave functions into their negatives. For example:

$$\mathcal{G}\,\pi^+ = -\pi^+,$$

$$\mathcal{G}\,\pi^0 = -\pi^0.$$

Here the particle symbol is used to represent the wave function: If the wave function changes sign the particles is said to have odd G-parity ("odd" is denoted $-$) and, if the wave function does not change sign, the particle is said to have *even* G-parity (denoted $+$).

Names for mesons are

T	Y	G	Name
0	0	+	η
0	0	−	ω
1/2	+1	X	K
1/2	−1	X	$\overline{\text{K}}$
1	0	+	ρ
1	0	−	π

You need not know any details of G-parity. Just remember that the π and ρ are the same except for an internal quantum number G. Similarly for the η and ω.

6c. Evolution of Names. All known hadrons can be placed in one of the meson or baryon categories. With the exception of the Δ these names are the same as are used for the particles which are stable under the strong interaction (N = nucleon, not be confused with n = neutron).

Be warned that some older names are still in use and that a proliferation of names as well as of particles exists. When a new particle is discovered it is impossible to place it in the scheme before its properties have been identified and the temporary name given to it may become more or less permanent.

6d. The Berkeley Particle Data Group Hadron Tables. Tables (see Guide) give a fairly complete list of known particles as of 1973. These tables and other data are published annually by the Particle Data Group at Berkeley. This group maintains a complete, up-to-date file of high energy data. In the Berkeley tables, the symbol I is used for isospin.

7. Hadron Structure

7a. All Hadrons: Possible Exchange Particles. All of the particles participate in the strong interaction and have lifetimes on the order of 10^{-24} sec. These times are too short to be measured directly but are inferred from the widths of the resonances. All could conceivably act as exchange particles (and hence could be the strong interaction, in a sense). Of course most of the masses are so great that they play little role except at very short range or at very high energies.

7b. The Excited State Hypothesis. This enormous number of hadrons leads physicists to believe that many are really excited states of others. This in fact is the basis of the naming scheme. Perhaps the hadrons have some sort of internal machinery (they are composed of smaller parts). Then the $N(1470)$ particle could be composed of the same constitutents as the $N(940)$, the stable nucleon. They are the same particle except that the constitutents have different internal motions and the particle has a different energy by virtue of the internal motions. This extra energy manifests itself as extra mass. The internal constitutents may have their own spin angular momentum plus orbital angular momentum and these then contribute to the spin of the particle.

7c. Quarks as Hadron Constituents. The particles which nature uses to build the hadrons are called quarks. All N particles have the same number and type of quarks but the motions of the quarks within them are different for the different N particles. This scheme can account for all properties, except mass, of all hadrons. We study the quark model in more detail in "SU(3) and the Quark Model" (MISN-0-282).

Acknowledgments

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