Neutrino Experiment to Test the Nature of Muon-Number Conservation

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This paper reports on a search for $\bar{\nu}_e$ from $\mu^+\to e^+\bar{\nu}_e\nu_\mu$, allowed by multiplicative but not additive muon conservation, and for ν_e from $\mu^+\to e^+\nu_e\bar{\nu}_\mu$, allowed by both. Neutrinos from the Clinton P. Anderson Meson Physics Facility have been used, together with a six-ton Cherenkov counter filled with H_2O (D_2O) to look for $\nu_e p\to ne^+$ ($\nu_e d\to ppe^-$). The branching ratio $(\mu^+\to e^+\nu_e\nu_\mu)/(\mu^+\to \text{all}) = -0.001\pm 0.040$ is in excellent agreement with the additive law. The cross section $\langle\sigma(\nu_e d\to ppe^-)\rangle = (0.52\pm 0.18)\times 10^{-40}\ \text{cm}^2$ agrees with theory.

Muon conservation, distinct from total lepton conservation, was introduced to account for the absence of $\mu\to e\gamma$, $\mu\to 3e$, $\mu Z\to eZ$, and $\nu_\mu Z\to eZ'$. Muon and electron numbers are defined by $L_\mu=+1$ (-1) for μ^-, ν_μ $(\mu^+, \bar{\nu}_\mu)$ and $L_e=+1$ (-1) for e^-, ν_e $(e^+, \bar{\nu}_e)$. In place of the usual, additively conserved quantum numbers, $\sum L_\mu=\text{const}$ with $\sum(L_\mu+L_e)=\text{const}$, one could, as Feinberg and Weinberg[1] pointed out, introduce a multiplicatively conserved muon number $\prod(-1)^{L_\mu}=\text{const}$ with $\sum(L_\mu+L_e)=\text{const}$. Most recently Derman[2] has considered multiplicative muon conservation in the context of gauge theories.

Both formulations prohibit the reactions above, but they are not equivalent. In particular, the additive law forbids muon decay with inverted neutrinos,

$$\mu^+\to e^+ + \bar{\nu}_e + \nu_\mu, \qquad (1)$$

allowed by the multiplicative law. Both laws allow the decay

$$\mu^+\to e^+ + \nu_e + \bar{\nu}_\mu. \qquad (2)$$

In order to test whether muon conservation is a multiplicative law, we have built an apparatus which is sensitive to either $\bar{\nu}_e$ from (1) or ν_e from (2) and used it to look at neutrinos from μ^+ decay at the neutrino area of the Clinton P. Anderson Meson Physics Facility (LAMPF) at Los Alamos. We utilized the neutrino reactions

$$\bar{\nu}_e p\to ne^+ \qquad (3)$$

and

$$\nu_e d\to ppe^- \qquad (4)$$

on protons and deuterons in a six-ton Cherenkov counter filled alternately with H_2O and D_2O. By comparing the rates of neutrino events in the water and heavy water, we measured the branching ratio for the exotic μ^+ decay mode (1),

$$R \equiv (\mu^+ \rightarrow e^+ \bar{\nu}_e \nu_\mu)/(\mu \rightarrow \text{all}), \qquad (5)$$

in a largely bias-free fashion. Previous information on R comes from Eichten *et al.*,[3] with $R < 0.25$, and recently from Blietschan *et al.*,[4] with $R = 0.13 \pm 0.15$.

Our source of μ^+ decays was the beam stop at LAMPF with an incident proton beam of 780 MeV producing π^+ and π^- mesons. The sequential decays of stopped π^+ and μ^+ yield neutrinos, while the π^- are mostly absorbed upon stopping, leaving a contamination of $\mu^-/\mu^+ < 0.2\%$. A measurement of $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ in a simulated beam stop by Chen *et al.*[5] gave (μ^+ decays)/proton $= 0.057 \pm 0.004$ at 720-MeV proton energy. Extrapolated to the LAMPF energy, this gives a rate of (μ^+ decays)/proton $= 0.069 \pm 0.007$ and a neutrino flux of about 2×10^7 cm^{-2} sec^{-1} into our detector.

Our experimental apparatus is shown schematically in Fig. 1. The LAMPF neutrino area was a steel and concrete blockhouse with a 1.2-m steel roof, separated from the beam stop by 6.3 m of steel shielding. The neutrino detector, described in detail elsewhere,[6] was a (180 cm)^3 nondirectional water Cherenkov counter used as an electron total-energy calorimeter. It contained 6000 liters of water with a dissolved wavelength shifter, had diffuse reflector walls, and was viewed by 96 12.5-cm phototubes. Its resolution was $\sigma = 12\%$ at the typical e^+ or e^- energy of 40 MeV. The expected event rates, for 300 μA of protons on the beam stop, were $70 \times R$/day on H_2O and 20/day on D_2O. To first order the rate on D_2O is independent of R, since deuterium provides a target for either ν_e or $\bar{\nu}_e$.

