Fermi National Accelerator Laboratory

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Lectures on Charmed Particles

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DEDICATION

Ben Lee was my colleague for seven years at Stony Brook and Fermilab. It was he who introduced me, in the Fall of 1974, to charm, the subject on which we and our colleagues were to spend much of the next three years. With affection and respect, I dedicate these lectures to his memory.

FOREWORD

These five lectures on charmed particles and the upsilons were prepared for the XIth International School for Young Scientists on High Energy Physics and Relativistic Nuclear Physics, held in Gomel, Byelorussia, in September, 1977. The audience was composed largely of experimentalists at the postdoctoral level, so the lectures concentrate on concepts and results rather than theoretical techniques. Some elementary calculations are done in detail, but the complexities of the subject are dealt with only in words. The lectures were repeated in the Fall of 1977 at the Enrico Fermi Institute of the University of Chicago, and in the Spring of 1978 at Fermilab. I am grateful to all three audiences for their questions and comments.

A transcript of the lectures was prepared from transparencies and tape recordings of the Gomel lectures by Igor Satsunkevich of the Institute of Physics in Minsk. I am deeply grateful to Dr. Satsunkevich for his care and thoroughness. In preparing the final text I have added a small number of references and updated some experimental information. The conversational tone of the transcripts has been retained. This is therefore a teaching document and not a comprehensive review article.

I thank the hosts of the Gomel School from the Byelorussian Academy of Sciences for their warm hospitality and generous assistance. Dr. N. Skachkov, the Rector of the School, and his colleagues from the Joint Institute for Nuclear Research at Dubna are to be congratulated for the pleasant atmosphere of a well-run school. Finally, I thank M.B. Einhorn and J.L. Rosner for extensive discussions on the topics discussed in these notes, and Trudi Legler for typing the final transcript.

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LECTURE 1. INTRODUCTION TO CHARM

While I make some introductory remarks I put up for you to look at a number of elementary references to the subject of charm. As we go along, I will cite more specific references to the literature, which may be helpful for the detailed points to be considered. I have chosen this list partly because the treatments given are very introductory and elementary, and partly also because these are published works and reports from large laboratories which should be easy to find.

Table I. Some elementary references

"Search for Charm," M.K. Gaillard, B.W. Lee and J.L. Rosner, Rev. Mod. Phys. 47, 277 (1975).

"Introduction to SU(4) and the Physics of Charmed Hadrons," M.B. Einhorn, Fermilab-Lecture-75/1-THY/EXP.

"Beyond Charm," H. Harari, in Weak and Electromagnetic Interactions at High Energy, edited by R. Balian and C.H. Llewellyn-Smith (North-Holland, Amsterdam, 1977).

"Elementary Charmonium Theory," L.B. Okun and M.B. Voloshin, ITEP-152 (1976).

"Hadron Production in e^+e^- Annihilation," V. Lüth, Lectures at the Baku School, SLAC-PUB-1873.

"Lectures on the New Particles," J.D. Jackson, in Proceedings of the 1976 SLAC Summer Institute on Particle Physics, edited by Martha C. Zipf, p. 147.

The new quantum number, charm, has caused a great deal of excitement for the past three years. In the course of these lectures I want to deal in great detail with some manifestations of charm and with some characteristics of the charmed particles.

However, first I would like to begin in a much more general manner and try to acquaint you with the reasons why charm is exciting without going into detail about its properties. There are a large number of important discoveries that have been made in our field, for which we have no ready explanation or for which we were not prepared when they came. People discovered CP-violation experimentally unexpectedly 15 years ago. Up to now this is a great puzzle because we do not really know how to explain it. On the contrary in the case of charm we were prepared for the experimental discovery and it came together with a large number of other experimental and theoretical developments which make us very happy and excited.

So at the beginning I shall deal mostly with the general situation and try to describe to you how people feel about high energy physics these days. My intention is to give some background and context for the discussion of charm that we will have in succeeding lectures. The other reason is that physics is done by people. So how we feel is very important; it is important how we think about these problems or why we think about them. The main material today will be quite introductory and general but at the end of the lectures I promise to talk about things that I do not understand; and so we shall get lost together along the way and perhaps make some discoveries.

1. CULTURAL ORIENTATION: POINTS OF VIEW

Let us begin our cultural discussion of points of view which many people hold about physics or ways of doing physics. Many theoretical physicists feel that we are very close to unifying, perhaps in a useful operational way, all interactions that we know now: strong, weak, electromagnetic and gravitational interactions. Perhaps I am more conservative than many of my colleagues, but I will try to describe to you what we believe in now, and to give you some reasons that support these beliefs.

The first reason that many theorists have confidence that a great unification of theory is near is the successful quark model in which the quark is a more or less fundamental particle. The main successes of the quark model come from the spectrum of observed hadrons and from a number of fruitful descriptions of the interactions that we wish to study. One of these is the quark-parton picture as an explanation for deep inelastic scattering of leptons on nucleons. Second, as we shall see in some detail later, are the properties of e^+e^- annihilation into hadrons. The following features are observed here: the large size of the inclusive cross sections, and the manifestation of jet structure in the angular distribution of hadrons. There is another kind of evidence for pointlike constituents. It is clear, at least it appears clear to a number of people, that scattering of hadrons, which results in the production of particles with large transverse momentum, is also well understood in terms of the collisions of billiard-ball-like objects and their subsequent decay.

The second current of thought has to do with gauge theories of weak and electromagnetic interactions. As you know, for many years it has been a goal to unify the theories of weak and electromagnetic interactions. For even a longer time it has been a goal of particle physics to have a description of weak interactions which is not simply a phenomenological one, though the Fermi description of weak interactions was successfully used for β-decay. But a real theory with which we could calculate in higher orders must be unitary, to conserve probability, and renormalizable, i.e. be calculable in the sense that electrodynamics is calculable. The gauge theories of the weak and electromagnetic interactions have a number of positive attributes. One is the appeal of finding theories which unify two or more interactions in a way that seems beautiful. Secondly these theories have been demonstrated to be unitary and renormalizable. Hence they may be taken seriously as candidates for ~~a~~ class of theories that may be true. The price of the achievement of unitarity and renormalizability of these theories is the necessity to invent new sorts of particles or interactions. You will see as we shall go through the development of the picture of elementary particles and weak and electromagnetic interactions how often theorists are forced to invent new particles for wanted or needed effects. And the great luck in recent years is that a number of these hypothetical particles and interactions have turned out to be real. In the case of the unified theory of the weak and electromagnetic interactions these particles are the intermediate bosons $W^{\pm}$ and Z^0, which carry the charged and neutral weak currents, and the so called Higgs-bosons. The latter have very little connection with the usual experiments in particle physics and absorb the final unpleasant divergence difficulties of these theories. I shall not be able to discuss the detailed properties of the Higgs bosons in these lectures.*

Unified theories of weak and electromagnetic interactions result in the prediction that in addition to the familiar charged current interactions that we know from radioactive decay there should be neutral current interactions in which the charge of the participants does not change. The observation of this effect in 1973 was of course psychologically a great encouragement for these theories.

In the case of the charged current we have interactions which preserve strangeness with large strength, with cosine of the Cabibbo angle. Here we also have strangeness-changing interactions, which come with the modest strength given by the sine of the Cabibbo angle. In the case of the neutral currents the suppression of the strangeness-changing neutral currents appears to be complete. There is a beauty to exact forbiddenness in nature and I shall speak about other details again in a few minutes.

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*For a summary of Higgs boson phenomenology, see M.K. Gaillard, CERN preprint No. TH2461, to appear in Comments on Nuclear and Particle Physics.

The final current of thought that gives rise to some problems which we must work out is the nonobservation of quarks. Free quarks, it seems, are not observed, and this stops our argument. But it is a usual practice to turn embarrassments into positive features. We invent a new concept, which is permanent confinement of quarks. According to this picture quarks can never get out of hadrons and that is why one cannot see them. It is a conjecture, not yet proved. Another gauge theory, a gauge theory for the strong interactions which involves as fundamental fields quarks and gluons, gluons holding quarks together as mediators of the strong interaction, is in many ways a parallel to the rather successful theory of weak and electromagnetic interactions. There is a belief that a theory of this kind can result in the permanent confinement of quarks. But that has not yet been demonstrated. Indications have been given but not a proof.

There is another property of these theories which has been established theoretically. It means that the quarks interact weakly at small distances. The usual interactions between them become very weak. This is the concept known as asymptotic freedom* and it provides an explanation of the nearly free behavior of light quarks inside a nucleon, which we believe is the case from the parton description of deep-inelastic scattering. The second success of this idea, at least a qualitative success, with which I shall deal briefly in the last lecture, is that the spectrum of the family to which the ψ-particles belong can be explained in terms of nonrelativistic quantum mechanics.

This is the first look at the general picture in which we shall work. Now I want to give some details about the experimental facts known to us because we will try to use them.

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*See H.D. Politzer, Phys. Rep. 14, 129 (1974).

2. LEPTONS

Let's begin our review with the properties of normal leptons, the known leptons which are in Rosenfeld's table. There are the following: the muon (μ^-), the electron (e^-) and a neutrino for each of them (ν_μ, ν_e). It has been demonstrated in many ways that they have spin ½ and behave as point-like particles in the weak and electromagnetic interactions. This has been shown down to very short distances. In the normal weak interactions, as we know them in μ-decay for example, only the left-handed helicity states participate. For the purpose of these lectures I assume the ν_e and ν_μ are exactly massless but distinct objects. Professor Mann in his lectures will perhaps say something about the peculiar possibility that the neutrinos may have a small mass and may oscillate over very large distances from one species to another. For our purposes we need not consider this possibility and I simply write here the present experimental limits of the neutrino masses. The first limit is a very good limit from the end points of β-decay spectra: for the ν_e($m_{\nu_e} < 6 \times 10^{-5}$ MeV); for the ν_μ($m_{\nu_\mu} < 0.65$ MeV).

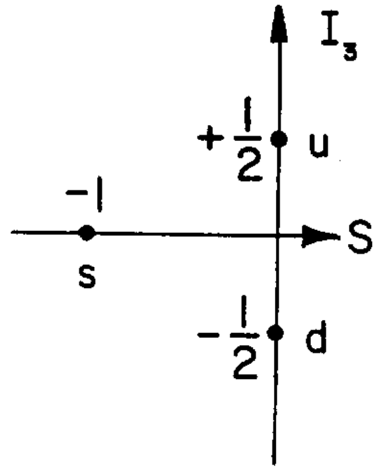
In the usual picture of the weak interactions (including gauge theories) we describe the weak interactions of these particles by two doublets $(\nu_e, e)_L$, $(\nu_\mu, \mu)_L$, where ν_e couples to e in a left-handed way. The same for the muon doublet. The subscript L means that the coupling between these particles has a V-A form. The space-time structure of these charged currents is extremely well established in experiments extending over 30 years up to 1960.

For the more recently discovered weak neutral currents the space-time structure is not yet clear. Professor Mann will tell you about the latest results in neutrino scattering, which begin to show some of the attributes of the weak neutral currents. But this is a situation which is much less definite than for the charged currents.

Experiments rule out the possibility of right-handed charged currents among the 4 known leptons. These would simply violate the decay correlations that we see for example in μ-decay and in other observables for the ordinary weak interactions. However if there were new leptons in addition to the 4 we listed here it is not excluded that there could be new couplings with the old leptons. The new leptons could be left-handed of the ordinary sort or right-handed. There is no principle to govern them. There may be left-handed couplings of old leptons to new ones, but each of the old leptons is already coupled in a left-handed way to something, exhausting the usual intermediate bosons. So we would have to invent several new intermediate bosons, mediators of new couplings. In the absence of principles to forbid them we would have to consider that possibility.

3. WHY WE BELIEVE IN QUARKS

Now there is considerable evidence for believing in quarks as useful objects. Quarks were first considered as a simple explanation for the spectroscopy of elementary particles. We know from analyses over the past 15 years that all the "ordinary" mesons not involving charm belong to SU(3) families which are singlets or octets (1 or 8). All the "ordinary" baryons, baryons that have no charm, are members of singlets or octets or 10-dimensional representations of SU(3). This is a remarkable rule of nature which is more restrictive than the requirement of nature to be SU(3)-symmetric. All this we can summarize in the hypothesis that there is a fundamental triplet of quarks, up (u), down (d) and strange (s) quarks (some people use the notation p, n and λ-quarks). So there are 3 quark flavors or fundamental objects, which are responsible for building up the observed multiplets of mesons and baryons. I display the weight diagram for this fundamental representation of SU(3). The u and d quarks form an isospin doublet. The u has isospin up and the d has isospin down. They are nonstrange. The s-quark is isoscalar and has a unit of strangeness.



With quarks we can build all the known mesons and baryons in a simple way. The known mesons lie in representations we reach as combinations of a quark with an antiquark ($q\bar{q}$). In the algebra of SU(3), that is the product

$$\underset{\sim}{3} \otimes \underset{\sim}{3}^{*} = \underset{\sim}{1} \oplus \underset{\sim}{8} \quad .$$

Baryons must be made of 3 quarks. In SU(3) language this is the direct product

$$\underset{\sim}{3} \otimes \underset{\sim}{3} \otimes \underset{\sim}{3} = \underset{\sim}{1} \oplus \underset{\sim}{8} \oplus \underset{\sim}{8} \oplus \underset{\sim}{10} \quad .$$

These representations exhaust all representations, which we see prominently in nature.

One may ask why it is not possible to have additional quarks inside of mesons and baryons. We do not know why. It is an empirical rule. "Exotic" particles, which would be required to have 2 quarks and 2 antiquarks in a meson or more than 3 quarks in a baryon, have not been convincingly observed. But recently some people have attempted to build theories which would explain why one quark and one antiquark might be bound strongly or why 3 quarks might be bound strongly to make a baryon. They find many models having weakly-bound, or merely heavier, larger systems. There is now considerable interest in looking for configurations more complicated such as $qq\overline{qq}$ or 6q combination for mesons and baryons (see Professor Matveev's lectures).*

*See R. Jaffe and K. Johnson, Comments Nucl. Part. Phys. 7, 107 (1977).

a) baryon number

What more do we know about quarks? We know that they have baryon number 1/3 because 3 quarks make a baryon. Consequently an antiquark has the baryon number -1/3.

b) electric charge

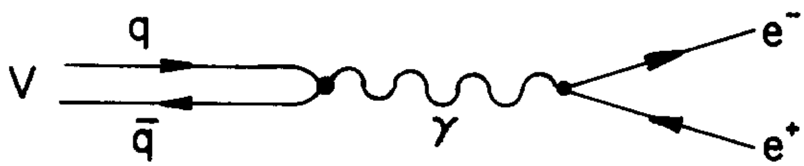
The Gell-Mann-Nishijima connection between the charge, isospin, and hypercharge operators gives us the charges of quarks

$$Q = I_3 + \tfrac{1}{2}Y = I_3 + \tfrac{1}{2}(B + S) \longrightarrow \begin{cases} 2/3 & u \\ -1/3 & d \\ -1/3 & s \end{cases} .$$

We have in addition some evidence that these charges are correct ones.

(i) The first piece of evidence is the most obvious one. We simply have baryons with charges 2, 1, 0, -1, which are made of 3 quarks.

(ii) There is also evidence from the decay of vector mesons into pairs of leptons $V^0 \to e^+e^-$. If we picture a vector meson as a bound state of quark and antiquark then there is some probability for these objects to meet and to make a single photon. The virtual photon then converts into a pair of e^+e^-



On the basis of this picture the reduced width $\tilde{\Gamma}(V^0 \to e^+e^-)$ for the vector meson decay into e^+e^--pair would be proportional to e_q^2, e_q being the charge of the quark. It is the charge that governs the strength of coupling of quarks with a photon. Then the reduced width would be also proportional to the probability for 2 quarks to meet and annihilate. So we have

$$\tilde{\Gamma}(V^0 \to e^+e^-) \propto e_q^{\,2}\,|\psi(0)|^2$$

The last factor in a nonrelativistic picture is the square of the wave function at the origin or at zero separation of the quarks.

For the moment I am going to assume that $|\psi(0)|^2$ should be approximately the same for all mesons we are talking about. We shall see at the finish that this seems to be a good approximation. If I make these assumptions I can write the structure of the familiar vector mesons in terms of their quarks. I immediately calculate the mean square charge of quarks inside particles

$$\rho^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}) \to e_q^{\,2} = \left[\frac{1}{\sqrt{2}}\left(\frac{2}{3} + \frac{1}{3}\right)\right]^2 = 1/2$$

$$\omega^0 = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}) \to e_q^{\,2} = \left[\frac{1}{\sqrt{2}}\left(\frac{2}{3} - \frac{1}{3}\right)\right]^2 = 1/18$$

$$\phi^0 = s\bar{s} \to e_q^{\,2} = 1/9 \quad .$$

So we expect in this way the relative reduced widths of the vector meson decays into lepton pair should be

$$\tilde{\Gamma}(\rho) : \tilde{\Gamma}(\omega) : \tilde{\Gamma}(\phi) : 9 : 1 : 2 \quad .$$

Experimental data for this in units of the ω partial width are $(8.3 \pm 2.9):1:(3.0 \pm 0.8)$. As you can see there is no indication for big variations of the wave function.

(iii) There is another potential way of measuring the quark charges. This can be done with very preliminary data obtained so far. Let's consider a Drell-Yan process in which a quark and an antiquark within hadrons annihilate into a virtual photon which itself converts into a lepton pair. In particular the Drell-Yan process on an isoscalar target such as carbon is of interest:

$$\pi^{\pm} C \rightarrow \mu^+\mu^- X$$

We are working in the approximation where the incident π-mesons can be described as only containing valence quarks, u and $\bar{d}$ quarks for π^+ and $\bar{u}$ and d quarks for π^-. Then there is only one fundamental process which takes place and leads to the production of lepton pairs. For π^+ it brings an antiquark which is a $\bar{d}$ to annihilate with a d-quark in the carbon to form a photon with relative probability 1/9 because 1/9 is the square of the d quark charge. So we have

$$\pi^+ C \backsim d\bar{d} \rightarrow \gamma \rightarrow \mu^+\mu^- \propto 1/9$$

$$\pi^- C \backsim u\bar{u} \rightarrow \gamma \rightarrow \mu^+\mu^- \propto 4/9 \quad .$$

The prediction for the ratio of the cross sections is

$$\pi^- C/\pi^+ C \approx 4 \quad ,$$

which violates the ordinary expectation from isospin symmetry because this is an explicitly electromagnetic interaction. Now preliminary data from the Chicago-Princeton experiment of K.J. Anderson, et al. at Fermilab using 225 GeV/c π^+ and π^- begin to show the ratio approaching 4, which again is a confirmation of the quark charges. For experts who have studied the Han-Nambu model with integer charges I should remark that below the threshold for color production the predictions of this model are identical to those with fractionally charged quarks. All we can say experimentally is that the evidence, which we mentioned, is evidence for the average charge of the quarks of a given flavor.

(iv) Finally there is evidence on quark charges from deep-inelastic electron scattering analyzed in the quark-parton model. The simple counting of quark charges tells you the ratio of the structure functions of electron-deuteron scattering to the sum of the structure functions for neutrino and antineutrino scattering on deuterons. I think that this prediction will be discussed in some detail in the other lecture courses, so we quote only the results in the valence quark approximation:

$$\frac{F_2(ed)}{F_2(\nu d) + F_2(\bar{\nu} d)} \simeq \frac{1}{2}(e_u{}^2 + e_d{}^2) = \frac{5}{18} \quad .$$

The experimental value is very close to this number.

c) spin

Finally we come to some evidence that quarks have spin ½.

(i) This comes on the one hand from the multiplet structure of mesons and baryons, in fact from the lowest-lying mesons and baryons which we describe as s-wave configurations of quarks. These particles have precisely the values of spin and parity which could occur in the binding of objects with spin ½ and even parity. Furthermore there are some combinations of spin and parity which cannot be obtained with any value of orbital angular momentum from quarks with spin ½. Especially in the meson system this restriction is powerful. So we have observed mesons

$$J^{PC} = \underbrace{0^{-+}, 1^{--}}_{L=0} \quad ; \quad \underbrace{0^{++}, 1^{++}, 1^{+-}, 2^{++}}_{L=1} \quad , \text{etc.}$$

Other combinations of J^{PC}, such as 0^{--}, 0^{+-}, 1^{-+}, have not been seen as low-lying particles. For the baryons the arguments are somewhat more complicated. One can summarize them by mentioning the relative success of the SU(6)-classification of particles in which the 56-dimensional representation with zero angular momentum and positive parity is the lowest-lying state. It includes the baryon octet and the baryon decimet.

(ii) Next we can measure with photons the longitudinal photon coupling to quarks and transverse photon coupling to quarks within the framework of the quark parton model. This can be done in the deep-inelastic scattering of electrons and also in studies of the jet-structure of e^+e^- annihilation into hadrons. In both cases the longitudinal coupling has been found to be smaller than the transverse one. If you work out the spinology this is equivalent to the statement that fundamental constituents have spin ½ rather than spin 0. In the case of the jet-structure in e^+e^- annihilation into hadrons the argument is simple. The jet axis has the same angular distribution as the muons in the reaction $e^+e^- \to \mu^+\mu^-$ and consequently one infers the same spin for quarks as for the muon.

d) color

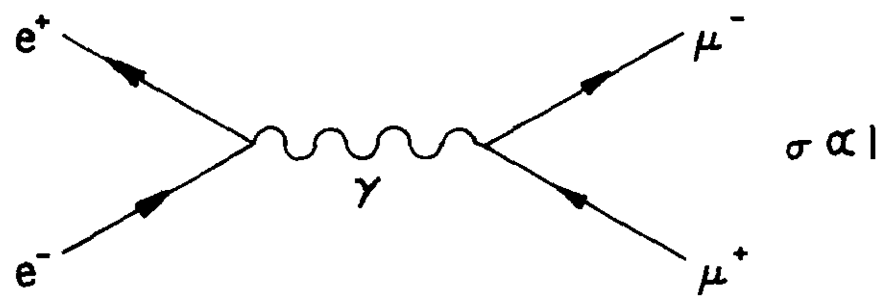
Now we come to the concept of color.* The quark model which we have discussed is indeed very successful but it has a flaw. Its origin is in producing the baryon spectrum as we know it. For example we can talk about Δ^{++}, which in the ordinary quark model is the 3-quark state with $L = 0$, spins aligned and isospins aligned ($S = 3/2$, $I = 3/2$). So it is a fully symmetric state of 3 u-quarks (uuu state). This state is symmetric under space reflection and also symmetric under spin and isospin interchanges. So it is an entirely symmetric state. But we have studied in school that if we had 3 fermions the state had to be antisymmetric not symmetric, the well-known exclusion principle for fermions. Some years ago in order to get around the problem a seemingly wild suggestion was made that there was a hidden

*See O.W. Greenberg and C.A. Nelson, Phys. Rep. 32C, 70 (1977).

degree of freedom possessed by these quarks. The wave function could be antisymmetric in the new degree of freedom and still symmetric in the known degrees of freedom. This may sound like an invention without much basis. But it turns out to be the basis of a good deal of understanding in later years, though it is still not firmly established by direct observation. The new degree of freedom these quarks possess is named color. In order to antisymmetrize the three-quark system there must be at least 3 colors. For some reasons I will give in a moment it seems like 3 is the right color. So we do not need 4, 5, 6 colors. Furthermore we require that all hadrons are neutral in color.

What is this proliferation of species of quarks--3 flavors, several colors? How is it observable? What consequences are there?

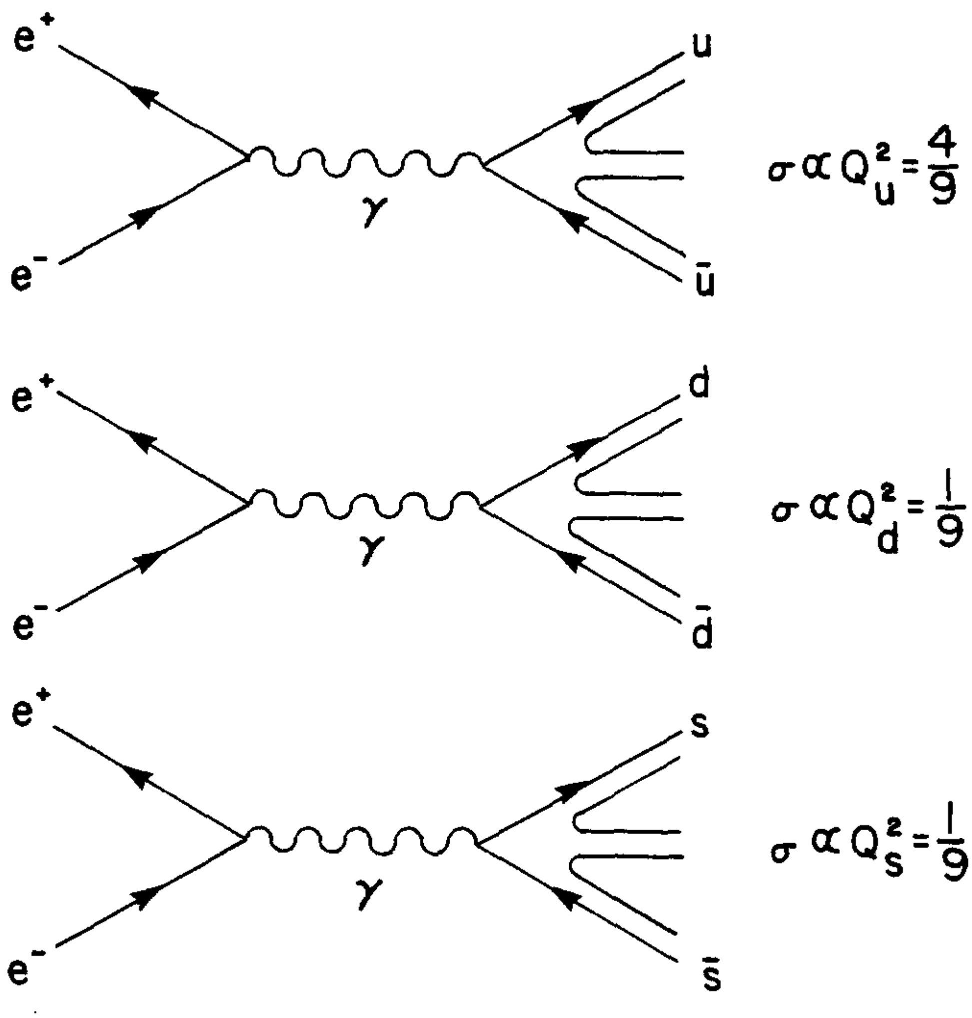
We consider the production of hadrons in e^+e^--annihilations. It is convenient to refer the cross section we observe to something that is understood. The production of $\mu^+\mu^-$ in e^+e^--annihilations is a process which is the production of pointlike constituents. So we can calculate it on the basis of quantum electrodynamics



Neglecting all kinematical factors this cross section is proportional to the charge squared of the muon, which is 1

$$\sigma \propto Q_\mu^{\,2} = 1 \quad .$$

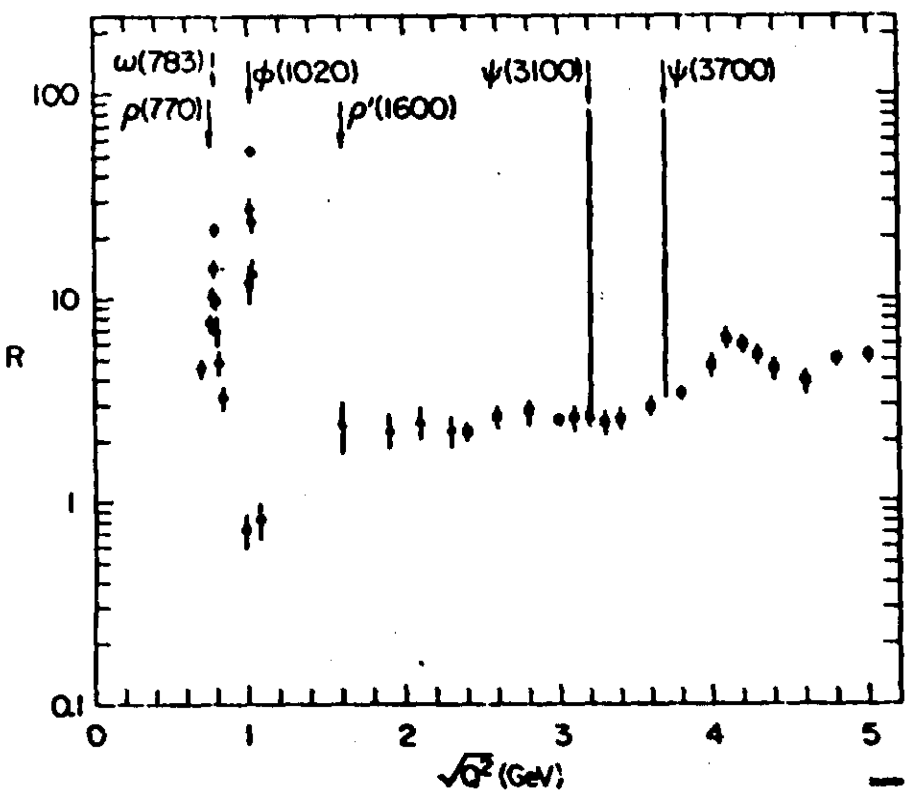
Let us use the quark-parton model for hadron production, which is to say that e^+ and e^- annihilate into a virtual photon and the virtual photon decays into a quark-antiquark pair (u, d or s quarks). No one has seen any quarks, so this pair in some way transforms itself with probability 1 into the hadrons which we observe. The basis of this theoretical description is the hope that one can calculate the cross section of $e^+e^- \to$ hadrons by calculating the cross section for the production of free quarks and assuring himself they will turn into hadrons and there will not be production of free quarks. So I find for the production of quarks (and the hadrons which evolve from them) the cross section is proportional to



I sum over these processes because they exhaust all quarks and have a cross section, which in units of the μ-pair cross section is 2/3. But finally there are 3 colors of quarks in addition to 3 flavors. In fact I have 3 diagrams for each one above (for red and green and yellow quarks). So I have to multiply my cross section by 3. Then the prediction of the model in the region of usual physics is

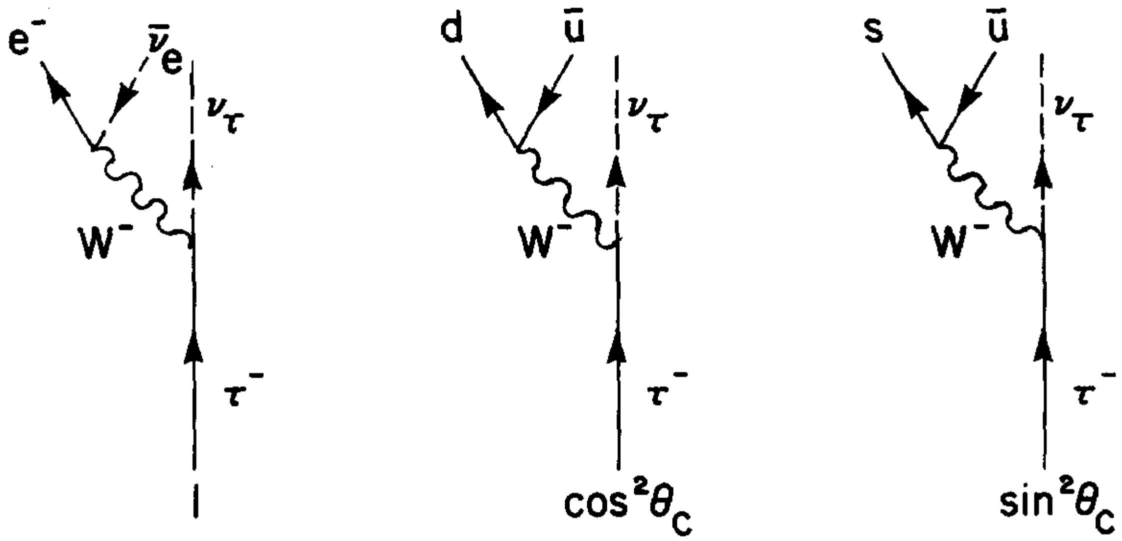
$$\sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-) = 2 \quad .$$

I show you here an old sample of data



R here is the ratio of cross sections for hadron production to μ-pair production. There are oscillations of the vector mesons being produced (ω, ρ, φ) and there is a region from 1.5 to 4 GeV, where this ratio is nearly constant and equal to 2 which is the predicted value of the SU(3) color theory. In fact the value is close to 2.5. The prediction without color would be 2/3 and is severely in disagreement with the data. This is one experimental evidence for color.

