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The τ Lepton*

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In the past few years we have witnessed an occurance which has happened only twice before in particle physics -- the discovery of a charged lepton. Since leptons are the simplest of the fermions our conception of the elementary particles and their interactions depends critically on the proporties of the τ. In the short interval since the first observation of τ events by the SLAC-LBL collaboration[1] in 1975, nine experiments[2] have made measurements of τ properties and a rather clear picture of the τ as a sequential lepton has begun to emerge. The purpose of this report is to sketch that picture.

1. Decay Modes

Figure 1 illustrates the three possible τ decay modes in the standard model. In each case the τ decays to its own neutrino, ν_τ, and the charged weak current, which can materialize as an $e\bar{\nu}_e$, a $\mu\bar{\nu}_\mu$, or a $d\bar{u}$ pair. The $d\bar{u}$ quark pair (or more precisely the d'u pair, where $d' \equiv d \cos^2\theta_C + s \sin^2\theta_C$) forms a hadronic system such as a charged π, ρ, or A_1. There are three general observations that can be made from these diagrams:

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(1) Each of the diagrams has equal weight since all of the couplings to the weak current are equal, with the proviso that the last diagram stands for three diagrams corresponding to the three colors of quarks. Thus, there are five equivalent diagrams and so the electronic branching fractions should be 20%. QCD corrections give an enhancement to the semi-hadronic final states and reduce the prediction for the electronic branching fraction to about 18%.[3]

(2) Many of the branching fractions for the semi-hadronic modes are precisely predicted. For example, the coupling of both the μ and the π to the weak current is known from the measurements of their lifetimes. Thus, the ratio of branching fractions for $\tau \to \pi\nu$ to that for $\tau \to \mu\bar{\nu}\nu$ is precisely predicted. We shall return to a discussion of the predictions for the semi-hadronic modes below.

(3) Most τ decays will contain only one charged particle. Clearly the decays to e's, μ's, π's and ρ's contain only one charged particle, and it will turn out that about half of the semi-hadronic modes contain only one charged particle. Thus $\tau^+ \tau^-$ production will be most prominent in events with only two charged particles.

From these considerations it is clear that $\tau^+\tau^-$ production can be most easily measured by studying e^+e^- annihilation events with two charged particles in which at least one is a lepton. There are five possibilities: eμ, ee, $\mu\mu$, ex, and μx, where x stands for any charged particle. By now seven experiments have made 15 independent measurements of one or more of these modes.[2]

From these measurements we want to derive the branching fractions for τ decay into $e\nu\bar{\nu}$ (B_e), $\mu\nu\bar{\nu}$ (B_μ), one charged hadron plus neutrals (B_{1h}), and three or more charged hadrons plus neutrals (B_{3h}), subject to the constraint that the sum of these four modes is unity. In general, experiments measure products or combinations of these four basic branching fractions, so simultaneous fits to all of these data are necessary. The results of such fits are given in Table I. One fit has been done leaving B_e and B_μ free and the other has constrained $B_\mu = 0.973\ B_e$, its theoretical value. Both fits are extremely good and, in fact, all measurements agree with the fit results within one standard deviation of the experimental errors. Although no single experiment has done a particularly sensitive job of testing e-μ universality in τ decays, the result of all measurements taken together provides a reasonably strngent limit on its violation. Also, it is impressive that there is excellent agreement between the theoretical prediction for the electronic mode, 18%, and the results of the fits.

Many details of the semi-hadronic decays are predicted in the standard model.[4] As mentioned previously, the ratio between the leptonic decays and the $\pi\nu$ mode is precisely predicted from the pion lifetime. The vector decays, which are decays to even numbers of pions plus a neutrino, are precisely predicted from measurements of e^+e^- annihilation via the conserved vector current hypothesis.[5] The decay to $\rho\nu$ is the largest component of this class. For the axial-vector decays, the A_1 plays the same role as the ρ does for vector decays. For this reason, it is hoped that τ decays will provide a convenient way to study the A_1, which has proved so difficult to isolate in hadronic interactions. The $A_1\nu$ branching fraction can be calculated from the $\rho\nu$ branching fraction with the aid of Weinberg's sum rules. τ decays involving kaons will be supressed by $\tan^2\theta_C$ in the standard model. Most of these modes have been studied experimentally and all of the results are consistent with the theoretical expectations, as summarized in Table II. The A_1 remains somewhat elusive. Two experiments see enhancements near 1.1 GeV in the three pion mass but have insufficient statistics to pin down the A_1 parameters.[7,8] Future studies of τ decays should be crucial in understanding the A_1.

