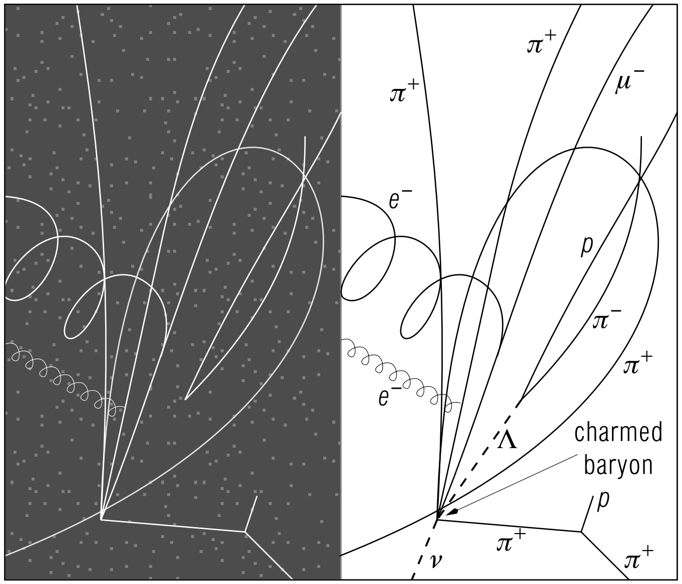
MISN-0-283

COLOR AND CHARM



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

COLOR AND CHARM
by
J. R. Christman, U. Coast Guard Academy

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Input Skills:

1. Discuss the basic principles of the quark model (MISN-0-282).

Output Skills (Knowledge):

K1. Vocabulary: charmed meson, charmed hadron, charmonium.
K2. Explain how the Pauli exclusion principle is satisfied by the introduction of color.
K3. Explain how the color singlet argument leads to the accepted quark bound states (mesons and baryons). Give examples of the three color singlet states.
K4. Discuss the concept of charm and the ways in which its introduction modifies the quark model.
K5. Give the properties of the charmed quark.
K6. Discuss how color may be responsible for the gluon theory of quark binding.

Output Skills (Rule Application):

R1. Given some of the properties of a hypothetical hadron, determine whether or not the particle's existence is possible under the four-quark model. If it is possible, state the hadron's quark content; if not, state why not.

External Resources (Required):

1. S. L. Glashow, "Quarks with Color and Flavor," Scientific *American* (Oct. 1975).

Post-Options:

1. "Current Work in Elementary Particles," (MISN-0-284).

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1. Overview

This module covers material which has been extensively studied experimentally and theoretically over the past decade. The ideas of charm and color are frequently in the news and are often invoked to explain new discoveries. Because the words are used in press releases you should be aware of the concepts behind them. You should remember that charmed particles have been observed in experiments, but that the evidence for color is still indirect.

2. Assigned Reading

S. L. Glashow, "Quarks with Color and Flavor," *Scientific American*, (Oct. 1975).

3. Color

3a. Introduction. Color is a new quantum number assigned to the quarks. It is postulated that each quark can exist in one of three different states which are distinguished from each other by a quantity called "color." The three states are designated red, yellow, and blue by most authors although several different sets of names are in use. It should be emphasized that color, as used here, has absolutely nothing to do with hue or frequency of light. It is simply a convenient designation for states. With the addition of color, there are essentially nine kinds of quarks (red u, yellow u, blue u, red d, yellow d, etc). The postulate of color solves two problems which arise in connection with the quark model, although it raises another, perhaps equivalent question.

3b. Apparent Quark-Spin Violation of Pauli Principle. The first problem solved by the introduction of color arises from the quark model for baryons in the spin 3/2 decimet. The masses of these particles lead one to believe that the particle spin arises from aligned quark spins and not from quark orbital angular momentum. If this is true there are cases for which 2 or more quarks have exactly the same quantum numbers — they are the same type of quark with the same spin and orbital angular momentum (namely zero). The most flagrant example is the Ω^- with quark content sss all in $\ell = 0$, $m_s = +1/2$ states. This quark content violates the Pauli exclusion principle which forbids more than one fermion from occupying the same state. This principle is derivable from long established principles of special relativity and to accept the violation would be tantamount to a rejection of relativity. The way out is to postulate that the three s quarks in the Ω^- are not really in identical states but rather differ in color; that is, one is red, one is yellow, and one is blue.

