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Particle Physics at LAMPF

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Particle Physics at LAMPF

by

Michael Martin Nieto

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PARTICLE PHYSICS AT LAMPF

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Michael Martin Nieto

ABSTRACT

We will discuss the theoretical basis of the interest elementary particle physicists have in certain experiments that could be done at LAMPF. These experiments include strong interaction processes (πN elastic scattering to obtain the Σ -term and πN , $\pi\pi$, and NN scattering length measurements), electromagnetic interactions (measuring the π form factor and testing muon QED), weak processes (weak π decays, tests of lepton conservation, and neutrino scattering), as well as some polarization experiments.

I. INTRODUCTION

Before I begin my talk there are two comments I would like to make about it. The first is that the type of experiments that I will be talking about are experiments that you might consider important from a theorist's point of view. I put in a boundary condition that they are in principle quite feasible to do at LAMPF; you know, not something totally impossible. But after that I will be talking about what is of interest to a theorist, so the set of experiments might be different than for instance what the program advisory committee would choose. The experiments that I will talk about range from some that I know are first in line and ready to go to some that have been deferred, shall we say. But they all are of interest to a theorist.

Second, as you all know, LAMPF is a machine which is of importance both to nuclear physics and also to elementary particle physics. One of the problems which has occurred in the last ten to fifteen years is that these two fields have diverged, at least in the minds of the people who belong to them. Part of that is due to the fact that particle physicists have developed their own jargon, and the jargon can become incomprehensible to people who haven't used it. But I am operating on the philosophy that physics is physics and all you need is

somebody to translate; i.e., if in 1927 somebody had taken Rayleigh's papers on sound and changed the notation we would have an English textbook in quantum mechanics without having to wait for Schiff. OK? Physics is physics, that is the idea.

You can see from the outline below that I have divided the experiments I am going to talk about into essentially three groups: strong interactions, electrodynamics, and weak interactions, adding a few comments on polarization experiments at the end.

II. Strong Interactions

- a) πN elastic scattering and the Σ -term
- b) $\pi\pi$ and πN scattering lengths
- c) NN scattering lengths

III. Electromagnetic Interactions

- a) Pion electromagnetic form factor
- b) Muon QED from muonium

IV. Weak Interactions

- a) Current-current theory of weak interactions
- b) $\pi^+ \rightarrow \ell^+ \nu$ decays and universality
- c) $\pi^+ \rightarrow \tau^+ \nu$ decays, CVC, and the Cabibbo angle
- d) Lepton conservation and neutral currents

V. Few comments on polarization experiments

VI. Conclusion and acknowledgements

VII. References

VIII. Discussion and Figures

You will notice that I have started using the jargon already, like the Σ -term, universality, the conserved vector current (CVC), and the Cabibbo angle. Further, as each of the transparencies comes on the screen you'll notice that there is more jargon on them. However, I ask you not to turn off until you have given me a chance. Hopefully I'm going to be able to show you that the jargon is just what you were taught in quantum mechanics and nuclear physics, only I've changed the name and maybe added an index or two.

Can I have the next transparency?

II. STRONG INTERACTIONS

a) πN Elastic Scattering and the Σ -term¹⁻³

Taking a quick glance at Figs. 1 and 2 and Eqs. (2) - (1) below, it looks bad, doesn't it? Let's see if we can do something about it.

In Figs. 1 and 2 I have given the combinations of eight mesons and eight baryons in the octet representation of the group $SU(3)$ that particle physicists have been talking about the last few years. Now, in case you didn't know it, isotopic spin is the group theorists call $SU(2)$. That is a subgroup of $SU(3)$, and in particular it goes along the x direction in Figs. 1 and 2. For example, $\pi^+ - \pi^0 - \pi^-$ in Fig. 1 or $p - n$ in Fig. 2. To generalize to $SU(3)$ all I've done is to add another direction, the y -axis, which corresponds to the quantum number strangeness (S) or hypercharge (Y), where

$$Y = S + B \quad , \quad (1)$$

and B is the baryon number.

You people are used to playing with isotopic spin operators (τ_x, τ_y, τ_z), or at least you've heard about them. Well, from now on when I write down an $SU(3)$ operator, just pretend that I'm really writing down an isotopic spin $SU(2)$ operator and forget about that other index. Then it's the same thing and you can follow the physics.

Now, there exist decays like $K \rightarrow \pi e \bar{\nu}$, that's a K meson goes to a π meson. The piece of the matrix element that corresponds to K goes to π is written as

$$V_\lambda = \langle \pi | V_\lambda | K \rangle \quad , \quad (2)$$

and is transmitted by what people call the vector current, V_λ . Well this vector current is considered to transform like these generalized isotopic spin operators; i.e., V_λ is also an operator in $SU(3)$ space. This is a generalization of how one would connect π^+ to π^0 by the isotopic spin lowering operator τ_- ,

$$(2)^{1/2} = \langle \pi^0 | \tau_- | \pi^+ \rangle = \langle \pi^0 | \tau_x - i\tau_y | \pi^+ \rangle \quad . \quad (3)$$

Then people complicate it. You've probably heard about something called PCAC, the "partially conserved axial vector current" (another piece of jargon). What that says is that as the pi meson can decay into something like an electron and a neutrino, the meson disappears. The pion is a pseudoscalar, so the only way you can get rid of that is by another pseudoscalar to make a scalar. That pseudoscalar is the derivative of the axial vector current, (A_λ). In other words, the 4-derivative of the axial vector is not equal to zero, it is equal to the meson field,

$$\partial_\lambda A_\lambda = f_\pi \mu^2 \phi \quad , \quad (4)$$

where f_π is the pion decay constant, μ is the pion mass, and ϕ the meson field.

Therefore, the piece of the matrix element giving the pion going to the vacuum in $\pi^+ \rightarrow \ell^+ \nu$ decay can be written as

$$V_\lambda^5 = \langle 0 | A_\lambda | \pi \rangle \quad , \quad (5)$$

where you say that the axial vector current also behaves like a group of $SU(3)$ operators. The V_λ and A_λ have commutation relations among themselves, these commutation relations being what is called current algebra and these two sets of $SU(3)$ operators combined being what is called $SU(3) \times SU(3)$.

That essentially is what there is to current algebra, $SU(3) \times SU(3)$ PCAC, and all the rest of the junk. Basically it is the same thing you have been playing with from the beginning, isospin. It is only that the particle physicists have added an index, done it twice, and put in some new names.

Now, Gell-Mann thinks⁴ that perhaps $SU(3) \times SU(3)$ symmetry breaking is described by

$$I = I^{00} + u_0 + cu_8 \quad , \quad (6)$$

where I^{00} is an $SU(3) \times SU(3)$ symmetric operator, u_0 and u_8 are the symmetry breaking operators, and c is a constant to be determined. Gell-Mann has a good track record, so let's see where Eq. (6) leads us.

There is an analogy to Eq. (6). In nuclear physics we say that there is charge independence of nuclear forces, at least to first approximation. In Eq. (6) that would correspond to the I^{00} term. In nuclear physics you then go on to say that the symmetry is broken by τ_z ; that is, the proton has a charge and the neutron does not. Well, the u_0 and u_8 play the same role as τ_z in nuclear physics. Again it is the same idea only for our case of $SU(3)$ there are two operators and I've added one new index.

To test Gell-Mann's Eq. (6) I have to measure the symmetry breaking operators u_0 and u_8 . That's like measuring τ_z , only you have to measure two of them and the constant, c .