Finally, there have been searches for unconventional decays of the τ, that is, decays which should not occur in the standard model. No evidence for such decays has been found. At the 90% confidence level, upper limits on branching fractions have been set at 0.6% for decay to any three charged leptons, at 2.6% for decay to $e\gamma$, and at 1.3% for decay to $\mu\gamma$.[9] Efforts are currently being made with the Mark II detector at SPEAR to reduce these limits by about an order of magnitude.

2. Masses, spin, lifetime, and τ-ν_τ coupling

Without exception, the measurement of τ properties other than branching fractions has been performed most precisely by the DELCO experiment at SPEAR.[10] This experiment uses large solid angle threshold Cerenkov counters to detect electrons with almost negligible misidentification. It has thus been able to obtain a clean, large statistics sample of ex events. The cross sections for these events are shown in Figure 2 as a function of e^+e^- center-of-mass energy. The clear threshold determines the τ mass to be 1782^{+3}_{-4} MeV/c^2. Other fairly precise mass measurements are 1807 ± 20 MeV/c^2 by the DASP experiment[11] and $1790 ^{+7}_{-10}$ MeV/c^2 by the DESY-Heidelberg experiment.[12]

The shape of the ex event excitation curve in Figure 2 also determines the τ spin to be ½ as long as one assumes that the τ does not have a form factor which varies rapidly over the range of a few GeV. All integer spins will require a β^3 theshold dependence and half-integer spins greater than ½ will lead to much too large cross section above 4 GeV when normalized to fit the threshold region. These points are illustrated in Figure 2 by the spin 1 and 3/2 curves.

The τ lifetime has been studied by examining the closest distance of approach to the interaction region of tracks from ex events. The upper limit is 2.3×10^{-12} sec. at the 95% confidence level.[10] For a full strength τ-ν_τ coupling to the weak current and assuming the ν_τ is massless, the τ lifetime, τ_τ is given by

$$\tau_\tau = B_e \left(\frac{m_\mu}{m_\tau}\right)^5 \tau_\mu = (2.8 \pm 0.2) \times 10^{-13} \text{ sec} ,$$

where the error is primarily from the uncertainty in the electronic branching fraction B_e. Thus the τ-ν_τ coupling has to be at least 12% of full strength.

The shape of the election spectrum has been used to determine V, A structure of the τ-ν_τ coupling. The spectrum in the absence of radiative effects, can be represented by

$$\frac{dN}{dz} = \propto z^2 \left[9(1-z) + 2\rho(4z-3) \right]$$

where z is the ratio of the election energy to its maximum possible value and ρ is known as the Michel parameter. The Michel parameter for a V-A τ-ν_τ coupling to the weak current would be 0.75, while it would be zero for V+A and 0.375 for either pure V or A. Using the electron spectrum shown in Figure 3 and correcting for radiative effects, the DELCO experiment has determined ρ to be 0.72 ± 0.15, in good agreement with a V-A interaction and completely excluding a V+A interaction.[10] The effect of a non-zero ν_τ mass would be to soften the electron spectrum. Assuming a V-A interaction, the DELCO experiment has set an upper limit of 250 MeV/c^2 (95% confidence level) on the ν_τ mass.[10]

3. What is the τ?

All of the evidence, then, is consistent with the τ being a sequential lepton decaying to its own massless neutrino with a V-A coupling.