Another piece of evidence involves a new particle which is not completely established but Prof. Wolf will convince you that it is real. This is the new heavy lepton $\tau^{\pm}$, which carries charge +1 or -1. I attempt to discuss its leptonic decay $\tau \rightarrow e\nu\bar{\nu}$ and to compare it with the semileptonic decay into a neutrino and ordinary hadrons. The τ-lepton turns into its own neutrino and a virtual W-boson which subsequently can decay into lepton and neutrino or into a pair of quarks ($\bar{u}$ and d or $\bar{u}$ and s)



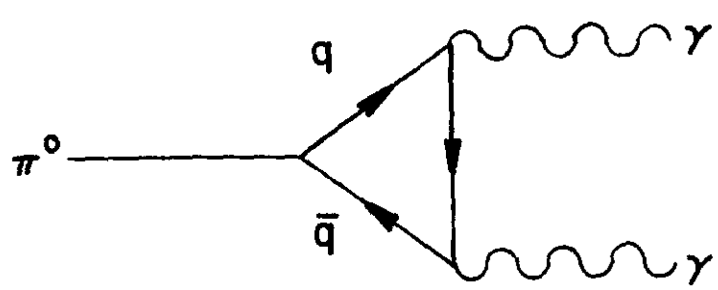
The first diagram for leptons occurs with probability 1. There is 1μ and 1e, one diagram of each kind. The second diagram with $\bar{u}$ and d has the W-boson coupling to $\bar{u}$ and d, which occurs with probability $\cos^2\theta_C$, θ_C is the Cabibbo angle. The third diagram gives a contribution proportional to $\sin^2\theta_C$. The sum of the last two diagrams is 1. But they are multiplied by the number of colors (3) to get the total hadronic rate. Consequently the branching ratio for the decay of this object into μ and 2 neutrinos compared with its decay into anything will be the rate to decay into a μ, which is 1, divided by everything which can happen. Everything that can happen is 1 for the muon, 1 for the electron and the number of colors for hadrons. We believe the number of colors is equal to 3. So the prediction is

$$\Gamma(\tau^- \to \mu^- \nu_\mu \nu_\tau)/\Gamma(\tau \to \text{all}) = 1/(2 + N_C) = 20\% \quad .$$

This number is in extremely good agreement with experiment. The latest numbers from SLAC are (18.6 ± 1.0 ± 2.8)%, where the first error is the statistical one, the second is the systematic one. I think Prof. Wolf will give fuller information from SLAC and from DESY in his lectures.

Lastly there is another argument one can make in order to predict the rate for the decay $\pi^0 \to 2\gamma$. A loop of quark and antiquark also counts the number of colors because it depends again upon the number of diagrams. We have again the result that 3 colors are needed in order to get the correct rate for this process and to understand the lifetime for the π^0-meson.

So we have a number of places in which we need, if you like, the same adjustment, the same factor of 3 in order to agree with experiments.



4.GAUGE THEORIES OF THE WEAK AND ELECTROMAGNETIC INTERACTIONS

Now I want to review very quickly the gauge theories of weak and electromagnetic interactions because we will be using them and this again is a favorite and famous stage for the discussion of charm.

The prototype for these theories was the Weinberg-Salam model of leptons. So I prefer to use it rather than speak in general terms because this is something that people may be familiar with and its properties do reflect the general properties.

As I said at the beginning we group all normal leptons into 2 leptonic doublets

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad .$$

We can write for them (without the coupling constant) the electromagnetic current J_μ^{em} which is

$$J_\mu^{em} = -\bar{e}\gamma_\mu e - \bar{\mu}\gamma_\mu \mu$$

with the name of the particle standing in place of the Dirac spinors. I also write the structure of the charged current (charge raising or lowering current) as the sum over these 2 leptonic doublets in the following form

$$J_\mu^{(\pm)} = \sum_i \bar{\psi}_i \tau_\pm \gamma_\mu (1 + \gamma_5)\psi_i$$

where $\bar{\psi}_i$ is the Dirac conjugate of ψ_i, $\tau_\pm$ are isospin raising and lowering operators, and $\gamma_\mu(1 + \gamma_5)$ means V-A space-time structure of the current. For the ordinary leptons $J^{(+)}$ has the schematic form

$$J_\mu^{(+)} = \bar{\nu}_e\gamma_\mu(1+\gamma_5)e + \bar{\nu}_\mu\gamma_\mu(1+\gamma_5)\mu \quad .$$

But in these models there is a contribution to the weak neutral current from a commutator of raising and lowering operators. This is because of an isospin-like symmetry among the contributions to the charged and neutral currents. I can write it in terms of an isospin projection operator

$$J_\mu^{(0)} = \tfrac{1}{2} \sum_i \bar{\psi}_i\tau_3\gamma_\mu(1+\gamma_5)\psi_i$$

from $[J^+, J^-]$. There is a second piece, which comes from the symmetry breaking of this model and which resembles the electromagnetic current. It is proportional to a mixing angle, the weak angle or Weinberg angle, in this way

$$J_\mu^{(0,W)} = -2\sin^2\theta_W J_\mu^{em} \quad .$$

In final form

$$J_\mu^{(0)} = \tfrac{1}{2} \sum_i \bar{\psi}_i\tau_3\gamma_\mu(1+\gamma_5)\psi_i - 2\sin^2\theta_W J_\mu^{em} =$$

or

$$= \tfrac{1}{2}\bar{\nu}\gamma_\mu(1+\gamma_5)\nu - \tfrac{1}{2}\bar{e}\gamma_\mu(1+\gamma_5)e + 2\sin^2\theta_W\bar{e}\gamma_\mu e + J(\mu)$$

$$= \tfrac{1}{2}\bar{\nu}\gamma_\mu(1+\gamma_5)\nu + L\bar{e}\gamma_\mu(1+\gamma_5)e + R\bar{e}\gamma_\mu(1-\gamma_5)e + J(\mu)$$

with

$$L = \sin^2\theta_W - \tfrac{1}{2} \quad , \quad R = \sin^2\theta_W \quad .$$

As I write out the neutral current I find it takes a form which couples the electron neutrino to itself lefthandedly. There are also both left and right-handed couplings of the electron to itself and similar pieces for the muon. An important thing to be observed is that e and μ remain separate in the neutral current. This is very good and important because we believe that muon and electron lepton numbers are conserved separately. If there were a weak neutral current that changed the e into μ we would have the wrong theory because this disagrees terribly with experiments. So let us repeat the observation that most theories of this kind have neutral currents. Effects of neutral currents were first observed in 1973. Since that time their general properties have nearly been established but the space-time structure is not yet determined (see lectures of Prof. Mann).

What may we say about the hadronic current? All ordinary hadrons are made up of u, d, s quarks. But nature seems not to have used the full spectrum of possibilities because the ordinary weak interactions that we know are specified by the Cabibbo theory. We may summarize this notationally in one lefthanded doublet $\begin{pmatrix} u \\ d_\theta \end{pmatrix}_L$ where the d-quark mixes with the s-quark through the Cabibbo angle

$$d_\theta \equiv d \cos\theta_C + s \sin\theta_C \quad .$$

Therefore the charged current is described by the common form

$$J_\mu^{(+)} = \bar{u}\gamma_\mu(1+\gamma_5)d\cos\theta_C + \bar{u}\gamma_\mu(1+\gamma_5)s\sin\theta_C \quad .$$

Two connected questions one may ask now are:

1) Why the hadron sector has an "extra" unused quark or why the orthogonal combination $s_\theta = s\cos\theta_C - d\sin\theta_C$ is not used in the doublet structure?

2) Why the hadrons and leptons are not more symmetrical? Bjorken and Glashow in 1964 proposed to restore symmetry by adding a new left-handed doublet*

$$\begin{pmatrix} c \\ s_\theta \end{pmatrix}_L \quad .$$

Here c is a new quark called the charmed quark, which has to have $Q = 2/3$, $I = S = 0$ and to be an SU(3) singlet. But let's pause here because in this form the idea seems rather crazy.

Now I want to proceed with the Cabibbo theory. So I calculate the neutral current there

$$J_\mu^{(0)} = \tfrac{1}{2} \sum_i \overline{\psi}_i \tau_3 \gamma_\mu (1 + \gamma_5) \psi_i - 2 \sin^2\theta_W J_\mu^{em} =$$

$$= \tfrac{1}{2} \{ \overline{u} \gamma_\mu (1 + \gamma_5) u - \overline{d} \gamma_\mu (1 + \gamma_5) d \cos^2\theta_C - \overline{s} \gamma_\mu (1 + \gamma_5) s \sin^2\theta_C -$$

$$- \overline{s} \gamma_\mu (1 + \gamma_5) d \sin\theta_C \cos\theta_C - \overline{d} \gamma_\mu (1 + \gamma_5) s \sin\theta_C \cos\theta_C \} - 2 \sin^2\theta_W J_\mu^{em} \quad .$$

It has a number of pieces. There is a piece which connects a u-quark to itself and a d-quark to itself with different strengths. That seems a little bit ugly but is acceptable. There is also a piece which connects an s-quark to a d-quark or vice versa. This is a problem because there are many weak neutral current processes which have been observed, but those involving strangeness-changing neutral currents have not been observed.

Let us look at the evidence. In summarizing the prediction of the weak neutral currents I said that a unified theory is likely to have a neutral current, in

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*Phys. Lett. 11, 255 (1964).

which the leptonic current is proved to be diagonal in the flavors. It does not change the names of the leptons. But the hadronic current of the Cabibbo theory mixes the d and s quarks. We express all this in terms of

$$J_3 \sim [J, J^+]$$

$$J_3^{(\text{leptonic})} \sim \bar{\nu}_\mu \nu_\mu - \bar{e}e - \bar{\mu}\mu + \bar{\nu}_e \nu_e$$

$$J_3^{(\text{hadronic})} \sim \bar{u}u - \bar{d}d \cos^2\theta - \bar{s}s \sin^2\theta - \bar{s}d \sin\theta \cos\theta - \bar{d}s \sin\theta \cos\theta \quad .$$

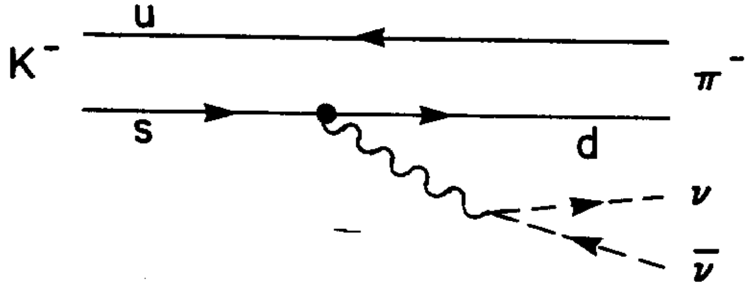
A very quick summary of the experimental situation is that a large number of neutral current effects have been observed in the scattering of ν and $\bar{\nu}$ on nucleons and electrons

$$\nu N \rightarrow \nu + \text{hadrons}$$

$$\bar{\nu} N \rightarrow \bar{\nu} + \text{hadrons}$$

$$\bar{\nu}_\mu + e \rightarrow \bar{\nu}_\mu + e$$

and so on. There is now an industry to study such things. But for another class of neutral current processes very strong limits apply. If one wants to know to which processes these strong limits apply it is necessary to look at strangeness-changing neutral currents such as the decay $K^- \rightarrow \pi^- \nu\bar{\nu}$. In quark language the K^- is made of $\bar{u}$- and s-quarks. This decay would require the s-quark to change into a d-quark by the neutral current while the neutral current decays into ν and $\bar{\nu}$.



That is not seen and therefore Cabibbo theory combined with the weak interaction gauge theories cannot be right. How can we avoid this strangeness-changing neutral current in gauge theories? Glashow, Iliopoulos and Maiani in 1970 noticed* that the same doublet with a charmed quark and a Cabibbo rotated s-quark,

$$\begin{pmatrix} c \\ s_\theta \end{pmatrix}_L$$

which had been proposed some years before by Glashow and Bjorken on the basis of the static SU(4)-symmetry, would solve the problem. Because if you do that, going back to our special neutral current calculated in the Weinberg-Salam model, the weak neutral current takes a diagonal form in which only quarks with the same name couple to each other

$$J_\mu^{(0)} = \tfrac{1}{2}\{\bar{u}\gamma_\mu(1+\gamma_5)u + \bar{c}\gamma_\mu(1+\gamma_5)c -$$

$$-\bar{d}\gamma_\mu(1+\gamma_5)d - \bar{s}\gamma_\mu(1+\gamma_5)s\} - 2\sin^2\theta_W J_\mu^{em} \quad .$$

This is precisely the form of the leptonic current with obvious changes in strength in the contributions that have to do with the charges of various particles (leptons and quarks). It has the same structure as the leptonic current and a very nice symmetry. In a modern language we say that the neutral current is "flavor conserving" or "diagonal in flavors."

Therefore in 1973 when neutral currents were discovered experimentally for the first time, first in the Gargamelle Bubble Chamber at CERN and very shortly

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*Phys. Rev. D2, 1285 (1970).

thereafter in counter experiments at Fermilab, they psychologically encouraged belief in gauge theories and also in charm because we found that the gauge theories gave us neutral currents and had models demanding charm. Somewhat later the discovery of ψ-particles, which were interpreted very quickly as the bound states of charmed quarks gave more impetus to the search for charm.

5. GAUGE THEORIES FOR THE STRONG INTERACTIONS

Let us close today with some remarks on the gauge theory of the strong interactions. These will be much more general remarks because much less is known precisely. There is an ideology that the nonabelian gauge theory of colored quarks and colored gluons (called Quantum Chromodynamics) is the solution of all our problems. According to this ideology a quark-quark interaction is mediated by vector glue, the vector gluons transforming as an octet ($\underset{\sim}{8}$) of SU(3). Then as we know that quarks don't get out of hadrons we simply say that color is permanently confined or all objects in nature must be singlets with respect to color. That then implies that the quarks which carry color cannot get out. So quarks cannot escape and free quarks cannot be seen. In most theories color is what distinguishes quarks from leptons. We can regard color as the "strong charge," which is probed by these vector objects called gluons. This theory has a property called "asymptotic freedom." This is proved or well established for the theories, but it is not proved or well established as something which occurs experimentally in the world. This property tells us that at short distances the interaction becomes weak and it is nearly true that the quarks may be regarded as free particles close together inside a hadron. This is a "justification" of the parton model.

The other side of this property is known as "infrared slavery." It is known that the effective coupling constant between quarks increases as the distance increases. In any normal picture of quark confinement such as quarks bound by strings (which like elastic bands exert a constant force per unit of separation) there is a belief that this increase of the coupling constant at large distances is the mechanism which would confine quarks. But this has not been demonstrated theoretically. Many people are working on this very exciting prospect but up to now it is only a prospect.

[I should mention that there is a recently reported experiment, a modern version of the Millikan oil drop experiment performed by W. Fairbank and his students at Stanford,* which has given some evidence for objects of charge -1/3. I don't want to describe it in detail but only to say that it is based on an idea of magnetic levitation of superconducting Niobium balls. The balls which are suspended in a magnetic field are driven up and down by electric fields. One measures the period of oscillation and deduces the charge from it.] It is in brackets because there are only a few examples of these things and few people find the evidence entirely convincing.

A last remark about gluons is that from energy-momentum sum rules in electron or neutrino scattering one finds only about ½ of the momentum of the nucleon is carried by the quarks. That is only ½ of the momentum is carried by the charged objects which we see with the photon or by weakly charged objects seen with the intermediate boson. Then the other half of the momentum must be carried by something or otherwise we are making a terrible mistake. It is natural to think that this something is electrically neutral glue, which we want to have here to hold the nucleon together. Summarizing this optimistic picture of modern particle physics we say that in spite of its great promise not very much has been proved and even less has been verified experimentally. But as you can see there is a current of a number of events, both theoretical and experimental. They indicate the gauge theories are useful, in addition to being beautiful and very powerful. Many optimistic people believe that we already know except for some details how

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*G.S. LaRue, W.M. Fairbank, and A.F. Hebard, Phys. Rev. Lett. **38**, 1011 (1977).

to unify the weak, electromagnetic and strong interactions. The only thing that requires a great deal of thought is to incorporate gravity.

6. AN ICONOCLASTIC VIEW

There is another point of view which I should mention before we end this lecture. Taken most extremely, it is that it is not a synthesis which is in at hand, but chaos. The reason some people believe we are entering a time of chaos is that if we count the objects which we now regard as fundamental fields, we have:

12 quarks: u, d, s, c (4 flavors, 3 colors),

4 leptons: ν_e, ν_μ, e, μ,

8 colored gluons are required,

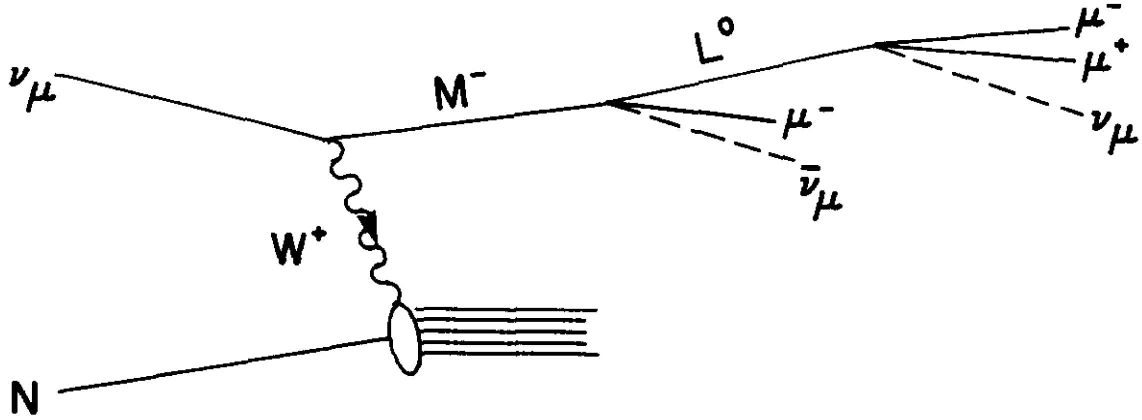
1 photon,

3 intermediate bosons are needed at least W^+, W^-, Z^0,

1 Higgs scalar is needed,

1 graviton, presumably the quantum of gravity.

The sum of the number of these fundamental objects is 30 which is seven times more than in ancient times (compare earth, air, fire, water!). But even more "fundamental" objects are on the way. The heavy lepton, τ, has been discovered. It is very likely that it has its own neutrino. That gives us two more objects. Prof. Mann in his lectures will tell us about the observation of neutrino induced events which lead to 3 fast muons in the final state, so-called trimuon events. These are not understood completely because there is a small number of this kind of events accumulated in experiments. But one interpretation requires the introduction of two more heavy leptons which are not the same as the τ-lepton. The conjectured picture of such an event is



In the last couple of months there has been found at Fermilab a new family of extremely massive states in the reaction

$$p + p \rightarrow \mu^+\mu^- + \text{anything} \quad .$$

This is the experiment of Lederman and his collaborators. They established at least two particles called upsilon

$$\Upsilon(9.4\ \text{GeV}/c^2),\ \Upsilon'(10.0\ \text{GeV}/c^2), \ldots$$

and maybe more. I will show you the data in the last lecture of my course. The observation of these events in Lederman's experiment likely signals the existence of at least one more quark, maybe two, because there are two objects.

There is some evidence in ν-experiments at Serpukhov for neutral heavy leptons of a new kind. This is again only a small number of events of preliminary form but also another indication that we have not yet found everything. We may ask ourselves how many "fundamental" objects are we willing to accept and whether we are indeed proceeding in the right direction.

LECTURE II. CHARMED PARTICLE SPECTROSCOPY

1. SU(4) Symmetry-Generalities

First of all we are interested in the quantum numbers of the quarks which are required for the description of the properties summarized yesterday. Our SU(4) symmetry includes 4 quark flavors with the following assignments of isospin (I, I_3), charge (Q), strangeness (S), hypercharge (Y) and charm (C)

Quark	I	I_3	Q	S	Y	C
u	1/2	1/2	2/3	0	1/3	0
d	1/2	-1/2	-1/3	0	1/3	0
s	0	0	-1/3	-1	-2/3	0
c	0	0	2/3	0	0	1

Now we can generalize the Gell-Mann-Nishijima formula for the charge of any state. The usual formula relates the charge to isospin and hypercharge. Now we add a piece which gives us the right charge for the charmed quark. This is a contribution equal to 2/3 of the charm quantum number. The general formula is

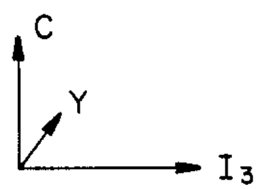
$$Q = I_3 + \frac{1}{2} Y + \frac{2}{3} C \quad .$$

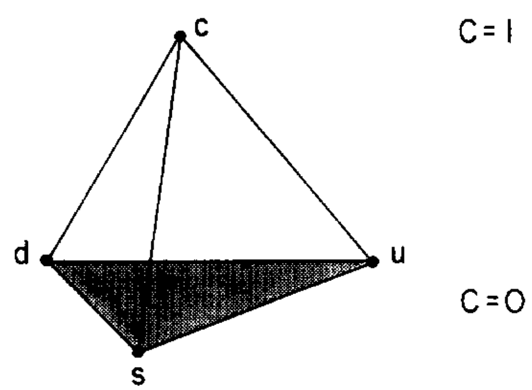
There are several papers summarizing the mathematics of SU(4) symmetry. I will be going only superficially here and you may consult some of these references for additional details and for applications.

1. D. Amati, H. Bacry, J. Nuyts, and J. Prentki, Nuovo Cim. **34**, 1732 (1964).
2. Einhorn's lecture notes (see first reference list).
3. M.B. Einhorn and C. Quigg, Phys. Rev. D**12**, 2015 (1975).
4. H.J. Lipkin, Lie Groups for Pedestrians, second edition (1966).

The first paper summarizes very nicely the mathematical properties and gives a detailed description of generators of SU(4) in a form useful for physics. The third paper has an appendix which summarizes many of the properties one needs, but it is not as complete. However it is a bit more attuned to modern applications. Finally on a more elementary level there is a section in the second edition of Lipkin's book, which introduces SU(4).

Let's begin by considering the fundamental representation of SU(4), the 4-dimensional representation ($\underset{\sim}{4}$) which contains 4 quarks up (u), down (d), strange (s) and charmed (c). It consists of two pieces if you decompose it under charm and SU(3). We have the normal SU(3) triplet [$\underset{\sim}{3}$] of noncharmed quarks u, d and s, for which the weight diagram is a triangle and is shown as the base plane of the tetrahedron.



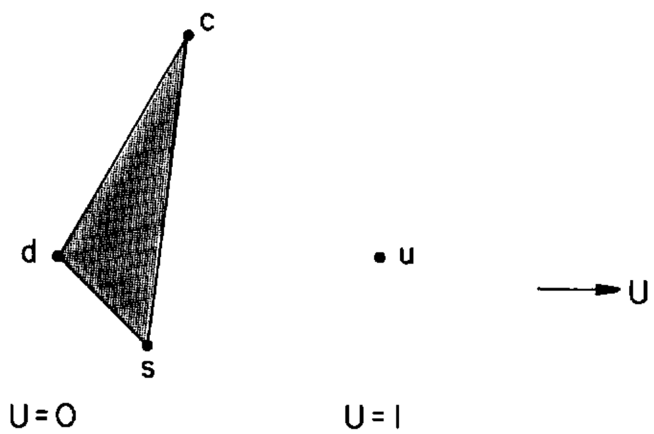


There is in addition an SU(3) singlet $[\underset{\sim}{1}]$, which is the charmed quark carrying charm +1. If we make a three-dimensional plot of the quarks with the third component of the isospin as a horizontal axis, charm as a vertical axis and the hypercharge as an axis into the page then the weight diagram becomes a tetrahedron, that is a shape made up of four triangular sides. In the notation I will use later to do calculations, the 4-dimensional representation of SU(4) can be considered as a sum of an SU(3) triplet with charm = 0 (the subscript means charm) and an SU(3) singlet which has charm = 1

$$\underset{\sim}{4} = [\underset{\sim}{3}]_0 + [\underset{\sim}{1}]_1 \quad .$$

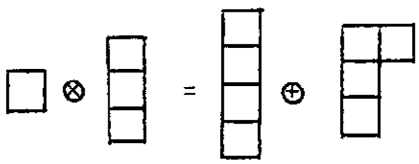
Now it is interesting to know this, and I will point it out a number of times in the course of this talk because it turns out to be useful for physics, that the decomposition of the fundamental representation of SU(4) can be made in three other ways. In the way we have made it, the charmed quark plays a special role because we have distinguished it in labeling things by the number of charmed quarks that appeared. But we could equally well set apart the u, d or s quark. The physics of our common experience does not give any reason to do this because the charmed quark seems much more massive and seems to hold a special role. But for exploring the symmetries it is useful sometimes to consider other triplets as belonging together and single out a different quark.

Let me indicate that if we want, for example, to single out the u-quark then a triangle consisting of the d-, s- and c-quarks represents a triplet of SU(3) with no u-quarks. We could say the u-quark number is 0. The u-quark represents then the decomposition, which looks in this direction and is an SU(3) singlet with u-quark number 1. You can do it with strange and down quarks as you like.



2. Mesons

As we have done in the case of SU(3) we will build the meson spectrum of quark-antiquark pairs. Let me say this in a number of ways. In group theory language the quark-antiquark pair will allow the representations that are obtained by taking the product of the fundamental representation $\underset{\sim}{4}$ with the conjugate of that representation $\underset{\sim}{4}^*$. For those familiar with language of Young diagrams:  is the fundamental representation $\underset{\sim}{4}$,  is its conjugate $\underset{\sim}{4}^*$. The product has two terms, a singlet  and the second  which turns out to be a 15-dimensional representation of SU(4). So

$q\bar{q} \subset 4 \otimes 4^*$ =  $= \underset{\sim}{1} \oplus \underset{\sim}{15}$.

