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Notes on Charmed Particle Searches in Neutrino Experiments*

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I. WHY CHARM?

Renormalizability rests on gauge invariance which in turn requires a weak coupling of the form:

$$\mathscr{L}_W \sim g\left(J^+_\mu W^-_\mu + J^-_\mu W^+_\mu + J^0_\mu W^0_\mu\right)$$

where the neutral current is determined by the equal time commutator of the charged currents:

$$J^0_\mu = \frac{1}{\sqrt{2}}\left[J^+_\mu, J^-_0\right]_{e.t.} \quad .$$

From low energy phenomonology we know that the charged currents must contain, at least, the Cabibbo currents and the lepton currents:

$$J^+ = \bar{p}(n \cos\theta_c + \lambda \sin\theta_c) + \bar{\nu}_\mu \mu + \bar{\nu}_e e + (?) \quad .$$

If no other terms are added, the neutral current obtained from the commutator will contain a term:

$$\cos\theta_c \, \sin\theta_c (\bar{n}\lambda + \bar{\lambda} n)$$

which would induce the decay $K_L \to \mu\mu$ at a rate comparable to $K^+ \to \mu\nu$. Following Glashow, Iliopoulos and Maiani[1] (GIM), we rectify this unwanted feature by adding another piece to the charged current:[2]

$$(?) = \bar{p}'(\lambda \cos \theta_c - n \sin \theta_c)$$

where p' is a fourth quark carrying the charge of the proton, zero isotopic spin and strangeness, and a new quantum number called charm.

Many other constructions are possible (involving new leptons as well as quarks) which will eliminate the unwanted $|\Delta S| = 1$ piece of the neutral current. However, we shall limit our discussion to the above model which has several attractive features:

a) It is compatible with the observed hadron spectroscopy, as the Gell-Mann Zweig quark model[3] is unmodified. However charmed states, filling out SU_4 representations, are expected to appear in a higher mass region.

b) It is the most economical model. Once new particles have been introduced to obtain the desired structure of the neutral current, it is generally necessary to add still more particles in order to suppress higher order contributions to $|\Delta S| = 1$, $\Delta Q = 0$ transitions. In the above model, the p' does the job in every order.

c) This model is not yet ruled out by experiment. The leptonic couplings are those of the Weinberg-Salam[4] model which appears to be compatible with present data from neutrino experiments.

II. MASSES OF CHARMED PARTICLES

Consideration of the p, p' cancellation mechanism in higher order weak and/or electromagnetic processes places severe limits on the masses of charmed particles. The second order weak amplitudes for K decay into neutral lepton pairs are of the order

$$A(K_L \to \bar{\mu}\mu, K \to \pi\bar{\nu}\nu, \text{etc.}) \sim G_F\alpha\left(\Delta M^2/M_W^2 \sin^2\theta_W\right)\ln(M_W^2/M^2)$$

where $\Delta M^2 = M_{p'}^2 - M_p^2$, M is the largest quark mass, and θ_W is the Weinberg angle. The $K_L - K_S$ mass difference is of the order:

$$M_{K_L} - M_{K_S} \sim G_F\alpha\Delta M^2/M_W^2 \sin^2\theta_W \quad ,$$

and the amplitude for $K_L \to \gamma\gamma$ is of the order

$$A(K_L \to \gamma\gamma) \sim G_F\alpha\Delta M^2/M^2 \quad .$$

The experimental observation that the first two amplitudes are highly suppressed with respect to $G_F\alpha$ while the third is not suppressed, tells us that the p, p' mass difference must be of the same order as the p' mass, but small compared to the mass scale of weak interactions:

$$\Delta M^2 \sim M_{p'}^2 \ll M_W^2 \sin^2\theta \approx (38\ \text{GeV})^2 \quad .$$