I can measure u_8 between baryon states by what is a Wigner-Eckart type theorem. The result is that

$$\langle B' | cu_8 | B \rangle = d_{B'B8} \frac{\sqrt{3}}{2} (M_{\Sigma^-} - M_{\Lambda}) + if_{B'B8} (M_N - M_{\Sigma^-}) / \sqrt{3}, \quad (7)$$

where the M 's are the masses of the baryons, and the d 's and f 's are the $SU(3)$ structure constant or coupling coefficients. These d 's and f 's are the $SU(3)$ generalizations of the ϵ_{ijk} (you know, +1 or -1) structure constants for isospin. Just grab onto isotopic spin and follow me down the line. When I put in the values of the masses and of the d and f $SU(3)$ coupling coefficients (the analogues of ϵ_{ijk}), it turns out that for nucleons Eq. (7) is equal to

$$\langle N | cu_8 | N \rangle = -209 \text{ MeV} \quad . \quad (8)$$

Next you use this current algebra and this PCAC and you play funny games with them. You know, you take the operators and you commute them. If

you've ever commuted angular momentum operators in quantum mechanics you get the basic idea. What happens is that people relate the nucleon matrix element of the sigma operator (something I'll come back to) to a combination of u_0 , u_8 , and c :

$$\begin{aligned} \langle \mu^2 f_{\pi}(t) N | \sigma | N \rangle &\equiv \mu^2 f_{\pi}(t) \Sigma(t) \\ &= \frac{\sqrt{2} + c}{3} \langle N | u_8 + \sqrt{2} u_0 | N \rangle \quad . \end{aligned} \quad (9)$$

Eq. (9) defines the " Σ -term" as a function of $t \equiv (\text{momentum transfer})^2$.

The next step is to get a value for c . Gell-Mann, Oaks, and Renner⁵ obtain

$$c \approx -1.25 \quad (10)$$

from fitting all this formalism to the masses of the octet of mesons in Fig. 1.

Finally (now here is where the physics is starting to come in) it turns out that you can relate the elastic πN scattering amplitude evaluated at the point $[t = 2\mu^2, \text{total center of mass energy squared} \equiv s = M^2]$ to the Σ -term:

$$F_{\pi N \rightarrow \pi N}(t=2\mu^2, s=M^2) = \frac{\mu^2}{f_{\pi}} \Sigma(t=2\mu^2) \quad . \quad (11)$$

Why do I get this? You might see the idea by noting that from Eq. (9) the r.h.s. of Eq. (11) has only a nucleon in the initial and final states, whereas the l.h.s. has a nucleon and a pion. I get rid of those pions by making them equal to derivatives of axial vector currents and I commute these axial vector currents to get the scalar σ operator. Basically that's the idea of the " Σ -term."

Let's review what I am saying. I am saying, from Eqs. (9) - (11) that

$$\begin{aligned} F_{\pi^+ p}(2\mu^2, M^2) &= \frac{\mu^2}{f_{\pi}} \Sigma(2\mu^2) \\ &= \frac{1}{f_{\pi}} \frac{\sqrt{2}+c}{3} \langle N | u_8 + \sqrt{2} u_0 | N \rangle \quad . \end{aligned} \quad (12)$$

From the above I know the matrix element of u_8 and the value of c . I want the matrix element of u_0 . I can do this either by theoretically making a model for $\Sigma(t)$, or by actually "measuring" $F_{\pi^+ p}(2\mu^2, M^2)$. Various models have given numbers for $\Sigma(t)$ of

$$\mu^2 f_{\pi} \Sigma = \{20, 40, 60, 99\} \text{ MeV (models)} , \quad (13)$$

but these models are really just a substitute for measuring F_{π^+p} , which would be the real test of the Gell-Mann idea.

Before going on, note that I am talking about F_{π^+p} at the unphysical point $t = 2\mu^2$, $s = M^2$. (Isn't this just like a theorist to ask an experimentalist to go out and measure something in the unphysical region?) Take a look at Fig. 3. The shaded regions define the physical s-channel we are interested in, and also the t-channel (which is $\pi\pi \rightarrow NN$ scattering), and the crossed u-channel. The boundary curves are given by

$$t = -s + 2(M^2 + \mu^2) + (M^2 - \mu^2)/s . \quad (14)$$

For the s-channel, the forward direction is the s-axis, and the backward direction is the curve of Eq. (14) with threshold at $s = (M + \mu)^2$. [In Fig. 3 I have plotted things with $\mu = M/2$ so that the curves are not too crowded.]

Now in asking for $F_{\pi^+p}(2\mu^2, M^2)$, theorists aren't just being ornery. It turns out that it is at this point that two terms cancel in $F_{\pi^+p}(t, s)$ which are of the order of the strong coupling constant. Further, correction terms of the size of the r.h.s. of Eq. (11) also cancel at $t = 2\mu^2$, $s = M^2$. Therefore, it is only at this point that the theorists can give any sort of prediction. That leaves it to people to try to extrapolate the data from the physical region of the s-channel up to the line $t = 2\mu^2$ in Fig. 3, and then to further extrapolate along this line to the point $t = 2\mu^2$, $s = M^2$. I want the amplitude at that point, or rather Gell-Mann does, and Dashen does, and all the boys do.

The problem is how do you actually extrapolate the data from the physical s-channel over to $t = 2\mu^2$, $s = M^2$? Different experiments cover different energy regions with different types of errors, and the errors on the imaginary and real parts are different. How do you do it? Well, generally speaking, people have just sort of waved their hands, combined the experiments together, and roughly extrapolated up. Answers like

$$\begin{aligned} \mu^2 f_{\pi} \Sigma \\ = \mathcal{O}[(60 \pm 30) \text{ to } (100 \pm 10)] \text{ MeV (rough extrapolation)} \end{aligned} \quad (15)$$

were obtained.

Recently, however, Cutkosky⁶ showed that there is actually an analytic theory of error extrapolation. This complicated analytic theory, which is very beautiful but very involved mathematically (you'd almost think a Russian did it), tells you how to extrapolate your data. Shih and Shepard⁷ have done such an extrapolation for this problem, and they find that given the present data,

$$\mu^2 f_{\pi} \Sigma = (-45 \pm 140) \text{ MeV} . \quad (16)$$

You're not going to test nothing with that!

What do you need?

Well, the answer is a function of all of the data in the physical s-channel region. But it turns out that most of the error in Eq. (16) is due to the errors which now exist in the π^+p elastic scattering data in the low energy region. If that (the error, that is) could be reduced by an order of magnitude, then the error in Eq. (16) could be reduced to something on the order of 20 - 30%. That is to say, the number in Eq. (16) would be a number with 20 - 30% error.

Therefore, to get the Σ -term out and to test Gell-Mann's thesis (and in general these days it is good to test a Gell-Mann thesis) one needs good, precise, low energy, π^+p elastic scattering data. There is a proposal to do that here at LAMPF; it is accepted; it's on line. Hopefully it'll answer this question. Many people in particle physics would be very happy with that data.

b) $\pi\pi$ and πN Scattering Lengths

I've mentioned current algebra, I've mentioned PCAC, now I'm going to mention a new piece of jargon, "soft pions." What does that mean? Well, often when you try to do real PCAC current algebra calculations, with the honest energy-momentum conservation relation

$$(E^2 - p^2) = \mu^2 , \quad (17)$$

it turns out to be hard. However, if one ignores the pion mass and sets the four-momentum-squared of

the pion equal to zero (this defines a "soft pion"),

$$(E^2 - \vec{p}^2) = 0 \quad , \quad (18)$$

then the calculations are simpler, or at least Weinberg could do the calculations more simply.