Let us do the arithmetic in a more pedestrian way. I can expand the product $\underset{\sim}{4} \otimes \underset{\sim}{4}^*$ in terms of the SU(3) subgroups

$$\underset{\sim}{4} \otimes \underset{\sim}{4}^* = ([\underset{\sim}{3}]_0 \oplus [\underset{\sim}{1}]_1) \otimes ([\underset{\sim}{3}^*]_0 \oplus [\underset{\sim}{1}]_{-1})$$

and then expand this product according to the rules familiar from SU(3) as

$$\underset{\sim}{4} \otimes \underset{\sim}{4}^* = \underbrace{[\underset{\sim}{1}]_0 \oplus [\underset{\sim}{8}]_0}_{\substack{3 \otimes 3^* \\ q\bar{q}}} \oplus \underbrace{[\underset{\sim}{3}]_{-1}}_{\bar{c}q} \oplus \underbrace{[\underset{\sim}{1}]_0}_{c\bar{c}} \oplus \underbrace{[\underset{\sim}{3}^*]_1}_{c\bar{q}} \quad .$$

For the product of the ordinary quarks, triplet with antitriplet, we get the ordinary mesons, a singlet plus an octet of SU(3) both with charm 0. So these are the normal 9 meson states, which we have experience with in the past. Then come the other terms of the product: an additional representation of SU(3) from an anticharmed quark and an ordinary quark, that is from this product I get a triplet of SU(3) with charm = -1. From the product of the charmed quark and antiquark I get a singlet which is charmless and finally from the opposite combination of the charmed quark and an ordinary antiquark I get a $[\underset{\sim}{3}^*]$ with charm = 1.

Both of these calculations, the group theoretical one and the more pedestrian one, tell us that the familiar nonet of SU(3) is expanded now to a 16-dimensional representation of SU(4) made up of a singlet plus a 15-plet, just as a nonet is made up of an SU(3) singlet plus an octet. We have here the SU(3) representations to which new mesons will belong. There will be a $c\bar{c}$ meson, which is an SU(3) singlet. In the case of the vector mesons that will be the ψ or J-particle. Then there will be a triplet and antitriplet of particles with charm -1 or 1. These are the new explicitly charmed particles which we seek to investigate.

Finally, there is a matrix notation for the meson states which is quite convenient for SU(3). We think about the 3 × 3 matrix by which we represent each vector meson in terms of its quark-antiquark contents, for example, a u-quark and anti-d-quark make ρ^+. We expand it to a 4 × 4 matrix by adding a charmed quark and charmed antiquark and then have a full set of 16 mesons for the vectors. The new particles are given conventional names. I will use the term ψ for the vector state made up of charmed quark and charmed antiquark. The states made up of a charmed quark and $\bar{u}$- or $\bar{d}$-quarks I will call D for the pseudoscalars and D^*, for the vectors (D means doublet). Finally for the combination of a strange quark and charmed antiquark I will refer to the F meson. So our 4 × 4 matrix for vector mesons looks like

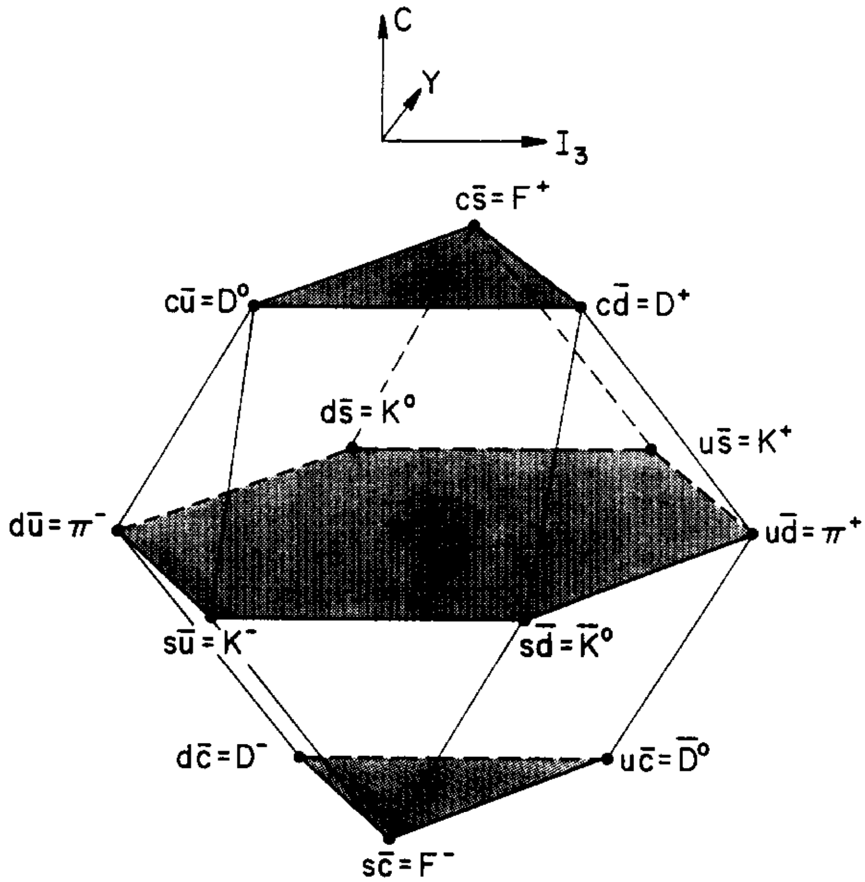
$$V = \begin{array}{c} \\ \bar{u} \\ \bar{d} \\ \bar{s} \\ \bar{c} \end{array} \begin{array}{c} \begin{array}{cccc} u & d & s & c \end{array} \\ \begin{pmatrix} \frac{1}{\sqrt{2}}(\omega + \rho^0) & \rho^- & K^{*-} & D^{*0} \\ \rho^+ & \frac{1}{\sqrt{2}}(\omega - \rho^0) & \bar{K}^{*0} & D^{*+} \\ K^{*+} & K^{*0} & \phi & F^{*+} \\ \bar{D}^{*0} & D^{*-} & F^{*-} & \psi \end{pmatrix} \end{array}$$

Let us summarize the spectrum of mesons that is expected by looking again at a weight diagram, now for mesons. I said a moment ago that the SU(3) singlet plus octet is expanded by addition of the charmed quark to an SU(4) singlet plus 15-dimensional representation

$$[\underset{\sim}{1}] \oplus [\underset{\sim}{8}] \rightarrow \underset{\sim}{1} \oplus \underset{\sim}{15} \quad .$$

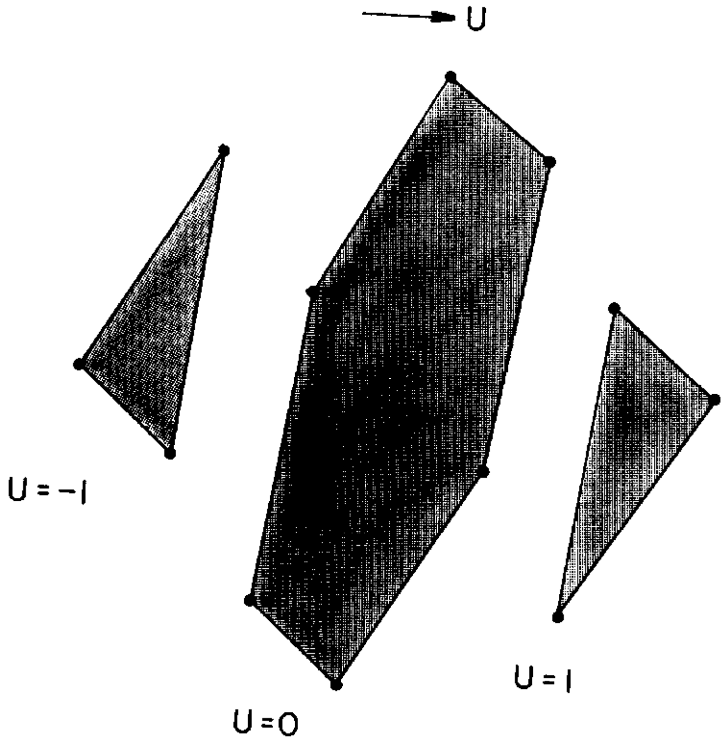
The weight diagram for the same convention of the axes is the 3-dimensional object of which the central plane with charm 0 is the familiar hexagonal representation of the octet of SU(3).

Then we add to that a single state made of $c\bar{c}$ at the center and an antitriplet and triplet as two triangles with charm +1 and -1.



The names that I list on this picture are those used for the pseudoscalars. In the pseudoscalar family there are similar new particles as the vectors have except for the pseudoscalar particle made of $c\bar{c}$, which is usually referred to as the η_c, the charmed analog of the η-meson.

Again let me make a remark that because of the way we perceive physics it is useful to draw the SU(3) decomposition in the way I have here, giving a special role to the charmed quark. I can make the decomposition instead with a special role for the u-quark. So we have in the SU(3) decomposition an octet of states with no u-quarks and antitriplet of states with 1 u-quark and a triplet of states with 1 $\bar{u}$-quark.



This decomposition again, like that for the fundamental representation, can be made in any of 4 directions which we choose.

3. Baryons

Let's turn now to the baryons. Since it is slightly more complicated I'll begin by reviewing the SU(3) result. Baryons we believe are made of 3 quarks and are contained in representations of SU(3) obtained from the product

$$qqq \subset [\underset{\sim}{3}] \otimes [\underset{\sim}{3}] \otimes [\underset{\sim}{3}] \quad .$$

This, as you remember the arithmetic, gives 4 representations in the product: a singlet, 2 octets and a 10-dimensional representation or decimet

$$= [\underset{\sim}{1}] \oplus [\underset{\sim}{8}] \oplus [\underset{\sim}{8}] \oplus [\underset{\sim}{10}] \quad .$$

For the baryons we have the additional complication that the final states we are dealing with are fermions. Therefore the wave functions must obey the exclusion principle. We talked yesterday about how it is achieved with symmetric wave functions of the quarks by the introduction of color. We have here an additional problem which is the presence of the singlet representation and one antisymmetric combination of octets. There is nothing we can do without introducing angular momentum to make those symmetric for color to act on. Therefore it develops that in the lowest-lying set of the baryons (the so-called 56-dimensional representation of SU(6) in which there is no orbital angular momentum of quarks) only two of these representations, the 10 and a symmetric combination of octets occur. This $(56)_{L=0}$ of SU(6) just counts the number of states with different quantum numbers and different spin states. And so for the familiar octet with spin ½ there are 16 spin states carrying spin up and spin down and for the 10-dimensional representation which contains N^*'s and Y^*'s of spin 3/2 there are 40 states because their spin multiplicity is 4. All this gives a 56-dimensional representation. In short we write

$$(56)_{L=0} \backsim \begin{array}{l} 8 \text{ spin } 1/2^+ \rightarrow 16 \text{ states} \\ 10 \text{ spin } 3/2^+ \rightarrow 40 \text{ states} \end{array} .$$

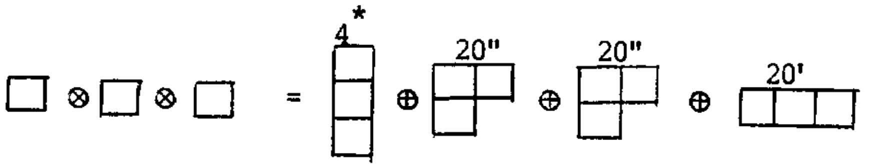
A similar kind of complication with picking out the representations of the lowest-lying states will occur in SU(4) but as we know what happens in SU(3), it is easier just to give the answer. Again we assume that baryons are made of 3 quarks and this time they will live in representations of SU(4), which are obtained from the product

$$qqq \subset \underset{\sim}{4} \otimes \underset{\sim}{4} \otimes \underset{\sim}{4} .$$

If I do the group theory for this I find

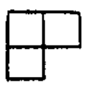
$$= \underset{\sim}{4}^* \oplus \underset{\sim}{20}'' \oplus \underset{\sim}{20}'' \oplus \underset{\sim}{20}' \quad .$$

I mark by primes two kinds of 20 dimensional representations which occur in SU(4). In Young diagram language



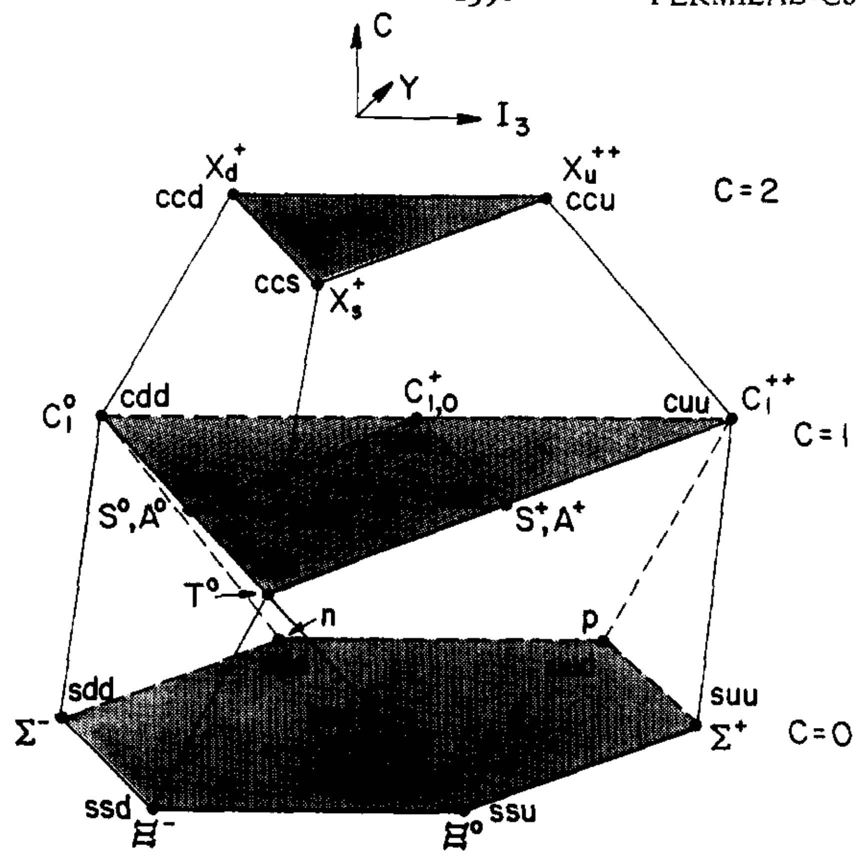
The first is a completely antisymmetric combination, the last is a fully symmetric object and others are combinations with mixed symmetry. In complete analogy to SU(3) we will have the fully symmetric representation 20' taking the place of the 10-dimensional representation of SU(3) and one symmetric combination of the two 20" entering the lowest-lying multiplet $(120)_{L=0}$ of SU(8). It's the last we'll say about SU(8)!

Now let's consider these baryons. In the case of spin ½ baryons we started with 8 in SU(3) and we know there are 20 in SU(4). So I will ask what the new states are. If I make an SU(3) decomposition of the 20" dimensional representation of SU(4) I do it just the same way as we did for mesons. So we find

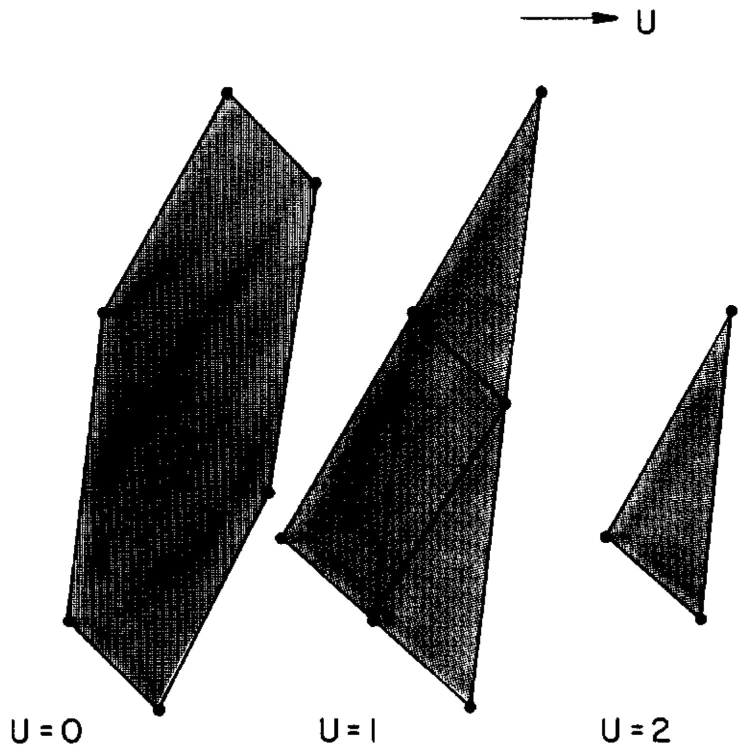


20" contains	$[\underset{\sim}{8}]$	C = 0
	$[\underset{\sim}{3}^*] + [\underset{\sim}{6}]$	C = 1
	$[\underset{\sim}{3}]$	C = 2 .

You can see the weight diagram for $\frac{1}{2}^+$ baryons in SU(4) before we enumerate all these states. Again we have the usual notation for the axes.



For charm = 0 we have the familiar hexagonal representation of the octet of SU(3), for charm = 1 we have on the second floor a sextet and an antitriplet. Finally at the top floor with charm = 2 we have a triplet of new states. Once again I make the point that we could single out a different quark rather than the charmed one. This diagram is fully symmetrical in respect to any changes of quarks. So if any quark is given a special role, we also get an SU(3) decomposition of octet, sextet, antitriplet and triplet. We show it in diagrams:

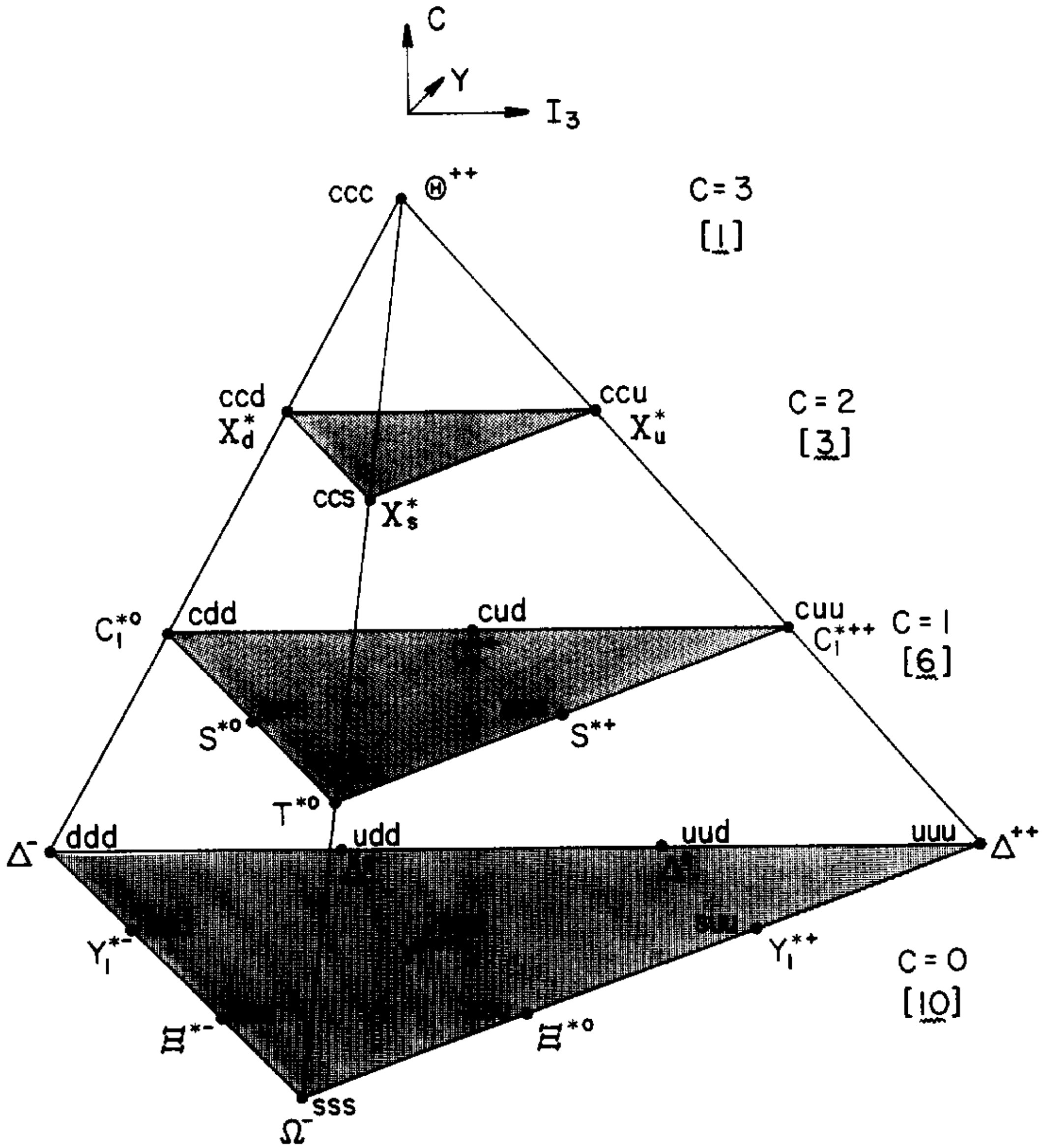


Let's return now to the names and properties of these new baryons. I haven't listed the old baryons, which had charm zero. I list only the ones having explicit charm. In the first column I give names which are the ones introduced by Gaillard, Lee and Rosner. I write in the next column the composition in terms of quarks with the notations: [ ] means an antisymmetric combination, {} means symmetric. For example, C_0 is so called for isospin 0, isospin 0 of the u and d quark combination. This isospin means the antisymmetric combination. Isospin 1 is the symmetric combination. Particles with isospin 1 combination we call C_1. So we have a table for the charmed ½$^+$ baryon states:

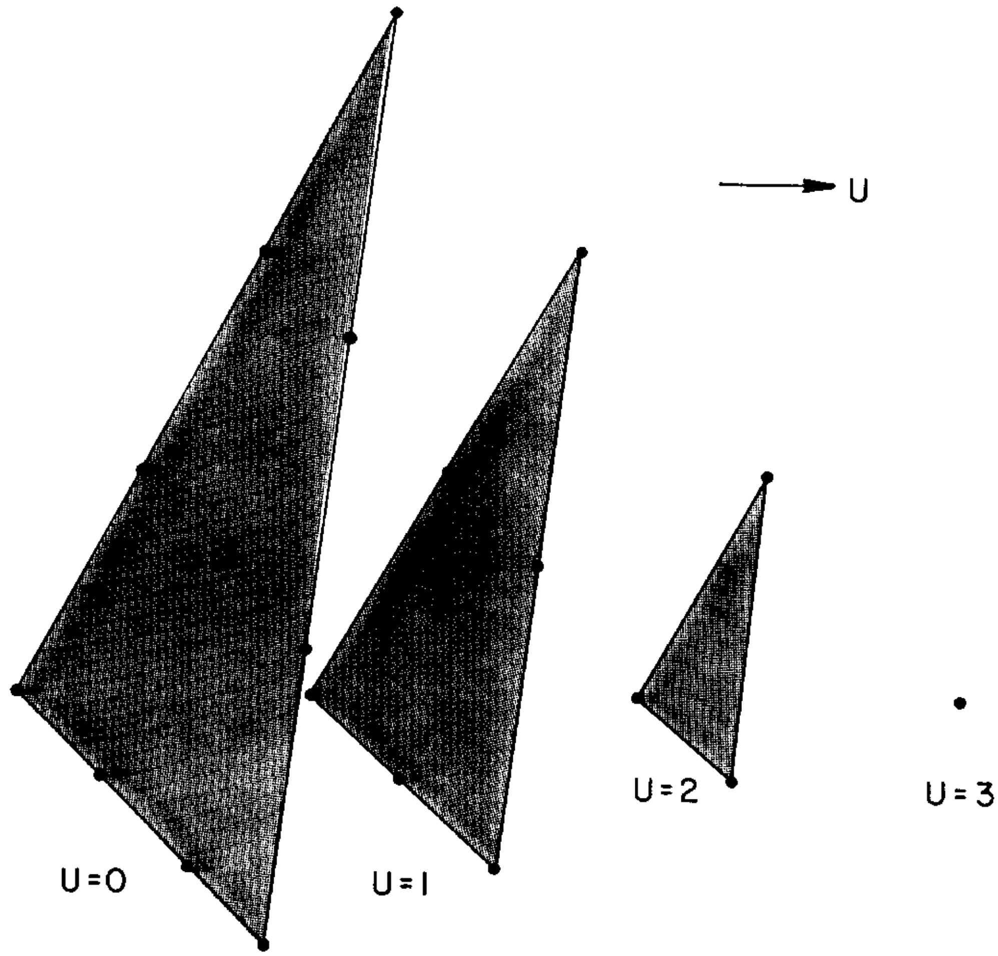
Name	Quark Content	Charm (C)	SU(3) multiplet	Isospin quantum numbers (I, I_3)	Strangeness (S)
C_0^{+}	c [ud]			(0,0)	0
A^{+}	c [us]	1	[$\underset{\sim}{3}^{*}$]	(1/2, 1/2)	-1
A^{0}	c [sd]			(1/2, -1/2)	
C_1^{++}	cuu			(1, 1)	
C_1^{+}	c {ud}			(1, 0)	0
C_1^{0}	cdd	1	[$\underset{\sim}{6}$]	(1, -1)	
S^{+}	c {su}			(1/2, 1/2)	-1
S^{0}	c {sd}			(1/2, -1/2)	
T^{0}	css			(0, 0)	-2
X_u^{++}	ccu			(1/2, 1/2)	0
X_d^{+}	ccd	2	[$\underset{\sim}{3}$]	(1/2, -1/2)	
X_s^{++}	ccs			(0, 0)	-1

We have a triplet with charm = 1, in which there is an isospin singlet without strangeness. This is the particle we shall be most interested in, of the baryons, because it is the most commonly produced one, which undergoes a weak decay. Then there is a doublet of strange particles. Then as a whole I list the other states, which I won't go through in detail. They make all the combinations that you can think of by substituting a charmed quark for an ordinary quark in terms of the usual baryons. I guess I must point out to you a rather strange set, which is in the sextet. C_1^{++}, C_1^{+}, C_1^{0} are relatives in some sense of the C_0^{+}. We can discuss without going into great detail a peculiarity this multiplet displays compared with the multiplets we know from ordinary experience. We compare it with the well-known triplet, isospin triplet, of Σ^{+0-}-particles. Now because of the new relation between charge and charm in the Gell-Mann-Nishijima formula we find that the isovector state C_1 has charges shifted from those normally expected: 0, +1, +2. The peculiar property of the new states to occur in shifted multiplets is a wonderful experimental signature that we can look for.

The generalization of the 10-dimensional representation of SU(3) also has 20 members but arranged in a different fashion. At the level of charm = 0 the SU(3) decomposition is again the familiar decimet of particles, at charm 1 is a 6-dimensional representation, at charm 2 is a triplet and at charm 3 is a singlet. The diagram version of this fundamental representation is the tetrahedron or pyramid:



An interesting thing can be said about the particles in this pyramid. It seems that the most spectacular way to observe charm would be to see the charmed analog of the Ω^- made of 3 charmed quarks. As a homework exercise I invite you to think of the cascade of weak decays which this particle undergoes, to find all this physics in a single event. At last I make the point that picking out another quark such as the u-quark we can obtain a similar SU(3) decomposition: 10-dimensional representation with no u-quark, 6-dimensional one with 1 u-quark, 3-dimensional one with 2 u-quarks and singlet representation or Δ^{++} particle with 3 u-quarks. So we have the picture


U
U=0
U=1
U=2
U=3

Now I give you the names of the new charmed $3/2^+$ baryon states

Name	Quark	C	SU(3)	(I, I_3)	S
C_1^{*++}	cuu			(1, 1)	
C_1^{*+}	cud			(1, 0)	0
C_1^{*0}	cdd			(1, -1)	
		1	[6]		
S^{*+}	cus			(1/2, 1/2)	
S^{*0}	cds			(1/2, -1/2)	-1
T^{*0}	css			(0, 0)	-2
X_u^{*++}	ccu			(1/2, 1/2)	
X_d^{*+}	ccd	2	[3]	(1/2, -1/2)	0
X_s^{*+}	ccs			(0, 0)	-1
Θ^{++}	ccc	3	[1]	(0, 0)	0

Again I call particular attention to those states, which will be most easily seen in experiments. These are the excited C_1^* states, which are members of the 6-dimensional representation and constitute an isospin multiplet of 3 states.

Three sorts of things we want to know before we look for all these states: what the masses of all the new states will be, how we will find them experimentally, i.e. how they decay, and, last, to have some idea how to produce them.

4. CHARMED PARTICLE MASSES

Let us first make some naive estimates of the masses. These naive estimates were of course chosen because they agree with reality. The trouble is that there are many naive estimates and in advance we do not know which one to believe! So I make a naive estimate here. Let's neglect the binding energy between quarks. Any masses of elementary particles we know represent simply the masses of the quarks, which they are made up of. Therefore for the vector mesons we can write

$$m_u = m_d \simeq \frac{m_\rho}{2} = 382 \text{ MeV}/c^2$$

because the ρ-meson is made up from u- and d-quarks. Then to get the mass of the strange quarks I can use the fact that the strange quark makes up the K^*-meson together with u- or d-quarks. Then

$$m_s = m_{K^*} - m_u = 510 \text{ MeV}/c^2 \quad .$$

There is another way to get the mass of strange quark. Note that the ϕ-meson is made up of two strange quarks. Then we have for the strange quark mass the same value as before

$$m_s = \frac{m_\phi}{2} = 510 \text{ MeV}/c^2 \quad .$$

Finally we have the vector state ψ, the lowest-lying vector particle made of two charmed quarks. So the charmed quark mass is approximately equal to ½ of the ψ-particle mass

$$m_c = m_\psi/2 = 1.548 \text{ GeV/c}^2 \quad .$$

I combine these ingredients to make rough predictions for the masses of charmed states. The D^*-meson is made up of a nonstrange quark and charmed quark. By adding quark masses I predict

$$M_{D^*} \approx 1.93 \text{ GeV/c}^2 \left[M_{D^*}^{\text{experim}} = 2.007 \pm .002 \text{ GeV/c}^2 \right] \quad .$$

The F^*-particle is made up of a strange quark and a charmed quark so we have $m_{F^*} \approx 2.057$. Experimentally this is less well established than the D-meson but recent indications exist that the experimental mass of this meson is $M_{F^*}^{\text{experim}} = 2.14 \pm 0.06$. So you see that by making naive estimates we were able to come reasonably close to recent experimental data.