Explicit evaluation of the above amplitudes using free quark diagrams gives the constraints:[5]

$$M_p \lesssim M_K << M_{p'} \lesssim 2\text{GeV} \quad .$$

Similar estimates based on pseudoscalar exchange rather than quark exchange indicate limits on the charmed pseudoscalar masses of the order

$$M_K << M_c \lesssim 5\text{GeV} \quad .$$

Since charmed particles have not been seen, and since too high a mass would imply the breakdown of the cancellation mechanism, we expect that charmed particle masses should lie in the range

$$2\text{GeV} \lesssim M_c \lesssim 10\text{ GeV} \quad .$$

(Since quark masses are apparently small compared to hadronic masses, the PCAC mass formulae, relating squares of pseudoscalar masses to quark masses, may be relevant:

$$2M_p/M_\pi^2 \simeq M_\lambda/M_K^2 \simeq M_{p'}{}^2/M_c^2 \quad .$$

Then the p, p' mass ratio must be extremely small:

$$M_p/M_{p'} \lesssim 1/200. \quad)$$

The relevant conclusion of this discussion is that, if charm is to adequately account for the observed phenomonology of K-decay, chamed particles must be light enough to be produced at NAL energies. Indirect tests for the presence of charmed particles include:

a) threshold effects

and

b) modification of the Adler sum rule.

However decisive tests must be direct, namely

c) the identification of a final state signature.

III. THRESHOLD EFFECTS

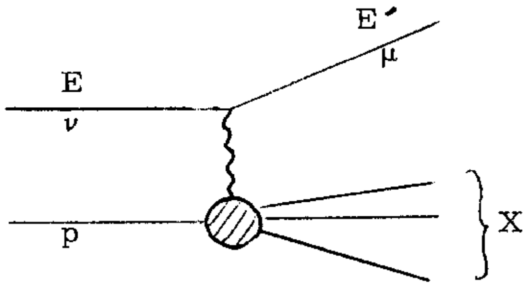
Near threshold the cross section for charmed particle production is expected to have the energy dependence[6]

$$\sigma_c \sim \left(E - E_{Th}\right)^2$$

where the threshold energy is related to the charmed particle mass by $(M_N << M_c)$:

$$E_{Th} \approx M_c^2/2M_N$$

and M_N is the physical nucleon mass. The allowed regions of phase space can be determined in terms of the usual kinematic variables $(M_N << E)$:



$$\nu = p\cdot q = M_N(E-E')$$

$$q^2 \simeq M_X^2 - 2\nu$$

or the "scaling" variables:

$$y = \nu/p\cdot p_\nu \quad , \qquad x = -q^2/2\nu \quad , \qquad 0 \le x, y \le 1 \quad .$$

The variable y is proportional to the total hadron energy in the final state; at threshold all the incident energy is used to produce the charmed particle:

$$E'_{Th} = 0 \;\; ; \;\; E_X^{Th} = E_{Th} \;\; ,$$

so above threshold:

$$y = (E-E')/E = E_X/E \ge E_{Th}/E \;\; .$$

The variable x is related to the total invariant mass of the final state hadronic system:

$$x = -q^2/2\nu \simeq 1 - M_X^2/2\nu \le 1 - M_c^2/2\nu < 1 - E_{Th}/E \;\; .$$

Thus for energies near threshold charmed particle production occurs only in the small x , large y region.[7]

IV. ADLER SUM RULE

The Adler sum rule[8] relates the difference of neutrino and anti-neutrino cross sections to the matrix element of the commutator of the weak charges. For the charge exchange process:

$$\nu(\bar{\nu}) + Z \to \mu^{\mp} + X$$

we have the sum rule:

$$\lim_{E\to\infty} \frac{\pi}{G_F^2}\left(\frac{M_W^2-q^2}{M_W^2}\right)^2 \left[\frac{d\sigma^{\bar{\nu}}}{d|q^2|} - \frac{d\sigma^{\nu}}{d|q^2|}\right]_Z = \langle Z|[Q^+, Q^-]|Z\rangle \; .$$

For the usual Cabibbo theory the weak charges are:

$$Q^+ = p^\dagger(n\cos\theta_c + \lambda\sin\theta_c) = (Q^-)^\dagger$$

giving for the commutator:

$$[Q^+, Q^-] = 2I_3 + \sin^2\theta_c\left(\frac{3}{2}Y - I_3\right)$$

+ parity and/or strangeness changing terms.

