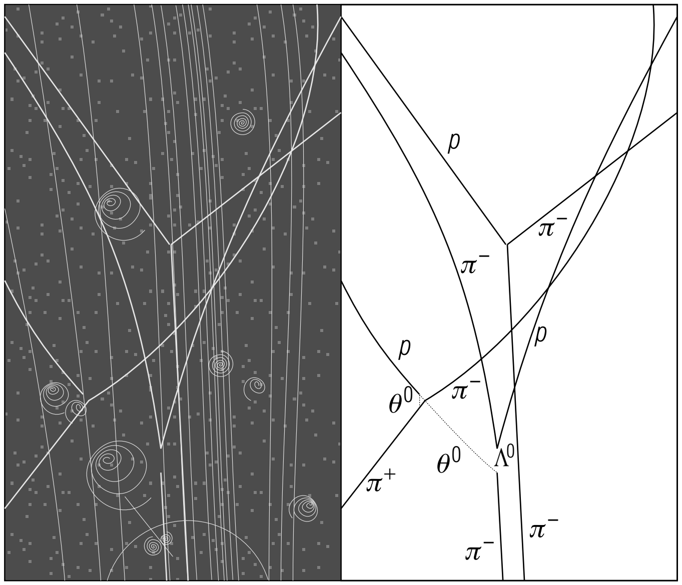
PHYSNET

MISN-0-284

CURRENT WORK IN ELEMENTARY PARTICLES



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

CURRENT WORK IN ELEMENTARY PARTICLES
by
J. Christman

Title: **Current Work in Elementary Particles**

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Input Skills:

1. Discuss the basic theory of weak interactions (MISN-0-281).
2. Discuss the concept of charm and the modified quark model (MISN-0-283).

Output Skills (Knowledge):

K1. List the types of particles currently sought and discuss their significance to high energy physics.

K2. Describe successful experiments in which new particles are produced and tell how they are carried out.

K3. Discuss how experimenters attempt to distinguish between new heavy leptons, new vector bosons, and new hadrons containing charmed quarks.

K4. Explain the difference in quark content between an uncharmed hardon containing charmed quarks and a charmed hadron.

K5. Discuss how ψ, ψ', ψ'', ψ''', are related and why only ψ is stable with respect to the strong interaction.

K6. Describe a dimuon experiment and discuss its significance.

External Resources (Required):

1. Several articles referenced in the unit text.

External Resources (Optional):

1. W. Heisenberg, "The Nature of Elementary Particles," *Physics Today*, (March 1976).

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1. Overview

This module covers portions of current work in high energy physics, particularly those portions which can be understood easily in terms of the concepts we have been discussing. Its intent is to give you some familiarity with current work and to provide some examples of how the concepts you have learned are used. The purpose of this section is to familiarize you with some of the current work in high energy physics, particularly work which has led, in the recent past, to the discovery of new particles. To be sure, theoretical high energy physics is proceeding but much of that is beyond the level of this course. We shall chiefly be interested in the new particles and their significance.

2. Assigned Reading

The reading material is referenced in the notes. Read those articles which are mentioned and be on the look-out for newer articles. All of the articles are available in the library.

3. Particles Sought

3a. Types Sought. The most sought after new particles are of three types:

i. a new heavy lepton (perhaps associated with a new neutrino),

ii. one or more of the postulated intermediate vector bosons, the carriers of the weak force (the W particles or their relatives),

iii. a new hadron which exhibits charm or at least contains charmed quarks.

3b. The W Particles. The intermediate vector bosons, as carriers of the weak interaction, are of interest because their existence means that the weak interaction can be formulated in the same form as the strong and electromagnetic interactions. Instead of a 4-particle vertex, the weak vertex would be a 3-particle vertex with a W particle created or destroyed there, just as hadronic mesons are created or destroyed at strong vertices and photons are created or destroyed at electromagnetic vertices. There would then be something fundamentally the same about the three interactions: each would have its own set of particles which are created and destroyed at the appropriate vertices and which carry the interaction.