For the $\frac{1}{2}^+$ baryons we will make the same kind of naive estimates. We know the proton is made up of 3 nonstrange quarks, 2 u's and a d-quark. We may say the masses of all these quarks are approximately equal to $M_p/3$. So we have

$$m_u = m_d \approx M_p/3 = 313 \text{ MeV/c}^2 \quad .$$

We don't know what the effective mass of a charmed quark in baryons is. So we must take the only estimate we know, that is the mass of the charmed quark in the ψ-meson. We predict $M_{C_0^+} \approx 2.173$ GeV/c^2, which is to be compared with the experimental indication of about 2.25 GeV/c^2.

There are of course more complete (sometimes deeper, sometimes just deeper sounding) descriptions of the charmed particle masses. The most complete is given in a paper by A. De Rujula, H. Georgi and S.L. Glashow, Phys. Rev. D12, 147 (1975). You can find a number of summaries or at least arguments in Jackson's lecture notes and in a paper by B.W. Lee, C. Quigg and J.L. Rosner, Phys. Rev. D15, 157 (1977).

5. DECAYS OF CHARMED PARTICLES

How will we know that we have observed charmed particles or in other words how do charmed particles decay?

I will give now a very superficial discussion of this subject. It is one of the most complicated subjects dealing with charmed particles. Because of its complications it is one of the most interesting. There are a great many questions we don't understand about weak decays of heavy objects but we hope that through the study of charmed particle decays we will begin to understand them. In this part of our course we will pay no attention to these complications and I'll talk in the most simple terms.

Charm is a conserved quantum number of the strong interactions. That is why the introduction of SU(4) symmetry for the spectroscopy of particles is useful. Therefore the lowest-lying charmed particles with particular quantum numbers will decay weakly. Weak decay is the only way one has to ascertain charm. Of all the charmed particles which can decay weakly I will only talk about the pseudoscalar particles D^0, D^+, F^+ and single out the charmed baryon ($\frac{1}{2}^+$) $C_0{}^+$. These are the ones which probably have been found in experiments so far and are likely to be most copiously produced.

a) Leptonic Decays of Charmed Mesons

We start by considering the simplest decays, which are leptonic decays of charmed mesons. I remind you from my discussion yesterday of the Weinberg-Salam model with the introduction of charm that the charm-changing charged current has two pieces. It has a piece which makes a transition from a charmed quark to a strange one with Cabibbo strength $\cos\theta_C$, and it has a piece which makes the transition from a charmed quark to a d-quark with strength $\sin\theta_C$. So the $|\Delta C| = 1$ charged current is

$$J_\mu \sim \bar{c}\gamma_\mu(1+\gamma_5)s\cos\theta_C - \bar{c}\gamma_\mu(1+\gamma_5)d\sin\theta_C \quad .$$

From this I can read off the selection rules for leptonic and semileptonic decays of charmed particles. In Cabibbo-favored decays the charge changes by the same amount as the charm and the strangeness $\Delta Q = \Delta C = \Delta S$. There is no also change of isospin ($\Delta I = 0$) for Cabibbo favored decays. For the once-suppressed decays the rule is that

$$\Delta Q = \Delta C, \quad \Delta S = 0, \quad \Delta I = \tfrac{1}{2}$$

with $\sin\theta_C$ transitions. Two-body purely leptonic decays of pseudoscalars can even be calculated. We will do it to prove we can compute something. The amplitude for the decay of pseudoscalar (P) into a lepton (ℓ) and a neutrino (ν)

$$P \to \ell\nu$$

is given by the product of the weak interaction coupling constant, which is the Fermi constant G divided by $\sqrt{2}$, times the matrix element for the pseudoscalar D to change into a no hadron state, that is to annihilate to the vacuum by the action of the hadronic charged current. Then there is as a factor the Dirac operators for the transition ν into ℓ by the weak charged current

$$M = \frac{G}{\sqrt{2}} \langle 0 | J_\mu | P \rangle (\bar{\ell}\gamma_\mu(1+\gamma_5)\nu) \quad .$$

The matrix element for annihilation of a pseudoscalar into the vacuum has the simple form

$$\langle 0 | J_\mu | P(q) \rangle = iF_P\, q_\mu \begin{pmatrix} \cos\,\theta_C \\ \pm\sin\,\theta_C \end{pmatrix}$$

where F_P is the pseudoscalar meson decay constant, and q_μ is the 4-momentum of P. The matrix element has a difference for the favored and suppressed Cabibbo transitions that is marked by expressions in round brackets. We can do the square of this matrix element and combining it with phase-space factors calculate the width or rate of the decay $P \to \ell\nu$

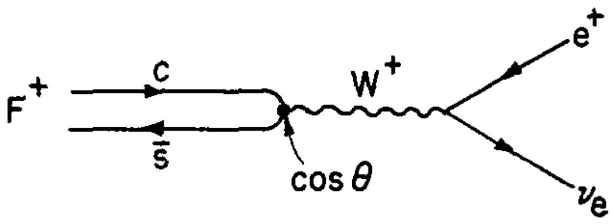
$$\Gamma(P \to \ell\nu) = \frac{G^2}{8\pi} F_P{}^2 m_\ell{}^2 M_P \left(1 - \frac{m_\ell{}^2}{M_P{}^2} \right)^2 \begin{pmatrix} \cos^2\,\theta_C \\ \sin^2\,\theta_C \end{pmatrix} \quad .$$

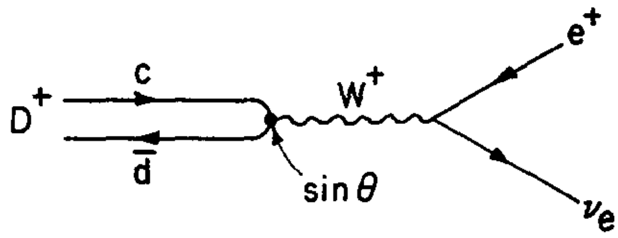
In the phase-space factor we neglect the ratio of masses m_ℓ/M_P which is small. The factor of m_ℓ^2 has its origin in the factor $q_\mu(\bar{\ell}\gamma_\mu(1 + \gamma_5)\nu)$. This reflects the fact that in a V-A theory of weak interactions both neutrinos and massive leptons would like to be left-handed. That means that if the particle is going in one direction and the antiparticle is going in the opposite direction then they would like to line up their spins in the same direction. Then it will give a net spin projection 1 while we started with a system of total spin projection 0. So that must be suppressed. Then the only way we can get a configuration of total spin 0 is for the massive lepton to have its spin pointing in the wrong direction. As you know from relativistic quantum mechanics the probability to have this happen is governed by the mass of that object. In the limit of zero mass for the V-A theory we have only a single helicity.

Now I invoke SU(4) symmetry for the rates by saying arbitrarily that the decay constants of all pseudoscalar mesons will be equal

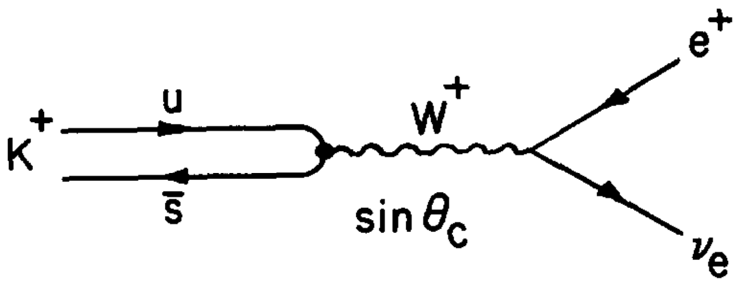
$$F_\pi = F_K = F_D = F_F \quad .$$

The purely leptonic decays of the F^+ and D^+ can be pictured as





F^+ has the annihilation of charmed quark and strange antiquark with Cabibbo strength $\cos\theta_C$ into W^+, which decays into the ℓ^+ and ν. D^+ decays in a similar way but with reduced strength. Both decays are analogous to the K_{ℓ_2} decay, $K^+ \to \ell^+\nu$, which is Cabibbo suppressed



In quark language the assumption of SU(4) symmetry for the decay constants is equivalent to the assumption that the wave function is such that the probability for two quarks to annihilate is the same for all our pseudoscalar mesons. So if the wave function at the origin is the same in all our cases we have

$$\frac{\Gamma(D^+ \to \ell^+\nu)}{M_D} = \frac{\Gamma(K^+ \to \ell^+\nu)}{M_K} = \tan^2\theta_C \frac{(F^+ \to \ell^+\nu)}{M_F} \quad .$$

With

$$\Gamma(K^+ \to \mu^+\nu) \simeq 0.5 \cdot 10^8 \text{ sec}^{-1}$$

we predict

$$\Gamma(D^+ \to \mu^+\nu) \simeq 1.9 \cdot 10^8 \text{ sec}^{-1}$$

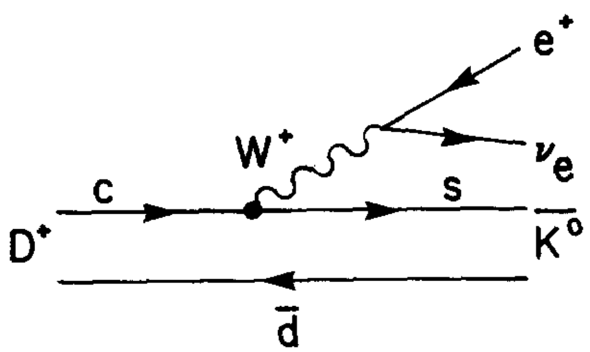
$$\Gamma(F^+ \to \mu^+\nu) \simeq 3.7 \cdot 10^9 \text{ sec}^{-1}$$

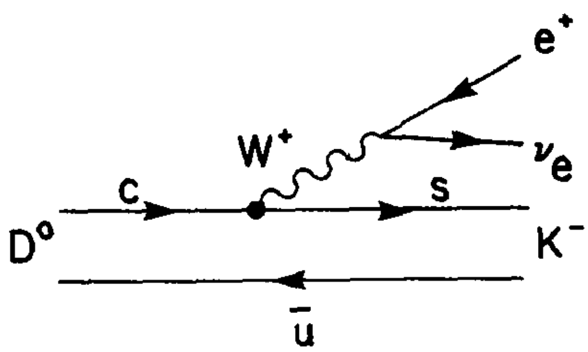
which give very long partial lifetimes (10^{-8} - 10^{-9} sec). The length of these partial lifetimes is due to the helicity suppression of the two-body decays.

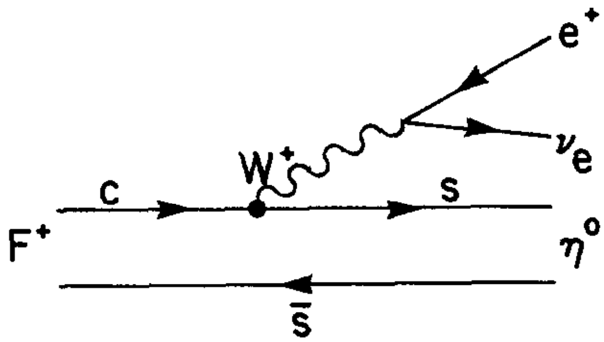
Therefore if we can find any other decay modes of these objects, we expect that the purely leptonic two-body modes will be rather unimportant because their rates are so slow.

b) Semileptonic Decays of Charmed Mesons

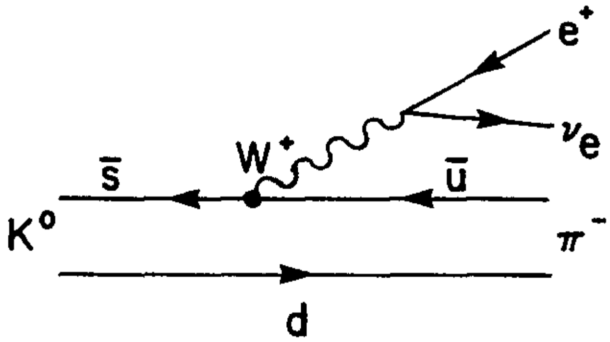
We may also consider semileptonic decays. I will treat them again by analogy with known decays but give less detail now. Let's consider three-body semileptonic decays, for an example, of D^+, which is made of a charmed quark and $\bar{d}$-quark. A charmed quark changes by emitting a W^+ into a strange one leaving a hadronic system with the quantum numbers of the $\bar{K}^0$. The W^+ decays subsequently into 2 leptons. So we have as the pictures for D^+, D^0 and F^+ decays:







which look similar to the picture of the K^0 decay



Again assuming SU(4) symmetry, this time for the form factors involved in these decays, one may say that the ratios of the partial widths are again given by phase space. Phase space for these three-body decays turns out to go as the fifth power of the mass of the decaying object. Consequently

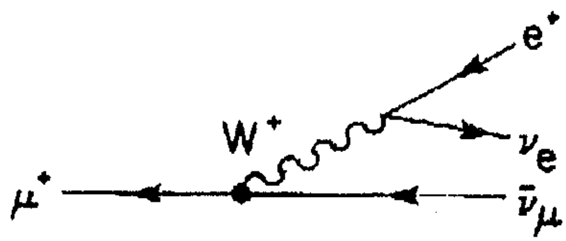
$$\Gamma(D^+ \to \bar{K}^0 e^+ \nu)/\Gamma(K^0 \to \pi^- e^+ \nu) \approx (M_D/M_K)^5 \cot^2 \theta_C \approx 1.4 \times 10^4 \quad .$$

Since $\Gamma(K^0 \to \pi^- e^+ \nu) \simeq 10^7 \mathrm{sec}^{-1}$ we expect

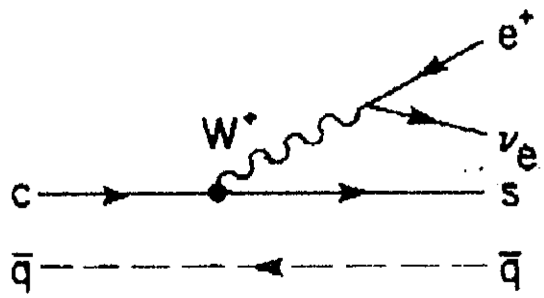
$$\Gamma(D^+ \to \bar{K}^0 e^+ \nu) \approx \Gamma(D^0 \to K^- e^+ \nu) \approx 1.4 \times 10^{11} \ \mathrm{sec}^{-1}$$

$$\Gamma(F^+ \to \eta^0 e^+ \nu) \approx 1.5 \times 10^{11} \ \mathrm{sec}^{-1} \quad .$$

As a result, of the decays we have considered so far, I expect the semileptonic decays to dominate. We have calculated a single semileptonic decay in each case, but that should trouble us because energetically there are a large number of semileptonic decays which are allowed. We can imagine that instead of decaying into K^0 we might have decays into K^* or just into K and π-mesons because all charmed states are so massive. How can we take care of these states? We can make a very simple estimate based on a quasifree quark model. In this model a charmed particle is made up of a charmed quark and an ordinary antiquark, which are roughly independent of each other. Therefore I treat the decay of charmed quark into a strange quark and ℓ, ν in the same way as the decay of μ^+ into positron and ν_e plus $\bar{\nu}_\mu$



In other words I will treat the charmed particle decay as the decay of an isolated charmed quark as in μ-decay, not worrying about the influence of the second quark. I call the second quark a spectator and picture it as a dashed line



If I do that then I know the rate of this decay because we can calculate the rate for μ-decay. I simply transcribe the familiar formula for μ-decay and have the rate

$$\Gamma(\text{charm} \to \text{hadrons} + \ell\nu) = \frac{G_F^{\,2} m_c^{\,5}}{192\,\pi^3}$$

with $m_c \simeq 1.5$ GeV we find finally $\Gamma(\text{charm}\to\text{hadrons}+\ell\nu) \simeq \Gamma(\text{charm}\to\text{hadrons}+\mu\nu) \simeq$ $\simeq 3 \cdot 10^{11}$ sec^{-1}, which is 2 or 3 times larger than our equally naive estimate for specific exclusive semileptonic decays.

c) Nonleptonic Decays

Now we want to look at nonleptonic decays. This is a subject of considerable complication, detail and beauty. So I would like to return to it in a later lecture. But for now I will speak in very simple terms. In the usual current-current picture of weak interactions the weak Hamiltonian is a product of leptonic and hadronic currents with its conjugate plus the opposite combination

$$H_W \sim JJ^+ + J^+J \quad .$$

I recall from my discussion of the Weinberg-Salam model that the charge-changing current has a number of pieces. I rewrite them suppressing space-time structure and coupling constants as

$$J \sim \bar{u}d \cos\theta_C + \bar{u}s \sin\theta_C + \bar{c}s \cos\theta_C - \bar{c}d \sin\theta_C \quad .$$

Here we have a transition from a d-quark to a u-quark with the strength $\cos\theta_C$, from a strange quark to a u-quark with the strength $\sin\theta_C$, from an s-quark to a charmed quark with the strength $\cos\theta_C$ and from a d-quark to a c-quark with the strength $\sin\theta_C$. Consequently we can see that the Cabibbo-favored transitions are given in quark language by transition $c \to s + u + \bar{d}$. In a current-current picture that takes the $\cos\theta_C$ piece from the charm-changing transition and the $\cos\theta_C$ piece from the $\Delta C = 0$ current.

Therefore we can read off the selection rules from these transitions again for the Cabibbo-favored decays. The change in charm is equal to the change in strangeness and is equal to -1

$$\Delta C = \Delta S = -1$$

(or +1 if we go in the other direction). The isospin changes by 1 because we start with an isoscalar. The s-quark is isoscalar and the combination of u and $\bar{d}$ quarks is like π^+, so I = 1 and the change is $\Delta I = 1, \Delta I_3 = 1$.

Given these simple rules for changing the charmed quark into the strange and ordinary quarks we can list some simple examples of the kinds of decays that will be of interest. For example, the D^0-meson made of c and $\bar{u}$-quarks will go to a final state, which is $K^-\pi^+$, i.e.

$$D^0(c\bar{u}) \rightarrow K^-\pi^+$$

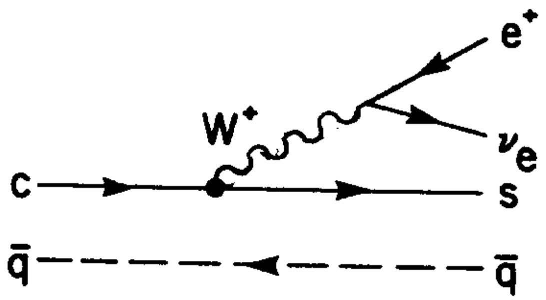
$$D^+(c\bar{d}) \rightarrow K^-\pi^+\pi^+$$

$$F^+(c\bar{s}) \rightarrow K^+\bar{K}^0$$

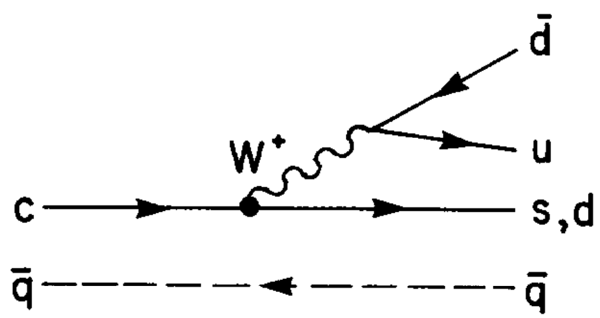
$$C_0^+(c[ud]) \rightarrow \Lambda(s[ud])\pi^+ \quad .$$

Before we do anything involving any details we should simply make the remark that charmed states are much more massive than the already known weakly-decaying states such as π and K-mesons. Therefore simply because of energetics there is likely to be a very large number of competing decay channels and the branching ratio into any channel is likely to be very small.

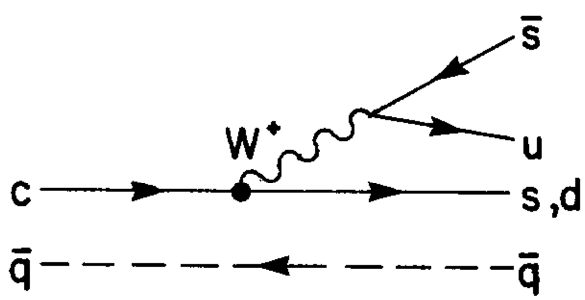
I will deal later with the calculations of the relative importance of specific nonleptonic final states. For the moment I simply want to make an inclusive estimate of the nonleptonic decay rate by the same technique we used for the semileptonic decays, again in the quasi-free quark picture. From the picture of semileptonic decay I have a width that in some units I define to be 1 ($\Gamma \propto 1$).



Nonleptonic decays in these pictures are



$$\Gamma \propto 3 \times \cos^2\theta_c$$



$$\Gamma \propto 3 \times \sin^2\theta_c$$

The tripled rate for the two last pictures means that we take into account three colors of each quark.

d) Charmed particle lifetimes

Consequently we have an estimate for the total decay rate of a charmed particle, which is proportional with some numerical factor A to the decay rate of the charm into hadrons plus lepton and neutrino

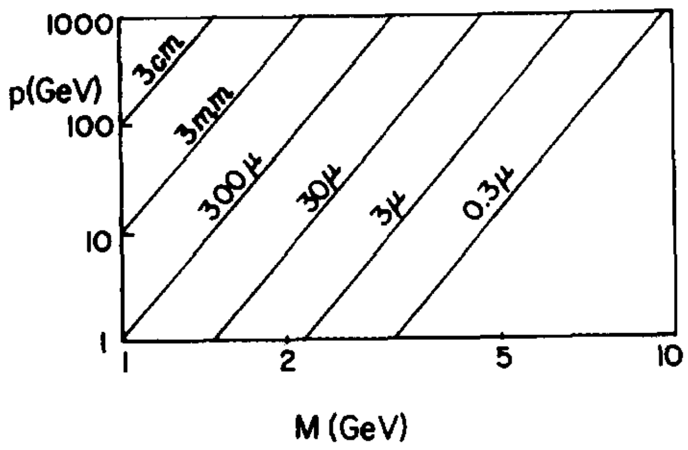
$$\Gamma(\text{charm} \to \text{all}) \approx A \times \Gamma(\text{charm} \to h \ell \nu) \quad .$$

The numerical factor is 3 from nonleptonic decay estimated from this naive quasifree quark model plus 1 for each of semileptonic decays into hadron and $\mu\nu$, hadron and $e\nu$. On the basis of this estimate we arrive at a total decay rate, which is

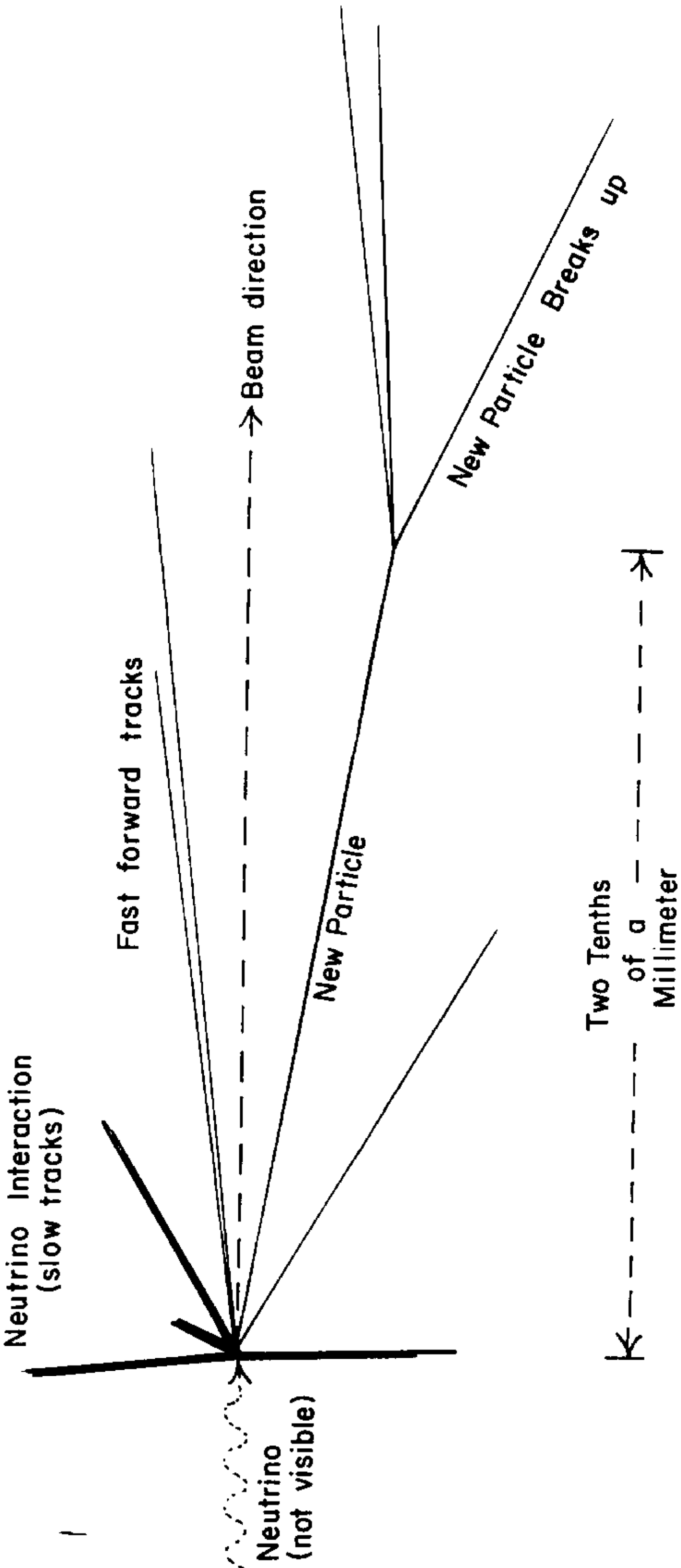
$$\Gamma(\text{charm} \to \text{all}) \approx 5\ \Gamma(\text{charm} \to h \ell \nu) \approx 2 \cdot 10^{12} \text{sec}^{-1} \quad .$$

There is a phenomenon which I would like to discuss tomorrow. It is called "nonleptonic enhancement" and in fact it increases rates for the ordinary hadron nonleptonic decays compared to what we would calculate on the basis of universality of the weak interactions and the known strength of leptonic and semileptonic interactions. If such an enhancement would operate in the case of charmed mesons the total rate of decay could be increased by a factor as much as 10.

Keeping this in mind, but not doing anything specific with it at the moment, we may say that before we find the charmed meson we expect a range of lifetimes, taking into account the simplicity of the calculations that have been done, between 10^{-11}–10^{-14}sec. These are interesting lifetimes because they are rather long on the scale of hadron physics. It is possible that particles with lifetimes of this kind travelling with a momentum of 100 GeV/c can leave tracks of finite or detectable length in a detector. Here for a reasonable assumption in this range of possibilities we show the mean path length traversed by a charmed particle before decay as a function of its mass and momentum. In this figure it is assumed that $\tau M^5 = 10^{-12}$sec GeV^5.



What you see is that for the mass range of interest we expect something of the order of 10^{-1}-10^{-2} mm to be a track length. Such track lengths are not resolved in conventional bubble chambers and certainly not in conventional spark chambers. However the emulsion technique which was used for a long time for cosmic ray research and also for the study of hadron interactions at accelerators is able to detect particles leaving such short tracks. There are now in the literature a number of observations of short tracks, which seem to be consistent with the detection of charmed particles. Because the number of examples is very small and because in emulsion it is very difficult to identify the species of particles, no one of these events is definitive. I simply show to you an example of such an event (E.H.S. Burhop, et al., Phys. Lett. 65B, 299 (1976)):


Neutrino
(not visible)
Neutrino Interaction
(slow tracks)
Fast forward tracks
Beam direction
New Particle
New Particle Breaks up
Two Tenths
of a
Millimeter

On the left side of the picture there is an interaction. This is the interaction of a neutrino with an emulsion nucleus making first the splash of slow particles. Then a number of fast particle tracks comes out to the right. The track of interest goes horizontally. It comes a long distance, 0.2 mm, and then appears to break up into 3 seen tracks and probably a K^0 or Λ. There appears to be farther away a neutral V-particle, which is plausibly pointing back to the same vertex. This event was found in Brussels by a large collaboration of European experimental teams with some institutions from the USA. The interpretation is ambiguous but appears to be consistent with the four-body decay of charmed baryon with a lifetime of about 10^{-13} sec. There are some additional experiments using other kinds of detectors such as at CERN, in which a large bubble chamber works together with an emulsion stack tagging the interesting events and pointing back to some position in the emulsion. People hope that experiments now in progress will give as many as 20 events of the interesting kind.