One can ask, however, what other possibilities could exist. The simplest case would be to have the τ, but no ν_τ in an SU(2) x U(1) gauge theory. The τ would then decay into a mixture of ν_e and ν_μ. An analysis of this case shows that it is excluded by several of the measured τ properties. For example, the τ would have to decay into 3 charged leptons at a rate an order of magnitude above the experimental upper limit, and B_μ/B_e would have to be close to 0.5 or 2.0.[13]

Another possibility is that the ν_τ exists, but is more massive than the τ. This is also excluded. The argument is that the sum of couplings to ν_e and ν_μ must be greater than 0.12 of full strength from the τ lifetime measurement. But the ν_μ coupling is limited to 0.025 by the absence of τ production by ν beams,[14] and the ν_e coupling is limited to be less than 0.006 more than the ν_μ coupling by the $\pi \to \mu\nu/\pi \to e\nu$ ratio.[15]

Dropping the requirement of an SU(2) x U(1) gauge theory, one can ask more generally whether it is possible that the τ^- has the same lepton number as either the e^-, e^+, μ^-, or μ^+; that is, whether it couples to the ν_e, $\bar{\nu}_e$, ν_μ, or $\bar{\nu}_\mu$. The τ^- cannot have the lepton number of either the μ^- or μ^+ or it would be produced in ν interactions. The τ^- cannot have the lepton number of either the e^+ or μ^+. If it did there would be two identical neutrinos in the final state and B_μ/B_e would be either .5 or 2.

The one possibility which cannot be excluded at present is that the τ^- has the same quantum number as the e^-. Detailed measurements of ν_e interactions, possibly from beam dump or tagged decay experiments, may be able to address this question in the future.

Of course, there are many more possibilities than the simple ones we have discussed here, and, in general, one must simply compare the predictions of a given model to the range of parameters allowed by the data. It is remarkable in the few years since the τ discovery, how tight the constraints have become.

REFERENCES:

1. M.L. Perl et al., Phys. Rev. Lett. 35, 1489 (1975).

2. For a complete list of measurements and references see G.J. Feldman in Proceedings of the 19th International Conference on High Energy Physics, Tokyo, August 23-30, 1978 edited by S. Homma, M. Kawaguchi, and M. Miyazawa (Physical Society of Japan, Tokyo, 1979), p. 777.

3. C.S. Lam and T.M. Yan, Phs. Rev. D16, 703 (1977); T. Appelquist in Particles and Fields (Proceedings of the Banff Summer Institute on Particles and Fields, Branff, Alberta, August 25 - September 3, 1977), edited by D. H. Boal and A. N. Kamal (Plenum, New York, 1978), p. 33.

4. H.B. Thacker and J.J. Sakurai, Phys. Rev. Lett. 36B, 103 (1971); Y.S. Tsai, Phys. Rev. D 4, 2821 (1971).

5. F.J. Gilman and D.H. Miller, Phys. Rev. D 17, 1846 (1978).

6. S. Yamada in Proceedings of the 1977 International Symposium on Lepton and Photon Interactions at High Energies, Hamburg, August 25-31, 1977, edited by F. Gutbrod (DESY, Hamburg, 1977) p. 69.

7. J. Jaros et al, Phys. Rev. Lett. 40, 1120 (1978).

8. G. Alexander et al, Phys. Lett. 73B, 99 (1978).

9. M.L. Perl in Proceedings of the 1977 International Symposium on Lepton and Photon Interactions at High Energies, Hamburg, August 25-31, 1977, edited by F. Gutbrot (DESY, Hamburg 1977), p. 145.

10. W. Bacino et al, Phys. Rev. Lett. 41, 13 (1978); 42, 749 (1979).

11. R. Brandelik et al, Phys. Rev. Lett. 73B, 109 (1978).

12. W. Bartel et al, Phys. Lett. 77B, 331 (1978).

13. D. Horn and G. G. Ross, Phys. Lett. 67B, 460 (1977); G. Altarelli, N. Cabibbo, L. Maiani, and R. Petronzio, Phys. Lett. 67B, 463 (1977).

