Resonant Scattering of Antineutrinos

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The hypothesis of an unstable charged boson to mediate muon decay radically affects the cross section for the process $\bar{\nu}+e\rightarrow\bar{\nu}+\mu^-$ near the energy at which the intermediary may be produced. If the boson is assumed to have K-meson mass, the resonance occurs at an incident antineutrino energy of $\sim 2\times 10^{12}$ ev. The flux of energetic antineutrinos produced in association with cosmic-ray muons will then produce two muon counts per day per square meter of detector, independently of the depth and the orientation at which the experiment is performed.

THE interaction responsible for muon decay also permits an inelastic scattering of antineutrinos by electrons,

$$\bar{\nu}+e\rightarrow\bar{\nu}+\mu^-.$$

With the conventional four-Fermion form of decay interaction, the cross section for this process is

$$\sigma_0=(E/m_e)1.5\times 10^{-45}\ \text{cm}^2,$$

where E is the energy of an antineutrino incident upon a stationary electron. However, if muon decay is mediated by a charged, unstable boson, this cross section becomes radically altered. The process will occur by the sequence

$$\bar{\nu}+e\rightarrow Z^-\rightarrow\bar{\nu}+\mu^-,$$

and at some antineutrino energy there will be a resonance, occasioned by the real production of an intermediary boson. The cross section, in this case, assumes a typical resonance form,

$$\sigma=\sigma_0\frac{E_0^2}{(E-E_0)^2+\Gamma^2},$$

in which the incident antineutrino energy at the resonance is $E_0=m_Z^2/2m_e$ and Γ denotes its width, $\Gamma=(m_Z/m_e)(1/\tau_Z)$ in terms of the lifetime, τ_Z, of the Z meson. Although σ_0 is proportional to the fourth power of the coupling constant of Z mesons to leptons, the average cross section near the resonance,

$$\frac{1}{2\Delta}\int_{E_0-\Delta}^{E_0+\Delta}\sigma(E)dE\cong\frac{\pi}{4}\left(\frac{E_0}{\Delta}\right)\left(\frac{E_0}{\Gamma}\right)\sigma_0,$$

depends only upon its square. If the Z-meson mass is not much greater than that of the nucleon, this enhanced cross section is not necessarily beyond experimental reach. We shall consider only values of the Z-meson mass such that $m_K\leqslant m_Z\leqslant m_N$, since smaller values of m_Z would prohibit the use of the Z meson to mediate K-meson decays.

The principal decay modes of the Z meson are expected to be $Z^-\rightarrow e+\bar{\nu}$ and $Z^-\rightarrow\mu^-+\bar{\nu}$. With coupling strengths of the Z meson to muon and electron currents chosen equal (in accordance with universality) and of magnitude determined by the muon lifetime, we find

$$\tau_Z=(m_N/m_Z)^3 10^6 m_N^{-1}\hbar c^2\ \text{sec}.$$

With $m_Z=m_N$, the energy of the incident antineutrino energy at the resonance is 9×10^{11} ev and the width of the resonance is 2×10^6 ev, while with $m_Z=m_K$, $E_0=2.3\times 10^{11}$ ev and $\Gamma=1.5\times 10^5$ ev.

Although the natural width of the resonance is quite small, a significant broadening is produced by the spread in velocity of the target electrons. In a collision with an electron of velocity βc along the direction of incidence, the resonance occurs at the antineutrino energy

$$E_0'=(1+\beta)^{-1}E_0.$$

Thus the experimental width of the resonance will be approximately $(\mathfrak{z}/137)E_0$, where $\mathfrak{z}$ is the mean atomic number of the target material. Upon earth, antineutrinos of energies within the resonance should have a mean free path of some hundreds of kilometers, corresponding to a cross section of 10^{-32} cm^2.

The only known source of antineutrinos of sufficiently great energies is the decay of cosmic-ray pions and K mesons. Practically all such antineutrinos are produced in association with muons, consequently their intensity and energy spectrum may be deduced from the known sea-level flux of muons.[1] We estimate that at 9×10^{11} ev the antineutrino flux is 10^{-11} cm^{-2} sec^{-1} Bev^{-1}, and at 2.3×10^{11} ev it is 10^{-9} cm^{-2} sec^{-1} Bev^{-1}. Exposed to these antineutrino fluxes, each target electron will act as a source of 4×10^{-40} muon per second if $m_Z=m_N$, or 10^{-38} muon per second at the lower value of $m_Z=m_K$.