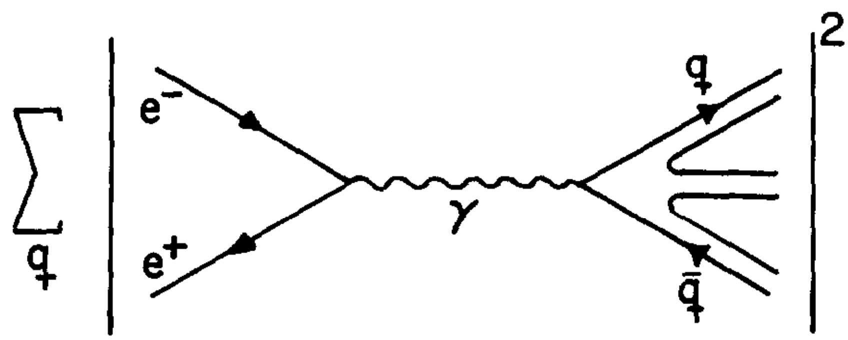
Now we have some idea of what we are looking for. We know the names of all the charmed particles, we have made guesses for their masses and we have formulated some elementary remarks about their decays.

LECTURE III. PRODUCTION OF CHARM

Allow me to discuss at greater length the production of charmed particles. With some simple arguments we may understand what the production cross section should be in various situations. So we may anticipate the best places to find charmed particles and the places where it will be more difficult to find them.

1. e^+e^- Annihilations

For e^+e^- annihilation we have done the calculations yesterday. We have calculated the total hadronic cross section. One may say that the production cross section for charmed particles is given by a diagram, in which e^+ and e^- annihilate into a virtual photon. The photon then decays into a charmed quark and charmed antiquark. These quarks arrange themselves with other quarks out of the vacuum into charmed hadrons in the final state. This occurs with relative probability 3 for color times $(2/3)^2$, which is the charge squared of the charmed quark. So we have $\sigma(e^+e^- \to \text{charm}) = 4/3\ \sigma(e^+e^- \to \mu^+\mu^-)$ used yesterday:



This should be an average cross section which is expected to be reliable close to threshold. "Close to threshold" means a kinematical regime where we make at most a pair of charmed particles, and do not make 2 or 3 pairs of charmed particles. Yesterday we also computed in the same kind of language that the non-charm cross section was in similar units

$$\sigma(\text{noncharm}) \sim 2 \quad .$$

Consequently above the charm threshold we expect the charmed particle production cross section will be about 40% of the total hadronic cross section. That is a very large number which gives rise to great enthusiasm because it means that the signal to background should be very favorable in e^+e^- annihilation for the observation of charm.

In real life there are some complications which were not anticipated theoretically. There seems to exist a heavy lepton with a mass almost identical to the mass of the lowest charmed particles. This is in some ways an analogy to the situation in the 1940's when the π-meson was searched for in experiments. The first experiments which reported the discovery of the π-meson in fact discovered the muon, which has a very similar mass. Because the mass of this heavy lepton is so close to the mass of charmed particles the thresholds to produce them almost coincide in e^+e^- annihilation. That probably delayed for a year and a half the finding of charmed particles.

With some reservations one may say that the heavy lepton does exist. We can calculate on the basis of the rules of quantum electrodynamics its production and can model its decay. If we do that we may subtract the cross section to make this heavy lepton from the observed cross section and deduce the true hadronic cross section in e^+e^- annihilation. I show here the ratio of the cross section for e^+e^- going to events detected with hadrons minus the cross section due to heavy leptons divided by the reference cross section to make a pair of muons. These are the most recent data* of the SLAC-LBL collaboration working at SPEAR. We see below charm threshold and below heavy lepton threshold the number 2.5, which I have

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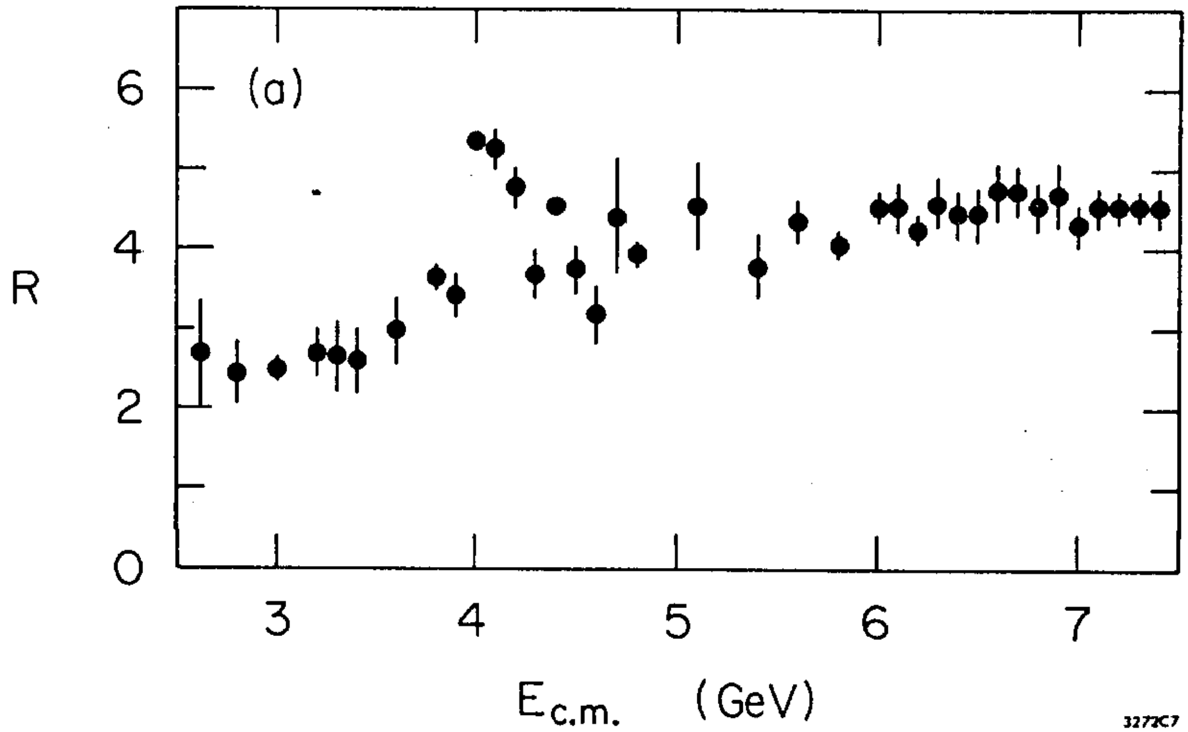
*V. Lüth, SLAC-PUB-2050.

discussed yesterday, then in the neighborhood of 4 GeV a rapid rise of the cross section ratio and also some oscillations. The ratio settles down at a new level, the relative amount of cross section here compared to the low energy data being roughly what we have calculated on the basis of the 40% ascribed to charm.



Looking in more detail at the threshold region we see that this is something that one cannot calculate by elementary arguments. Look at the cross section of e^+e^- annihilation into hadrons in units of μ-pair production cross section as a function of the center of mass energy $\sqrt{s}$ (next page). Again these recent data are from SPEAR.* In this picture, ψ' looks like a long line. A new resonance is shown very clearly here with a mass M = 3772 MeV. It has a width of about 30 MeV and it seems to decay almost exclusively into a charmed meson D and an anti-charmed

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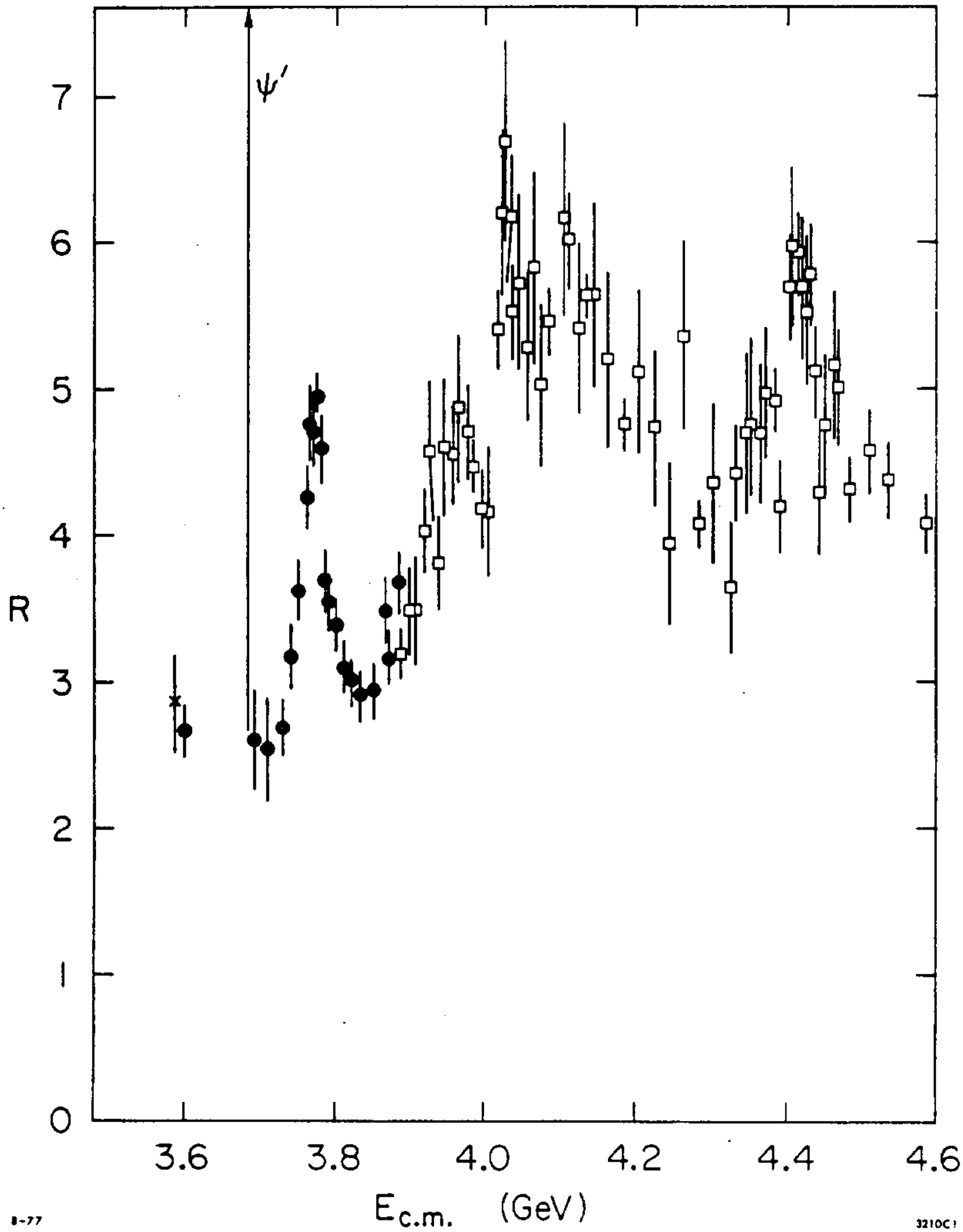
*P.A. Rapidis, et al., Phys. Rev. Lett. 39, 526 (1977).


ψ'
7
6
5
4
R
3
2
1
0
3.6
3.8
4.0
4.2
4.4
4.6
Ec.m. (GeV)
8-77
3210C1

meson $\bar{D}$. In addition there are the other structures, which were known for some time but are not still completely resolved. There is a very large cross section point at about 4.0 GeV, which is the place where charmed mesons were first observed in e^+e^- annihilations. There are also other details still to be understood. For example, there is a rather broad enhancement at 4.4 GeV, where charmed mesons have also been seen at SPEAR and where recently some evidence for the charmed-strange mesons, F and F^* mesons, was obtained at DESY. You see again that the general level of this cross section is well above the pre-threshold value.

So we expect, if we believe the arguments of this kind, that the discovery of this step in the ratio R means e^+e^- annihilation would be an especially favorable place to look for charm. This is because in electromagnetic production it is the charge of quarks that is measured and the charmed quark has the largest charge 2/3.

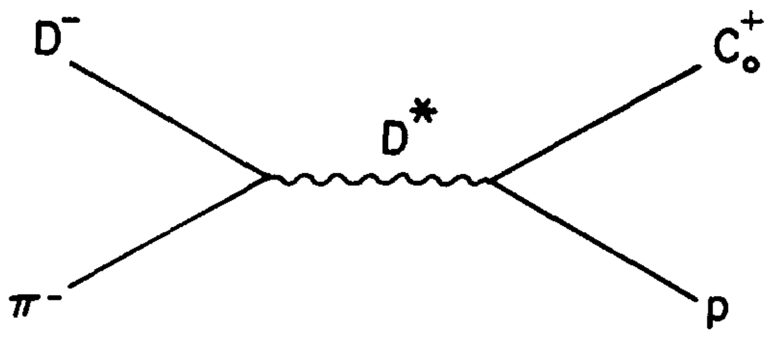
2. Peripheral production in hadron collisions

Let us consider some of the other places, where we might consider looking for charm. One can ask about the peripheral production of charmed particles in hadron collisions. We have experience with the discovery of strange particles many years ago in which strange particles were seen to be produced in pairs, the so-called associated production reactions such as $\pi^- p \rightarrow K^0 \Lambda$. We may ask whether the same kind of reaction would be favorable for the production of charm. It is at this point that one usually uses the substitution property of SU(4) representations. By substituting the strange quark for the charmed quark it turns out to be an easy exercise to read off the couplings of these reactions in terms of SU(4) symmetry. This is simply by a substitution. I list here a few reactions that one may consider.

Some charm-exchange reactions

Reaction	Exchange trajectory	SU(4) analog
$\pi^- p \to D^- C_0^+$	D^*, D^{*-}	$\pi^- p \to K^0 \Lambda$
$\pi^+ p \to \bar{D}^0 C_1^{*++}$	"	$\pi^+ p \to K^+ Y_1^{*+}$
$K^- p \to F^- C_1^+$	"	$\pi^- p \to K^0 \Sigma^0$

The associated production type produces a charmed meson with charm -1, D-mesons, and the charmed baryon with charm +1, C_0^+ baryon. In the peripheral exchange language this requires the exchange of a charmed meson trajectory, the vector or tensor trajectories:



It has a full analogy with the familiar associated strangeness production reactions such as $\pi^- p \to K^0 \Lambda$, which proceeds by K^* exchange.

On the basis of this analogy for the couplings, then, we know the strength with which these reactions would proceed. The conventional way to make an estimate of a cross section in high-energy regions is to resort to Regge phenomenology. To do that, there is one more ingredient we need, which is the Regge trajectory of the charmed mesons. This one can invent in a number of ways before the discovery of the charmed mesons. "A number of ways" means, for example, to take the $D^* - D^{**}$ Regge trajectory from mass formulas and then to estimate cross sections by conventional Regge pole techniques (see Field and Quigg, Fermilab-75/15). In the most optimistic way (of estimating the trajectory) the largest prediction at any energy is then 10 nb. In perhaps more realistic ways, the prediction is 2 or 3 orders of magnitude smaller. This is simply because of the great mass of the charmed mesons, which makes it very difficult to exchange charmed particles. Experimentally no signal has been seen. That is consistent with the estimates!

3. Inclusive production in hadron collisions

Let us now consider the inclusive production of charm in hadron-hadron collisions. In the peripheral production case at least we have the Regge pole model, which is reasonably well defined. For inclusive production of very massive particles in hadron collisions we have no well-founded model but only a very large number of guesses, which have been made. I review only a couple of them here.

There are statistical-thermodynamical arguments, which seem to be more in the nature of folklore than precise theory, which may be applied to the pair production of a new quantum number. By these arguments the charmed meson cross section should be proportional to an exponential damping factor

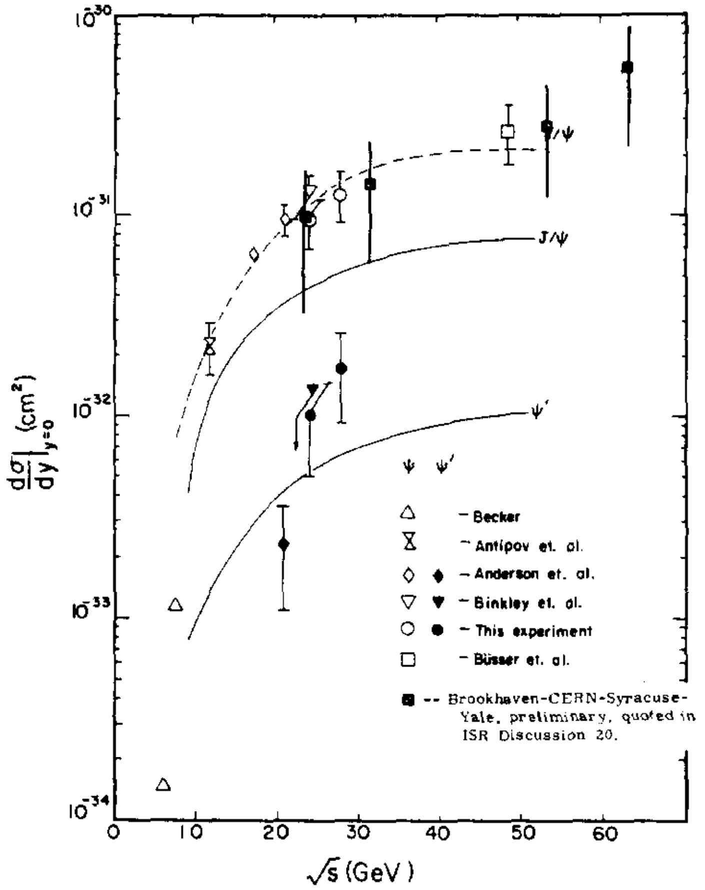
$$\sigma(D\bar{D}) \sim \exp\left[-2M_D/160\ \mathrm{MeV}/c^2\right] \quad .$$

Here $2M_D$ is the mass of the charmed meson pair, and 160 MeV/c^2 means the universal hadronic temperature. If you make such an assumption, then you find that the production of charmed pairs should be only approximately 2% of the production of the ψ, i.e.

$$\sigma(D\bar{D})/\sigma(\psi) \sim 0.02 \quad .$$

This is a very tiny cross section indeed.

I show you a smooth curve representing the excitation curve for ψ production in pp-collisions as a function of the center of mass energy.



The vertical axis points out the cross section as a function of rapidity y at zero rapidity in the center of mass. So the integrated cross section is perhaps one or two times larger than this. You see that we are dealing with a cross section on the order of 10^{-31} cm^{2} even at ISR energies. A cross section two orders of magnitude below the ψ cross section would make it virtually impossible to search to for charm in such a reaction. It seems that on this basis the thermodynamical argument is very discouraging.

There are also numerous schemes which argue in just the opposite way. They say that to produce charmed quarks is not any harder than to have them stick and form a ψ-meson. They argue therefore that the production of unbound charm should be easier than the production of bound charm. There is a little bit of justification for this point of view because if you look at the cross section to produce a pair of strange particles compared with the cross section to produce the ϕ-meson this cross section ratio is approximately equal to 20,

$$\sigma(K\bar{K})/\sigma(\phi) \sim 20$$

for pp-collisions at 24 GeV/c.* It is therefore popular to guess, although this is not defended by any very convincing theory, that charm production is 20 to 30 times larger than ψ-production at high energies. A guess that people make by this technique is that the cross section for the inclusive production of charm in hadron-hadron collisions should be about 1 μb at 400 GeV/c. Because of small branching ratios into visible final states the cross section times branching ratio is much smaller. We expect, therefore, an unfavorable signal to background ratio in hadronic collisions. The searches which have been carried out so far have failed to find any charmed particles in hadron collisions. There is not yet any interesting limit compared with this projection of 1 μb. [Note added: Recent beam-dump experiments at CERN have yielded evidence for a new source of prompt neutrinos: P. Alibran, et al., Phys. Lett. 74B, 134 (1978); T. Hansl, et al., ibid., p. 139. P.C. Bosetti, et al., ibid., p. 143. A Caltech-Stanford calorimeter experiment at Fermilab has observed prompt muons in coincidence with missing energy: M. Shaevitz, talk at the 1978 Vanderbilt Conference. These experiments can be explained as the production and semileptonic decay of charmed particles. The inferred production cross section is $\sim$10-100 μb. at 400 GeV/c.]

4. Production in $(\nu, \bar{\nu})N$ reactions

Another place which is more favorable for the observation of charm is in neutrino reactions. Here we have at our disposal, since we know everything about

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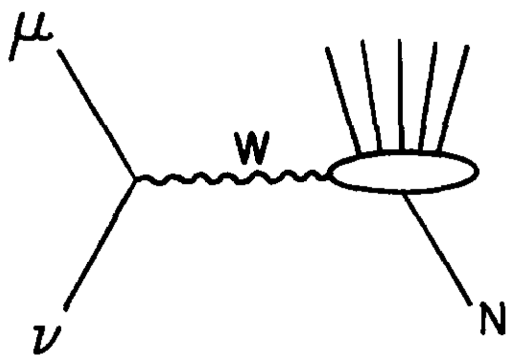
*V. Blobel, et al., Phys. Lett. 59B, 88 (1975).

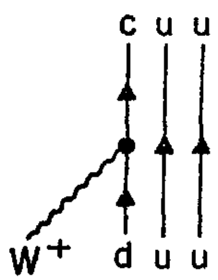
the weak interactions of charmed particles, all the ingredients we need to estimate the cross section for charm production. To do so we use the quark-parton picture. We will regard the reactions



as the neutrino (antineutrino) turns into $\mu^-(\mu^+)$ by emitting a virtual $W^+(W^-)$, the virtual $W^+(W^-)$ then interacts with a quark inside nucleon to produce the final state. I write down again the form of charm-changing charged current

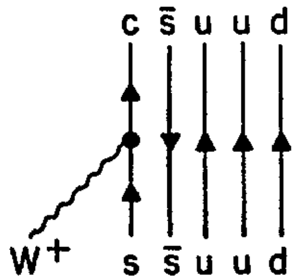
$$J_\mu^{(+)} \sim \bar{c}\gamma_\mu(1+\gamma_5)s\cos\theta_C - \bar{c}\gamma_\mu(1+\gamma_5)d\sin\theta_C \quad .$$

We can now enumerate many weak processes by which charmed particles can be produced in ν collisions. I start with ν collisions and show you 3 examples. For ν nucleon scattering there is an interaction of W^+ with a d-quark, and the d-quark is obviously present in the valence regime for the nucleon. So that occurs rather frequently here but with Cabibbo-reduced strength by $\sin\theta_C$ because of the structure of charged current. We have therefore a picture

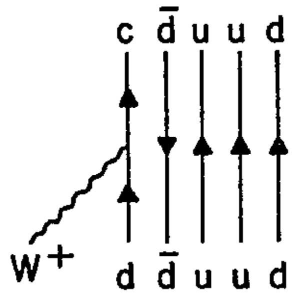


$\sin\theta_C$ valence quarks

There are then two other diagrams. If I consider the nucleon as being made of more than 3 quarks and having a sea of quarks and antiquarks in it, a strange quark from the sea can be changed into a charmed quark with a cos θ_C factor or a d-quark again from the sea can be changed into a charmed quark with a sin θ_C factor. So we picture all this as



$\cos\theta_C$ sea quarks



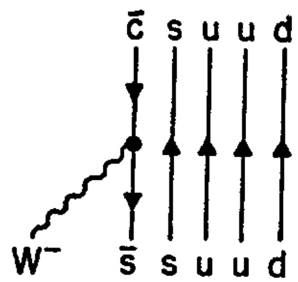
$\sin\theta_C$ sea quarks

If one takes reasonable models for the distribution of partons in the nucleon, then it is possible to make a calculation. One finds that far above threshold the production of charm occurs at the 10% level from the non-charm production cross section.

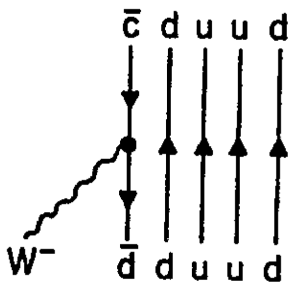
$$\sigma(\text{charm})/\sigma(\text{non-charm}) \approx 0.1 \quad .$$

This is again a rather favorable and large cross section. The distinction as opposed to e^+e^- annihilation is that the total number of events one can accumulate is very small in most neutrino experiments.

We can have the same kinds of interactions for $\bar{\nu}$ collisions. Now there are no allowed transitions from valence quarks. The strongest contribution is from the $\cos\theta_C$ transition of a strange antiquark into a charmed antiquark, the first being from the sea. There is also a transition of $\bar{d}$-quark from the sea into a $\bar{c}$-quark, which is Cabibbo-suppressed. We picture these processes:



$\cos\theta_C$ sea quarks



$\sin\theta_C$ sea quarks

Far above threshold, making the same kind of reasonable assumption as for the neutrino case, we expect charm to be about 13% of noncharm production. Now let us remember that the total cross section for $\bar{\nu}$ scattering is about 1/3 of the total cross section for ν scattering, i.e.

$$\sigma_{\bar{\nu} N}/\sigma_{\nu N} \simeq 1/3 \quad .$$

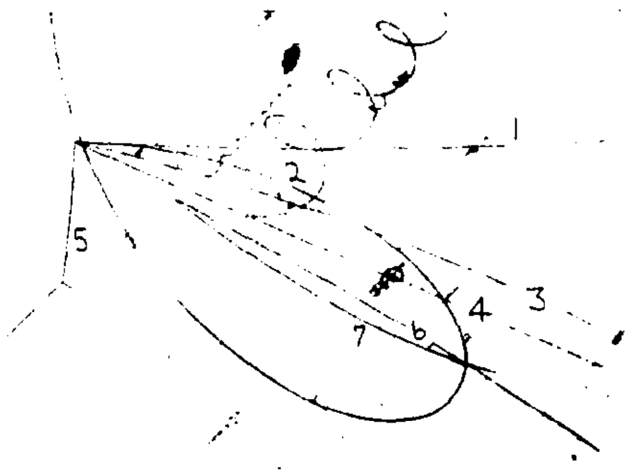
We see that the total charm production in antineutrino collisions is smaller than in neutrino collisions by a factor of 1.3/3 or

$$\sigma_{\bar{\nu}}(\text{charm})/\sigma_{\nu}(\text{charm}) \simeq 40\% \quad .$$

It appears that both reactions are appropriate, from the point of view of the signal to noise ratio, to search for charm. As we already saw in e^+e^- annihilation reactions it is possible to sit at a single energy and to accumulate a large number of events. Therefore one can expect to have good invariant mass distributions for various combinations of particles and to search for peaks. In the case of neutrino scattering, event rates are rather small. So the observation of peaks in invariant mass distributions is very hard. However, it is probable that the first example of charmed particle production and decay was seen in a neutrino bubble chamber experiment. There is a single event, which is quite exceptional. It was found in a Brookhaven experiment in 1975 (E.G. Cazzoli, et al., Phys. Rev. Lett. 34, 1125 (1975)). The experimenters interpreted it as the production of C_1^{++} charmed baryon, which undergoes strong decay into π^+ and C_0^+ baryon, the last weakly decaying into $\Lambda\pi^+\pi^+\pi^+\pi^-$. So the production and decay chain looks like

$$\begin{array}{l} \nu + p \rightarrow \underset{(4)}{\mu^-} + C_1^{++}\ (2425\ \text{MeV}/c^2) \\ \qquad\qquad \lfloor \text{strong} \rightarrow \underset{(2)}{\pi^+} C_0^+\ (2250\ \text{MeV}/c^2) \\ \qquad\qquad\qquad \lfloor \text{weak} \rightarrow \underset{(67)}{\Lambda}\ \underset{(5)}{\pi^+}\ \underset{(3)}{\pi^+}\ \underset{(1)}{\pi^-} \end{array} \quad .$$

I show to you this possibly historic event. The tracks are labeled as indicated above.



A neutrino enters the chamber from the left. Of course, it is a single event and it is difficult to draw a strict conclusion from a single event. But it is quite an exceptional one because if you do not interpret it as a charmed particle event this event would be something else we had never seen before. That is, it would be the first observed violation of the rule for the strangeness-changing semileptonic decays, by which the charge and strangeness of the hadronic system must change by the same amount. This is a rule which we can read off from the hadronic charged current

$$J^{(+)} \sim \bar{u}d \cos\theta_C + \bar{u}s \sin\theta_C \quad .$$

where the last term changes the strangeness and charge of quarks by 1 unit so that we find $\Delta S = \Delta Q = 1$. The initial state of this process, p, has $Q = 1$, $S = 0$. The final state $\Lambda\pi^+\pi^+\pi^+\pi^-$ has $Q = 2$, $S = -1$. The charge changes by 1, the strangeness changes by -1.

$$p \rightarrow \Lambda\pi^+\pi^+\pi^+\pi^- \quad .$$

In the absence of any experimental interpretation for it as a misidentification, it would be a very special event by itself. Confidence that it is probably a charmed baryon grows because in a photoproduction experiment last year at Fermilab some, evidence not completely convincing but very strong, which I will show you tomorrow, indicates that this is in fact the correct mass for the charmed baryons.

Let us discuss for a few minutes the inclusive indications for charm in ν, $\overline{\nu}$ interactions. In most counter experiments, which are capable of accumulating a large number of events, the individual hadrons are not identified. But the bubble chamber experiments, where one can see some interesting events, typically have very low rates. So the problem is how to find some way by which we can make use of the large signal to noise or signal to background ratios as we expect in neutrino interactions, to see evidence for charmed particles. One of the things we can do is to observe that the semileptonic decays of charmed particles will lead sometimes to events having two charged leptons in the final state. By now there are a large number of examples in the bubble chambers of reactions such as

$$\nu N \rightarrow \mu^- + e^+ + \text{hadrons}$$

where the muon comes from the original charged current interactions and the e^+ comes, it seems, from a semileptonic decay of charm. There are about a hundred of these events reported so far and many of them have accompanying strange particles among the hadrons, the decay into strange particles being another of the signals which is seen for charmed particles. The experiments listed here are references for experiments with the Gargamelle bubble chamber at CERN (the first two) and the last two for two different experiments using the 15 foot bubble chamber at Fermilab.