14. A.M. Cnops et al, Phys. Rev. Lett. 40, 144 (1978).

15. D.A. Bryman and C. Picciotto, Phys. Rev. D 11, 1337 (1975); E. DiCapus, R. Garland, L. Pondrom, and A. Strelzoff, Phys. Rev. 133B, 1333 (1964).

Table I: Results of constrained fits

	B_e and B_μ free	$B_\mu = 0.973\ B_e$
B_e(%)	16.5 ± 1.5	17.5 ± 1.2
B_μ(%)	18.6 ± 1.9	17.1 ± 1.2
B_{1h}(%)	34.3 ± 4.2	35.0 ± 4.0
B_{3h}(%)	30.6 ± 3.0	30.4 ± 2.9
B_μ/B_e	1.13 ± 0.16	

Table II: Predictions and measurements of τ semi-hadronic branching fractions under the assumption that $B_e = B_\mu = 0.18$

Mode	Predicted branching fraction (%)	Theoretical input	Measured branching fraction (%)	Experimental Reference
$\pi\nu$	10	π decay	8.3 ± 1.4	2
$\rho\nu$	20	CVC + e^+e^- annihilation	24 ± 9	6
$(4\pi)\nu$	10	CVC + e^+e^- annihilation	11 ± 7	7
$A_1\nu$	9	Weinberg sum rules	10.4 ± 2.4	8
$(k+n\pi)\nu$	3	$\tan^2\theta_c$		
$(3\text{or}5\pi)\nu$	12	remainder		

FIGURE CAPTIONS:

1. τ decay modes.

2. The ratio of ex events to μ pair production as a function of center-of-mass energy. The solid curve is a best fit to the spin 1/2 τ pair production cross section. The dashed and dot-dashed curves represent typical cross sections for spin 1 and spin 3/2 particle production. The data are from the DELCO experiment.[10]

3. The election momentum spectrum from ex events measured by the DELCO experiment.[10] The curves represent fits to V-A and V+A τ-ν_τ couplings.