The mass of the W particle is intimately related, through the uncertainty principle, to the range of the weak interaction. As experiments using higher and higher energies are performed without finding a W particle, the lower limit on a mass estimate increases and the upper limit on the weak interaction range decreases. An infinite mass particle is associated with a point interaction.

Interest in finding the W particles goes beyond a desire to formulate the three interactions in the same way. The weak and the electromagnetic interactions may be even more closely related than just having the same form. A theory, called the spontaneous breaking of gauge symmetry, formulated by Weinberg and Salam, predicts that the W particles and the photon form a family. Just as a single quantum field, the strong field, is responsible for all the hadronic mesons, they show that a single quantum field can be invented which is responsible for the photon and the W particles. It is of theoretical interest to find the W's and measure their masses and other properties, as a check on the theory.

3c. Heavy Leptons. Some types of broken gauge symmetry theories also predict the existence of other leptons beside those in the electron and muon families. These heavy leptons are sought as verification of the theory or to give clues as to how it should be modified.

3c. Unified Theories. A unified field theory which brings the electromagnetic and weak interactions under one umbrella so that they can be understood in terms of a single physical law is a giant step forward in our understanding of nature.

3d. Charmed Quarks. Charm was originally proposed to explain the rarity of certain kaon decays. If the charmed fourth quark exists as a possible component of some hadrons, the observation of these "charmed" hadrons is of prime importance. Even if hadrons with a new quantum number are found (and some say they have been found), physicists must show whether or not the new hadron quantum number is indeed responsible for the rarity of strangeness-changing kaon decays. There may be more than one new quantum number. It is fashionable to call all new hadron quantum numbers "charm," but it remains to be seen how many kinds of charm there are. It is important to note these particles are sought not only because they are new particles but also because they are related to important theories.

3e. Missing Members of Supermultiplets. One possibility for new particles was omitted from the above list. We noted before that not all of the supermultiplets of hadrons constructed from the original three types of quarks have been completed with experimentally observed particles. The search goes on for the missing particles. However, these will cause a stir only if a particle is found which has only the old quark quantum numbers and does *not* fit into the supermultiplet scheme.

3f. The Quark Hunt. No isolated quark has ever been observed. Some activity was directed toward quark observation several years ago and none was found. Many physicists believe that the nature of the quark-quark interaction is such that quarks cannot be isolated: when two are pulled apart the binding energy may be used to create quark-antiquark pairs, each member of which becomes bound to one of the original quarks. Only a modest effort is being expended at present toward trying to isolate a quark. The reading material is referenced in the notes. Read those articles which are mentioned and be on the look-out for newer articles. All of the articles are available in the library.

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4. Analyzing Experiments

4a. Producing New Particles. There are many ways to attempt the production of new particles. The interaction of almost any two particles, if the center of mass energy is great enough, will do the job. However, most of the new particles discovered recently have been created following the annihilation of electron-positron pairs, an electromagnetic interaction, or have been created in the interaction of muon’s neutrinos with nucleons, a weak interaction.

Consider, for example, the production of *charmed* hadrons. The strong interaction conserves charm and this interaction, starting with uncharmed hadrons, must produce 2 charmed hadrons if it produces any. This requires more energy than a process which produces a single charmed hadron.

On the other hand, the weak interaction need not conserve charm and is capable of producing a single charmed hadron through the conversion of an uncharmed quark to a charmed quark. The energy requirement is much less than via the strong interaction. This advantage must be balanced, of course, against the disadvantage that the probability of interaction is much less for the weak interaction than for the strong.

Many of the present searches for new particles start with neutrino beams incident on targets containing nucleons. At present, beams of the muon’s neutrino are easier to produce than beams of the electron’s neutrino and it is the former which are used. This technique has been used at Fermilab.