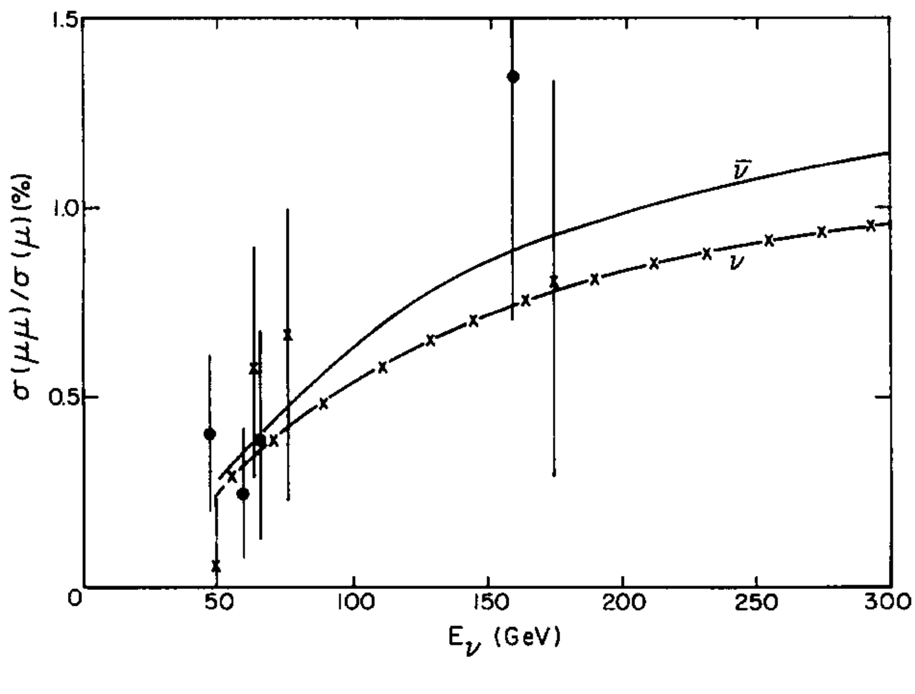
H. Deden, et al., Phys. Lett. 58B, 361 (1975).

J. Blietschau, et al., Phys. Lett. 60B, 207 (1976).

J. von Krogh, et al., Phys. Rev. Lett. 36, 710 (1976).

C. Baltay, et al., Phys. Rev. Lett. 37, 62 (1977).

Actually one of the earliest indications for charm was the observation of dimuon events in $\nu(\bar{\nu})N$ scattering in the Fermilab counter experiment that Prof. Mann will describe (A. Benvenuti, et al., Phys. Rev. Lett. 34, 419 (1975)). This phenomenon has now been studied in other large counter experiments at Fermilab and CERN by Caltech-Fermilab and by CERN-Dortmund-Heidelberg-Saclay teams. I show you here just an example of some recent measurements. It comes from the Caltech-Fermilab experiment (B.C. Barish, et al., CALT 68-603).

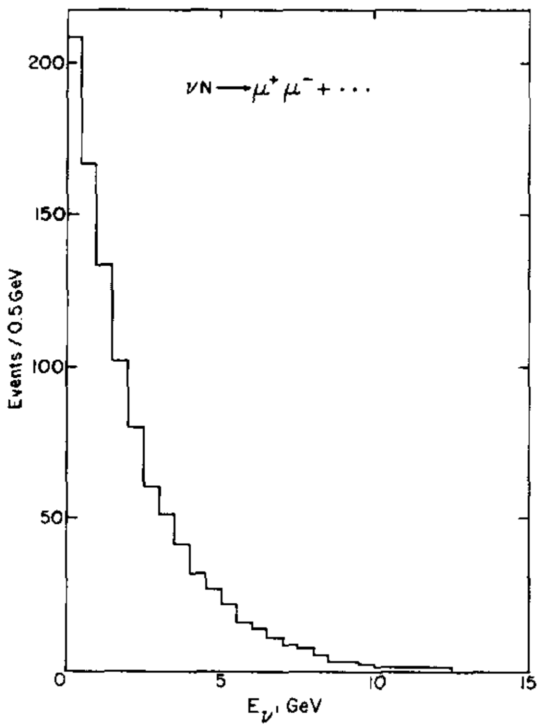


What is plotted here is the cross section to observe dimuon events divided by the cross section to observe the muon final state as the function of neutrino energy. I use a cross for ν data. The curves show the prediction of a quark-parton model for charm production. As we have said in our brief discussion there are more charmlike events in antineutrino interactions than in neutrino scattering. As a whole these data appear to be consistent with the charm hypothesis for production and decay, because of the magnitude for the cross section which one expects. [See C.H. Lai, Fermilab-Pub-78/18-THY.]

These dimuon events now are being studied in great detail in order to give specific masses for the charmed particles. If we can verify that these are coming from charmed particle decays then because of our specific ideas for charmed particle production we can learn something about the dynamics of neutrino interactions from the observation of these events. So we are using now charm as a tool to understand neutrino physics.

Let us discuss the other expected characteristics of dimuon events:

1) There is a missing neutrino which is not detected and should carry off some energy in the final state.



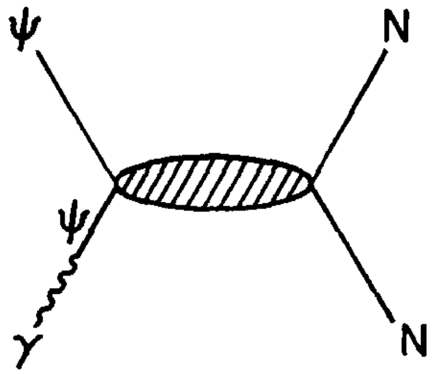
I show you a calculation appropriate for the neutrino spectrum at Serpukhov, which shows the amount of missing energy of dimuon events in νN scattering. Then you see that there is typically 1 or 2 GeV of missing energy in a broad band environment, which is a very difficult thing to detect. What one can hope to learn from a broad-band experiment is that the total energy spectrum that you deduce from your two-muon events would be different from that in the one-muon events, by a systematic shift to lower energies. There have been some observations now in a narrow-band beam at CERN by the CERN-Dortmund-Heidelberg-Saclay collaboration, which indicate that in their dimuon events there is indeed some missing energy, typically on the average about 8% of the incident energy. This is consistent with what one expects on the basis of charm particle production and decay.

2) Now there are also many kinematical distributions which reflect the production mechanism. But I think that Prof. Mann will be dealing with it in detail so I only mention an obvious one, which we now are ready to accept from our discussion. We said that charm production by antineutrinos came from quarks in the sea. This is concentrated at small momenta, small values of x, whereas it is possible for neutrino production to make charm from valence quarks at some larger values of x. This kind of difference in the distribution is indeed seen as expected, i.e.

$$\langle x \rangle_{\bar{\nu}} \ll \langle x \rangle_{\nu} \quad .$$

5. Photoproduction of Charm

The last place that one can think of looking for charmed particles is in photoproduction, because the photon can couple to the charmed quark charge and you hope to have a large signal. We argue that in the timelike region above the charm threshold the hadronic composition of the photon is about 40% $c\bar{c}$. In the case of photoproduction one can ask with what probability does this $(c\bar{c})$ component materialize as charmed particles? There is a very simple argument one can make based on an analogy with ψ photoproduction in the reaction $\gamma N \to \psi N$. In a vector dominance picture we interpret ψ-photoproduction as an incident photon turns into a virtual ψ, which elastically scatters from the target and becomes a real ψ.



This is a process now very well studied from 12 GeV up to about 250 GeV. On the basis of those experiments it is possible to conclude within a factor of 2, I should say, that the elastic cross section for ψN scattering is very small compared to total cross section for ψN scattering. So perhaps

$$\sigma_{elastic}(\psi N)/\sigma_{tot}(\psi N) \sim 5\% \quad .$$

Then because of our arguments about peripheral reactions it is hard to exchange charm quantum numbers from one side of the reaction to the other. It is a reasonable guess that inelastic scattering of the ψ N system leads to the dissociation of the ψ into explicitly charmed pair states. If we make such a guess then the photoproduction of charm would be

$$\sigma(\gamma N \rightarrow \text{charm}) \approx 20\,\sigma(\gamma N \rightarrow \psi N) \sim 1\ \mu b$$

at 150 GeV.

This concludes our survey of the names, masses, decay modes and production mechanisms of charmed particles. Next I will give you a summary of the experimental situation with respect to the spectrum of charmed particles.

LECTURE IV. EXPERIMENTAL STATUS OF CHARM

1. Summary of the data

Today I will deal with two separate topics in two hours. In the first hour I will survey only charmed particles and in the second hour I will give a discussion of the new particles, newer than the charmed particles, which were recently discovered at a mass of approximately 10 GeV/c^2.

In the first part of this lecture I would like to survey the experimental status of charmed particles, and of particles with "hidden charm." There are now a rather large number of well-established states. I list here the states which are bound states of charmed quark and charmed antiquark, together with the spin-parity and charge conjugation assignments for these levels

	J^{PC}
$\psi(3095)$	1^{--}
$\psi(3684)$	1^{--}
$\psi(3772)$	1^{--}
$\psi(4414)$	1^{--}
$\chi(3415)$	0^{++}
$\chi(3508)$	1^{++}
$\chi(3552)$	2^{++} .

These include 2 narrow vector states ψ, ψ' and a recently found state at 3772 MeV/c^2. They include also 2 other states, which are broader than the first, which are vector states above the charm threshold. There is an enhancement at 4414 MeV which seems to have a well-defined existence as a single state. There is also an accumulation of states around 4.01 GeV, which are not yet resolved into separate levels. We have then a number of states of even charge conjugation. I adopt the SLAC terminology and call them χ states. Their spins are reasonably well established as 0, 1, 2 and the masses are as shown. In the second hour I will tell a little more about the spectroscopy of the levels made of $c\bar{c}$ bound states. Of the states explicitly carrying charm, four states are now established and studied in some detail.

$D^0(1863)$	0^{-+}
$D^+(1868)$	0^{-+}
$D^{*0}(2006)$	1^{--}
$D^{*+}(2009)$	1^{--} .

These are the D^0 and D^+ mesons, which are nearly proved to have spin-parity 0^-. They have two vector partners D^{*0} and D^{*+} lying higher. In addition there is evidence for some other states. I regard these states as not fully established because they were seen in only a single decay mode. But the fact that they have specific masses attached to them means that there is some confidence that in the near future these states will become firmly established. In the $c\bar{c}$ system we include the levels which are probably pseudoscalars, the so-called η_c, named X and discovered at DESY, and η_c' with mass 3455 MeV/c^2 which is seen in electromagnetic transitions between ψ' and ψ. Neither of these has been seen in any hadronic decay modes yet and that is the reason I refuse to move them into the company of well-established states. So we can say there is some evidence for

$$\begin{array}{lll} \eta_c' & X(3455) & 0^{-+} \\ \eta_c & X(2830) & 0^{-+} \end{array} \quad .$$

There are also charmed mesons, which have both strangeness and charm, the so-called F mesons. Recently there has been evidence reported for the decay of the F-meson into $\pi^+\eta$ and the accompanying electromagnetic transition from the F^* to the F. These are seen in a few events so far, with very little background but nevertheless a small sample.* So I continue to list the F in not well-established company

$$\begin{array}{ll} F^+(2030) & 0^{-+} \\ F^{*+}(2140) & 1^{--} \end{array} \quad .$$

There is also evidence, again circumstantial and not completely convincing, for the existence of a number of charmed baryons

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*R. Brandelik, et al., Phys. Lett. 70B, 132 (1977).

$$C_0^{+}(2250),\ C_1^{0,++}(2400),\ C_1^{*0,++}(2475) \quad ,$$

in total five. All but the charmed baryon candidates have been discovered in e^+e^- annihilations. I will summarize for you their properties this morning and try to derive inferences of a more or less theoretical nature from them. The detailed discussion of the discovery will be given by Dr. Wolf.

There are in addition some very useful and accessible summaries of the discovery of charmed mesons:

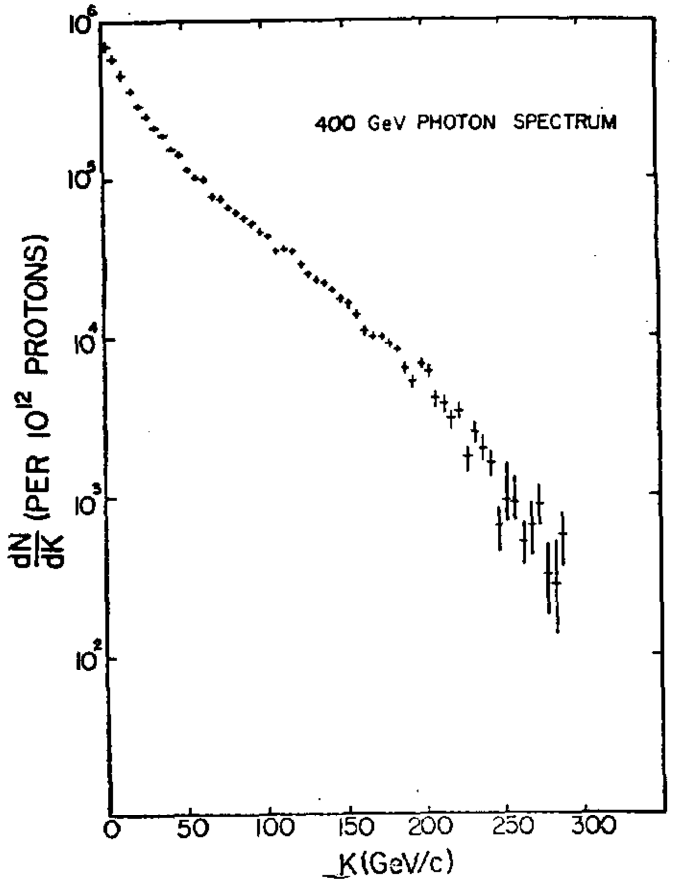
V. Lüth-Baku Lectures-SLAC PUB-1873.

G. Goldhaber-LBL-6481.

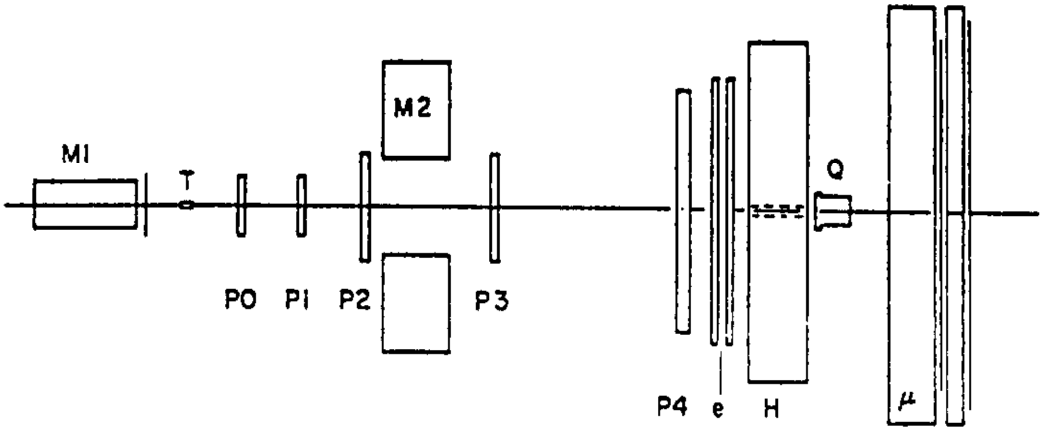
G. Feldman-SLAC-PUB-2000.

Since the charmed baryon candidates are the least well established I will talk about them first. Because they are not well established it is necessary to talk in some detail about the indications for them. Let me describe the evidence for them. We mentioned yesterday the single exceptional event, which appears to be a $\Delta S = -\Delta Q$ transition in the Brookhaven neutrino experiment. This is interpreted as a quasielastic production by a ν of a single charmed baryon, which decays into a $\Lambda 3\pi^+\pi^-$ system. There are additional events of this character found in a Fermilab photoproduction experiment, in which a Beryllium target is exposed to the broad band photon beam: γ + Be$\rightarrow$ ... The evidence for charmed antibaryons discovered in this experiment was published by B. Knapp, et al., Phys. Rev. Lett. 37, 882 (1976). I shall describe the experiment very quickly. It is a forward spectrometer in a broadband photon beam. I will show you a picture in just a moment. The trigger for this experiment is "high" multiplicities. The selection of events was to search for charm candidates between 3-8 tracks in the forward spectrometer. The total momentum of all these tracks must not exceed 250 GeV/c. The upper limit on the momentum of particles was imposed to reduce the background of neutrons and K_L-mesons in the photon beam. In this experiment, (I will show you the data as we go along) they found evidence for the antiparticle of the object seen in the Brookhaven neutrino experiment. That is the decay of the particle $\bar{C}_0^-$, the lowest-lying spin ½ charmed antibaryon decaying into $\bar{\Lambda}\pi^-\pi^-\pi^+$. As is expected for charmed particles there is no signal in the channel $\bar{\Lambda}\pi^+\pi^+\pi^-$. So this is the signature expected for charm. A difficulty in this experiment is that in a photon beam you will expect to make both particles and antiparticles equally, but nevertheless one cannot produce any convincing evidence for the particles C_0^+ in this case. There are a number of complicated arguments that the background is much higher in the particle channel than in the antiparticle channel. This is plausible to some degree but not entirely convincing.

This is the photon beam available at Fermilab with 400 GeV protons:



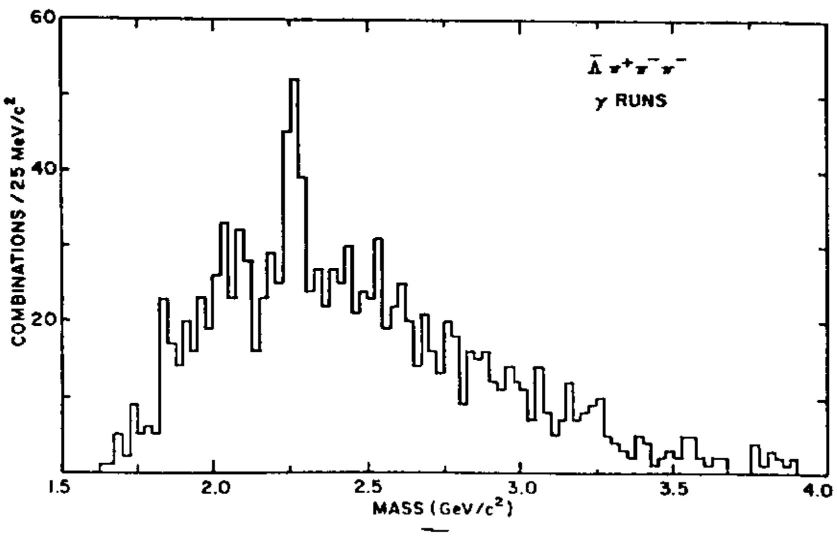
You see that there are large numbers of photons in the region of energy between about 50 and 200 GeV, which are useful in this kind of experiment. The spectrometer is rather standard.



There is a magnet (M1) to sweep away charged particles in the beam, T means a target, a number of chambers, a magnet (M2) and downstream chambers. Momenta are analyzed by the magnet. The most interesting picture from the experiment is the invariant mass distribution for

$$\bar{\Lambda}\pi^-\pi^-\pi^+ \quad .$$

the state in which one may expect a charmed baryon.



There is a prominent peak at a mass about 2.250 GeV. That is the basis of the claim one has observed a charmed antibaryon here.

There are also some indications that the C_1 or C_1^* has been seen as an object that cascades by π^- or π^+ emission to the observed C_0:

$$\bar{C}_1^{--} \text{ or } \bar{C}_1^{*--} \rightarrow \pi^-\bar{C}_0^-$$

and

$$\bar{C}_1^{0} \text{ or } \bar{C}_1^{*0} \rightarrow \pi^+\bar{C}_0^- \quad .$$

It's my view that this experiment is probably right. The charmed baryons probably exist with the masses observed here, but it is not proved yet by this experiment. It is still a circumstantial case. The experimenters are building new apparatus and expecting to have more running soon, which, if they are lucky, will confirm and expand this analysis.

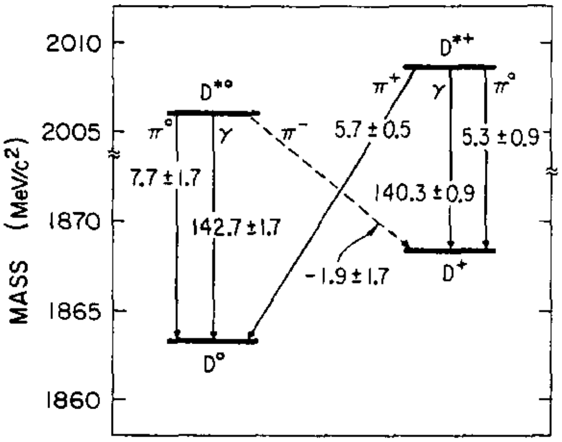
There were two recent detailed discussions of the expected properties of charmed baryons:

De Rujula, Georgi, Glashow, Phys. Rev. Lett. 37, 398, 785 (1976) and
Lee, Quigg, Rosner, Phys. Rev. D15, 175 (1977).

In both papers the possibilities of making and observing charmed baryons were discussed in very great detail.

So here we have a subject about which there is very little more to say of a decisive and concrete nature because the experimenters so far provide us only with hints, and not detailed information.

The situation is rather different in the case of charmed mesons. In the case of charmed mesons we now begin to have a well-defined and well-established spectroscopy of their states. I restrict myself for the rest of this talk to the D mesons because those are the ones that have been seen in a number of decay modes and from themwe can begin to draw some conclusions. Here is the level diagram of D^0, D^{*0}, D^+ and D^{*+}:



By a complicated spin analysis that I have no time to discuss, it has been made extremely likely that the correct spin assignments are pseudoscalar lower and vector upper levels.* The arrows indicate the observed transitions between the excited vector states and the pseudoscalar states. The D^{*0} has been seen to decay by π^0 and photon emission to D^0. You notice that the Q-value available, the energy left over for a decay into π^0 and D^0 is only about 8 MeV. Because the separation nearly forbids the strong decay energetically we have a unique situation in hadron physics in that the electromagnetic decay is comparable to an allowed strong decay. For $D^{*0} \to D^0\pi^0$ one has about 55% and for $D^{*0} \to D^0\gamma$ one has 45%. D^{*+} has been also observed to decay by π emission into D^0, a large fraction of the time, approximately 65%, and by π emission to the D^+. Because of the

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*H.K. Nguyen, et al., Phys. Rev. Lett. 39, 262 (1977).

isospin Clebsch there is a smaller rate, about 30%. Another number which is not very well known now but seems to be in the neighborhood of 5% is the branching ratio of D^{*+} into γ and D^+. So again there is a competition, a successful one as in the neutral case, among the electromagnetic and strong decays. It appears that the decay D^{*0} into $D^+\pi^-$ is energetically forbidden.

The D mesons have been observed in large numbers at the center of mass energies of 3772 MeV, 4028 MeV and 4414 MeV. Most recently with the discovery of the object at 3772 MeV, which decays almost exclusively into $D\bar{D}$, it becomes possible for the first time to estimate the branching ratios of the D-meson. The data are new, and subject to a number of clarifications of the assumptions underlying the analysis, but for present purposes let us regard them as representing the correct answer.* It appears to be reliable within a small factor that four channels have been observed for D^0-decay, with the following branching ratios:

$$\begin{aligned} D^0 \rightarrow\ & K^-\pi^+ && 2.2 \pm 0.6\% \\ & \bar{K}^0\pi^+\pi^- && 4.0 \pm 1.3 \\ & K^-\pi^+\pi^0 && 12 \pm 6^{**} \\ & K^-\pi^+\pi^+\pi^- && 3.2 \pm 1.1 \end{aligned} \quad .$$

The D^+ has been seen recently in the decays

$$D^+ \rightarrow \bar{K}^0\pi^+ \quad 1.5 \pm 0.6\%$$

and first in the decay

$$K^-\pi^+\pi^+ \quad 3.9 \pm 1.0 \quad .$$

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*I. Peruzzi, et al., Phys. Rev. Lett. 39, 1301 (1977).

**D.L. Scharre, et al., Phys. Rev. Lett. 40, 74 (1978).

These branching ratios are very small numbers. Roughly speaking we expect them to be small numbers because these states are so massive and have a large number of final states available to their decays.

It has to be demonstrated that these particles decay weakly, one of the main requirements for them to be interpreted as charmed particles. If I slightly modify the arguments that have been given, we can only deal with the D^+-meson. The D^+ decays into $\bar{K}^0\pi^+$, that is decays into 2 pseudoscalars. Therefore D^+ has natural spin-parity. On the other hand we have information about the decay $D^+ \to K^-\pi^+\pi^+$. For a 3-body decay one can examine its structure by the Dalitz plot, in which the momenta of three particles are displayed. That distribution has certain symmetries depending upon the spin-parity of the decaying object.

From the consideration of 3-body Dalitz plot for D^+-decay one can demonstrate that in the decay of $D^+ \to K\pi\pi$ the D^+ acts as if it has unnatural spin-parity. Consequently, we have the same object appearing to be in a natural parity state and in an unnatural parity state. The obvious interpretation is that parity is violated in these decays. More elaborate proof that the decays are weak can be found in the papers

Lee, Quigg, Rosner, Comments Nucl. Part. Phys. VII A, 49 (1977).
J. Wiss, et al., Phys. Rev. Lett. 37, 1531 (1976).

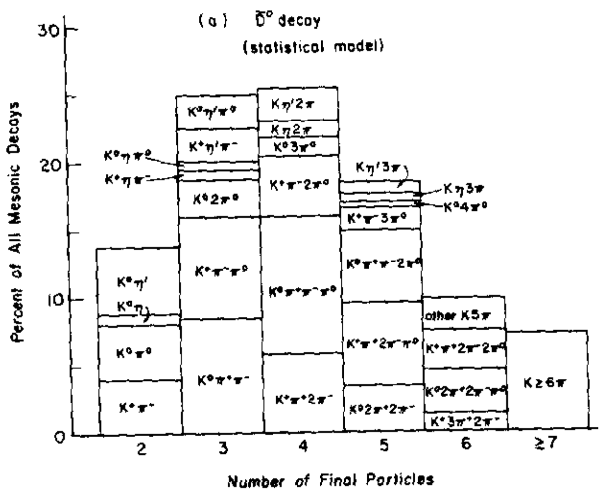
The next topic which we are interested in now, is what we can learn of a dynamical nature from the study of charmed particle decay modes. We want to know is there any "interesting" relation among the various decay modes. It is hoped that we would gain some new information about weak decays in this fashion because charmed particles give us the first opportunity to study multi-body weak decays. In order to know what to make of the data one needs some theoretical guidance. In constructing a theoretical guide of this kind it is often useful to do something as simple as possible and hope to learn from the deviations from a simple model how the real world actually works. For this purpose we construct a very crude statistical model of heavy meson decays. We hope that this takes account of obvious kinematical effects and we can learn from comparing with the data what are the dynamical effects involved. The ingredients of this model are:

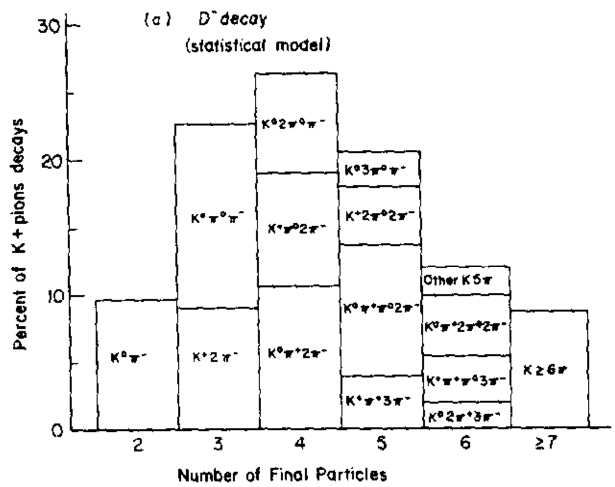
1) To invent an estimate for the mean multiplicity of particles in a decay or class of decays using a variant of the Fermi statistical model, which we have checked agrees with ψ, and ψ' decays and also with charged multiplicity observed in e^+e^- annihilation into hadrons at center of mass energies below 5 GeV.

2) We then assume, for no good reason but simplicity, a Poisson distribution for the multiplicities making up this mean number. It has been checked that for the decays of ψ and ψ' this is a good description of the multiplicity distributions.

3) Finally we use a statistical isospin model to assign relative weights of specific charge states. This assumption has been checked only in $\bar{p}p$ annihilation into hadrons, for which it is found to underestimate somewhat the number of neutral particles. We have not checked this assumption for the heavy mesons because the neutral signal has not been observed yet. By this kind of a model and using SU(3) symmetry to relate various kinds of decay modes we can predict everything. For the decay of D^0 one can make a rough prediction for the relative importance of various decay modes (see Quigg and Rosner, Phys. Rev. D17, 239 (1978)). Now the point is not for you to look at this and to record all the possibilities, but to know that it is possible to arrive at reasonable guesses for the multiplicity distribution and for the branching ratios into specific final states. We then compare this prediction with the data. The point now is not to learn that this

is a true description of the world, because we would be very disappointed if something so naive would be true, but to learn something from deviations from it.