Using this soft pion technique, Weinberg⁸ was able to calculate the $\pi\pi$ and πN scattering lengths. The results are in terms of a quantity L , given by

$$L = \mu f_\pi^2 / 8\pi = 0.09 \mu^{-1} \quad (\text{experimental } f_\pi) \quad (19)$$

$$\approx \frac{g_{\pi NN}^2}{8\pi} \frac{\mu}{M^2} \left(\frac{G_V}{G_A} \right)^2 = 0.11 \mu^{-1} \quad (\text{theoretical } f_\pi) \quad .$$

The second line of Eq. (19) is from the Goldberger-Treiman relation, which theoretically relates f_π to $g_{\pi NN}$ (the strong pion-nucleon coupling constant) and the vector and axial vector weak coupling constants G_V and G_A . Since there is not exact experimental equality between these two lines, I have listed both numbers. I am using the "experimental" value $0.09 \mu^{-1}$. So, you can raise all the theory numbers in this section by 20% if you like the "theory" number for f_π better than the "experimental" number for f_π (as many people do, actually).

Well, playing with and commuting these "generalized isotopic spin operators," and using soft pions (all the fun and games), Weinberg calculated the following πN and $\pi\pi$ isospin (T) scattering lengths a_T :

πN scattering lengths (Weinberg)

$$a_{1/2} = \frac{2L}{(1 + \mu/M)} = 0.16 \mu^{-1} \quad (20)$$

$$a_{3/2} = \frac{-L}{(1 + \mu/M)} = -0.08 \mu^{-1} \quad (21)$$

$$a^+ \equiv a_{1/2} + 2a_{3/2} = 0 \quad (22)$$

$\pi\pi$ scattering lengths (Weinberg)

$$a_0 = \frac{7}{4} L = 0.16 \mu^{-1} \quad (23)$$

$$a_2 = -\frac{1}{2} L = 0.045 \mu^{-1} \quad (24)$$

Notice that what is called a^+ in Eq. (22) is equal to zero.

Now, before I go on, I mention that McDonald, Rosen, and Kuo⁹ have pointed out that, you know, you really can't say that the world has soft pions. Pions really are hard pions. Using hard pion corrections and general symmetry considerations¹⁰ involving SU(3) invariance and parity, they were able to make different predictions for a_0 and a_2 of:

$\pi\pi$ scattering lengths (McDonald, Posen, and Kuo)

$$a_0 = \frac{12}{7} L = 0.25 \mu^{-1} \quad (25)$$

$$a_2 = 0 \quad (26)$$

Well, as long as no one could really measure these things there was no problem. But it turns out that people are now beginning to measure them honestly; in particular in K_{e4} decay. That's a K^+ meson goes to $\pi^+\pi^-e^+\nu$. The pions are the only two strongly interacting particles in the final states and the rest of the theory I know very well. Therefore I can relate¹¹ the K_{e4} amplitude to the isotopic spin zero phase shift δ_0 minus the p-wave phase shift δ_1^1 . Further, in this $\pi\pi$ energy region, δ_1^1 is small.

As mentioned, these experiments are just starting to be done with any sort of precision. Zylbersztein, Basile, et al.¹² got

$$a_0 = (0.60 \pm 0.25) \mu^{-1} \quad (27)$$

Big errors in Eq. (27), but it is much larger than Eq. (23). Recently, the Penn group,¹³ including Mann and McFarlane, got this:

$$(\delta_0 - \delta_1^1) = (0.22 \pm 0.06) \text{ radians} \quad (28)$$

They are still analyzing their data to extract the scattering length from the phase shift in Eq. (28). I have roughly calculated this number from Eq. (28):

$$a_0 = (0.35 \pm 0.10) \mu^{-1} \quad (29)$$

MacFarlane tells me that this number is not too far off, but remember they are still analyzing their data.

Let's talk about a_0 for the time being. Weinberg says from Eq. (23) that it is supposed to

be $[0.16 \mu^{-1}]$. OK, that's only two standard deviations away from the result in Eq. (29) and you wave your hands. But you know, it's bothersome. It appears to say that there is a problem. If it turns out that the error reduces, and a_0 is really $\sim 0.35 \mu^{-1}$, then Weinberg's whole list of Eqs. (20) - (24) is suspect, and particle physicists would want someone to go out and measure all of them.

In principle there are a number of ways in which you can measure these numbers. π^+p elastic scattering measures $a_{3/2}$. π^-p elastic scattering measures $[2a_{1/2} + a_{3/2}]$. π^+d elastic scattering exactly measures this $a \equiv (a_{1/2} + 2a_{3/2})$, which Weinberg says should be equal to zero. πd scattering also gives some information on the p waves and $\delta_{3/2}^{3/2}$.

The data which exist on $a_{1/2}$ and $a_{3/2}$ supposedly yield numbers that are as good as 10%, but everybody's 10% is at a different place on the experimental map. π^+p and π^+d experiments are on line to try to measure $a_{1/2}$ and $a_{3/2}$ to a percent or two. These experiments are supposed to go. They are important.

$\pi N \rightarrow \pi \pi N$. OK, what about these experiments? These experiments measure combinations of a_0 and a_2 . Olsson and Turner¹⁴ have extrapolated data from various processes to get

$$a_0 = (0.24 \pm 0.03) \mu^{-1} . \quad (30)$$

You notice that Eq. (30) agrees with the second theory of Eq. (25), but not with Weinberg's Eq. (23). But we just told you that all these extrapolations are in doubt. So, you know, let's try to really measure things well.

One experiment is to try $\pi^-p \rightarrow \pi^-\pi^+n$. The matrix element is proportional to

$$M(\pi^-p \rightarrow \pi^-\pi^+n) \propto [-0.15\gamma - 3.5(2a_0 + a_2)] \quad (\text{soft pion}) \quad (31)$$

$$\gamma \equiv [f_\pi(\text{experiment})/f_\pi(\text{theory})]^2.$$

Therefore, here we are measuring a combination of a_0 and a_2 . Further, if this experiment were generalized to $\pi^+p \rightarrow \pi^+\pi^+p$, then you could measure a_2 separately, since

$$M(\pi^+p \rightarrow \pi^+\pi^+p) \propto [0.3\gamma + 20.8a_2] \quad (\text{soft pion}) . \quad (32)$$

Processes (31) and (32) would then give you both a_0 and a_2 .

The $\pi^-p \rightarrow \pi^-\pi^+n$ experiment is proposed because you only need a single arm spectrometer to get the π^+ , whereas you have to get both π 's in $\pi^+p \rightarrow \pi^+\pi^+p$. But still it would be awfully nice if in addition to $\pi^-p \rightarrow \pi^-\pi^+n$ going, $\pi^+p \rightarrow \pi^+\pi^+n$ would also go. That is, if everything I have mentioned so far went, then you'd be measuring every phase shift. In other words, you'd be testing every prediction of Weinberg.

ABC Effect. Finally, I mention that there is what is known as the ABC (Abashian, Booth, and Crowe) effect.¹⁵ [Maybe I should let him (Crowe) talk about it.]

What happens is that people are getting a peaking in the reaction

$$p + d \rightarrow {}^3\text{He} + M^0 , \quad T = 0, 1 \quad (33)$$

around a M_0 missing mass of 310 MeV. However, in

$$p + d \rightarrow {}^3\text{H} + M^+ , \quad T = 1 \quad (34)$$

the peaking is not found. The experiments have been repeated and the results have been corroborated, and so people are guessing that there might be a large $T = 0$ scattering or resonance around this energy. It would be nice to check that, since obviously this is related to the entire scattering length problem.

c) NN Scattering Lengths

This has nothing to do with PCAC or anything, it is good old fashioned nuclear scattering lengths. But since I am talking about scattering lengths, why not talk about them? The isotopic spin one scattering lengths (b_1) for pp, and np and nn are sort of reasonably well known. Listed along with np b_0 they are¹⁶

$$pp: \quad b_1 = -17.1 \text{ Fermi} \quad (35)$$

$$np: \quad \begin{cases} b_0 = +5.378 \text{ Fermi} \\ b_1 = (23.714 \pm 0.028) \text{ Fermi} \end{cases} \quad (36)$$

$$nn: \quad b_1 = -(16.4 \pm 1.9) \text{ Fermi} , \quad (37)$$

[For the pp scattering length you have to start from -7.3 Fermi and take out the coulomb contribution.]