With the GIM modification the commutator becomes:

$$[Q^+, Q^-] = 2I_3 - S + C \quad + \text{parity odd terms.}$$

Since the target nucleus carries no charm (C) or strangeness (S), the effect of the modification is proportional to $\sin^2\theta_c \approx 0.04$. However since for a heavy nucleus:

$$Y = B = N_p + N_n >> 2I_3 = N_p - N_n$$

the effect will be enhanced. Bég and Zee[9] found for iron ($I_3 = -2, Y = 56$):

$$\langle Z | [Q^+, Q^-] | Z \rangle = \begin{cases} -0.56 & \text{Cabibbo} \\ -4 & \text{GIM} \end{cases} .$$

V. PRODUCTION OF CHARMED PARTICLES IN NEUTRINO EXPERIMENTS

Since the basic quark transitions are

$$p' \rightarrow \lambda \qquad \sim \cos\theta_c$$

$$p' \rightarrow \lambda \qquad \sim \sin\theta_c$$

charmed particles will decay predominantly into strange particles, providing a characteristic signature. However, the same amplitude ratio works against us in the production process. The elementary transitions are

$$\nu + n \rightarrow p' + \mu^- \qquad \sim \sin\theta_c$$

$$\nu + \lambda \rightarrow p' + \mu^- \qquad \sim \cos\theta_c \qquad .$$

Since there are probably few λ's in the nucleon, production rates are expected to be damped.

In order to get some quantitative estimates, we use the parton model and assume that it is relevant at Gargamelle energies so that we may use existing data to determine the parton content of nucleons.[10,11]

If $f_q(x) = xp_q(x)$ is the distribution function for quark q in the proton, weighted by its momentum fraction, we define the integral:

$$F_q \equiv \int dx \left[f_q(x) + f_{\bar{q}}(x) \right] \quad .$$

From the sum of electromagnetic cross sections on proton and neutron we can determine the quantity:

$$F_p + F_n + \frac{2}{5} F_\lambda + \frac{8}{5} F_{p'} \simeq 0.50 \pm 0.05 \quad .$$

On the other hand, the sum of neutrino and anti-neutrino cross sections for $\Delta S = 0$ transitions on heavy nuclei $\left[\sigma^{\nu Z}/A \simeq (\sigma^{\nu p} + \sigma^{\nu n})/2\right]$ determines the combination:

$$F_p + F_n + \tan^2\theta_c F_{p'} = 0.505 \pm 0.015$$

Upon comparison of these two quantities, the positivity of the distribution functions, $F_q \gtrsim 0$, implies that the λ and p' distributions in the nucleon are small. Specifically:

$$F_\lambda/(F_p+F_n) \lesssim 0.25 \quad , \quad F_{p'}/(F_p+F_n) \lesssim 0.06 \quad .$$

A further indication that few p''s are present in the nucleon is the fact that no surplus of events with $\Delta S = \pm 1$ is observed, since a p' converts most readily into a λ .

A further piece of information from the neutrino experiments is the relative number of anti-quark nucleons in the physical nucleon. Since particle-anti-particle cross sections for point particles are a third of particle-particle cross-sections, the total cross section ratio:

$$\frac{\sigma^{\bar{\nu}}}{\sigma^{\nu}} = \frac{F_{\bar{N}} + 1/3\ F_N}{F_N + 1/3\ F_{\bar{N}}} = 0.38 \pm 0.02$$

determines the relative anti-quark content of the nucleon:

$$F_{\bar{N}}/F_N = 0.05 \pm 0.02$$

where we have defined

$$F_N = \int dx \left[f_n(x) + f_p(x) \right]$$

$$F_{\bar{N}} = \int dx \left[f_{\bar{n}}(x) + f_{\bar{p}}(x) \right]$$

and have assumed $F_{p'} = 0$.

On the grounds that we expect the λ and $\bar{\lambda}$ content to be roughly equal $\left[\int \left(p_\lambda(x) - p_{\bar{\lambda}}(x) \right) dx = 0 \right]$, we shall assume the following:

$$F_{p'} \simeq 0 \quad , \quad F_{\bar{N}} \simeq 0.05\ F_N$$

$$\int f_\lambda dx \simeq \int f_{\bar{\lambda}}\, dx \simeq F_\lambda/2 \lesssim 0.1\ F_N \quad .$$

Further, we assume an incident energy well above threshold so that the parton model is applicable:

$$E \gg E_{Th}$$

and we assume that charmed states are not sufficiently long lived for their decay paths to be observable:

$$\gamma\beta c\tau \ll \text{cm} \quad .$$

On general dimensional grounds, since

$$\Gamma \sim \text{mass} \sim G_F^2 (\text{mass})^5 \quad ,$$

we expect widths for charmed particle decays to scale with respect to widths for strange particle decays by a factor:

$$\Gamma_c \simeq \Gamma_S \, (M_c / M_S)^5 \cot^2\theta_c \quad .$$

There is an additional enhancement from the Cabibbo angle; since strange particle life times are typically of the order of 10^{-10} sec , if $M_c / M_S \gtrsim 2$, we have

$$\tau_c \lesssim 10^{-13} \text{ sec} \quad , \quad c\tau_c \lesssim 3 \times 10^{-3} \text{ cm} \quad .$$

In the following, we discuss possible signatures for charmed particle production, using the parton model results as input.

