Polarization of Prompt Muons

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(Received 9 February 1976)

The polarization of 185-GeV prompt muons produced in the forward direction by the interaction of 400-GeV protons has been measured to be $P=0.00\pm0.10$ along their direction of flight. The null value for the polarization suggests that the muons are produced through electromagnetic interactions.

It seems most probable that the anomalously large direct lepton flux observed in many experiments[1] is either derived from electromagnetic production mechanisms which are not now thoroughly understood or from the weak-interaction decays of particles[2] which have not been previously identified. If the production process is indeed electromagnetic, we will expect that the polarization of the leptons in the direction of their momentum will be zero, inasmuch as the electromagnetic interactions are known to conserve parity. However, if the leptons are produced through the weak decays of intermediate particles, the leptons will probably be polarized. For interactions mediated by the charged weak currents, this polarization will be $+1$ for positive leptons produced with velocities near c in the system of the parent particle if there is no kinematic constraint on the spin direction or -1 when the spin direction is constrained as for the two-body decays of spin-zero mesons to neutrinos and leptons. The polarization of leptons from weak decays mediated by neutral currents is not yet known. In view of the importance of measurements which will better define the character of the production of prompt leptons, we have measured the polarization of 185-GeV prompt positive muons produced by the nuclear interactions of 400-GeV protons from the Fermilab accelerator.

The polarization of the muons was determined in a manner similar to that used previously in measurements of the polarization of muons produced through the interactions of protons from accelerators[3] and in the measurement of the polarization of cosmic-ray muons.[4] The muons were stopped in a "polarimeter" constructed of 25 3-ft$\times$2-ft$\times$2-in. slabs of aluminum backed by a covering of scintillation counters. Coils were energized which produced a magnetic field of about 30 G through the polarimeter in a direction perpendicular to the direction of incidence of the incoming muons. The position of the stopped muon was determined by the registration of the scintillation counters in the muon path and clocks were started at the time of the stop. The passage of the decay electron through the counter upstream (back) or downstream (front) of the stop position then stopped the clock assigned to that counter, defining the decay time and the direction of decay. Since a positive muon decays such that the high-energy electrons are emitted preferentially in the direction of the muon polarization, the recorded direction defines the direction of polarization in a statistically defined way. In particular, the ratio of decays (front $-$ back)/(front + back) will vary sinusoidally with the precession frequency and the amplitude of the sine wave will be proportional to the polarization. Such a measurement of the Fourier component of the variation of the decay asymmetry with time is insensitive to the systematic sources of error which tend to plague more straightforward measurements of front-back asymmetries.

A brief description of the experimental arrangement has been published previously.[5] The polarimeter was housed in a building placed in a pit dug in the soil about 1200 ft from the target area of the proton central beam area. The center of the polarimeter lay on a line to the target which made an angle of 22 mrad with the extension of the proton beam line. Only muons with an energy of about 185 GeV will pass through the 13 kg/cm^2 of material (mostly steel) in the target area and the 57.6 kg/cm^2 of earth in the region between the end of the target hall and the polarimeter and then stop in the polarimeter. In the course of the measurements, the muons from the target were bent through the requisite angle of 22 mrad into the polarimeter by means of a bending magnet downstream of the target. Therefore the measurements concerned positive muons produced in the forward direction upon production. However, since the rms momentum transfer due to multiple Coulomb scattering in the target and the material directly downstream of the target is about 630 MeV/c, the measurements can be considered as sampling the production of muons up to transverse momenta near 1.0 GeV/c.

Since the muons produced by the interaction of the protons in the copper target are derived from the decays of mesons produced in the target as well as from the direct interactions, it is necessary to measure the polarization of the direct, or prompt, component in a manner which allows the exclusion of the muons from meson decay. We do this in a manner similar to that used to construct the intensity of direct muons from a flux of direct muons and muons from meson decay; we measured the polarization as a function of target density. Since the probability of a meson decaying before it is effectively removed from the beam through interactions is inversely proportional to the target density, an appropriate extrapolation of the polarization measured as a function of the inverse density to the value at zero inverse target density (or infinite density) will define the polarization of the prompt muons.

The graph of Fig. 1 shows the measured decay-asymmetry amplitudes plotted as a function of (precession) time from the time when the muon stopped. Measurements were made of the polarization of the muons produced from a copper-air target with an effective density of one-third that of copper and a solid copper target. Muon flux measurements were made at the same densities and with a target which had an effective density of one-half that of copper. The results of these intensity measurements, interpreted as described previously,[5] show that about 65% of the flux at density one-third was generated by meson decays and about 35% was from the direct processes. With the solid copper target, about 37% of the muons were from meson decays and 63% were

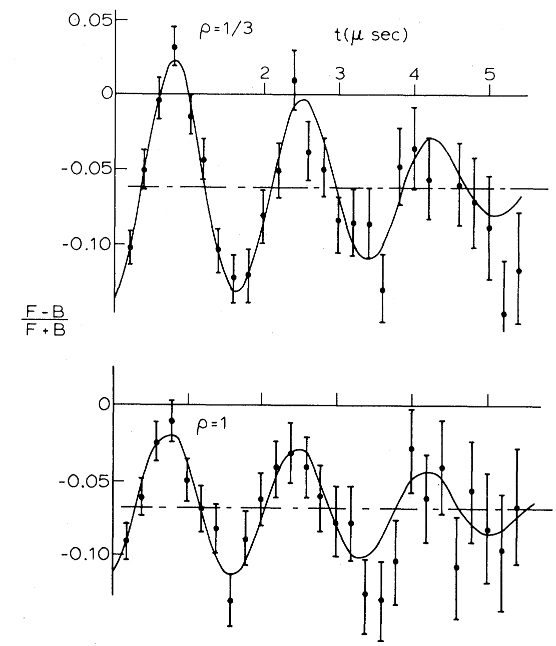

FIG. 1. Muon decay asymmetries as a function of precession time for target densities of one-third [$A(3) = 0.0782 \pm 0.0062$] and one [$A(1) = 0.0490 \pm 0.0073$] times the density of copper.