People are reasonably happy with these things now, except Henley and Keliher¹⁷ are not happy with Eq. (37). Why aren't they happy with that? Well, because they have developed a particle mediated nuclear force which has allowed them to explain the different binding energies of the mirror nuclei Helium-3 and Hydrogen-3. (And you know, after Hydrogen-2, that's the first problem.) Further, the same nuclear force which takes care of the ${}^3\text{He} - {}^3\text{H}$ binding energy difference predicts that

$$nn: b_1 \text{ (Henley-Keliher)} = -17.9 \text{ Fermi} \quad (38)$$

That is, Henley and Keliher predict the nn scattering length is more negative than the pp scattering length, not less negative.

Well, obviously you want to measure various combinations of these scattering lengths in Eqs. (35) - (37). Of course I quickly mention np elastic scattering would be good. But how about trying to measure $b_1(nn)$? There are about three ways you could try it.

The first is

$$np \rightarrow nn\pi^+, \quad (39)$$

assuming you could separate the π . In other words, pick that energy region where the π has a large momentum and the two n 's sort of cluster together as they come out. Hopefully you could then extract the nn scattering length from the π^+ final state interactions. In principle it can be done, but it's rough. You are not really sure you can actually do it.

Most of the experiments which have tried to measure $b_1(nn)$ use

$$\pi^- d \rightarrow nn\gamma \quad (40)$$

The advantage is that the two neutrons are the only two strongly interacting final states. But there turn out to be certain experimental problems, I gather.

What would be really nice, since you have pions and muons all over the place at LAMPF, would be to try

$$\mu^- d \rightarrow nn\nu_\mu \quad (41)$$

(Like I said, an experiment just has to be "feasible.")

To conclude this section, what I am saying is that the low energy data that you can get out of this machine can be of great importance to particle physics, independent of its importance to nuclear physics, which the next two speakers will talk about. Specifically, you can settle an awful lot of questions. You can throw an awful lot of papers into the trash heap, and you can start an awful lot of theoretical students on their theses--whether that is good or bad is another question.

III. ELECTROMAGNETIC INTERACTIONS

a) Pion Electromagnetic Form Factor

Let's go to electromagnetic interactions that can be studied here at LAMPF. In particular, let's start with the pion form factor. As of right now, there are two main ways the pion form factor has been studied. One is by positron-electron colliding beams. Essentially e^+e^- goes to gamma goes to $\pi^+\pi^-$ as shown in Fig. 4. The solid disk is what you are trying to measure, the pion form factor.

The data I show now, as well as that I will come to in a second, is taken from the 1971 Cornell Conference on photon and electron interactions.¹⁸ You notice that the data in Fig. 5 is in the high energy region, and the error is large.¹⁹ In this high energy region you expect the data to be dominated by the ρ meson; i.e., photon $\rightarrow \rho$ meson, ρ meson decays into $\pi^+\pi^-$. This data doesn't look like that and some people are worried. However, lower energy e^+e^- data²⁰ shown in Fig. 6 can be fitted to a ρ - ω double resonance.

But you see, $e^+e^- \rightarrow \pi^+\pi^-$ obviously cannot measure anything at an energy lower than the rest mass of the two pions. And what we want most of all is the pion form factor as the energy goes to zero, you know, $F_\pi(0)$. How can you do that?

A possible way is to do electroproduction;

$$ep \rightarrow en\pi^+ \quad (42)$$

Now this is complicated, theoretically. Why is it complicated? Well, take a look at the nice little diagrams in Fig. 7. In Fig. 7a the electron comes in and the proton comes in. They exchange a photon

(that is just coulomb scattering), but then the proton goes out and ejects a π^+ . That is a strong interaction which tells me nothing and just gets in the way. The same thing would happen with Fig. 7c if you believe the neutron has a form factor. You can probably ignore Fig. 7c but really, it's there. In Fig. 7d the proton turns into an N^* that decays strongly. [The N^* is the $T = S = 3/2$ first resonance at 1238 MeV.] Finally, in Fig. 7b we get what we want. A photon goes and emits a $\pi^+\pi^-$ pair, the π^- being absorbed by the proton. It is the $\gamma\pi^+\pi^-$ vertex which yields the form factor.

So, we have this problem. We want to measure the solid circle vertex in Fig. 7b, but we've got to get rid of all the other junk [Figs. 7a,c,d]. Can one do it? Well, you read the literature and serious doubts exist. Among other things there are questions involving what kinds of interactions²¹ you use for the πNN vertex and ambiguities in momentum transfer factors.²² So, you sort of hope you can extract the form factor from the data²³ and you get Fig. 8. About all that can be said with certainty is that it is not G_E , the proton electric form factor, but it looks like it might be F_1 or F_ρ , I mean it is consistent with them.

The charge radius obtained from Fig. 8 (now this is interesting) is about

$$\langle r_\pi \rangle \sim (0.6 - 0.7) \text{ Fermi.} \quad (43)$$

[The charge radius is related to the slope of $F_\pi(q^2)$ at $q^2 = 0$.]

In other words, it looks like the pion is "smaller" than the proton. But with this sort of data?

What could you do at LAMPF?

Well, you might have learned that in Feynman diagrams like those in Fig. 7 you can change the time direction anyway you want, just by twisting some legs. Let's twist some legs. Wherever there is a π^+ take it down to the bottom (making it an incoming π^-), and send all the incoming e^- 's at the bottom up to the top (making them outgoing e^+ 's). Everything else stays the same. It's a problem in topology. For example, Fig. 7b becomes Fig. 9, and you see we are looking at

$$\pi^- p \rightarrow n e^+ e^- . \quad (44)$$

That is what you could do here.

You have the same kinds of ambiguities as in electroproduction [from the crossed diagrams of Fig. 7], so this process is not going to clear up everything. But I think one can argue that given the total uncertainty of the whole mess, it would be nice to have data which compliments the electroproduction data. Since process (44) is at a different s-t region than electroproduction, you can get that here, and you can probably do it better than anybody else can do it. That is why I feel this should be considered an important experiment--again from a theorist's point of view. I don't want to start any fights with the program advisory committee.

b) Muon QED from Muonium

This has to do with the hyperfine structure of muonium. In Eqs. (45) - (46) I have written down the part of the muonium Hamiltonian which involves the interaction of the total angular momentum of the electron $\vec{J}_e$, the muon spin $\vec{S}_\mu$, the magnetic moments of the electron $\vec{\mu}_e$ and muon $\vec{\mu}_\mu$, and an external magnetic field, $\vec{H}$:

$$\mathcal{H} = h(\Delta\nu) \vec{S}_\mu \cdot \vec{J}_e - (\mu_e \vec{J}_e + \mu_\mu \vec{S}_\mu) \cdot \vec{H} , \quad (45)$$

$$(\Delta\nu) = \left[\frac{\mu_\mu}{\mu_e(B)} \right] \left(1 + \frac{m_e}{m_\mu} \right)^{-3} f \left(\alpha, \frac{m_\mu}{m_e} \right) \quad (46)$$

$$\mu_{\mu,e} = g_{\mu,e} \left(\frac{eh}{2m_{\mu,e}c} \right) \equiv g_{\mu,e} \mu_{\mu,e}(B) .$$

$(\Delta\nu)$ is called the hyperfine structure splitting. If you believe QED, it is a known function. It's really known. From the above you see it involves only the magnetic moment of the muon, the electron and muon masses, and a known function f of $\alpha \equiv e^2/\hbar c$, and m_μ/m_e .