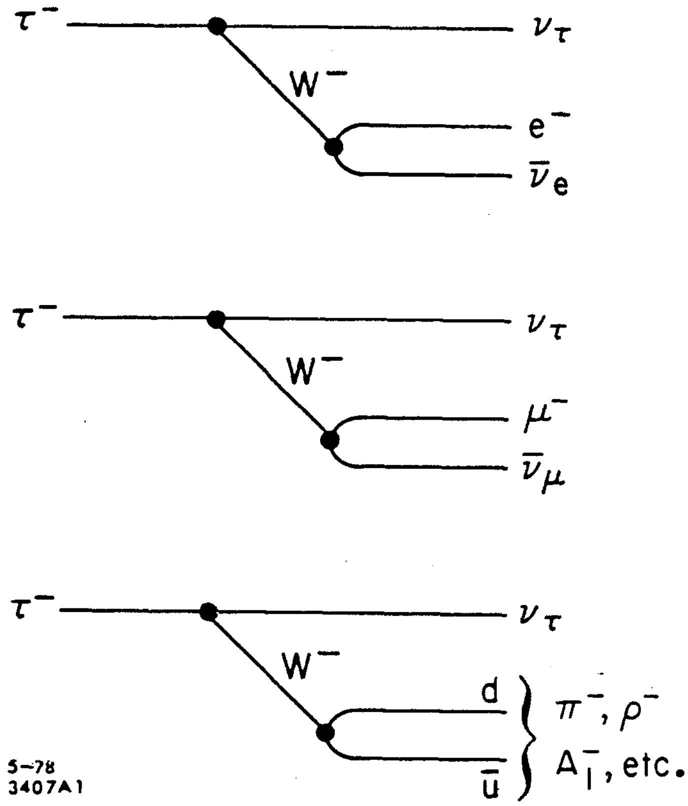

Fig. 1

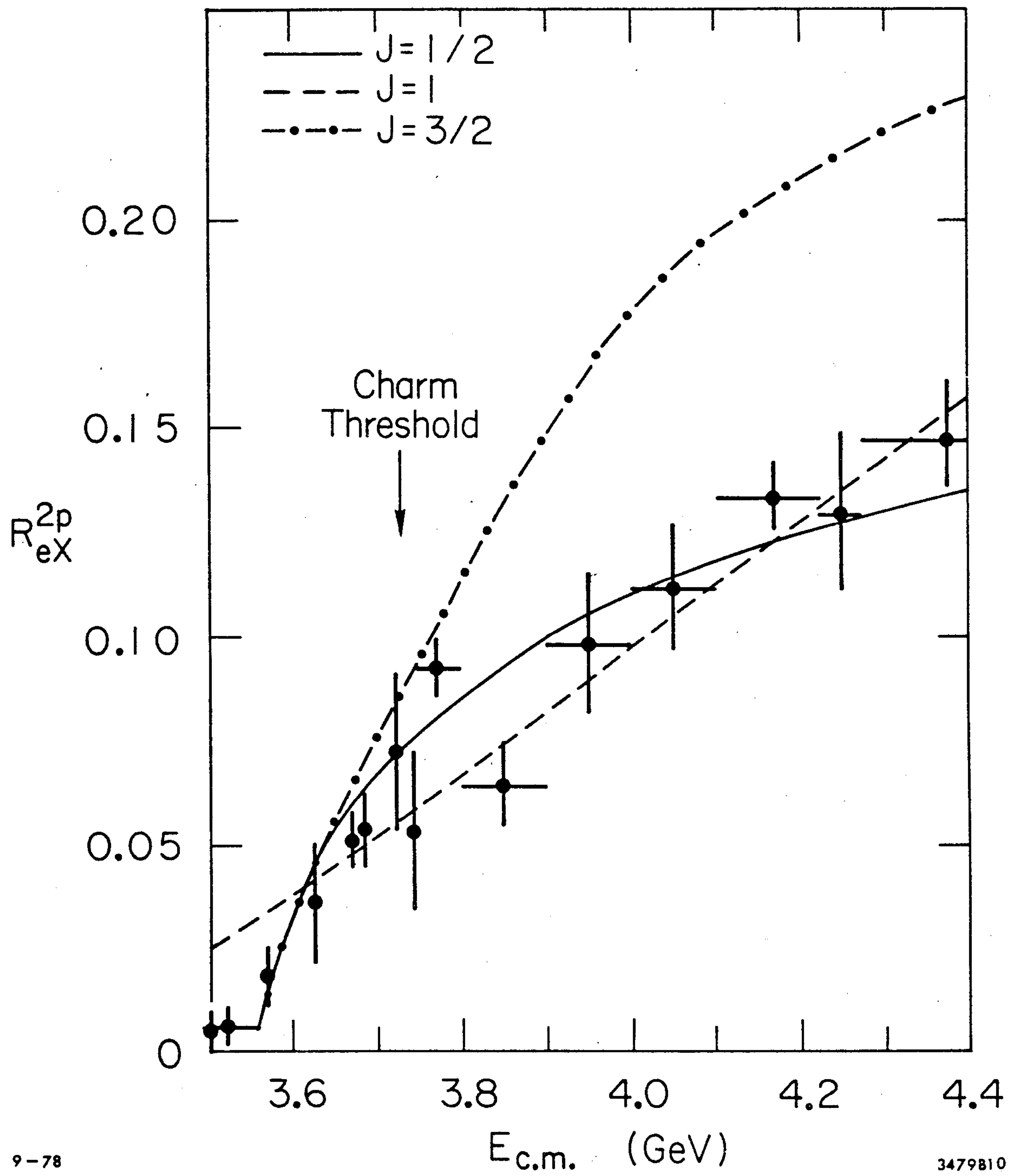
J = 1/2
J = 1
J = 3/2
0.20
0.15
0.10
0.05
0
Charm Threshold
R^{2p}_{eX}
3.6
3.8
4.0
4.2
4.4
$E_{c.m.}$ (GeV)
9-78
3479B10

