Hadron polarization in heavy-lepton decays

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(Received 9 July 1981)

In the decay of the τ lepton into a spin-one meson and a neutrino, the meson state with helicity opposite its charge is forbidden by angular momentum conservation if the decay is mediated by the conventional $V-A$ current. The laboratory momentum distribution of pions in the decay chain $\tau\to\rho\nu$, $\rho\to\pi\pi$ reflects the polarization of the ρ meson and provides an experimental check of the nature of the decay current. This method requires the identification of the decay mode $\rho\nu$ but does not depend on finding the τ laboratory direction.

The nature of the current mediating the heavy-lepton[1] decay has been convincingly established for the leptonic modes for which the $V-A$ theory fits the electron and muon spectra.[2,3] Of the identified semileptonic modes the $\pi\nu$ decay distributions are sensitive to the coupling structure only for polarized τ's which have not been obtained so far. However, the decays of the τ into a spin-one meson and a neutrino offer the possibility of observing effects reflecting the nature of the current. Weak decays involving vector mesons have been discussed previously in another context.[4] As shown in Fig. 1, if the τ neutrino is massless and the decay proceeds via the $V-A$ current, the helicity state of the meson opposite the sign of its charge is forbidden by angular momentum conservation. This polarization of the meson is *independent of the polarization state of the* τ, and is present in the observed events in existing electron-positron colliding-beam rings. Further, for the decay $\tau\to\rho\nu$,[5] the decay of the ρ into two pions is a good analyzer of the ρ polarization.

While the measurement of the ρ density matrix seems too ambitious experimentally,[6] noticeable effects persist in the laboratory energy distribution of pions and these can be readily measured.

Many features of the $\tau\to\rho\nu$ process have been discussed before.[7,8] The angular distribution of the ρ in the τ rest frame is given by

$$\frac{dN}{d\Omega_\rho}=\frac{M_\rho^2}{4\pi(M_\tau^2+2M_\rho^2)}(1+\lambda\eta)[1+\eta(\vec{k}\cdot\vec{s})/|\vec{k}|] \qquad (1)$$

for helicities $\lambda=\pm1$, and by

$$\frac{dN}{d\Omega_\rho}=\frac{M_\tau^2}{4\pi(M_\tau^2+2M_\rho^2)}[1-\eta(\vec{k}\cdot\vec{s})/|\vec{k}|] \qquad (2)$$

for helicity $\lambda=0$. Here, η is the charge of the τ, $\vec{s}$ is a unit vector directed along its spin, and $\vec{k}$ is the rest-frame ρ momentum. When both orientations of the τ spin are equally probable, the ρ distribution becomes isotropic, but the state with $\lambda=-\eta$ is nevertheless forbidden, while the zero-helicity state is favored in the ratio $M_\tau^2/2M_\rho^2$ with respect to the $\lambda=\eta$ state. Thus, in the ρ rest frame, the angular distribution of pions with respect to the line of flight of the ρ in the τ rest frame is given by

$$\frac{dN}{d\Omega_\pi}=\frac{3}{4\pi(M_\tau^2+2M_\rho^2)}[M_\rho^2+(M_\tau^2-M_\rho^2)\cos^2\theta] \qquad (3)$$

and appears in Fig. 2.

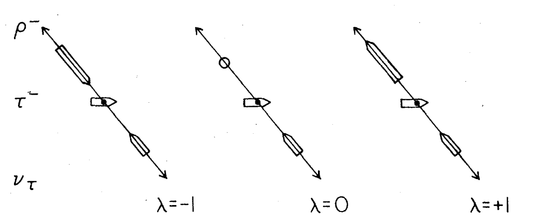

FIG. 1. Schematic of the τ decay to a ρ meson and a left-handed neutrino, with arrows representing the indicated helicities. The $V-A$ weak coupling forbids one ρ helicity state and favors one of the two allowed.

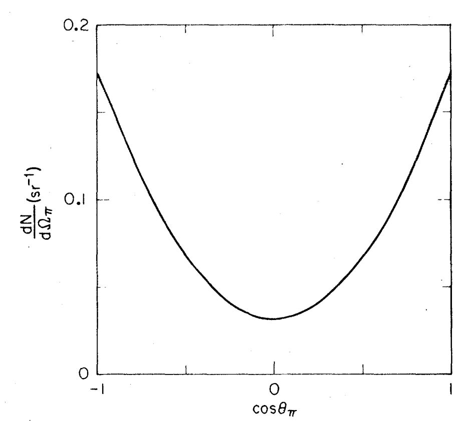

FIG. 2. The angular distribution of the pions in the ρ rest frame relative to the ρ direction of flight in the τ rest frame. The marked anisotropy results from preference for helicity 0 over helicity -1.