Now, I'm going to ask a question. Is the muon the same type of lepton as an electron (only it's just got a bigger mass)? One of the ways you can test this is with weak interactions and another way is with electromagnetic interactions, cause those are the only interactions they've got. For now we'll concentrate on QED (and return to weak interactions later).

Is the QED of muons the same as the QED of electrons? If the answer is yes, then in Eqs. (45)-(46) I have a self-consistency condition between $\langle \bar{\psi} \psi \rangle$, the ratio m_μ/m_e , the fine structure constant α , and the ratio of the magnetic moments (really muon to proton). Part of this is clearer by noting from Eq. (46) that

$$\frac{m_\mu}{m_e} = \left(\frac{\mu_e}{\mu_p} \right) \left(\frac{\mu_p}{\mu_\mu} \right) \frac{g_\mu}{g_e} \quad (47)$$

The "g factors" g_μ and g_e experimentally agree with QED predictions to a fraction of a part per million.

In Table I below we list the current values of these quantities and the experimental accuracy in parts per million.²⁴ We also give the accuracy that is hoped for by a proposal to measure these muonium quantities in the stopped muon channel. (The ratio of masses is obtained given an improved value of α from, say, the Josephson effect.)

TABLE I

Quantity	Accuracy (ppm)	Possible Accuracy
$\Delta\mu = 4,463.325 \text{ Mhz}$	2	0.2
$\frac{m_\mu}{m_e} = 206.7688$	13	1 (given α)
$\alpha^{-1} = 137.03602$	1.5	0.5
$\frac{\mu_\mu}{\mu_p} = 3.183347$	2.8	1

Now I remind you, let's be honest. QED is our only real theory. Nuclear physics-particle physics-weak interactions: if you get 5% accuracy you jump up and down at the APS meeting. QED is good to the experimental accuracy of parts per million. So, the question of testing the equivalence of muons vs. electrons as leptons is important. I.e., if something is going wrong with QED for muons, this could test it. I'll come back to this again for weak interactions in about five minutes or so. Let me drop it for the time being.

IV. WEAK INTERACTIONS²⁵

a) Current-Current Theory of Weak Interactions

OK, let's go on to weak interactions.²⁵ I'm going to start by giving you some more jargon, the current-current theory of weak interactions.

Let me make an analogy to electromagnetic scattering. Everybody knows about e scatters off of p, right? A photon goes in between, as shown in the Feynman diagram in Fig. 10. Well, if I'm fancy and pretend I'm taking a graduate course in quantum mechanics I write the interaction down this way:

$$M = - e (\bar{\psi}_e \gamma_\mu \psi_e) \left[\frac{\delta_{\mu\nu}}{q^2} \right] e (\bar{\psi}_p \gamma_\mu \psi_p) \quad (48)$$

$$\equiv - e J_\mu^L [\text{propagator}]_{\mu\nu} e J_\nu^H \quad (49)$$

This over here is the lepton current, the charged current of the electron. We see that the first parentheses in Eq. (48) contain the electron electromagnetic current and the second the hadron current. These two currents are intermediated by the photon in Fig. 10, which is represented by the propagator.

If I was going to have proton-proton electromagnetic scattering, it would be the hadron current off of the hadron current. Electron-electron scattering would be the electron current off of the electron current. In other words, if I just write the entire electromagnetic current as the lepton current plus the hadron current,

$$J_\mu = J_\mu^L + J_\mu^H \quad (50)$$

I have a current-current description of the electromagnetic interaction of leptons and hadrons.

That's what formally happens in the Cabibbo current-current theory of weak interactions. That's what they say it's like (with a couple of changes).

First, the current is formally the same, it's the sum of the lepton current and the hadron current:

$$j_\mu = j_\mu^L + j_\mu^H \quad (51)$$

However, instead of having only a vector coupling, it's a vector coupling plus an axial vector coupling. You know, Gell-Mann and Feynman, V-A, that's all it means:

$$\gamma_\mu + \gamma_\mu (1 + \gamma_5) \quad (\text{V-A}) \quad (52)$$

The propagator? Well you see QED is a real theory, and so you say it's a photon propagator that goes in Eq. (49) or Fig. 10. Weak interactions, though, is not a real theory yet. What happens is

that you admit that you don't know what it is, so you put in a general coupling constant that takes the place of $(-e)$, $(+e)$, and the propagator.

Well, with that this coupling constant has to have units of inverse-mass-squared. It is most precisely measured by observing the muon decay rate and turns out to be²⁶

$$G \equiv G_\mu = [1.4354 \pm 0.0004] \times 10^{-49} \text{ erg cm}^3 \\ \sim 1.026 \times 10^{-5} / m_p^2 . \quad (53)$$

That is most of the current-current theory of weak interactions. Eq. (53) is the coupling constant which takes the place of $(-e)$, $(+e)$, and the propagator. The two currents are listed in Eq. (51), so the matrix element is given by

$$M = G j_\mu^+ j_\mu . \quad (54)$$

Eq. (54) in principle describes all weak processes like $\mu^+ \rightarrow e^+ \bar{\nu}_\mu$ and $ep \rightarrow \nu n$ of Fig. 11, or the ordinary neutron beta decay obtained by turning Fig. 11's legs around.

There is just one more change. The change is due to the fact that in addition to those decays which do not change the quantum number strangeness, like the decays

$$\left. \begin{array}{l} n \rightarrow p + e + \bar{\nu} \\ \pi^+ \rightarrow \pi^0 + e^+ + \nu \end{array} \right\} \Delta S = 0 \quad (55)$$

(see Figs. 1 and 2), there are also weak decays which change strangeness, like

$$\left. \begin{array}{l} K^+ \Sigma^- \rightarrow n + e + \bar{\nu} \\ K^+ \rightarrow \pi^0 + e^+ + \nu \end{array} \right\} \Delta S = 1 . \quad (56)$$

Now early in the game it was observed that the hadron decays that did not change strangeness, like those in Eq. (55), had a coupling constant G_V that was about 2% lower than G_μ , and that the strangeness changing decays had a coupling constant that was about 1/20 times G_μ . The closeness of G_V to G_μ made people feel there had to be a connection,

and this connection was found by Cabibbo. He pointed out that if $SU(3)$ decays amounted to a rotation of an angle θ (the "Cabibbo angle") in $SU(3)$ space, then the two factors of 2% and 1/20 could be related to G_μ by the ansatz that the hadron piece of the weak current in Eq. (51) is given by

$$j_\mu^H = \sin \theta [j_\mu^H(\Delta S = 1)] + \cos \theta [j_\mu^H(\Delta S = 0)] \quad (57)$$

$$\theta = 0.2 \text{ radians} . \quad (58)$$

The Cabibbo hypothesis is theoretically very pleasing, because it allows a clear interpretation of the idea of there being an $SU(3)$ "conserved vector current" (CVC). To understand the meaning of this "CVC", let's go back to electromagnetism again. When all else fails, go back to something you know!