So we compare with the data, first for D^0. I compute the ratio of the predictions to the measurements for the four decay modes seen up to now:

Mode	Prediction/measurement
$D^0 \rightarrow K^-\pi^+$	$(1.82 \pm 0.50)f$
$\bar{K}^0\pi^+\pi^-$	$(2.10 \pm 0.68)f$
$K^-\pi^+\pi^0$	$(0.62 \pm 0.31)f$
$K^-\pi^+\pi^+\pi^-$	$(1.82 \pm 0.62)f$

The prediction was for the Cabibbo-favored decay into mesons. We did not consider the decays into baryon and antibaryon because they are energetically forbidden. We did not consider semileptonic decays in this analysis. So we must take care of them in some way. We did not consider the small fraction of Cabibbo-suppressed decays. So we must multiply all the numbers that I have deduced by a factor f, which is the fraction of the decays considered divided by all decays

$$f = \frac{\text{Cabibbo-favored decays into mesons}}{\text{all decays}} \quad .$$

If the factor was ½, these numbers would approach 1 and we would have reasonable agreement between the simple model and the data. We can ask if ½ is a reasonable number or such an odd number that something unexpected must be going wrong. In fact it is not too unreasonable if semileptonic branching ratios are large. We estimated in a crude quasi-free model for the inclusive decay rates that each semileptonic decay, that is the decay into electron, neutrino plus hadrons and the decay into muon, neutrino plus hadrons, could be about 20% of the total. So we see that the other hadronic decays would be approximately 60% of the total. I could reduce it more because Cabibbo-suppressed decays are not considered, and I could arrive at a number around ½. The semileptonic branching ratios are only now beginning to be measurable independently. They are not yet known well enough to fix the fraction f with great precision.

The indications are that the semileptonic branching ratios are close to 10% but there is some variation among experiments. This model also predicts that mean charged multiplicity for the hadronic decays should be

$$\langle n_{ch} \rangle \simeq 3 \quad (2.3 \pm 0.2) \quad .$$

This one can compare with the measured value in parentheses. The measurement includes again some semileptonic decays. So before the effects of semileptonic decays are separated all we can say about the D^0-decays is that they are in reasonable agreement with the simplest model that we can imagine.

It is also possible to construct such a model for the D^+ decays. The experimental uncertainties in almost all branching ratios are much larger, but it is possible already that the comparison of the prediction of the simple statistical model with the measurements is "interesting." We find that the ratio of the prediction to measurement is a very large number with large errors

Mode	Prediction/measurement
$D^+ \rightarrow \bar{K}^0\pi^+$	$(6.47 \pm 2.59)F_{K\pi}$
$K^-\pi^+\pi^+$	$(2.32 \pm 0.60)F_{K\pi}$.

Again we must correct for the fact that we have considered only a fraction of the decays in this case, only the decays into K plus pions, so

$$F_{K\pi} = \frac{\bar{K} + n \text{ pions decays}}{\text{all}} \quad .$$

In order for these numbers to be changed to 1 we need this fraction of decays to be about 30%. This seems to me extremely hard to imagine, unless something interesting is going on such as a dynamical suppression. I will show you in a few minutes that there is some reason to hope that in the case of D^+ decay there would be such an interesting dynamical suppression. Again there is some difference between the charged multiplicity of the model and of the data

$$\langle n_{ch} \rangle = 3.1 \quad (2.3 \pm 0.3)_{\text{exper.}} \quad .$$

The data again include semileptonic decays and their multiplicities are not understood.

This is a brief survey of the data as they stand now. They are accumulating very rapidly now, new states or new decay modes being established every month and there is a great deal of activity and very hard work among the experimenters. Now they are beginning to obtain data which speak to detailed and important questions. We will next turn to the more complicated theoretical issues which have to do with these weak decays. This goes largely under the rubric of nonleptonic enhancement.

2. Nonleptonic Enhancement

This is a subject which is rather difficult to discuss. It is difficult to discuss because we do not understand it. Most of the arguments are qualitative, based on experience and calculations which oversimplify, rather than real explanations of anything. I will try to describe them to you in rather qualitative and I may say nonexpert terms but I think it reflects the theoretical situation.

What is known with certainty is that we have to invent this concept. If we look at the nonleptonic decay rates of the known strange particles, hyperons and the strange mesons, those for the nonleptonic decays are larger than predicted with the universal strength from leptonic and semileptonic weak interactions by a factor of up to 20.

A second ingredient is the regularities which occur from time to time experimentally in the study of weak decays which do not have an immediate theoretical explanation, and for which we must invent a rule such as the $\Delta I = \frac{1}{2}$ rule for the strangeness-changing decays. An example is the $K_S \to \pi\pi$ decay. A comparison of decay rates indicates that the amplitude which leads to isospin 2 final states is very tiny compared with the amplitude which leads to isospin 0 final states. In terms of the amplitudes

$$|A_2/A_0| \lesssim 5\% \quad .$$

The piece of the interaction Hamiltonian which leads from the K_S meson to isospin 0 is a $\Delta I = ½$ piece. The piece that would lead to isospin 2 would be a $\Delta I = 3/2$ piece. So a puzzle appears. On the one hand we find the nonleptonic Hamiltonian enhanced, on the other hand we find only a piece of it benefits from the enhancement. There is a rather nice review of the experimental situation by M.K. Gaillard and J.-M Gaillard: "Nonleptonic Interactions," in Weak Interactions, edited by M.K. Gaillard, a volume in the series Textbook on Elementary Particle Physics, edited by M. Nikolic. This review is based on lectures at a summer school in Zagreb.

Another piece of evidence for the suppression of the $\Delta I = 3/2$ part in the weak interactions is the small decay rate for $K^+ \to \pi^+\pi^0$. This is necessarily a $\Delta I = 3/2$ transition and the fact that the decay rate is small again points out that there is no enhancement.

The first thing we will do as theorists is try to take this nonleptonic enhancement and give it another name or another excuse for happening and then try to explain the explanation.

In the usual Cabibbo theory with only u,d and s-quarks and suppressing the space-time properties of the weak current I can write the weak current as a Cabibbo-favored transition of a d-quark to a u-quark and a Cabibbo suppressed transition from an s-quark to u-quark

$$J_h = \bar{u}(d \cos\theta + s \sin\theta) \quad .$$

This current transforms in SU(3) like a member of an SU(3) octet. Then I may inquire into the transformation properties of the weak Hamiltonian. The weak Hamiltonian is the symmetric combination:

$$H_W = \tfrac{1}{2}(JJ^+ + J^+J) \quad .$$

Therefore it transforms as the symmetric sum of products

$$([\underset{\sim}{8}] \otimes [\underset{\sim}{8}^*]) \oplus ([\underset{\sim}{8}^*] \otimes [\underset{\sim}{8}]) \quad .$$

There is a number of contributions to the product $[\underset{\sim}{8}] \otimes [\underset{\sim}{8}]$. I will use a subscript s for symmetric combinations and subscript a for antisymmetric ones:

$$[\underset{\sim}{8}] \otimes [\underset{\sim}{8}] = [\underset{\sim}{1}]_s \oplus [\underset{\sim}{8}]_s \oplus [\underset{\sim}{8}]_a \oplus [\underset{\sim}{10}]_a \oplus [10^*]_a \oplus [27]_s \quad .$$

When I symmetrize the weak Hamiltonian the antisymmetric combinations drop away and I am left with the weak Hamiltonian which contain only the symmetric pieces for its transformation properties

$$H_W \simeq [\underset{\sim}{1}] \oplus [\underset{\sim}{8}]_s \oplus [\underset{\sim}{27}] \quad .$$

This includes a singlet which of course doesn't participate in strangeness-changing interactions, an octet piece and a 27-dimensional piece. If I now look at the parts of these representations which change strangeness by one unit, I can ask about the isospin content of them. The octet of course contains only a doublet of SU(2) that is to say, a piece which changes isospin by ½.

$$|\Delta S| = 1; \quad [\underset{\sim}{8}] \supset (\underset{\sim}{2}): \quad |\Delta I| = \tfrac{1}{2} \quad .$$

The $\underset{\sim}{27}$, on the strangeness-changing level, contains two pieces, an SU(2) doublet or $|\Delta I| = \tfrac{1}{2}$ piece and an SU(2) quartet which can change isospin by 1/2 or 3/2.

$$|\Delta S| = 1;$$

$$[\underset{\sim}{27}] \supset \begin{cases} (\underset{\sim}{2}): & |\Delta I| = 1/2 \\ (\underset{\sim}{4}): & |\Delta I| = 1/2,\ 3/2 \end{cases} .$$

So if we had some reason to exclude or minimize the importance of the 27-dimensional representation from the weak Hamiltonian, we would be given a reason why the $|\Delta I| = ½$ piece of the Hamiltonian operates because that is the only part which is available in the octet. So we change our terminology from nonleptonic enhancement to octet enhancement and have a new doctrine that the octet is an important piece of the weak Hamiltonian. One can try to give a reason why it should be so.

The modern belief is that it is the strong interactions which accomplish the feat of octet enhancement. The strong interactions among the constitutents at short distances result in this enhancement. Two works which led to the current language of understanding have been done by Gaillard and Lee, Phys. Rev. Lett. 33, 108 (1974), and Altarelli and Maiani, Phys. Lett. 52B, 351 (1974).

We do not yet have a full explanation for the $|\Delta I| = ½$ rule, but we at least manage to incorporate it into our theoretical framework. So it is very natural that we try to make a generalization to SU(4) and thus to the weak interactions of charmed particles. This was suggested in the "Search for Charm" paper by Gaillard, Lee and Rosner and then made explicit in 1975 by Altarelli, Cabibbo and Maiani, Nucl. Phys. B88, 285 (1975) and by the Princeton group of Kingsley, Treiman, Wilczek and Zee (Phys. Rev. D11, 1919 (1975)). The group theory for this was explained in detail in a paper by Einhorn and Quigg (Phys. Rev. D12, 2015 (1975)). After all that, a critical analysis was done by Ellis, Gaillard and Nanopoulos (Nucl. Phys. B100, 313 (1975)). This is a subject about which there is great interest and occasionally great passions and misunderstandings. We must appeal to experiment for a final verdict.

In any case let me write the weak current now in the presence of charm in the usual way proposed by Glashow, Iliopoulos and Maiani. The usual Cabibbo current plus the charm changing pieces is

$$J = \bar{u}(d \cos\theta + s \sin\theta) + \bar{c}(s \cos\theta - d \sin\theta) \quad .$$

We can write it in terms of the fundamental representation of SU(4)

$$\psi^{\alpha} = \begin{pmatrix} \psi^0 \\ \psi^1 \\ \psi^2 \\ \psi^3 \end{pmatrix} \equiv \begin{pmatrix} c \\ u \\ d \\ s \end{pmatrix}$$

as $J = \bar{\psi}\,\mathcal{O}\psi$ or, if we denote $\psi^{\alpha +}$ as ψ_α, in the form $J = \psi_\alpha \mathcal{O}_{\alpha\beta}\psi^\beta$. This is a linear combination of states transforming as the product $\underset{\sim}{4}^* \otimes \underset{\sim}{4} = \underset{\sim}{1} \oplus \underset{\sim}{15}$. Since trace $(\mathcal{O}) = 0$, J transforms like a member of 15, just as the ordinary Cabibbo current transforms as the SU(3) octet. So we may do the same arithmetic that we did for SU(3) this time for SU(4) to discover the representations contained in the weak Hamiltonian

$$H_W = \tfrac{1}{2}(JJ^+ + J^+J) \quad ,$$

which transforms as

$$(\underset{\sim}{15} \otimes \underset{\sim}{15}^*) \oplus (\underset{\sim}{15}^* \otimes \underset{\sim}{15})$$

$$\underset{\sim}{15} \otimes \underset{\sim}{15} = \underset{\sim}{1}_s \oplus \underset{\sim}{15}_s \oplus \underset{\sim}{15}_a \oplus \underset{\sim}{20}_s \oplus \underset{\sim}{45}_a \oplus \underset{\sim}{45}^*{}_a + \underset{\sim}{84}_s \quad .$$

So we find that in the general case the weak Hamiltonian could contain only symmetric representations

$$H_W \simeq \underset{\sim}{1} \oplus \underset{\sim}{15}_s \oplus \underset{\sim}{20}_s \oplus \underset{\sim}{84}_s \quad .$$

The 20-dimensional representation is distinct from the 20' and 20" that we saw before. It turns out that for the specific Glashow-Iliopoulos-Maiani form of the current the coefficient of the 15-dimensional representation is 0. So that is absent from the Hamiltonian of interest. Now we continue to proceed completely in parallel to our discussion of SU(3). We have a charm changing weak Hamiltonian, which contains pieces transforming as 20- and 84-dimensional representations of SU(4). If we examine this for the charm-changing pieces we find for changing charm by one unit the $\underset{\sim}{20}$ corresponds to the 6-dimensional representation of SU(3). It also transforms at the level of charm-conserving currents as an octet. The $\underset{\sim}{84}$ is more complicated and at the level of charm conserving currents, it contains the octet and $[\underset{\sim}{27}]$. So the immediate generalization of the doctrine of octet enhancement for the Cabibbo current is that as the $[\underset{\sim}{27}]$ was eliminated from the charm-conserving charged currents before we will eliminate it again. I will do that by eliminating the $\underset{\sim}{84}$ representation in which it occurs. We generalize the octet enhancement idea for the charm-preserving charged currents and decide that the representation containing the octet and only octet, that means the 20-dimensional representation of SU(4) is the dominant one in charm theory. So let me summarize this situation. The SU(4) representation $\underset{\sim}{1}$ does not occur for charm or strangeness-changing decays. The 15-dimensional representation is also absent, because the trace $(\mathcal{O}) = 0$ and $\{\mathcal{O}, \mathcal{O}^+\} = 1$. The weak Hamiltonian then would contain

$$H_W \simeq \underline{20} + \underline{84} \quad .$$

But the SU(3) contents for these two are

	$\underline{20}$	$\underline{84}$
$\Delta C = 2$		$[\underline{6}^*]$
1	$[\underline{6}]$	$[\underline{3}^*] \oplus [\underline{15}_M{}^*]$
0	$[\underline{8}]$	$[\underline{1}] \oplus [\underline{8}] \oplus [\underline{27}]$
-1	$[\underline{6}^*]$	$[\underline{3}] \oplus [\underline{15}_M]$
-2		$[\underline{6}]$

Therefore with our idea for enhancement we will stay with the first part of the Hamiltonian which transforms as a 20-dimensional representation of SU(4).

This has a certain appeal because we have used only symmetry arguments. It also has a certain danger. Although we managed to obtain the $|\Delta I| = 1/2$ rule in symmetry terms by talking about the SU(3) representations responsible for it, to try to give an explanation we are forced to appeal to some dynamical mechanism. Now we are assuming by pursuing $\underline{20}$ dominance in SU(4) that the same dynamical mechanism is present in SU(4) as in SU(3). This signals that all the effects may be sensitive to the very severe breaking of the symmetry which is revealed by the very different masses of noncharmed and charmed mesons.

What will be the consequences of this enhancement of the 20-dimensional representation?

1) In the absence of $\underline{84}$ the decay $D^+ \to \bar{K}^0 \pi^+$ is absolutely forbidden. The same is true for all Cabibbo-favored two-body decays of D^+. Therefore the strengths of these transitions measure the presence of the $\underline{84}$-dimensional representation. Consequently it is very important to measure not simply the

branching ratios for these decays, as has been done, but the absolute rates also. We may note that the decay modes with the measured branching rates were rather small in comparison with the prediction of the statistical model. It is too soon to know whether this is an indication of the suppression of the decay or not. It is an important question to answer.

2) There are also many specific relations between various decay modes that have been worked out in the papers I mentioned.

3) If we proceed with the idea of nonleptonic enhancement for the charm-changing decays it will be the case that nonleptonic modes will dominate over semileptonic decays. The question is what is the amount of enhancement here: Is it equal to the factor 20 seen in the ordinary weak interactions or is there a smaller factor because the dynamics is different? This will be cleared up by precision measurements of the semileptonic branching ratios. The deviation of the semileptonic branching ratios from the naive quasi-free quark model predictions of 20% will be some indication of the strength for the nonleptonic enhancement. So we repeat that $\Gamma(D \to \text{hadrons} + \mu\nu)/\text{all} < 20\%$ will indicate nonleptonic enhancement.

4) There is another amusing possibility, which follows from the tentative explanation of the nonleptonic enhancement as a consequence of the strong interactions. If strong interactions cause the enhancement then it is conceivable that the channels in which strong interactions are strong benefit from this enhancement. Specifically it may be the case that transitions which result in "exotic" final states, that is mesons which lie outside of SU(3) nonets, would not be enhanced. For this purpose one would like to compare the rate $\Gamma(D^+ \to K^-\pi^+\pi^+)$, with a 10-dimensional state in SU(3), with the fully allowed transition of D^0 into octet final states. It is very likely that by next year experiment will give answers

to these questions for us and we will know the degree of enhancement and suppression in the charm-changing nonleptonic interactions.

Before leaving the subject of charm let me summarize some of the remaining issues.

1) As you can see there is a large number of detailed calculations which can be done. There is also a large number of ideas which were tried out for the first time in the charm system. What remains to be learned of a qualitative nature?

First, is the spectrum seen what we really expect? Will there really be 16 pseudoscalar mesons, 16 vector mesons, 20 spin ½ baryons, 20 spin 3/2 baryons and so on? Will there be extra states or missing states, or what?

2) Secondly we have a certain basis for belief in the Glashow-Iliopoulos-Maiani form of the charged current

$$J^{(+)} = (\bar{u}d + \bar{c}s)\cos\theta_C + (\bar{u}s - \bar{c}d)\sin\theta_C \quad .$$

We saw there were problems with strangeness-changing neutral currents and indeed the Cabibbo-favored decays of the charmed mesons indicate the charmed quarks do indeed like to turn into strange quarks. We have not yet seen direct evidence for the last piece of the current, in Cabibbo-suppressed charm-changing decays, although the x distribution for ν-induced dimuon events strongly hints at the presence of a $d \to c$ transition. So there is some interest in observing Cabibbo-suppressed decays on the expected level. Probably the clearest way of doing that would be the comparison for Cabibbo-allowed and Cabibbo-suppressed transitions in

$$D^0 \to K^- e\nu \quad \text{and} \quad D^0 \to \pi^- e\nu \quad .$$

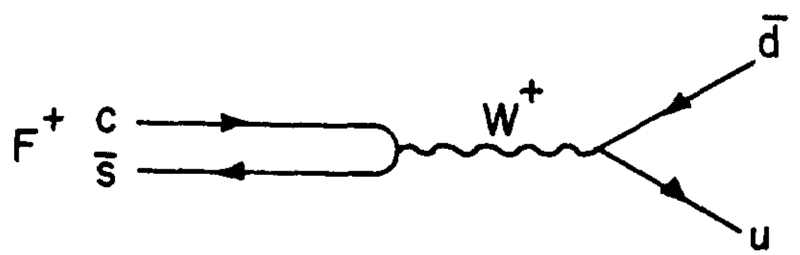
Branching ratios for these channels must be different by $\tan^2\theta$.

3) Finally we can ask what are the lifetimes of the charmed mesons? Because of the various theoretical possibilities for the way in which nonleptonic weak interactions are influenced by strong interactions it is possible that the lifetimes of the various pseudoscalar states may be very different. Let me list some of the possibilities.

i) If everything we have said about $\underset{\sim}{20}$ enhancement is realized in nature, that is if only the $\underset{\sim}{20}$ Hamiltonian piece were present and furthermore something inhibits the transitions to "exotic" final states, then there will be no Cabibbo-favored nonleptonic decays of D^+. Consequently the lifetimes of D^+ and D^0 are restricted as

$$\tau(D^+) \gg \tau(D^0) \qquad .$$

ii) For the F^+ there is another possibility which may give us abnormally long lifetimes. We may represent one contribution to the nonleptonic decay of the F^+ as the annihilation

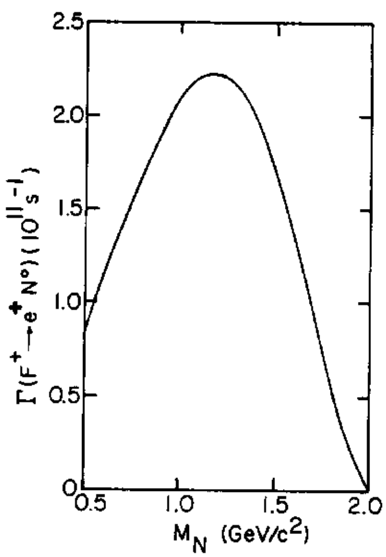


This has the same shape as the picture we have drawn for the leptonic decay of the F or D. We are constantly regarding the ordinary u and d quarks as very light objects. We don't know precisely what the concept of quark mass means inside of hadrons. But if we assume that it has some meaning it is possible that the diagram may suffer from helicity suppression because of the light mass of the fermion products, just as the purely leptonic two-body decays were suppressed and gave rates which were proportional to masses of the objects into which they decay. To make this prediction one takes very seriously an extremely naive picture of the quark model, but this does not rule it out. Then the lifetime of the F^+ would be long compared with that of D^0 because its nonleptonic decay, although being full strength according to the dynamics, would be suppressed by the kinematics.

A last possibility is that, and this is just to be wild, the same diagram would not be suppressed if we had a neutral heavy object in the decay. By postulating the existence of a new heavy lepton N^0 with a large mass, the decay

$$F^+ \to e^+ N^0$$

could be significant.* I draw here the leptonic decay rate in units 10^{11} $\sec^{-1}$ as a function of mass for such an object. The F-mesons make a good place to search for such objects.



*J.L. Rosner, Nucl. Phys. B126. 124 (1977). For a search, see D. Meyer et al. Phys.

LECTURE V. THE NEW NEW PARTICLES

Now I shall try to acquaint you with the most recent experimental data on the new states with masses approximately 10 GeV/c^2, which have been discovered this summer. But since this is a school I must teach someone, at least myself. Consequently, it will be useful to have some kind of theoretical apparatus to describe these states. Such a tool was developed recently. So I will try to show you what to do with the new quarks which we will discuss at this last lecture.

A very rich spectrum of $(c\bar{c})$ bound states has been observed in e^+e^- annihilations at SPEAR and DORIS. There are some recent summaries of the spectroscopy of these states.

1. G.J. Feldman and M.L. Perl, SLAC-PUB-1972 (1977) prepared as a Physics Reports paper.

2. J.D. Jackson, CERN-TH-2351 (Budapest Conference invited talk).

Dr. Wolf also will talk in detail about these states.

Some time ago it was suggested on the basis of asymptotic freedom arguments by T. Appelquist and H.D. Politzer (Phys. Rev. Lett. 34, 43 (1975)) that bound states of heavy quarks might be described as a nonrelativistic hadronic analog of positronium. An exhaustive six-part review of this subject by the ITEP group has just appeared.* I will say much more and much less.

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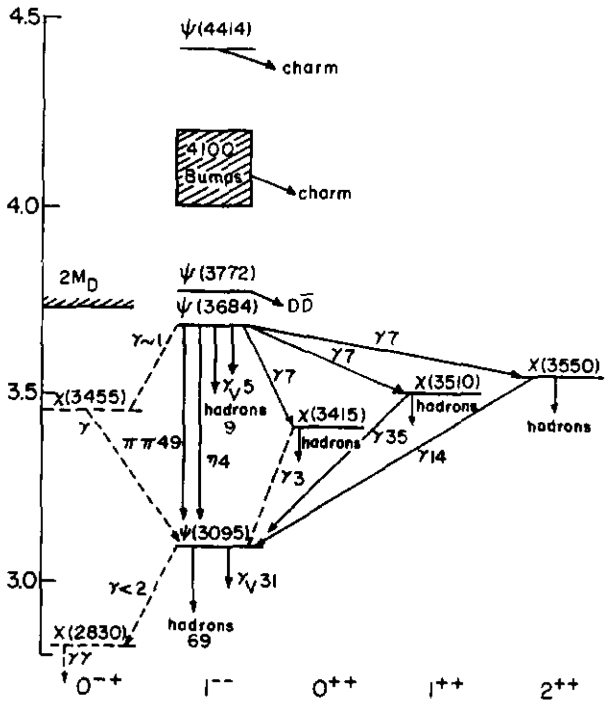
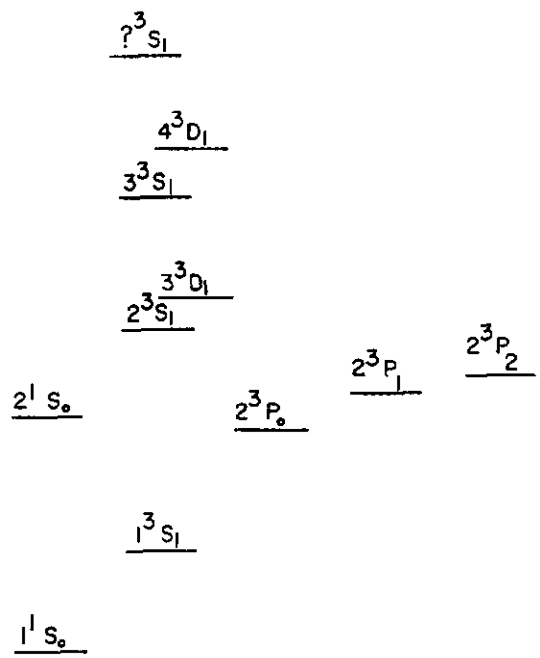
*V.A. Novikov, et al., ITEP-57, 58, 65, 42, 79, 83.

1. The Spectrum of Charmonium

Here is the spectrum of the so-called charmonium system, which is the hadronic analog of positronium.



I list the states according to their spin-parity assignments. On the left hand you can see charm threshold at twice the D-meson mass. The states below charm threshold have a very complicated and rich spectroscopy with γ-transitions and hadronic transitions between the states. The numbers near the names of modes indicate the branching ratios in percent for the mode indicated. For example, ψ(3684) goes 49% of the time to ψ(3095) by emission of a ππ-pair. The γ-transitions of this system are interpreted as electric dipole transitions among the various states and are extremely similar to the structure of the electromagnetic transitions among the various states and are extremely similar to the structure of the electromagnetic transitions among a simple atomic system. In fact it has been the case that a very simple analogy to the atomic system, namely a nonrelativistic Schrödinger equation approach, agrees very well, remarkably well I should say, with the observed levels. It also gives rough agreement with the size of the radiative transitions. The levels with the assigned spectroscopic notations are shown below.



We have the ψ as a spin triplet, total spin 1, angular momentum 1 level of the ground state shifted from η_c by a spin-spin force. The ψ' is interpreted as a radial excitation of the ψ. Then there are P- and D-states. These two pictures are very impressive and are in very good agreement with each other except for the splitting, which is too large if we regard the X(2830) state as the pseudoscalar state of our system. So with one exception the picture is very beautiful and very successful.

Let's acquaint ourselves with some details of this nonrelativistic approach. In the usual picture (E. Eichten and K. Gottfried, Phys. Lett. 66B, 286 (1977)) the potential in the Schrödinger equation is taken as a sum of two terms

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + r/a^2 \quad .$$

The first term is a Coulomb term reflecting the behavior of massless gluon exchange between quarks at small distances. The second term, usually taken to be linear, is contrived to confine the quarks inside a hadron. One has at his disposal 3 parameters-the quark mass (m_c), the strong coupling constant α_s in the Coulomb term and the parameter a from the linear term-in order to reproduce the features of the psion spectrum. It has been done by many people. According to the theoretical idea of asymptotic freedom we expect that α_s decreases slowly as the quark mass increases. The nonrelativistic approximation should improve for heavier objects.

2. Bound States in the Schrödinger Equation

The ψ system is the hydrogen atom of hadronic physics. Then we should review what we know about the hydrogen atom. So I make a brief excursion in which we review properties of bound states in the Schrödinger equation. It may be viewed as remarkable, that five years ago anyone describing hadrons in terms of a nonrelativistic equation would have been laughed out of the room but now we can say "asymptotic freedom," and everyone takes it all seriously. I begin by writing down the Schrödinger equation, the s-wave radial equation:

$$\left\{ -\frac{1}{mr^2}\frac{d}{dr}\left(r^2\frac{d}{dr}\right) + V(r) - E \right\} \psi(r) = 0 \quad .$$

As we have learned at school the way to turn it into a form suitable for solution is to define the reduced wave function $\psi(r) = u(r)/r$. This function has the boundary conditions $u(0) = 0$ and $u'(0) = \psi(0)$. So we have

$$-u''/m + Vu = Eu \qquad ,$$

which looks like the Schrödinger equation in one dimension.

There are a number of consequences of the Schrödinger equation which are useful in the atomic physics of the positronium system and hence will be useful in the discussion of the $(c\bar{c})$ system.