The marked anisotropy in Eq. (3) is due to both the angular-momentum selection rule and the relative probability that the $V-A$ interaction ascribes to the allowed helicity states of the ρ. The laboratory energy distribution of pions is obtained by applying the appropriate Lorentz boosts. We evaluate it at electron-positron energies of 2.5 and 14.5 GeV/beam and compare it in Fig. 3 with that obtained neglecting the ρ polarization. The ρ resonance is described by a Breit-Wigner function around the mass $M_\rho = 0.776$ GeV with width $\Gamma_\rho = 0.155$ GeV. Radiative effects have been neglected. The difference between the energy distributions in Figs. 3(a) and 3(b) can be expressed by the second moment (variance) of each distribution. At 2.5 GeV the energy distribution has a variance of 0.034 while if polarization is neglected it drops to 0.028. An experiment with 2000 events would measure this parameter to better than 0.001. Likewise, at 14.5 GeV a 2000-event experiment easily distinguishes the two distributions since the second moment is 0.051, while it drops to 0.044 when the polarization is neglected. The 2000-event experiment would have an uncertainty of slightly more than 0.001.

In conclusion, we have stressed that the decay of a heavy lepton into a spin-one particle and a neutrino results in a polarization of the meson if the decay proceeds via the conventional $V-A$ current. Furthermore, the laboratory energy distribution of pions carries through the polarization information even though the τ leptons themselves are not polarized. This experimental verification of the nature of the decay current does not require knowledge of the τ laboratory direction.

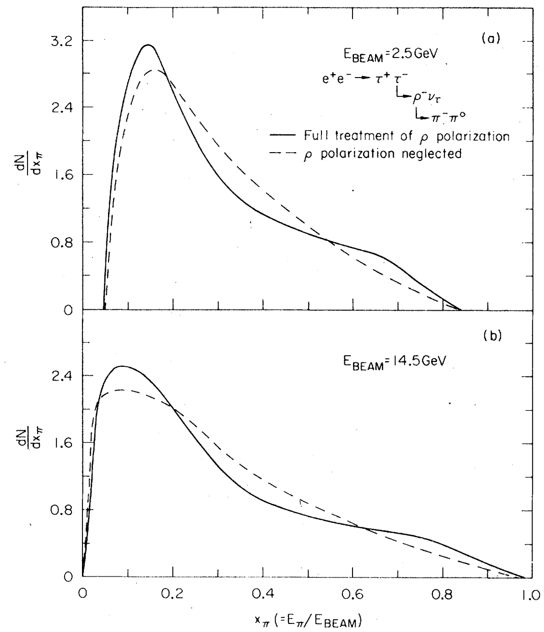

FIG. 3. The pion energy distributions in the laboratory where the full ρ polarization effects have been compared to the absence of such effects. The second-moment calculations described in the text quantify the differences.

We acknowledge useful discussions with our colleagues at SLAC. This work was supported by the Department of Energy, Contract No. DE-AC03-76SF00515.

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[6]The nonvanishing elements of the ρ density matrix are

$$\rho_{00} = CM_\tau^2/M_\rho^2\,[1-\eta p(\vec{s}\cdot\vec{k})/|\vec{k}|]\,,$$

$$\rho_{0\lambda} = C\sqrt{2}\,\frac{M_\tau}{M_\rho}\,\frac{(1+\lambda\eta)}{2}\,\eta p\,|\vec{s}\times\vec{k}|/|\vec{k}|\,,$$

$$\rho_{\lambda\lambda} = C(1+\lambda\eta)[1+\eta p(\vec{s}\cdot\vec{k})/|\vec{k}|]\,,$$

where C is a normalization function, and p is the polarization of the τ. If the direction of τ spin and the neutrino were known, as foreseen in the future linear colliders, the angular distributions of pions in the ρ-rest frame would show the azimuthal anisotropy expected from the finite off-diagonal density-matrix elements.

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