In electromagnetism, if one assumes that the absolute values of the bare charge of the electron and the bare charge of the proton are equal:

$$|\hat{e}(e)|^2 = |\hat{e}(p)|^2 ; \quad (59)$$

and one further accepts the statement that the divergence of the electromagnetic current is zero:

$$\partial_\lambda J_\lambda = 0 ; \quad (60)$$

then the above two Eqs. (59) and (60) imply that the absolute values of the real physical charge of the electron and the real physical charge of the proton are equal:

$$|e(e)|^2 = |e(p)|^2 . \quad (61)$$

CVC is a similar statement for the weak charge. If I believe that the bare weak charge of the muon is equal to the bare weak charge of the hadrons;

$$\hat{G}_\mu^2 = \hat{G}_H^2 (\sin^2 \hat{\theta} + \cos^2 \hat{\theta}) ; \quad (62)$$

and further I believe in CVC, i.e., that the divergence of the free vector current is zero:

$$\partial_\lambda j_\lambda = 0 ; \quad (63)$$

then the above two statements imply that the real physical weak charges should be the same, so that

$$G_{\mu}^2 = G_H^2(\sin^2\theta + \cos^2\theta) = G_H^2 \quad (64)$$

This last statement can be tested experimentally by measuring $\cos\theta$ and $\sin\theta$, as we shall come to briefly.

In any event, that, in a nutshell, is 30 years of weak interaction theory. You just have to think in terms of electromagnetism and you've got it. So you don't have to be too impressed when somebody starts yelling all the in words in front of you. The above is essentially all there is to it.

Now, before I go on to the next sub-section, there are going to be a couple of formulas in it. Again, I ask you don't turn off before you give me a chance to tell you what they mean. They mean something simple.

b) $\pi^+ \rightarrow \ell^+ \nu$ Decays and Universality

Universality is the statement that just as we believe that the QED interactions of electrons and muons are the same, so we also believe that the weak interactions of electrons and muons are the same. There is a "oneness" or "universality" of the weak interactions of all leptons, be they electron leptons or muon leptons--again the only difference is that muons have a larger mass.

The most exact test of this belief turns out to be the decays $\pi^+ \rightarrow \ell^+ \nu$. Let's look at the matrix element for $\pi^+ \rightarrow \mu^+ \nu_{\mu}$:

$$M = \frac{1}{\sqrt{2}} G \langle 0 | A_{\lambda}^0(0) | \pi(p) \rangle \times \left(\frac{m_{\mu} m_{\nu}}{E_{\mu} E_{\nu} v^2} \right)^{1/2} \bar{u}(k') \gamma_{\lambda} (1 + \gamma_5) v(k) \quad (65)$$

The piece on the right,

$$X_{\lambda} \equiv \bar{u}(k') \gamma_{\lambda} (1 + \gamma_5) v(k) \quad (66)$$

describes the muon and the neutrino. Forget about that for a second. The bra-ket in Eq. (65) shows the pion decaying into nothing, so here is that good old PCAC of Eq. (4) again, relating the pion field to the axial vector current. Well, I'm missing a derivative of the axial vector current in Eq. (65), so that gives us a momenta, and in particular

$$\langle 0 | A_{\lambda}^0(0) | \pi(p) \rangle = i p_{\lambda}^{\pi} f_{\pi}(\mu) / (2E_{\pi} v)^{1/2} \quad (67)$$

But note that just by energy-momentum conservation and the Dirac equation

$$p_{\lambda}^{\pi} X_{\lambda} = m_{\mu} \bar{u}(k') (1 + \gamma_5) v(k) \quad (68)$$

so that M is proportional to the mass of the lepton. Therefore, when I calculate the decay rate, by squaring M and integrating over phase space (the whole rigamarole), the decay rate will be proportional to the mass of the lepton squared times a phase space factor. In particular:

$$\Gamma(\pi^+ \rightarrow \mu^+ \nu_{\mu}) = \frac{G^2 f_{\pi}^2(\mu) m_{\mu}^2}{8\pi} \left(m_{\pi}^2 - m_{\mu}^2 \right)^2 \quad (69)$$

Universality says that if the muon is like the electron (no hanky-panky it really is), then I can obtain the formula for $\Gamma(\pi^+ \rightarrow e^+ \nu)$ by just changing m_{μ} to m_e in Eq. (69) and hopefully I will find that $f_{\pi}(\mu) = f_{\pi}(e)$. Universality predicts

$$R \equiv \frac{\Gamma(\pi^+ \rightarrow e^+ \nu)}{\Gamma(\pi^+ \rightarrow \mu^+ \nu_{\mu})} = \left[\frac{f_{\pi}(e)}{f_{\pi}(\mu)} \right]^2 \left(\frac{m_e}{m_{\mu}} \right)^2 \left[\frac{m_{\pi}^2 - m_e^2}{m_{\pi}^2 - m_{\mu}^2} \right]^2 \quad (70)$$

$$= \left[\frac{f_{\pi}(e)}{f_{\pi}(\mu)} \right]^2 [1.278 \times 10^{-4}] \quad (71)$$

Actually, there are some radiative corrections, largely for $\pi^+ \rightarrow \ell^+ \nu_{\ell}$. But these corrections are well known theoretically and I can correct for them. When that is done the predicted ratio turns out to be

$$R_{\text{rad}} = \left[\frac{f_{\pi}(e)}{f_{\pi}(\mu)} \right]^2 [1.228 \times 10^{-4}] \quad (72)$$

Eq. (72) should really be true if the muon is like the electron in its coupling to the pion. Now there has been a lot of theoretically fuzzy stuff I've talked about before. This is not fuzzy. This is clean. This is very clean theoretically.

The current experimental value for R , which goes back to 1964, is

$$R_{\text{expt}} = [1.247 \pm 0.028] \quad (73)$$

or

$$\frac{f_{\pi}(e)}{f_{\pi}(\mu)} = [1.007 \pm 0.014] \quad (74)$$

This result is almost a 3% experiment. Perhaps at LAMPF this could be reduced to 1/2%. In other

words, perhaps you could show that $f_{\pi}^2(\mu) = f_e^2(e)$ to half a percent.

Now why have I been emphasizing tests of the QED and weak universality of electrons and muons as leptons? To answer that let me show a little card I have stolen from the blackboard of Dick Silbar. I'd like to put it up on the screen, it's my Fig. 12.

That's why! If I had one type of lepton, fine! If I had 27 types, also fine. But why two? I think that is very important and I think nature is trying to say something. But we're all just too stupid to figure it out. All experiments which test the similarity of muons to electrons may help us in obtaining a solution to this puzzle.

c) $\pi^+ \rightarrow \pi^0 e^+ \nu$ Decays, CVC, and the Cabibbo

Angle

In Section IV-a we explained the conserved vector current (CVC) and its connection to the Cabibbo angle; i.e., Eqs. (57), (58), and (64). We pointed out that the way to test this hypothesis is to measure the decay constants of various processes to see if they yield the identical value for the Cabibbo angle. In Table II we have listed various results, which we shall discuss.