VI. AN OPTIMISTIC ASSUMPTION: $F_\lambda \neq 0$

If there are as many as 10% of λ's and 10% of $\bar{\lambda}$'s in the nucleon, there will be an appreciable production of charmed particles with two characteristic signatures.

a) Enhancement of associated production. The elementary production and decay processes are (in terms of quarks):

$$\nu + \lambda \rightarrow \mu^- + p' \quad , \quad p' \rightarrow \lambda + \bar{n}p$$

and the charge conjugate process. Typical events will be of the form:

$$\nu + Z \rightarrow \mu^- + K^+ + (K^- \text{ or } Y) + X \qquad (\lesssim 17\% \text{ of total } \sigma^\nu)$$

$$\bar{\nu} + Z \rightarrow \mu^+ + K^+ + (K^- \text{ or } Y) + X \qquad (\lesssim 33\% \text{ of total } \sigma^{\bar{\nu}})$$

where X represents non strange hadronic matter.

The increase in associated production could be observed as a threshold effect which would be about three times more prominent in anti-neutrino events. This is because the cross section for $\bar{\nu} + \bar{\lambda} \rightarrow \bar{p}' + \mu^+$ does not have the 1/3 suppression factor.

b) associated production accompanied by a di-lepton. In this case the p' decays into leptons:

$$p' \rightarrow \lambda + \ell^+ \nu \quad .$$

Typical events are:

$$\nu + Z \to \mu^- \ell^+ + K\bar{K} + X \qquad (E^+ > E^-)$$

$$\bar{\nu} + Z \to \mu^+ \ell^- + K\bar{K} + X \qquad (E^- > E^+)$$

Near threshold most of the incident energy goes into producing the charmed particle; thus the decay lepton is expected to be faster than the production lepton. This process provides a clearer signature, but it will be suppressed by the branching ratio for leptonic decay which may be small.

VII. STRANGENESS CHANGING EVENTS

Independently of the λ content of the nucleon, one expects charmed particles to be produced at the level of $\sin^2 \theta_c$. Again there are two characteristic signatures.

a) Apparent violation of the $\Delta S = \Delta Q$ rule. The elementary process for ν events is:

$$\nu + n \to p' + \mu^-, \qquad p' \to \lambda + p\bar{n}$$

which globally satisfies $\Delta S = -\Delta Q$. This process is enhanced relative to the usual $\Delta S = \Delta Q$ process which must occur by ν scattering on an anti-proton or a λ :

$$\nu + \begin{pmatrix} \lambda \\ \bar{p} \end{pmatrix} \to \begin{pmatrix} p \\ \bar{\lambda} \end{pmatrix} + \mu^-$$

The situation is reversed for $\bar{\nu}$ events, where charmed particle production:

$$\bar{\nu} + \bar{n} \rightarrow \bar{p}' + \mu^{+}$$
$$\qquad \bar{p}' \rightarrow \bar{\lambda} + n\bar{p}$$

is suppressed for want of anti-partons, but the $\Delta S = \Delta Q$ process is allowed:

$$\bar{\nu} + \begin{pmatrix} p \\ \bar{\lambda} \end{pmatrix} \rightarrow \begin{pmatrix} \lambda \\ \bar{p} \end{pmatrix} + \mu^{+}$$

Using the parton content assumed above, we find the following cross sections relative to the total ν or $\bar{\nu}$ cross sections:

$$\sigma^{\nu}(\Delta S = \Delta Q) \lesssim 0.8\ \%$$
$$\sigma^{\nu}(\Delta S = -\Delta Q) \simeq 4\ \%$$
$$\sigma^{\bar{\nu}}(\Delta S = \Delta Q) \simeq 4\ \%$$
$$\sigma^{\bar{\nu}}(\Delta S = -\Delta Q) \simeq 0.6\ \%$$

b) Change of strangeness accompanied by a di-lepton. The leptonic decay of the charmed particles provides a unique signature:

$$\nu + Z \rightarrow \mu^{-}_{(\mathrm{slow})} + \ell^{+}_{(\mathrm{fast})} + (K^{-} \text{ or } Y) + X$$

$$\bar{\nu} + Z \rightarrow \mu^{+}_{(\mathrm{slow})} + \ell^{-}_{(\mathrm{fast})} + K^{+} + X \quad .$$