With a muon-sensitive area of one square meter, placed underground, the experimenter might anticipate a counting rate of two per day (at $m_Z=m_K$) or of 0.1 per day (at $m_Z=m_N$) independently of the depth at which the experiment is performed. The counting rate should be relatively insensitive to the orientation of the experimental apparatus with respect to the vertical, since the muons should be produced isotropically in the

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[1] A. Subramanian and S. D. Verma, Nuovo cimento 8, 572 (1959).

upper hemisphere. A positive result to this experiment would be evidence both for the existence of an intermediary boson and for the absence of a selection rule that prevents those neutrinos produced in association with muons from interacting with electrons.

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Magnetic Quenching of Hyperfine Depolarization of Positive Muons*

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The depolarization of positive muons being slowed down in an insulating material can only be accounted for by the capture of an electron into a bound state. The ground-state muonium formed in flight can be expected to break up in a time short compared to 10^{-10} sec (the time necessary for the electron to flip the muon spin via the hyperfine interaction). The effect of an external magnetic field in locking the electron spin in its initial orientation, and thereby quenching the action of the hyperfine coupling, is a useful test of the assumption of muonium as the depolarizing mechanism. If x is the magnetic field strength measured in units of 1.58 kilogauss, and τ is twice the mean life of the muonium atoms with respect to breakup, measured in units of 3.58×10^{-11} sec, then it is found that the amount of depolarization for one formation and breakup process is equal to one-half of the quantity $(1+\tau^{-2}+x^2)^{-1}$. By introducing n, the number of times that the capture-breakup process is repeated, one has two parameters and can achieve good fits to the experimental data of Sens et al. for nuclear emulsion and fused quartz. It is pointed out that the interpretation by Sens et al. of their magnetic quenching data, also based on a two-parameter formula, is not tenable, since it depends on assuming that a certain fraction of the muons are not subject to the capture and loss process.

It is known that when a fast positive muon enters condensed matter, in many substances it loses some or all of its initial polarization in the slowing down process. To account for this depolarization, it is necessary to invoke the spin-spin interaction of the magnetic moments of the muon with the electrons in the matter, as there is not available any other sufficiently strong interaction to give the observed effect.[1] In addition to this requirement, it is necessary that the muon not be exposed in rapid succession to many different electrons with random spin orientation, as this would average out the effect and give essentially no depolarization. Thus it is necessary that the muon capture an electron and form a muonium atom. It is only in this way that it may be exposed to just one electron of a definite spin orientation for a sufficiently long period of time to result in a secular precession of the spin of the muon. This requirement is consistent with the fact that metals do not exhibit the depolarization of muons, while insulators generally do. Thus, in metals the muon is always exposed to a random distribution of conduction electrons and does not accumulate any secular precession leading to a loss in its spin orientation. In addition to the requirement that the muon should capture an electron and form the muonium atom it is necessary that the atom should be in the ground state, as the excited states have too weak a hyperfine interaction to give sufficient depolarization.

In testing any such depolarization mechanism as muonium, it is very useful to apply a laboratory magnetic field, and to study the dependence of the depolarization mechanism on the strength of the field. Since the flipping of the muon spin in the muonium atom is accompanied by a recoil flip of the electron spin, as required by conservation of angular momentum, it is clear that the depolarization mechanism can be controlled by having the electron be acted upon by the external magnetic field. Thus, if the field is made strong enough, the electron can be locked in its initial orientation by the Paschen-Back effect. The muon spin is then locked into position by a kind of indirect Paschen-Back effect. (The direct action of the external field on the muon is negligible compared to this indirect effect through the electron.) The simplest possible theoretical treatment which satisfies the requirements of the preceding paragraph is that of "one-time" muonium formation. In this picture a fast muon enters a solid material, is very quickly stopped, and then captures an electron, which subsequently remains bound to the muon until the latter decays. The effect of an external magnetic field on such a simple depolarization process has been studied by Breit and Hughes[2] and by Ferrell and Chaos.[3] It has been shown by Orear, Harris, and Bierman,[4] and also in reference

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[1] Here we include the magnetic quenching effect discussed below. Hyperfine interaction with nuclei would be quenched much more easily than is found to be the case.

[2] G. Breit and V. W. Hughes, Phys. Rev. **106**, 1293 (1957).
[3] R. A. Ferrell and F. Chaos, Phys. Rev. **107**, 1322 (1957).
[4] J. Orear, G. Harris, and E. Bierman, Phys. Rev. **107**, 322 (1957).