Fig. 2

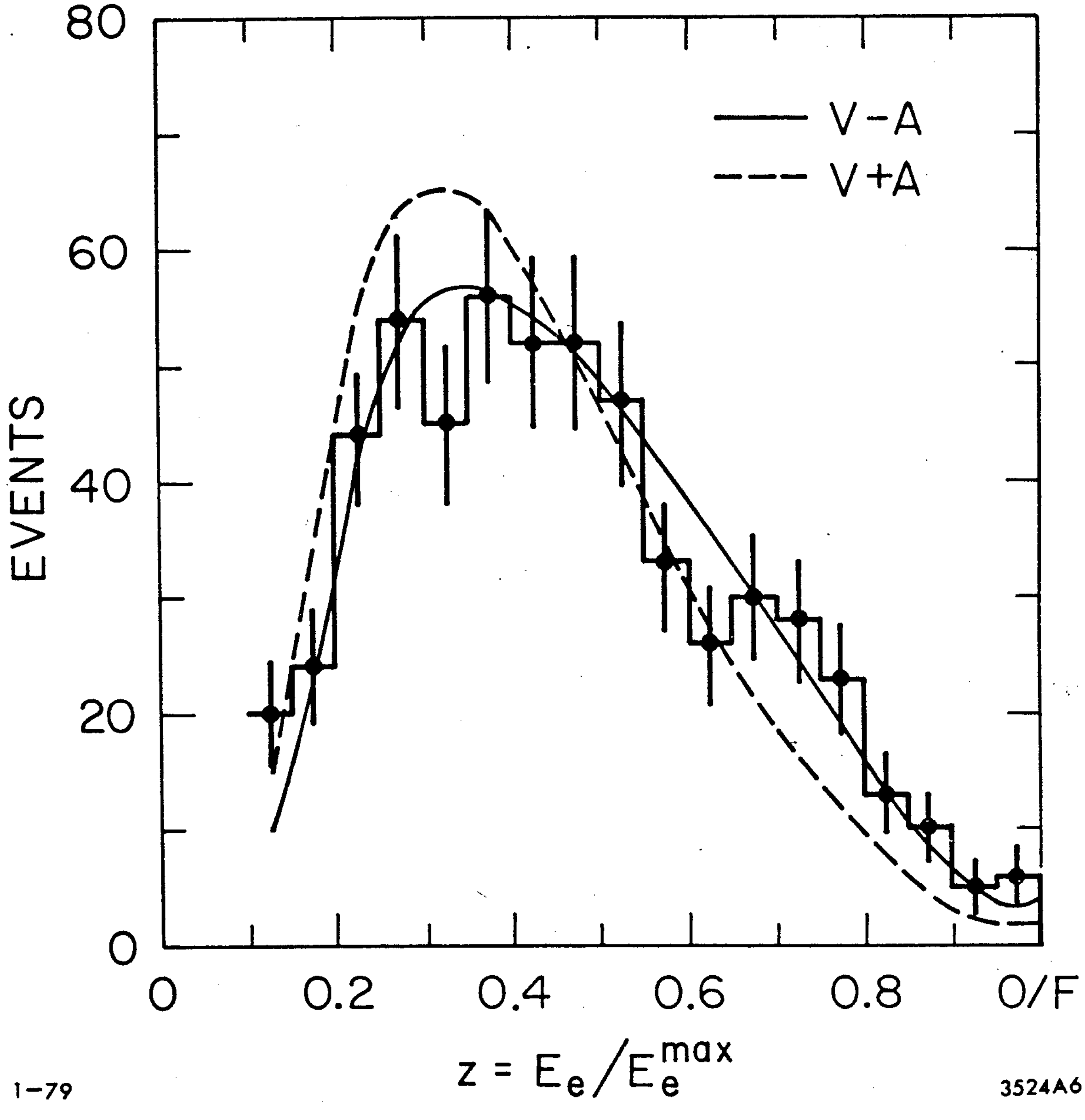

Fig. 3