(A) First we show that

$$|\psi(0)|^2 = \frac{m}{4\pi} \left< \frac{dV}{dr} \right>$$

i.e. the wave function at the origin is connected with the expectation value of the gradient of the potential. Let's prove this. From the Schrödinger equation we can find the gradient of the potential by taking a derivative

$$\frac{dV}{dr} = \frac{1}{m} \frac{d}{dr} \left(\frac{u''}{u} \right) \qquad .$$

Then we may calculate the expectation value by inserting this object into an integral weighted with the square of the wave function

$$\left< \frac{dV}{dr} \right> = \frac{4\pi}{m} \int_0^\infty dr\, |u(r)|^2 \frac{d}{dr} \left(\frac{u''}{u} \right) \qquad .$$

Integrating this by parts we have a piece which because of the boundary conditions vanishes at both the origin and infinity and a second piece which turns out to be the total derivative of the square of u'. So it is equal to

$$= \frac{4\pi}{m} uu'' \Big]_0^\infty - \frac{4\pi}{m} \int_0^\infty dr(2uu') \frac{u''}{u}$$

$$\frac{4\pi}{m} uu'' \Big]_0^\infty \to 0 \qquad 2u'u'' = \frac{d}{dr}(u')^2$$

$$= \frac{4\pi}{m} (u'(0))^2 \equiv \frac{4\pi}{m} |\psi(0)|^2$$

according to the definition. So one is able to compute roughly from the potential the behavior of $|\psi(0)|^2$, which is included in our previous calculation of leptonic widths.

(B) A second useful property of the Schrödinger equation is the virial theorem, which relates the energy eigenvalue E to the expection value of the potential V and to the expectation value of $\frac{r}{2}\frac{dV}{dr}$

$$E = \langle V \rangle + \langle \frac{r}{2}\frac{dV}{dr} \rangle \quad .$$

The proof of this equation is more serious. It requires three steps! (a) Let's multiply the Schrödinger equation by u(r) and then integrate from 0 to ∞. An integration by parts gives

$$\int_0^\infty dr \frac{(u'(r))^2}{m} + \int_0^\infty V(r)(u(r))^2 dr = E \int_0^\infty dr\, u^2 \quad .$$

(b) Secondly let's multiply the Schrödinger equation by u' and integrate it from r to ∞. That gives me a second expression

$$\frac{(u'(r))^2}{m} - V(r)(u(r))^2 - \int_r^\infty \frac{dV}{dr}(u(r'))^2 dr' = -E(u(r))^2 \quad ,$$

which I again integrate from 0 to ∞. This gives

$$\int_0^\infty \frac{dr\,(u')^2}{m} - \int_0^\infty dr\,Vu^2 - \int_0^\infty \frac{r dV}{dr} u^2 dr = -E \int_0^\infty dr\,u^2$$

which contains some pieces from the first step. So if I take the difference between these two things I will have a simple expression for E and combining these things I reproduce the stated theorem, which has the equivalent statement that the expectation value of the kinetic energy T is connected with the expectation value of $\frac{r}{2}\frac{dV}{dr}$

$$\langle T \rangle = \langle \frac{r}{2}\frac{dV}{dr} \rangle \quad .$$

(C)And a third useful property, which is valid in the quasi-classical approximation, connects the expectation value of the kinetic energy and a derivative of the energy eigenvalue with respect to the principal quantum number:

$$\langle T \rangle = \frac{1}{2}\frac{dE}{dn}(n + \frac{1}{2}) \quad .$$

The proof of this starts from the definition of the kinetic energy in natural units

$$\langle T \rangle \equiv -\frac{1}{m} \int_0^\infty dr\, u_n u_n''$$

which is equal to

$$= \frac{1}{m} \int_0^\infty dr\,(u_n')^2$$

after a simple integration by parts. Then I insert the WKB wavefunction into this integral and obtain the stated connection.

With these 3 intermediate results, two of which came exactly from the Schrödinger equation and one of which was derived from the quasiclassical approximation, we may prove four interesting rules for a potential $V(r) \sim r^{\varepsilon}$:

$$\text{(i)} \quad |\psi(0)|^2 \sim m^{3/(2+\varepsilon)} \quad ,$$

where m is the mass of the bound object.

$$\text{(ii)} \quad \Delta E \sim m^{-\varepsilon/(2+\varepsilon)} \quad ,$$

here ΔE is the splitting between the eigenvalues. These two results are exact for $\varepsilon > 2$.

(iii) The third result is semiclassical and valid when the principal number n is large and ε also more than 2.

$$E \sim n^{2\varepsilon/(2+\varepsilon)} \quad .$$

$$\text{(iv)} \quad |\psi(0)|^2 \sim n^{2(\varepsilon-1)/(2+\varepsilon)} \quad .$$

The last result holds only if $\varepsilon \geq 0$ for large n. So I give as a problem to you to complete the derivations of (i), (iii), and (iv) by using the simple scaling arguments of the Schrödinger equation. As an example of this I derive (ii) from the equation

$$-\frac{u''}{m} - [E - ar^{\varepsilon}]u = 0 \quad .$$

Set $r = \rho/m^p m_0^{1-p}$. Then we have

$$u(r) \rightarrow v(\rho) = v(rm^{p}m_0^{1-p})$$

$$u''(r) = m^{2p}m_0^{2-2p}v''$$

and

$$-m^{2p-1}m_0^{2-2p}v'' - [\,E - a\rho^{\varepsilon}m^{-\varepsilon p}m_0^{-\varepsilon(1-p)}\,] = 0 \qquad .$$

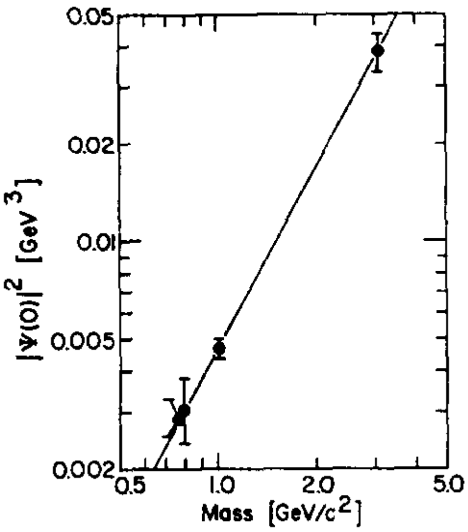
Let's divide this by m^{2p-1} and fix $2p - 1 = -\varepsilon p$ to scale the potential. So $p = 1/(2 + \varepsilon)$ and finally, $E \sim m^{2p-1} \sim m^{-\varepsilon/(2 + \varepsilon)}$ as we stated before.

Now how can we use these results? Our dream is that we could use these scaling laws to read off the effective potential from the data. Let me do this in a precise but rather meaningless way just to show to you the kind of thing that might be possible for high energy physics in a couple of years.

The rate for decay of a vector meson into lepton pairs is

$$\Gamma(V^0 \rightarrow e^+e^-) = 16\pi \frac{\alpha^2 Q^2}{M^2} |\psi(0)|^2 \qquad .$$

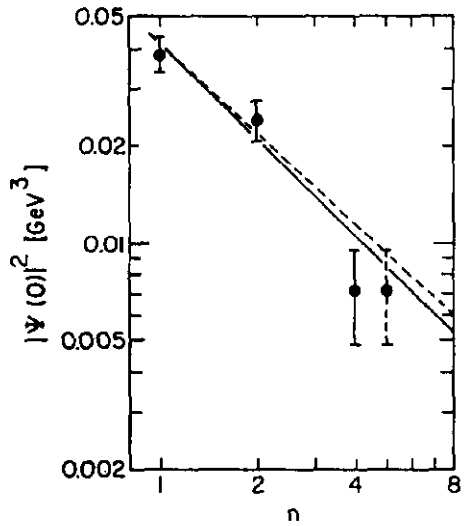
This is a process quite analogous to the calculation of the weak, purely leptonic two-body decay of mesons, in which the 2 quarks annihilate by coming together at the origin, this time into a photon which subsequently materializes into lepton pairs. We have two scaling laws for the behavior of the wave function at the origin: as a function of the mass of the constituent quarks and also as a function of their principal quantum number. So the $|\psi(0)|^2$ deduced from the observed leptonic widths of the known vector mesons may be pictured as a function of the mass of the vector mesons which is proportional to the mass of the constituent quarks. If we do this the result is a power law for ρ, ω, ϕ and ψ all of which are, we believe, the ground states of their respective systems.



Then $|\psi(0)|^2$ goes as $M^{1.88\pm0.11}$. This means that we have for the parameter ε of the potential the value

$$\varepsilon \simeq -0.41 \pm .13 \quad .$$

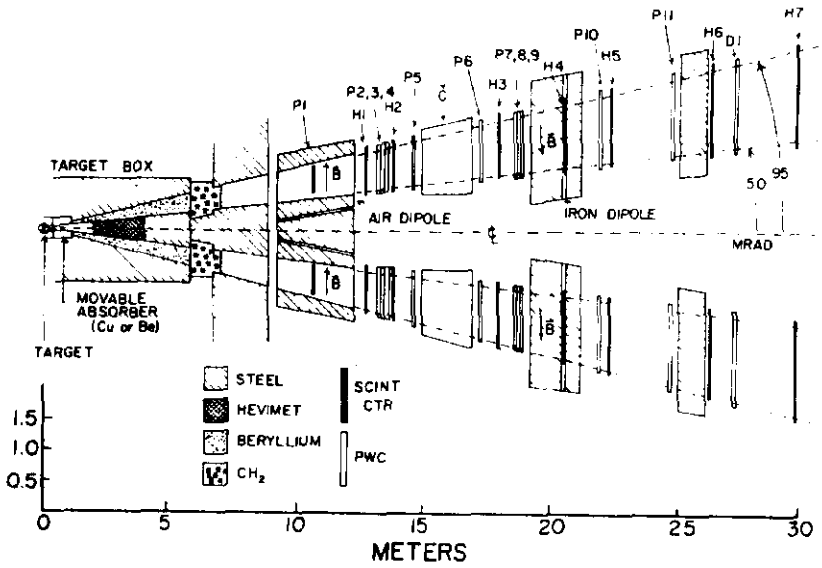
It lies between the values given by the Coulomb potential and the linear potential. This is of course rather a joke because nobody still believes that these light mesons can be described as nonrelativistic systems. The exercise would be a more useful one if one repeats this using the ψ as the lightest state going on to the other states that will be discovered in the intervening time. Secondly we may try to use the scaling law valid in the semiclassical limit for the determination of the dependence of $|\psi(0)|^2$ on the principal quantum number n. In this case there are three s-states of the system whose leptonic widths are well known. There are the ψ and ψ', which we believe to be the first and the second states, and the state $\psi(4.414)$ which is variously assigned as the fourth and the fifth s-states. We have only a few points but one can ask also for a straight-line fit.



The $|\psi(0)|^2$ looks roughly like $\sim n^{-1}$. We then deduce that the effective power of the potential is $\varepsilon \lesssim 0$. Again it is between the Coulomb and linear results. This gives us some qualitative feeling for why this potential model is able to describe the data.

3. Discovery of the Upsilons

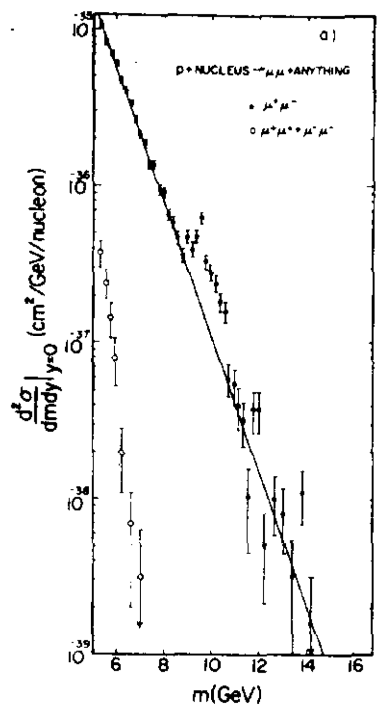
Now I will show you the data about the new particle at 10 GeV. They came from a Fermilab experiment led by L. Lederman and involving people from Columbia University, Fermilab, and the State University of New York (Stony Brook). Experimenters scatter the 400 GeV/c proton beam from two targets (Pt or Cu) and observe $\mu^+\mu^-$ accompanied by anything else. I will spend a little bit of time to describe the apparatus in this case because it is of some importance in discussing the results.



The double-arm spectrometer is seen which has a good mass resolution at high masses, $\frac{\Delta m}{m} \sim 2\%$ rms. The targets are extremely tiny. They are 0.7 mm wide and transverse to the beam and the length is that one calculates 30% of protons will interact. Immediately after the target, as is clear from the picture, there is a hadron filter to eliminate hadrons from the chambers which consists of 18 interaction lengths of Beryllium. Beryllium was chosen because it has good absorption properties for the hadrons but having a small atomic charge does not cause appreciable multiple scattering of the muons. As calibrations of the apparatus experimenters observed 15,000 ψ, 1000 ψ' and were able to study the mass resolution of their lines. The first 30 cm of hadron filter can be switched between Be and Cu. Cu has the advantage of allowing a somewhat larger rate to be taken by the experimenters. The first publication of the observation of these particles was made by S.W. Herb, et al., in Phys. Rev. Lett. 39, 252 (1977).

The first analyzing magnet bends the particles in a vertical plane with the transverse momentum $P_t \sim 1.2$ GeV/c. The second analyzing magnet in each arm provides a second measurement of the muon momentum, which is less precise than the first.

The first publication was based on results obtained in May-June 1977. This apparatus was created as the result of 5 years of different experiments. It has extremely high sensitivity. There are 9000 events in early data with pair mass greater than 5 GeV/c^2.



One sees in the data a roughly exponential form for the most part and then in the region of 10 GeV an excess of events above the exponential curve. This group once suggested on the basis of 20 events the existence of an enhancement at 6 GeV. You can see from the smoothness of this curve now that it does not exist.

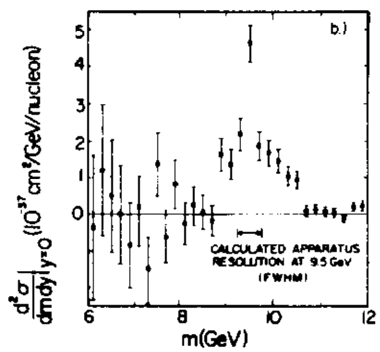
Then I identify this excess of events at 10 GeV as a new particle or family of particles with a mass

$$M(T) = 9.54 \pm 0.04 \text{ GeV}/c^2 \quad .$$

They found as one can see on the next picture that the width of this object is about 1.2 GeV to be compared with the calculated resolution of about 0.5 GeV. Assuming the calculated resolution is correct, and it is checked in various ways, one is driven to the conclusion that accepting the data, either there is more than one resonance present or something extraordinary has happened. Because we have a broad resonance decaying with a great branching ratio into lepton pairs. On the basis of these data the branching ratio into μ-pairs times $\frac{d\sigma}{dy}$ at $y = 0$ is equal to

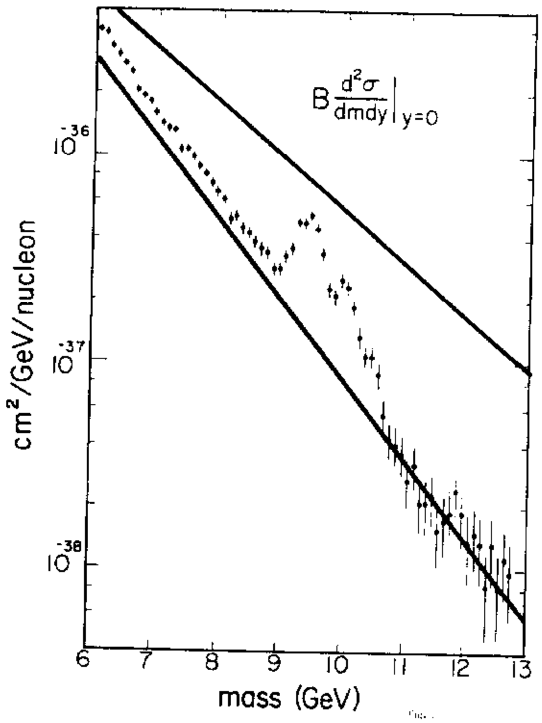
$$B \frac{d\sigma}{dy}(0) \approx (3.4 \pm 0.3) 10^{-37} \text{ cm/GeV nucleon}$$

or about $3 \cdot 10^{-37}$ in the same units. To examine this structure the experimenters substracted this exponential fit from the data and obtain the following picture.

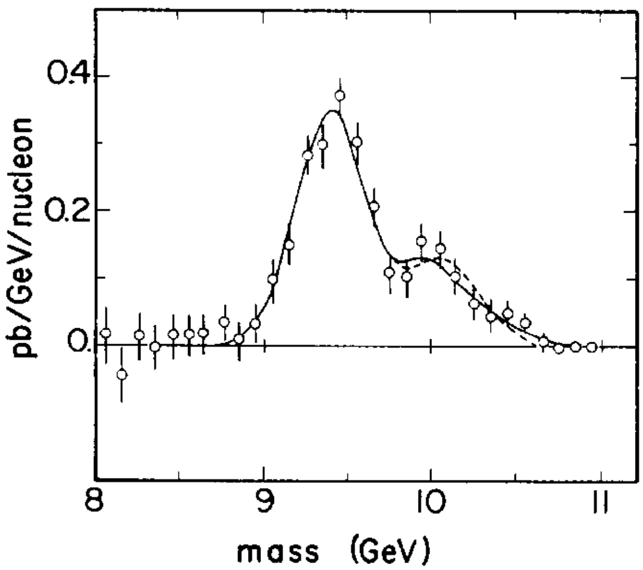


It contains in the peak 420 events above the continuum and the shape of this peak is very unclear because of statistics but gives a very poor fit to a single resonance.

In July and August 1977 more events were accumulated. There are now 26,000 events with $M_{pair} > 5$ GeV/c^2, with 1200 events in the peak over background. These data show that there are at least 2 resonances. The data now look like this.



Again there is a roughly exponential behavior up to 9 GeV and a clear indication of 2 peaks about 10 GeV and perhaps even a shoulder just after 10 GeV. Once again we can make a straight line fit to the data. The form $(1.26 \pm 0.02) \cdot 10^{-33} \exp\left[-(0.953 \pm 0.01)m\right] \frac{cm^2}{\text{GeV nucl.}}$ gives a good description of the data outside the region of the resonance. For general interest I also include in the figure what I regard as the rough lower and upper limits for Drell-Yan production of μ-pairs in pp collisions. We see that the lower curve is in rough agreement with the data outside the resonance region. So there are some indications that the Drell-Yan description of μ-pair production may actually be correct. But the principal interest here is the resonances themselves. I again make a subtraction of the exponential fit from the data. On a linear plot the data then look like this:



We should first look at the data points rather than at the curves. We see now statistics that have been improved and that the first bump and a second bump are nearly resolved. Of course, one can play a large number of games with these things and the experimenters have done that. They have tried fits to one, two or three resonances. A fit with a single resonance is now completely unacceptable statistically. The fits to two or three resonances cannot yet be distinguished. Assuming now two peaks and that both resonances have zero intrinsic width, so their width is given entirely by the resolution of apparatus, one obtains a χ^2 fit at 18 degrees of freedom, which has a very high confidence level of 35%, has a first peak at 9.41 GeV and a second peak at about 10.0 GeV. The cross section for the first bump is about three times the cross section for the second bump. It is also possible to make a fit to the three peak hypothesis. This has somewhat better χ^2, and a higher confidence level at about 60%. You can see from the picture that the case for the third resonance is by no means clear. It requires at least more running, perhaps improved resolution to be proved. However making the hypothesis the first mass turns out to be about 9.4 GeV again, the second mass is at 10 GeV, again very close to that of the two-peak hypothesis. A smaller cross section is ascribed to a third particle at 10.4 GeV. Again the ratio of cross sections for the first object to the second one is about three. So let me assemble all resonance fit parameters in a table

Name	Value (Units)	2 Peak Hypothesis	3 Peak Hypothesis
	M_1 GeV/c^2	9.41 ± 0.013	9.40 ± 0.013
Υ			
	$B \frac{d\sigma}{dy}\Big\|_0$ pb	0.18 ± 0.01	0.18 ± 0.01
	M_2 GeV/c^2	10.06 ± 0.03	10.01 ± 0.04
Υ'			
	$B \frac{d\sigma}{dy}\Big\|_0$ pb	0.069 ± 0.006	0.065 ± 0.07
	M_3 GeV/c^2		10.40 ± 0.12
Υ''			
	$B \frac{d\sigma}{dy}\Big\|_0$ pb		0.011 ± 0.007
χ^2/d.o.f.		19.3/18	14.2/16
CL		≈ 35%	≈ 60%

I give to you one of the applications of this. First if we take seriously the positions of the first two resonances we have an indication that the mass difference between the second object and the first one is the same as the mass difference between ψ' and ψ

$$M(\Upsilon') - M(\Upsilon) \approx M(\psi') - M(\psi) \quad .$$

Two more remarks about this table. Of course Υ'' is not firmly established at this time; it is just a dream. From the stability of the resonance positions between the two-peak fit and three-peak fit and also from making fits with slightly different shapes for the background it is found that the positions of the two resonances are not very sensitive to the details of the background subtractions. So these numbers of about 9.4 GeV and about 10 GeV are expected to be rather stable ones.

Let us spend a few minutes on the interpretation of these objects. In the usual potential which was so successful in describing the charmonium system we had a Coulomb piece, which according to our scaling laws gives a mass splitting proportional to the mass of the quark involved, and a linear piece which gives a splitting proportional to the inverse 1/3 power of the quark mass

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + r/a^2 \quad .$$

The parameters $\alpha_s = 0.19$ and $a = 2.22\ \mathrm{GeV}^{-1}$ gave a "good" description of psions. Eichten and Gottfried had calculated some time ago the splitting between first, second and third levels that they expected on the basis of their model as constrained by the ψ system, for a system with more massive quarks. For a quark of about 5 GeV mass, which would make a 10 GeV hadron, they expected a splitting which decreased because of the relative importance of the linear term of the potential to about 2/3 of the splittings between the ψ' and ψ.

$$M(\Upsilon') - M(\Upsilon) \approx \frac{2}{3}\left[M(\psi') - M(\psi)\right] \quad .$$

We believe the data because the number of events is very large, but we may be reminded that the data are only three weeks old and they can change slightly. There seems to be a disagreement between the prediction and data. This disagreement gets worse if the strong coupling constant decreases as the mass of the quark increases because the linear potential will dominate further.

If we take too seriously the scaling arguments and try to infer the potential for quarks, we can suppose that the splitting is actually independent of the quark mass. Then from our scaling law we deduce that the potential goes like r^0. That is

$$\Delta E \sim m^{-\varepsilon/(2+\varepsilon)} \rightarrow \text{const., means } \varepsilon = 0 \quad .$$

A logarithmic potential would give the same splitting for all families of particles. You can see this discussion of the potential $V(r) \sim C \ln r$ in a paper by Quigg and Rosner, Phys. Lett. 71B, 153 (1977).

There are of course a large number of possible interpretations for this new family of particles. But one can see the most attractive is that what happened last year will happen this year. It will turn out to be economical to describe this family as bound states of a new heavy quark.

Let me say a few words about the experiments from which we anticipate new results in the near future. The experiment of Lederman and collaborators will continue until the end of 1977. In addition to the run at 400 GeV they will take some data at 200, 300 and 500 GeV to try to find the excitation curve of this object. They also have some experimental devices with small chambers, which they hope will take very high rates and increase the mass resolution and give very precise data.

There are two other experiments running at Fermilab which will probably accumulate some information about these particles. There is an experiment of the

Chicago/Princeton group (Pilcher, Smith, et al.) running $\pi^{\pm}p$ at 225 GeV/c with similar resolution to the Lederman experiment. Given the sensitivity they will probably see only about 12 events in the new experiment. They have a much less intense beam than in Lederman's experiment. There is another experiment by physicists from Northeastern University and the University of Washington (pp collisions at 400 GeV/c). Their detector is a large block of magnetized iron, which has a very good acceptance, much better than the Lederman experiment, but much poorer resolution. They hope to accumulate approximately 10 Υ per hour. But given the poor resolution it is unlikely that they will make a very incisive contribution to the subject.

There are a number of experiments in progress at the ISR to look at lepton pairs. None of those has results on the interesting region yet. There is a single upper limit on the cross section at a center of mass energy $\sqrt{s} = 62$ GeV, which is less than 45 pb. It comes from the experiment of Darriulat and collaborators. The upper limit at 62 GeV is 170 times the cross section observed at 27 GeV. This is not yet an interesting level.

Of course we expect in analogy to the brilliant success of the storage rings in the charmonium system that the definitive contribution to this subject will be made there. There are three machines under construction which have the potential to investigate this region. These are the Cornell University Electron Storage Ring (CESR), a new machine PETRA being built at DESY, and the new PEP machine at SLAC. One can ask what a probable signal would be. For this you have to make up a leptonic width Γ_{ee} of the object by assuming a definite potential, log (r), for example. If you do this you can predict that the integrated cross section for the Υ would be about 180 nb MeV (assuming $e_Q = -1/3$) to be compared with about

11,000 nb MeV for the ψ. However because of their much higher mass the cross section of the background has fallen by a factor 1/s. So it should be a relatively prominent object nevertheless.

State	$\int \sigma(E)dE$(nb MeV)
$\Upsilon(9.4)$	180
$\Upsilon(10.0)$	72
$\Upsilon(10.3)$	43
$\Upsilon(10.5)$	31

I understand there are also some discussions about extending the energy of the existing DORIS storage ring at DESY to 10 GeV but I don't know yet what is to be done.

Finally one may think of making this object in photoproduction. This obvious thing has been done with the ψ almost immediately. At the two accelerators at CERN SPS and Fermilab, which have enough energy to make these things in large numbers , there is no apparatus yet with big enough acceptance to catch μ-pairs from Υ-decay. The experiment of Wonyong Lee and collaborators, which I mentioned this morning when I reviewed the evidence for charmed baryons, even with the new approved apparatus cannot see the Υ-decay because of the very large opening angle. The cross section one can estimate again by making the assumption $\sigma(VN) \propto M_V^{-2}$ as

$$\frac{d\sigma}{dt}(\gamma N \to \Upsilon N)\Big|_0 \approx ½\ \text{nb/GeV}^2$$

at 200 GeV, which is small!

If the new particles are made of a new quark we would like to know what the new quark is. In the case of the psions we had a theoretical reason and desire to have a charmed quark with specific properties. At the moment we have no burning desire to have any other specific quark with specific properties under the weak interaction, which resolves some specific problem we know about. So speculations there are wide open as to what this new quark might be and what its interactions would be. Maybe in the next few years we will be pursuing this as we spent the last three years trying to learn about the properties of charmed particles.

It is attractive to explain Υ in terms of a new quark, but this is not proved. What one can do is to remember the wrong explanations for ψ and try to apply them again. I list here some wrong explanations of the ψ.

i) One possibility is that this new particle could be a Higgs scalar. This is a particle which has the property of fixing up divergence problems in wrong-helicity couplings to leptons. Therefore it couples to leptons (or two fermions) with a strength proportional to the mass of the fermion. That means that it would be coupled 10^4 times as strongly in rate to μ-pairs as to electron-pairs. There is some evidence based on the earlier experiments of the Columbia-Fermilab group, in which they observed pp goes to electron pairs, that the coupling to electron or muon is more or less universal. On the basis of the measured cross section for pp into μ-pairs and on the basis of the sensitivity of their experiments to measure electron pairs they would expect to see 5 events in electron-pairs in the mass region around 9.5 GeV. In the whole experiment they accumulated 6 events there. So it means that there is a rough universality between coupling muons and electrons to Υ

$$\sigma(pp \to \Upsilon X)\big|_{\Upsilon \to \mu^+\mu^-} \approx \sigma(pp \to \Upsilon X)\big|_{\Upsilon \to e^+e^-} .$$

That is an argument against it being a Higgs scalar.

ii) It could be the Z^0 boson, the intermediate boson for weak neutral currents. The only thing that I could state at the moment is that theorists would prefer a mass of 80 GeV instead of 10 GeV. But there is no experimental evidence against it at the moment, either from this experiment or from the energy dependence of the total cross-section of the neutral weak current interactions with neutrinos.

iii) It could be colored states that is to say states which are neutral members of a color octet. For these states one expects the existence of electromagnetic transitions to ordinary hadrons which this experiment was not able to see. So a real test of this interpretation would have to wait for the electron-positron machines.

iv) An obvious possibility is to be $Q\bar{Q}$ bound states of one or more new heavy quarks. There could be more than one because we see two peaks and each one might go with new quark. But it is much more conservative to think that there is one new quark.

I am sure that there are other explanations, and that at the XIIth School you will be able to hear a less breathless review of the successful ones!

FOR FURTHER READING

In addition to the papers cited in the text, three reviews are to be recommended:

J. Ellis, "Charm, Après-Charm, and Beyond," CERN-TH.2365, lectures at the Cargèse Summer Institute, 1977.

T. Appelquist, R.M. Barnett, and K. Lane, "Charm and Beyond," SLAC-PUB-2100, to appear in Annual Review of Nuclear Science, vol. 28.

H. Harari, "Quarks and Leptons," WIS-77/56-Ph, lectures at the SLAC Summer Institute, 1977.

The Proceedings of the 1977 International Symposium on Lepton and Photon Interactions at High Energies, edited by F. Gutbrod (DESY, Hamburg) is a good general source. The topics addressed in these lectures are treated by K. Gottfried, p. 667; T.F. Walsh, p. 711; and L. Maiani, p. 867.

A more complete account of the properties of bound states in the Schrödinger equation is given by C. Quigg and J.L. Rosner, "Scaling the Schrödinger Equation," Fermilab-Pub-77/90-THY, to appear in Comments on Nuclear and Particle Physics.