4b. Annihilation Products. It is suspected that some of the new particles are uncharmed (have zero net charm) but contain charmed quarks in the combination $c\bar{c}$. Such particles can evidently be created singly by the strong and electromagnetic interactions. Such particles have been sought in the products of electron-positron annihilation. The annihilation produces a virtual photon which can decay to lepton pairs or hadrons, some of which, perhaps, contain charmed quarks. (A real photon is not produced since any photon which conserves the original momentum cannot conserve energy. For example, if the electrons and positrons have the same energy and approach each other head-on, the initial momentum is zero. The photon must have non-zero energy but zero momentum. Only a virtual photon can have those properties simultaneously.)

4c. Charmed Hadrons in Decay Products? . Once an uncharmed hadron containing charmed quarks is found, charmed hadrons can be sought among its decay products. If the decay is strong, the products will include 2 charmed hadrons, one containing the charmed quark and one containing the charmed antiquark of the original particle. The lowest mass charmed hadrons decay weakly since their decay requires the transition of a charmed quark to an uncharmed quark.

Experiments along these lines have been carried out at SPEAR, the electron-positron colliding beam facility at SLAC (Stanford Linear Accelerator) and at DORIS, a similar facility at DESY in Germany.

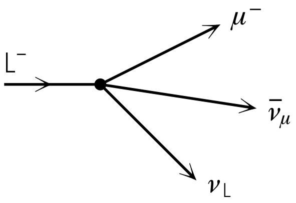
4d. Analyzing Decay Products. One must be able to look at the decay products of an interaction and determine if a new particle has indeed been created. The argument is usually based on the mass of the particle, which can be measured as the energy (in the center of mass frame) at which the particle is created, and on the type of decay the particle underwent. If the mass is sufficiently high so that the particle could have decayed strongly (conserving all known quantum numbers conserved in strong decays) but it actually decayed via the weak or electromagnetic interaction, then one can claim a new strong-stable particle, possessing a new quantum number.

For a new hadron, the mass will be greater than the masses of hadrons in the lowest mass supermultiplets of each type (singlet, octet, or decimet). For leptons and W particles, the mass will be greater than the mass of the muon.

Two methods are available to show that the decay is weak: the lifetime of the particle (calculated from the width of the production peak) and the presence of neutrinos among the decay products of the particle. Since neutrinos are hard to detect, the usual procedure is to determine the number and kind of charged leptons among the decay products and infer the presence or absence of neutrinos by using the lepton conservation laws. It is also sometimes possible to show that the decay violates parity or charge conjugation invariance.

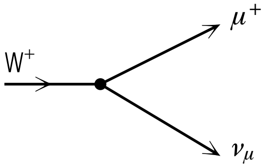
4e. Identifying Particle Types. Although difficult, it is easier to identify the signals for the *appearance* of a new particle than it is to identify the *type* of particle. Charmed hadrons, heavy leptons, and W particles all produce nearly the same signals when one considers those experiments which yield only leptons.

A typical dimuon event (production of two muons) which arises from the decay of a heavy lepton is



Here L^- is the heavy lepton and ν_L is its neutrino. The L^- must have been created in association with an antilepton, L^+ say, and the decay of this antilepton produces another muon.

A W particle has lepton number 0 and it will decay to 2 leptons of the same family with family numbers of opposite sign. A typical decay might be:



A single neutrino ν_μ entered the interaction and, at the creation of the W, a muon must have been created also. To conserve charge, it must have been a μ^- for the above example. This experiment, like the heavy lepton experiment, produces μ^+, μ^-, and ν_μ.

The weak decay of a charmed hadron is similar to that of a W particle. One expects 2 leptons of the same family with family numbers of opposite sign and, of course, a baryon if the decaying hadron is a baryon. A muon's neutrino entered the original interaction so there will be another muon coming out in addition to the two leptons from the decay of the hadron.

The difference between the W decay and the hadron decay is that since there is overwhelming probability that the W is charged, the two muons seen in that experiment are of opposite sign charge whereas the two muons seen in the hadron experiment can have any combination of signs of charge.