However this process is again suppressed by the leptonic decay branching ratio:

$$\sigma^{\nu} / \sigma^{\nu}_{\mathrm{Total}} \simeq 0.04\ B_{\ell}$$

$$\sigma^{\bar{\nu}} / \sigma^{\bar{\nu}}_{\mathrm{Total}} \simeq 0.006\ B_{\ell}$$

VIII. WHAT IS THE LEPTONIC BRANCHING RATIO?

The strangeness changing leptonic and non-leptonic decays are a priori of the same order of magnitude:

$$p' \to \lambda + \ell^+ \nu \qquad \sim \quad \cos\theta_c$$
$$p' \to \lambda + p\bar{n} \qquad \sim \quad \cos^2\theta_c \quad .$$

However the same is true for the decays of strange particles:

$$\lambda \to p + \ell^- \nu \qquad \sim \quad \sin\theta_c$$

$$\lambda \to p + n\bar{p} \qquad \sim \quad \sin\theta_c \cos\theta_c$$

while the experimentally determined amplitudes for non-leptonic decays are effectively of order 1 . Until the mechanism for the enhancement of these amplitudes is understood, one cannot predict whether it will also play a role in the decays of charmed particles.

If we consider quarks as very light and quasi-free within hadronic states, the fundamental decay mechanism is just a four fermion coupling; the partial width is proportional to the fifth power of the energy release:

$$\Gamma \sim G_F^2 Q^5$$

If, as suggested by PCAC and the analysis of $\Delta S = 1$, $\Delta Q = 0$ amplitudes,

$$M_\ell,\ M_p,\ M_n \ll M_\lambda \ll M_{p'}$$

we have $Q \simeq M_\lambda$ and $Q \simeq M_{p'} - M_\lambda$ for both leptonic and non-leptonic decays of strange and charmed particles, respectively. In any case, we expect both leptonic and non-leptonic decay rates to scale in the same way, roughly as the fifth power of the charmed to strange mass ratio.

For strange particle decays the leptonic branching ratio is very small; typically:

$$B_\ell^S \sim 10^{-3} \sim \sin^2\theta_c \times \text{ (3-body phase space) } .$$

All observed leptonic decay modes are suppressed either by three body phase space or by forbidden helicity states as in π or $K \to \ell\nu$. Phase space suppression should not be important in the decay of heavy charmed states. Therefore if the enhancement of non-leptonic amplitudes is operative for charmed particle decay, we expect:

$$B_\ell^c \sim \sin^2\theta_c \sim 4\%$$

In the case of no enhancement the leptonic branching ratio could be much higher:

$$B_\ell^c \sim 50\%$$

However we should not count on such a high leptonic decay rate.

IX. SUMMARY OF SIGNATURES

We recapitulate the characteristic signatures for charmed particle production (specific to the Weinberg-Salam model as modified by GIM) in neutrino experiments.

a) Increased associated production appearing in the low x, high y region. Above threshold the effect could rise to, say, 10% of the total ν cross section and 20% of the total $\bar{\nu}$ cross section if the $\lambda, \bar{\lambda}$ sea comprises 10% of the parton distribution.

b) Associated production accompanied by a di-lepton: slow μ^-, fast ℓ^+ in ν events; slow μ^+, fast ℓ^- in $\bar{\nu}$ events. The effect is three times more prominent in $\bar{\nu}$ events, but is suppressed by the leptonic branching ratio.

c) Apparent violation of the $\Delta S = \Delta Q$ rule. Well above the charm threshold energy we would see 4% of $\Delta S = -1$ events and about a half a percent of $\Delta S = +1$ events in both ν and $\bar{\nu}$ beams.

d) Change of strangeness accompanied by a dilepton: slow μ^-, fast ℓ^+, $\Delta S = -1$ in ν events; slow μ^+, fast ℓ^-, $\Delta S = +1$ in $\bar{\nu}$ events. The effect should be about 10 times more prominent in the ν beam, but suppressed by the leptonic branching ratio.

The first two signatures depend on the presence of λ-partons in the nucleon and may be entirely absent. If the GIM mechanism is the correct one, signatures c) and d) must be present at the level of

$\sin^2\theta_c \sim 4\%$ at NAL energies.[12]

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