3c. Quark Triplets. The second problem that color helps to solve is the riddle of why our observable particles formed only from 3 quarks, 3 antiquarks or a quark-antiquark pair. Why not $(\mathrm{uuds}\bar{\mathrm{d}})$ for example? To answer this it is assumed that:

1. there are 3 different colors;
2. the colors obey a color SU(3) symmetry, just like the SU(3) symmetry of the quarks themselves, but the color operators change the color instead of the quark type; and
3. all observable particles are color singlets (that is, they have zero net color).

There are exactly 3 ways to combine quarks and meet these conditions:

1. *A quark-antiquark pair* where both quark and antiquark are of the same color at any time and with the pair spending one-third of the time being each of the colors. The π^+ state, for example, is written (using the subscript "r" for "red" and similarly for yellow and blue):

$$\frac{1}{\sqrt{3}}\left[(\mathrm{u}\bar{\mathrm{d}}_\mathrm{r}) + (\mathrm{u}\bar{\mathrm{d}}_\mathrm{y}) + (\mathrm{u}\bar{\mathrm{d}}_\mathrm{b})\right].$$

2. *A quark triplet* in which each of the three quarks is a different color than the others and with each permutation of color occurring with equal probability. The p state, for example, can be written:

$$\frac{1}{\sqrt{6}}\left[\mathrm{u_r u_y d_b + u_y u_b d_r + u_b u_r d_y - u_y u_r d_b - u_b u_y d_r - u_r u_b d_y}\right]$$

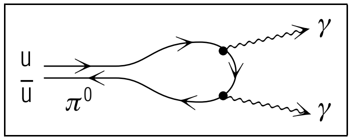

Figure 1. The decay of π^0 according to the quark model.

3. *An antiquark triplet* in which each of the three antiquarks is a different color than the others and with each permutation of color occurring with equal probability. If the color SU(3) symmetry is exact, all three uquarks have the same mass, spin, isospin, strangeness, hypercharge, baryon number, and charge. Similar statements can be made for the three dquarks and the three squarks.

These postulates lead to the new question: why are the particles color singlets? At present this question has not been answered.

3d. Quantitative Implications of Color. The existence of color has quantitative implications. According to the quark model the decay $\pi^0 \to \gamma + \gamma$ proceeds according to the diagram in Fig. 1, where q is either a u or a d quark. Without color considerations, this diagram leads to a prediction for the decay rate which is about one-third the observed rate. If color is included, there are 3 routes for the decay (via red quarks, via blue quarks, and via yellow quarks) and the predicted rate is close to the observed rate.

Production of hadrons from electron-positron annihilation proceeds according to the process illustrated in Fig. 2. Here each set of two adjacent parallel lines stands for a quark-antiquark pairs, representing a meson. Again, the predicted rate for hadron production, without color, is too low by a factor of 3. When color is introduced, the resulting agreement of predicted and observed rates can be taken as a strong argument for color.

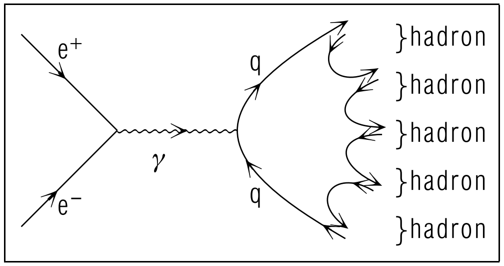

Figure 2. The annihilation of an electron-positron pair according to the quark model.

4. Charm

4a. Values, Conservation. Charm is a new particle quantum number that is somewhat similar to strangeness. Like strangeness it is embodied in a quark, denoted by c, that is called the charmed quark. The charmed quark has charm +1, the charmed antiquark has charm −1, and the other three quarks (u,d,s) have charm 0. Charm is evidently conserved in strong interactions.