from the direct processes. It is obvious upon inspection that the polarization of the muons from the target of solid copper is appreciably smaller than the polarization of the muons from the target of density one-third, indicating that the polarization of the prompt muons is different from, and much smaller or of opposite sign than, that of the muons from meson decays. Since the magnetic field varied somewhat over the dimensions of the apparatus, the precession frequency varied correspondingly and the mean asymmetry then diminished with time. It is then an adequate approximation for our purpose to consider that the asymmetry varies with time as

$$(F-B)/(F+B) = A\cos(\omega t)\sin(Dt)/Dt,$$

where A is the amplitude at $t=0$, ω is the mean precession frequency, and D is a measure of the spread of frequencies. The values of A derived from a least-squares fit[6] of the data by this form are $A(3) = -0.0782 \pm 0.0062$ and $A(1) = -0.0490 \pm 0.0073$, where $A = (F-B)/F+B)$ with F the intensity of decays forward and B the intensity of decays backward, and the argument of A is the inverse density in units of the density of copper.

The amplitude of the prompt or direct portion of the flux can be determined simply by extrapolating the values of I_μ, the intensity, and $I_\mu A$ to

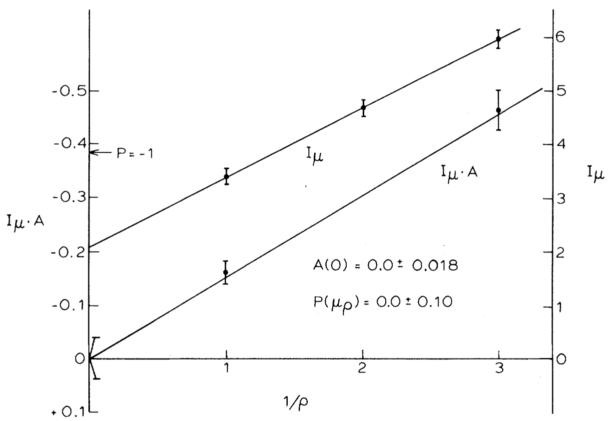

FIG. 2. Intensity versus inverse density of the target and intensity times the muon decay-asymmetry amplitude versus inverse target density. The intensity is measured in arbitrary units. The position of the intercept expected for a prompt muon polarization of −1.0 is shown; the corresponding intercept for a polarization of +1.0 would lie at a value of $I_\mu A$ of +0.38. The points show the raw data while the solid line represents a best fit after small corrections are made for the effects of proton interactions upstream from the target.

the values at $1/\rho = 0$ as both of these quantities should vary linearly with $1/\rho$. The graph of Fig. 2 shows the measured intensity, I_μ, and the product $I_\mu A$ as functions of $1/\rho$. The points show the uncorrected data and the solid line gives the values of $I_\mu P$ after a small correction for the presence of muons produced by the interaction of the proton beam with material upstream of the target. The extrapolation of the (corrected) values of $I_\mu P$ to zero inverse density gives the amplitude for the prompt muons of 0.00 ± 0.018. This can be converted to the polarization, if the polarization of the muons from the meson decay is known. This polarization depends upon the spectrum of meson production as, roughly speaking, muons which are produced from pion and K-meson decays in the forward direction in the meson center-of-mass system retain a negative polarization in the laboratory system, while those which decay backwards in the meson center-of-mass system will have a positive polarization in the laboratory system. Since the meson production spectrum has a steep energy dependence, there are many more relatively low-energy mesons which decay forwards in their system to produce 185-GeV muons than there are higher-energy mesons which decay backwards to give muons with a laboratory energy of 185 GeV and, hence, there is a net negative polarization.

As a consequence of kinematic effects, for muons emitted from a parent particle with velocities near c in the parent-particle system, the mean polarization in the laboratory system will be nearly equal to the center-of-mass polarization if the production spectrum of the parent is sufficiently steep (as for pions or K mesons). Detailed calculations using meson spectra from 24-GeV protons on copper[7] scaled to 400 GeV indicate that the polarization of muons from pion decays is about − 0.62 and polarization of muons from K-meson decays is about − 0.98. These values are not especially sensitive to the production spectrum. With about 22% of the meson-derived muon flux from K^+-meson decay, the polarization of the muons from all meson decays will be − 0.70. Using this value for the polarization of the muons from meson decays, we find that the asymmetry amplitude A equals $0.172P$, where P is the polarization, and the polarization of the prompt muons is $P = 0.00 \pm 0.10$. The muons produced by the direct processes are then not polarized in the direction of flight in the laboratory system. This lack of polarization suggests that the muons are produced electromagnetically.

While the conduction of this measurement was made possible by the existence of the Fermi National Accelerator Laboratory, it was made easy and pleasant by the exemplary cooperation we have received by everyone at Fermilab. We feel indebted particularly, however, to Dr. Roy Rubinstein who provided solutions for the real parts of the complex problems we posed him and taught us to ignore the imaginary parts.

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[6]We are indebted to Dr. G. Takhtamyshev for adapting the Dubna fitting program FUMILI for use on the PDP-11 computer.

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