It might be possible to distinguish between a hadron and a W on the one hand and a lepton on the other by a careful analysis of the momenta of the muons coming out. Both the hadron and the W decay to two particles while the lepton decays to three. In the latter case there are severe constraints on the relative directions of the momenta of the decay products.

5. Recent Findings

5a. The Psi Particle. The ψ or J particle was discovered at both SLAC and Brookhaven in the Fall of 1974. (It was given different names at the two places and a common name has not yet been agreed upon.)

The two experiments were, in a sense, the inverses of each other. At SPEAR (the electron-positron storage ring facility at SLAC), bursts of high energy electrons and positrons were beamed at each other and the interaction products studied. For the interaction e^+ - $e^- \rightarrow$ hadrons, an enormous enhancement of hadron yield occurred when the center of mass energy was in the neighborhood of 3.1 GeV—the signal for a resonance particle of that mass. Evidently, the electron-positron pair annihilate to form a virtual photon, which, in turn, produces the ψ. The ψ then decays to hadrons.

At Brookhaven, a Be target was bombarded by high energy protons and the yield of electron pairs was studied. At about 3.1 GeV an enhancement of this yield occurs.

By measuring ΔE, the width of the production peak, the lifetime of the ψ can be found:

$$\Delta t \approx \hbar \Delta E$$

and for the ψ, $\Delta t \approx 10^{-20}$ sec. This is a very long lifetime for so massive a particle—massive enough to decay strongly to hadrons, no matter what its quark content, as long as the quarks are u, d, and squarks.

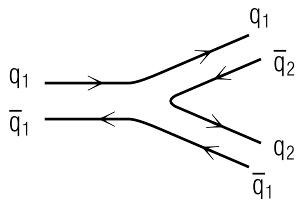
Because of the great mass and long lifetime, physicists suspect a new quantum number is involved. It is currently thought that ψ is composed of the charmed quark c and its antiquark $\bar{\text{c}}$, a combination that is called "charmonium."

Charmonium can decay to *charmed* mesons provided there are charmed mesons with mass less than half that of charmonium itself. For example

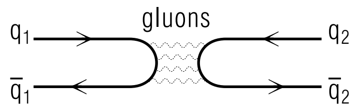
$$c\bar{c} \rightarrow c\bar{d} + \bar{c}d$$

might be a possible strong decay provided the total mass of the products is less than that of $c\bar{c}$. If ψ is $c\bar{c}$, then the absence of this decay is explained by the lack of sufficiently light charmed mesons.

The decay $c\bar{c} \rightarrow$ uncharmed hadrons does occur but the decay time is longer that the usual strong decay and shorter (by a factor of about 20) than the usual electromagnetic decay. The process is believed to be strong, nevertheless. The long decay time is consistent with a rule which is believed to be generally true and is called Zweig's rule. Zweig's rule states that diagrams for which the initial quarks mutually annihilate via the strong interaction are suppressed (i.e., are associated with rates that are less than the usual strong rates). The rule seems to hold for all quarks, not just charmed quarks. This rule is an expression of the observation that a quark-antiquark pair decays at a faster rate according to



than according to



Decays for which the initial quarks retain their identity but get distributed among the decay products are more probable than decays for which the initial quarks mutually annihilate.

Other examples, beside charmonium, are the decay of the π^0 and η mesons.

Charmonium is long lived because the only strong channel available for its decay is the one of mutual annihilation. The creation of second quark-antiquark pair and the subsequent switching of partners requires more energy than is available in the mass of charmonium.

The $c\bar{c}$ system has been studied theoretically. The two quarks can be in any one of a variety of states, just as the electron and proton of the hydrogen atom can be in any one of a variety of states. For $c\bar{c}$, the different states manifest themselves as different particles with different masses. Evidently ψ is the lowest energy state of this system and, according to theory, is a state of zero orbital angular momentum. The spins of the quarks are aligned and produce the spin 1 of the ψ.