TABLE II

Process	Decay Constant
1) $\mu \rightarrow e \bar{\nu}_{\mu} \nu_{\mu}$	$G_{\mu} = [1.4354 \pm 0.0004] \times 10^{-49} \text{ erg cm}^3$
2) $K \rightarrow \pi e \nu$ (KG)	$G_{\mu} \sin [0.235 \pm 0.019]$
3) $0^+ \rightarrow 0^+$	$G_{\mu} \cos [0.188 \pm 0.007]$ $G_{\mu} \cos [0.174 \pm 0.007]$
4) $K \rightarrow \pi e \nu$ (DKP)	$G_{\mu} \sin [0.192 \pm 0.016]$
5) $\Sigma^+ \rightarrow \Lambda e^+ \nu$	$G_{\mu} \cos [?]$
6) $\Sigma^- \rightarrow n e^- \nu$	$G_{\mu} \sin [?]$
7) $\pi^+ \rightarrow \pi^0 e^+ \nu$	$G_{\mu} \cos [?]$

Process (1) is muon decay, which of course is the coupling constant²⁶ we shall compare to; it being the universal weak coupling constant. Process (2) is K_{e3} decay, so it should measure $\sin \theta$. If one analyzes the data using the standard assumption that mesons obey the Klein-Gordon spin-0 wave equation

$$(\square + \mu^2) \phi = 0, \quad (75)$$

then one gets the result,²⁷ listed in Table II,

$$\theta [K_{e3} - KG] = 0.235 \pm 0.019. \quad (76)$$

Process (3) is nuclear beta decay. For a long time these difficult measurements of $\cos \theta$ sort of agreed with Eq. (76), but recently it hit the fan. Blin-Stoyle and Freeman did an analysis of $^{26}\text{Al}^m \rightarrow ^{26}\text{Mg} e^+ \nu$, and got²⁸

$$\theta [0^+ \rightarrow 0^+] = 0.188 \pm 0.007. \quad (77)$$

Their experiment, extended to other nuclei, has just been repeated by Hardy et al. They got even lower:²⁹

$$\theta [0^+ \rightarrow 0^+] = 0.174 \pm 0.007. \quad (78)$$

Now remember, the Cabibbo angle obtained from all these processes has to be the same angle, or else the whole thing comes crumbling down.

To pound my own drum for half a minute, we happen to believe the discrepancy can be explained (we being Ephraim Fischbach, C. Keith Scott, myself, and co-workers).²⁷ We propose^{27,30} that instead of obeying the Klein-Gordon equation, mesons obey the first order spin-0 equation of Duffin, Kemmer, and Petiau:

$$(\partial \cdot \beta + \mu) = 0, \quad (79)$$

$$\beta_{\mu} \beta_{\nu} \beta_{\lambda} + \beta_{\lambda} \beta_{\nu} \beta_{\mu} = \delta_{\mu\nu} \beta_{\lambda} + \delta_{\mu\lambda} \beta_{\nu}, \quad (80)$$

which formally is similar to the Dirac equation. If one accepts this and reanalyzes the K_{e3} data, the value one obtains for the Cabibbo angle from process (4) is²⁷

$$\theta [K_{e3} - DKP] = 0.192 \pm 0.016. \quad (81)$$

That is my own game, we say there is no discrepancy. But if you believe standard KG dogma, right now there looks like there is. How do you settle it? You measure the Cabibbo angle another way.

One possibility is to analyze all the leptonic decays of baryons, like those in processes (5) and (6). [Note that neutron decay is a special case.] However, there are too many uncertainties involving

strong interaction effects which cannot be removed as in mirror nuclei. I know, I've tried it.³¹ Perhaps with the new data now available a further attempt can be made with this idea, but for now about all you can say from these processes is that the Cabibbo angle is ~ 0.2 .

So what's left? How about $\pi^+ \rightarrow \pi^0 e^+ \nu$ [process (7)], which measures $\cos \theta$? If the Cabibbo angle is that given in Eq. (76), then the theoretically clean prediction for the π_{e3} branching ratio B (including radiative corrections) is

$$B_{th}[\theta = 0.235] = 0.99 \times 10^{-8} \quad (82)$$

However, if the nuclear beta decay (and DKP K_{e3} decay) value is correct, then the prediction for B is²⁷

$$B_{th}[\theta = 0.188] = 1.01 \times 10^{-8} \quad (83)$$

The currently accepted value is

$$B_{expt} = [1.02 \pm 0.07] \times 10^{-8} \quad (84)$$

To distinguish between the two values in Eqs. (82) and (83) you need better than a two percent experiment, an improvement over Eq. (84) approaching an order of magnitude. There is a proposal accepted where they claim they're gonna do it to 2%. Their claim maybe they can do it to 1% (and if God smiles on them maybe they could even do it to a number approaching 1/2 %).

d) Lepton Conservation and Neutral Currents

My time is getting on, so let me go through this quickly and refer you elsewhere for a more general discussion.³² What we are talking about now is lepton conservation vis a vis neutrinos.

To rapidly review our knowledge about neutrinos, we know from laboratory experiments that the mass of the electron neutrino is less than 60 eV and the mass of the muon neutrino is less than 1.5 MeV. (They both are conservatively less than about 200 eV if you believe certain cosmological arguments.³³)

From double beta decay experiments of ¹³⁰Te and ⁸²Se we know that the electron neutrino is orthogonal to the electron anti-neutrino to a part in a thousand:

$$|\langle \bar{\nu} | \nu \rangle| \leq 10^{-3} \quad (85)$$

This statement is one of either opposite helicity or particle-anti-particle. Further, we know the electron neutrino is left-handed to about 5-10%. Similar, although not quite as precise, statements can be made about the muon neutrinos.

Finally, the evidence that electron neutrinos and muon neutrinos are distinct to within 10% comes from the second reaction in Eq. (86) not being observed:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad (86)$$

$$\quad \quad \quad \downarrow + n \rightarrow p + e^-$$

All of the above information is usually summarized in the statement that there are two separate additive (additive like strangeness) conservation laws for electron and muon leptons. The two sets of quantum numbers are

$$A_\mu = \begin{cases} +1 & \text{for } \mu^-, \nu_\mu \\ -1 & \text{for } \mu^+, \bar{\nu}_\mu \end{cases} \quad (87)$$

$$A_e = \begin{cases} +1 & \text{for } e^-, \nu \\ -1 & \text{for } e^+, \bar{\nu} \end{cases} \quad (88)$$

However, it has been observed that to within the present accuracy, the above data can also be explained by other conservation law schemes. The most commonly proposed alternative is the multiplicative lepton number conservation law. (Here one multiplies the values of all the particles in the system, like for parity.) The scheme yields

$$M = \begin{cases} -1 & \text{for } \mu^+, \mu^-, \nu_\mu, \bar{\nu}_\mu \\ +1 & \text{for all other particles} \end{cases} \quad (89)$$

How can we test between the two conservation laws? Let me quickly mention two ways.

The first would be by looking for muonium going to anti-muonium:

$$\mu^+ e^- \rightarrow \mu^- e^+ \quad (90)$$

This is not allowed by the additive laws of Eqs. (87) - (88), but it is allowed by the multiplicative

scheme of Eq. (89). Clearly a search for this process could be done at LAMPF.

Another test is based on the observation that although only the μ^- decay process

$$\mu^- \rightarrow e^- + \bar{\nu} + \nu_\mu \quad (91)$$

is allowed by the additive conservation laws, the multiplicative law also allows

$$\mu^- \rightarrow e^- + \nu + \bar{\nu}_\mu \quad (92)$$

Therefore, if we scattered μ^- decay products off of ^{37}Cl , we could search for the two-step reaction

$$\mu^- \rightarrow e^- + \begin{array}{|c|} \hline \bar{\nu} + \nu_\mu \\ \hline \nu + \bar{\nu}_\mu \\ \hline \end{array} \xrightarrow{\quad} + ^{37}\text{Cl} \rightarrow e^- + ^{37}\text{Ar} \quad (93)$$

The additive laws, which only allow the initial decay Eq. (91), would forbid the second step of Eq. (93). However, the multiplicative law allows both initial decays in Eqs. (91) and (92). Therefore the products of the first step in Eq. (93) would allow the final step in Eq. (93) to go with a cross section smaller than the prediction from a standard V-A theory calculation.

There is another question, related to lepton conservation, which involves neutral currents. There have been all sorts of big discussions about them recently, specifically concerning implications for neutrino scattering.