4b. Relationships: C, Q, B, S, T_3 **.** The charmed quark has baryon number 1/3, spin 1/2, strangeness 0, isospin 0, and charge 2/3. With the advent of charm, the relationship between charge, baryon number, strangeness, and isotopic spin must be modified to:

$$q = \frac{1}{2}(B + S + C) + T_3.$$

Just as a hadron that exhibits net strangeness is called a strange particle, so a particle which exhibits net charm is called a charmed particle. Since a charmed particle and its anti-particle have opposite charm, the cbc meson is not charmed but ubc is a charmed meson and udc is a charmed baryon.

4c. Postulated Lepton-Quark Symmetry. The postulate of a charmed quark was made on several grounds. One is purely aesthetic. It is believed by many physicists that leptons and quarks are the truly fundamental particles and that nature must show a symmetry between these two set of particles. Since there are four leptons, it is not unreasonable to expect four quarks.

4d. Rarity of Strangeness - Conserving Neutral Interaction Decays. The other reason for introducing charm is more compelling. It has to do with a special class of weak interactions, called strangeness changing neutral interactions, in which the net strangeness of the hadrons involved changes but the net charge of the hadrons does not (hence the name "neutral"). Two examples are $K^0 \to \mu^+ + \mu^-$ and $K^+ \to \pi^+ + \nu_\mu + \bar{\nu}_\mu$. These interactions, described in terms of quarks, involve the transformation $s \to d$ and they are extremely rare; less than 0.7×10^{-3} per cent of hadron decays are via such strangeness-changing neutral interactions.

The theoretical problem which arises is this: why are these decays so rare? There is no conservation law which prevents $s \to d + W^0$, for example. The old answer to this question was that the W^0 does not exist. Its existence has now been implied by neutrino scattering experiments and a new reason must be sought.

The theory here is too complex to discuss in detail but the general idea is: the existence of a charmed quark provides another route by which these decays can take place. Classically, the existence of two routes to a particular final result increases the probability of reaching that result. However, quantum mechanically the probability amplitudes for the two routes can interfere destructively with each other and considerably reduce the probability of reaching the result. This mechanism gave rise to the name of this quark.[1] A charm wards off evil; the evil in this case is the direct, weak, neutral decay of the kaon.

5. Consequences of Color and Charm

5a. Multiplicities: Comparison of Charm and Color. Color, with the postulate that particles be color singlets, does not increase the number of particles predicted by the quark model. Charm, however, enormously increases the number of hadrons possible. The meson octets become 15 particle figures with the addition of $c = +1$ and $c = -1$ particles. The baryon octets become 20 particle figures with the addition of $c = +1$, $c = +2$, and c = +3 particles. There are also new $c = 0$ hadrons: particles with the combination $\mathrm{c\bar{c}}$ and also perhaps in combination with other quarks.

5b. Color-Changing Gluon Exchange. Color enters into new theories in another, more fundamental, way. It is thought to be the characteristic that is responsible for the binding between quarks. Just as electric charge produces the electromagnetic field and photons, color ("charge") is responsible for the gluon field and gluons. The change from one color combination to another is accompanied by the emission or absorption of a gluon. These ideas are currently being studied.

Acknowledgments

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[1] Glashow, *Physics Letters*, (1964).

MODEL EXAM

1. See Output Skills K1-K6 in this module's *ID Sheet*. The actual exam may contain one or more of these skills.

2. Determine which of the following particles can exist, according to the 4-quark model. For each allowed particle, give a possible quark content. For each unallowed particle, tell why the 4-quark model prohibits it.

    a. a baryon with charm +1, strangeness +1, isospin 1.

    b. a baryon with charm -1, strangeness 0, charge 0.

    c. a meson with charm +2.

Brief Answers:

1. See this module's *text*.

2. a. No.

    This baryon would be [$\mathrm{c\bar{s}}$(uor d)], but since c and $\mathrm{\bar{s}}$ each have isospin of 0 and u and d have isospin 1/2, the baryon would have isospin 1/2 (not 1).

    b. Yes. ($\mathrm{\bar{c}\overline{dd}}$).

    c. No. This meson would have to be cc, but a meson consists of a quark-antiquark pair.