Since the discovery of ψ, other particles which are believed to be other states of the $c\bar{c}$ system have been found: ψ' at 3.7GeV, ψ'' at 4.1GeV, ψ''' at 4.4GeV, and P_c at 3.5GeV. The first three are believed to be states with 0 orbital angular momentum and total angular momentum 1, while the last is a state with orbital angular momentum 1 and total angular momentum 0 (both spins are antiparallel to the orbital angular momentum). All of these were created by means of colliding electron-positron beams. Up to now, none have been created by the Brookhaven technique.

The ψ' makes the transition to P_c by emitting a 200 MeV photon and P_c can decay to ψ by emitting a 400 MeV photon. It was, in fact, the detection of these photons which first led to the discovery of P_c.

The ψ'' and ψ''' reveal themselves as very broad peaks in the plot of hadron production vs. center of mass energy. They have short lifetimes and presumably decay via the strong interaction. It is in their decay products that one might expect to find charmed hadrons.

It is the existence of all these particles with masses that closely match the theoretically predicted masses of the charmonium system that leads physicists to believe ψ and its brethren are really $c\overline{c}$ and thus that a fourth quark exists.

A very nice review of the properties of ψ and the related particles is given by C. Wu in "The State of US Physics-1976," *Physics Today*, April, 1976 (see particularly pp. 28-30).

Ms. Wu shows the theoretical energy level diagram for charmonium. Using this diagram, you should pick out the particles that have been seen experimentally and those that have not.

Here are some short articles which were published as data became available:

a. "Two New Particles Found: Physicists Baffled and Delighted," *Science*, December 6, 1974, p. 909.

b. "New Particles Excite Experimenters and Puzzle Theorists," *Physics Today*, January 1975, p. 17.

c. "More Data on the New Particles: Theory Uncertain," *Physics Today*, March 1975, p. 443.

d. "The New Particle Mystery: Solid Clues Now Lead to Charm," *Science*, August 8, 1975, p. 443.

e. "Sequel To the Psi: DESY, SLAC See Intermediate States," *Physics Today*, September 1975, p. 17.

It is worthwhile to read these articles in the order listed above since they are in the nature of news stories.

A more detailed account of the $e^- + e^+$ experiments is given by S. D. Drell in his article "Electron-Positron Annihilation and the New Particles," *Scientific American*, June 1975.

If ψ'' is indeed a state of charmonium which decays strongly to two charmed mesons, the lightest of these decay products should have a mass between 1.55 GeV and 2.05 GeV. The lower limit is greater than half the ψ mass and has been selected because ψ does not decay strongly to charmed hadrons. The upper limit is chosen to be less than half the ψ' mass. For this value of mass the decay of ψ'' can occur strongly without violating conservation of energy.

In early l976, a new particle was discovered at SLAC using the colliding electron-positron beams. Its mass is 1.865 GeV and it decays to a charged kaon and either a single charged pion or three charged pions. The width ΔE of the production peak is small enough, and hence the lifetime is long enough, to conclude that the decay is not strong. It is likely that this new particle is a charmed hadron.

A broad peak in the production curve was also found in the region from 2.0 to 2.2 GeV. If the 1.865 GeV particle is indeed a charmed hadron, the second peak could represent its partner. One of them carries the c quark and one carries the $\overline{c}$ quark.

Note also that 1.865 GeV is slightly larger than half the mass of ψ'. Conservation of energy may also prevent the strong decay of ψ' to two charmed hadrons.

These attempts to produce a charmed hadron revolve around the strong decay of a state of charmonium, in which quarks already exist.

These experiments are discussed in more detail in:

a. "Another New Particle: Charmed Quarks Look Better Than Ever," *Science*, June 18, 1976, p. 1219.

b. "Colliding-beam Data Offer Evidence for Charmed Particle," *Physics Today*, August 1976, p.17.

