Particle Physics II

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Problem Set XI

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In-class exercises

Exercise 55 *Discovery of neutral currents*

The process $\bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^-$, investigated by the Gargamelle experiment at CERN, provided the first evidence for the existence of neutral currents (NC). Let's have a look at the seminal paper, and sketch the setup of the Gargamelle experiment.

Note that another neutral-current process investigated by Gargamelle — with neutrinos scattering off nuclei, producing hadrons – produced evidence for neutral currents almost at the same time, handed in for publication only two months later. Since for this process a closely related charged-current (CC) process exists, producing a muon and hadrons, the ratio NC/CC could be measured, allowing the determination of the Weinberg angle more accurately.

Let's have a look more closely at the following questions:

(a) What are neutral currents?

(b) Which inconsistency of V-A theory was the main theoretical reason for predicting the existence of neutral currents?

(c) The process $\bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^-$ produced the first experimental evidence for neutral currents. Motivate why this process was optimal for this purpose - for example, why use neutrinos at all? What is the advantage of anti-neutrinos over neutrinos? Of muon neutrinos over electron neutrinos?

(d) Sketch the signature of the process of interest in a bubble chamber (label the tracks).

(e) What were the backgrounds? Explain how the contribution of the main background source was estimated.

Links to the original papers (available within the university network):

$\bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^-$: "Search for elastic muon-neutrino electron scattering",
F J Hasert et al. 1973a Phys. Lett. 46B 121:
`http://www.sciencedirect.com/science/article/pii/0370269373904942`

$\bar{\nu}_\mu N \to \bar{\nu}_\mu +$ hadrons: "Observation of neutrino-like interactions without muon or electron in the Gargamelle neutrino experiment",
F J Hasert et al. 1973b Phys. Lett. 46B 138:
`http://www.sciencedirect.com/science/article/pii/0370269373904991`
F J Hasert et al. 1974 Nucl. Phys. B73 1:
`http://www.sciencedirect.com/science/article/pii/0550321374900388`

Homework

Exercise 56 *Ratio of D^0 meson decay rates* **6 Points**

D^0 mesons can decay in several ways; for example,

- $D^0 \to K^-\pi^+$
- $D^0 \to \pi^-\pi^+$
- $D^0 \to K^+\pi^-$

The quark contents of these particles are: $D^0 = c\bar{u}$, $K^- = s\bar{u}$, $\pi^- = d\bar{u}$.

(a) Draw the Feynman diagrams for the three processes and assign Cabibbo factors to the vertices.

(b) Determine the ratio of the decay rates of these three channels.

(c) Compare to the ratio of the literature values of the branching ratios of these three channels: BR($D^0 \to K^-\pi^+$)=0.038, BR($D^0 \to \pi^-\pi^+$)=0.0014, BR($D^0 \to K^+\pi^+$)=0.00014. The agreement is not bad, but not perfect. List possible reasons for the discrepancy - which effects have been neglected in this simple calculation?

Exercise 57 *Decay rate of $D^0 \to K^- e^+ \nu_e$* **3 Points**

The decay rate $K^+ \to \pi^0 e^+ \nu_e$ is $\Gamma = 4 \times 10^6\ \mathrm{s}^{-1}$. Draw the Feynman diagram of this process, and of the decay $D^0 \to K^- e^+ \nu_e$. Use the relation

$$\Gamma = \frac{G_F^2}{30\pi^3}(\Delta m)^5 V_{qq'}^2$$

to determine the decay rate for $D^0 \to K^- e^+ \nu_e$. Here, Δm is the mass difference of the mesons in the initial and final state, G_F the Fermi constant, and $V_{qq'}$ the Cabibbo factor.

Exercise 58 *W propagator* **7 Points**

Consider electron-neutrino scattering $\nu_\mu(p_1)e^-(p_2) \to \mu^-(p_3)\nu_e(p_4)$ in the context of the intermediate vector boson model. Remember that during the lectures, the W propagator has been introduced as

$$\frac{-i\left(g^{\mu\nu} - \frac{q^\mu q^\nu}{m_W^2}\right)}{q^2 - m_W^2}$$

(a) Draw the Feynman diagram and show that the matrix element of this process can be written as

$$\mathcal{M} \sim \mathcal{M}' = \bar{u}(p_3)\gamma_\mu(1-\gamma^5)u(p_1)\frac{-i\left(g^{\mu\nu} - \frac{q^\mu q^\nu}{m_W^2}\right)}{q^2 - m_W^2}\bar{u}(p_4)\gamma_\nu(1-\gamma^5)u(p_2)$$

(omitting constant factors and delta functions). Express the momentum transfer q in terms of the external momenta of the incoming and outgoing particles.

(b) Show that terms proportional to $\frac{q^\mu q^\nu}{m_W^2}$ can be written as

$$\mathcal{M}'' = \frac{m_\mu m_e}{m_W^2}\frac{1}{q^2 - m_W^2}\bar{u}(p_3)(1-\gamma^5)u(p_1)\bar{u}(p_4)(1+\gamma^5)u(p_2)$$

(c) Explain why this term can be neglected.

Hint: Use the covariant form of the Dirac equation, $(\not{p} - m)u = 0$ and $\bar{u}(\not{p} - m) = 0$, and that the neutrinos are massless in the Standard Model.

Exercise 59 *Chirality Components of Spinors* **4 Points**

The spinor u (that satisfies the momentum space Dirac equation) can be broken down into left- and right-handed chiral components

$$u = u_R + u_L.$$

A similar expression can be found for the spinor $\bar{u}$.

Show the following expressions hold:

$$\bar{u}\gamma^\mu u = \bar{u}_R\gamma^\mu u_R + \bar{u}_L\gamma^\mu u_L$$
$$\bar{u}\gamma^\mu\gamma^5 u = \bar{u}_R\gamma^\mu\gamma^5 u_R + \bar{u}_L\gamma^\mu\gamma^5 u_L,$$

signifying that chirality is conserved at the weak interaction vertex.
Write down the vertex vactor for the weak interaction in terms of the sum of left- and right-handed chiral currents.