We'll get lots of π^+ 's here. If we get lots of π^+ 's we'll get lots of μ^+ 's, and therefore plenty of ν_μ 's, $\bar{\nu}_\mu$'s, and ordinary neutrinos from the reactions

$$\pi^+ \rightarrow \mu^+ + \nu_\mu + e^+ + [\nu + \bar{\nu}_\mu + \nu_\mu] \quad (94)$$

Take the three neutrinos in Eq. (94) and shoot them into electrons. (We've got a lot of electrons around, too.) With additive lepton conservation, only

$$\nu + e^- \rightarrow \nu + e^- \quad (95)$$

scattering (Fig. 13a) will go if the standard

Cabibbo current-current theory is correct. However, if in addition to the charged Cabibbo currents there are neutral currents (Figs. 13b and 13c), then I can also scatter ν_μ 's and $\bar{\nu}_\mu$'s off of electrons:

$$\nu_\mu + e^- \rightarrow \nu_\mu + e^- \quad (96)$$

$$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^- \quad (97)$$

Further, with neutral currents Eq. (95) will go with a different value because of interference between the charged current (j_μ) and the neutral current (j_μ^0). This is summarized in Table III.

TABLE III

	$\nu e \rightarrow \nu e$	$\nu_\mu e \rightarrow \nu_\mu e$	$\bar{\nu}_\mu e \rightarrow \nu_\mu e$
Charged current (j_μ)	GO	NO GO	NO GO
Cabibbo theory			
Neutral currents (j_μ^0) added	GO with (j_μ^+, j_μ^0) interference	GO	GO

These experiments could be done (or at least attempted) here, and would be quite important.

V. FEW COMMENTS ON POLARIZATION EXPERIMENTS

Let me finish with a few comments on polarization experiments.

It has been observed³⁴ that there is a large asymmetry in the photoproduction of π^+ mesons off of a target of polarized protons:

$$\gamma p \rightarrow \pi^+ n \quad (98)$$

A proposed experiment here would use a secondary beam of polarized protons and see if there is a similar asymmetry in the production of π^+ 's via

$$pp \rightarrow \pi^+ np \quad (99)$$

The interest is due to the existence of the asymmetry in the process given in Eq. (98).

Another proposal, which has just come in a preliminary form, wants to use (if we ever get it) a real honest-to-God (Cockcroft-Walton, the whole

thing) primary beam of polarized protons. These polarized protons would be scattered off of protons, deuterons, and nuclei. This would allow an investigation of parity violation in nuclear forces since the helicity dependence in the parity violating parts of nuclear forces allows you to split them out.

The reason for the interest is that the people who study nuclear forces are coming to the conclusion that parity violation in nuclei is about 20 times too large,³⁵ and they don't understand it. This would be an ideal way to study the problem.

VI. CONCLUSION

That is what I have to say, so let me reemphasize a point. I think this machine could really perform a number of very important experiments; experiments that would be of interest to physicists when they put on their "particle physics hat" as well as when they put on their "nuclear physics hat." If a reasonable number of these experiments could be done, it would be very exciting.

ACKNOWLEDGMENTS

Before I stop I want to take time out to thank a number of people who by phone, letter, and conversation have greatly aided me in preparing this talk. If I were to single out anyone, it would be Eugene Golowich of the University of Massachusetts, Amherst. My interest in the " Σ -term" was aroused by a series of stimulating conversations and letters with him over the past four months.

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OK, that's all. Thank you.

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DISCUSSION

McFarlane, Temple--I'd just like to comment on the pion beta decay measurement. I think what we have said is that we would plan to do a 2% measurement, the first time around. We hope that we would learn enough in that first experiment to tell whether or not a more precise experiment is possible. I also just comment that I think you're a little bit more optimistic than many another person about the radiative corrections. There is some doubt of order one or two percent in pion beta decay as to what are the correct radiative corrections. So, an experiment to, you know, a half a percent, if it were possible, which we don't know yet, might not settle the question.

Nieto--The statement of the radiative corrections is something like this. There is a divergence problem, you have to use a cutoff. If you use standard calculational techniques and a cutoff of about 1 GeV, or something like that, then you'll get a

1.2% radiative correction (the same for both KG and DKP). If you go up to 10's of GeV, that changes to about 2%. The success of radiative corrections elsewhere, without having to go to a large cutoff, makes me feel that the uncertainty can, I think, be eliminated to within a fraction of a percent. Now, the point is that obviously I want that experiment done. This is my bag. If it were a 1% experiment, really a 1% experiment, I think with luck you could pick it out. Again, I'll be honest. Obviously, I'm pounding your drum 'cause I want you to pound mine.

McFarlane--We'd like to do a 1% experiment if we could.

Nieto--OK, fair enough. I hope you do, I really hope you do.

Fenyves, University of Texas at Dallas--Could you comment on electron-neutrino scattering?

Nieto--In what way?

Fenyves--Your way.

Nieto--Pardon? Well, I think it can be done, and I think it is an important question right now. I think it is important from purely a fundamental point of view. However, certainly it's also important if you have any sense of bandwagon physics (although there is too much of that around). You

see, there is a lot of current interest in Weinberg's proposed alternate theory of electron and neutrino interactions. LAMPF could help settle some of those questions from the different types of neutrinos scattering or not scattering and by how much. So, from that point of view I guess it is important, too. I'd like to see it done.

Fenyves--We too.

Heller, LASL--One comment to the last question.

In Weinberg's theory the elastic scattering of mu-neutrinos and mu-antineutrinos off of electrons is very small, and probably could not be detected at LAMPF, at least probably not for a long time. But with the electron neutrino one has a distinctly different scattering cross section.

Fenyves--If you are measuring the complete kinematics, namely the kinematics of the neutrino, electron, and the Weinberg alpha parameter, I can show you that for the alpha parameter being in a certain region there is some hope. Obviously there is a small chance that alpha will be just in this region, so that you are right that there is a larger probability that alpha will be outside of the relatively small region where you could measure things at the present at LAMPF. But if you are very lucky, you can't exclude it.

Fig. 1. SU(3) meson octet.

Fig. 2. SU(3) baryon octet.

Fig. 3. $\pi\pi$ elastic scattering kinematics.

Fig. 4. Feynman diagram for $e^+e^- \rightarrow \pi^+\pi^-$.

"Pion" form factor squared (BCF and $\mu\pi$ Groups).

Pion form factor with $\omega\rho$ mixing.

Fig. 5. Pion form factor data from Frascati.

Fig. 6. Pion form factor data from Orsay.

Fig. 7. Feynman diagrams for pion electroproduction.

Fig. 8. Low energy pion form factor data.

The world's data on the pion charge form factor as measured in $\pi^+ n$ electroproduction. The error bars on the pre-1971 data include an estimate of the model dependence; the error bars on the recent data do not. F_2 denotes the simplest VDM form for F_{π^+} , that is $m_\rho^2/(Q^2 + m_\rho^2)$; F_1^V is the nucleon Dirac isovector form factor; G_E^p is the proton charge form factor.

Fig. 9. Feynman diagram containing the pion form factor in $\pi^- p \rightarrow e^- e^+ n$.

Fig. 10. Feynman diagram for ep scattering.

Fig. 11. Current-current $ep \rightarrow \nu n$ weak scattering.

GIVEN MY PRESENT UNDER-
STANDING, IF I HAD
CREATED THE UNIVERSE,
I WOULD NEVER HAVE
INVENTED THE MOON.

Fig. 12. Why muon physics is important (stolen from Dick Silbar).

(a)

(b)

(c)

Fig. 13. Feynman diagrams for possible neutrino-electron scattering processes.