5b. Neutrino-Nucleon Interactions. Charmed particles, if they exist, should also be produced by the interaction of neutrinos with hadrons. Since the weak interaction can change the nature of the quarks in the hadrons (u to d, etc.), this process is capable of producing a single charmed hadron.

Experiments along these lines were performed at Fermilab, where neutrino-nucleon interactions which produce two muons were studied. These events are called dimuon events. In late 1975, dimuon events were observed. As discussed previously, these events can be the signal for either a new heavy lepton, the W particle, or a new hadron. Momentum data indicate either a W or a hadron (i.e., a decay to 2 leptons rather than 3) but the mass of the particle is less than that expected for a W. The experimenters conclude that they probably produced a new hadron, perhaps charmed.

A short note appears in *Physics Today*, March 1975, p. 24 and a news article appears in *Physics Today*, January 1976, p. 17, "Dimuons at Fermilab Suggest New Form of Hadronic Matter."

You should note that the above articles indicate the possibility of some ambiguity in classifying the new particle as a hadron. Details of the interaction may also force some relationship on the kinematics of the decay products and if the constraints are of the right kind, the data could be interpreted as indicating a decay to three particles and one must conclude the new particle is a lepton. Current belief, however, is that the particle is a new hadron.

More background information and more details of the Fermilab experiment appear in:

"The Search for New Families of Elementary Particles," by D.B. Cline, A.K. Mann, and C. Rubbia in *Scientific American*, January, 1976.

6. Ongoing Work

6a. Properties of the Weak Interaction. Much of the activity discussed so far has to do with new hadrons which display a property which is conserved by the strong interaction but is not conserved by the weak interaction. Meanwhile, work is proceeding to understand the weak interaction, apart from the production of hadrons. Some of the important questions are listed by D. B. Cline, A. K. Mann, and C. Rubbia in their article "Probing the Weak Force With Neutrinos" in *Physics Today*, March, 1975.

Some of the questions have to do with the way in which the weak interaction enters the quantum field description of particle interactions. Discussion of these questions and of some of the terms used (such as vector current, axial vector current, etc.) are beyond the level of this lesson. However, you should be aware of the other questions:

a. Is the weak interaction point-like? If it is, this is consistent with a W particle of infinite mass.

b. Is there a *universal* weak interaction? The fact that certain kaon decays are different from weak decays of non-strange hadrons has led many physicists to believe that there might be more than one type of weak interaction. The difference can be explained in terms of charm and so our belief in the universality of the weak interaction is coupled to the existence of the charmed quark. But is it the same charmed quark that keeps the ψ from decaying strongly?

Universality can be tested in other ways, as indicated by some of the other questions listed in the article.

c. Are there massive vector bosons (W particles)? The limit on the mass goes up year by year as experiments at higher energies fail to uncover them. The search goes on.

d. Are there heavier leptons? We have discussed one experiment in which such leptons might have been seen.

6b. Search for a Theoretical Framework. High energy work continues and you should be on the look out for reports of new discoveries. *The New York Times*, *Science*, and *Physics Today* are excellent sources of information.

The work is not wholly experimental. Many physicists feel that physics is on the verge of a grand synthesis in which many of the phenomena of high energy physics can be understood in terms of a comprehensive theory. The search is on to find relationships between the various types of interactions and to understand how the interactions produce what appears to be regular, systematic relationships among the particles: the families and the supermultiplets.

The quark model has gone a long way toward uncovering the systematic relationships among the hadrons, but it is not the ultimate answer to the questions of high energy physics.

The quark model can be likened to the periodic table of the chemical elements, which displays the systematic relationships among the atoms.

Deep understanding of atomic phenomena came only after the invention of quantum mechanics, which deals with the dynamical interaction of electrons and nuclei. In high energy physics, deeper answers must be sought in the dynamical relationships of the fields.

We end by referring you to an article which makes a strong argument along these lines. Read the article by Werner Heisenberg, “The Nature of Elementary Particles,” *Physics Today*, March, 1976.