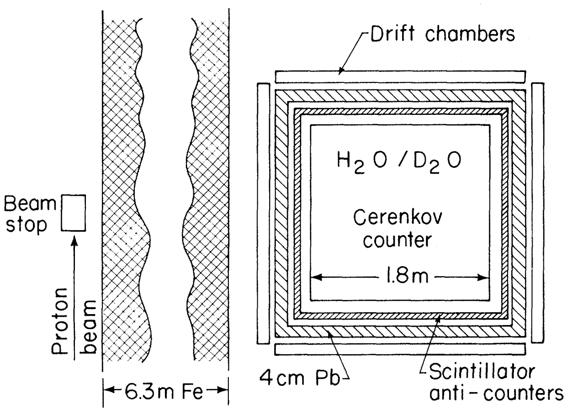

FIG. 1. Schematic plan view of apparatus.

There are no significant neutrino reactions competing with (3) and (4). Muon neutrinos from pion and muon decay at rest are below threshold for charged-current reactions. Inverse β decay by ν_e (or $\bar{\nu}_e$) on the oxygen in the water is expected to be a very small background since the cross sections are greatly reduced by Pauli exclusion effects and the negative Q values involved.[7]

We reduced the cosmic background by 10^4 with the cosmic-ray shield shown in Fig. 1. Plastic scintillators completely surrounded the Cherenkov detector to veto charged cosmic rays. Neutral backgrounds from muon and electron bremsstrahlung were attenuated by covering layers of lead and drift chambers. In addition, we accepted neutrino events only during the beam spill (6% duty factor) for a final cosmic background of 120/day (30–60 MeV). To subtract this background, which dominated our observed neutral events, we also accumulated data between beam spills, renormalizing to the live time during the beam. This beam-in, beam-out subtraction, monitored continuously, was bias-free to 0.2%.

Beam-associated neutron backgrounds were studied with partial shielding, 4 and 5 m of steel, between the detector and the beam stop. Exponential extrapolation of the observed rate of neutron-induced high-energy events gave 1.3 ± 0.2 d^{-1} for our full shielding. We tolerated a large flux of few-megaelectronvolt γ rays from low-energy neutron capture, present even in the final shielding configuration. The pileup and resolution tail of these events did not extend above our chosen energy threshold of 25 MeV; 22% of $\bar{\nu}_e$ and 31% of ν_e events fall below this cut.

Data were accumulated at accelerator currents between 225 and 500 μA for a total of 1270 and 400 C of protons on the beam stop for H_2O and D_2O, respectively. Figures 2 and 3 show the background-subtracted energy spectra for D_2O and H_2O, respectively; the dashed lines are the expected neutrino event spectra for D_2O and for H_2O ($R = 1$). Fits to the expected spectra yield $R_D =$ (observed rate)/(expected rate) $= 1.09 \pm 0.37$ for D_2O and $R_H =$ (observed rate)/[expected rate ($R = 1$)] $= -0.001 \pm 0.044$ for H_2O. The expected rates use cross-section calculations by O'Connell.[8] Both R_H and R_D have had small corrections applied for beam-associated backgrounds. These corrections are $\Delta R_D = -0.06$ and $\Delta R_H = -0.025$ for neutrons, and $\Delta R_D = -0.02$ and $\Delta R_H = -0.004$ for neutrino events on oxygen and on the counter walls. The errors are dominated by the statistical error of the cosmic subtraction but include

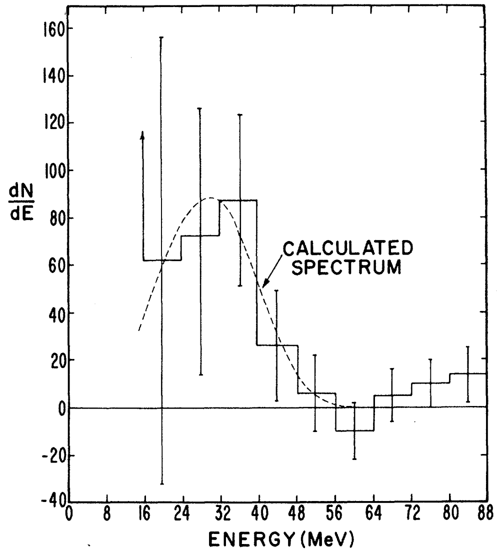

FIG. 2. Background-subtracted energy spectrum for D_2O data.

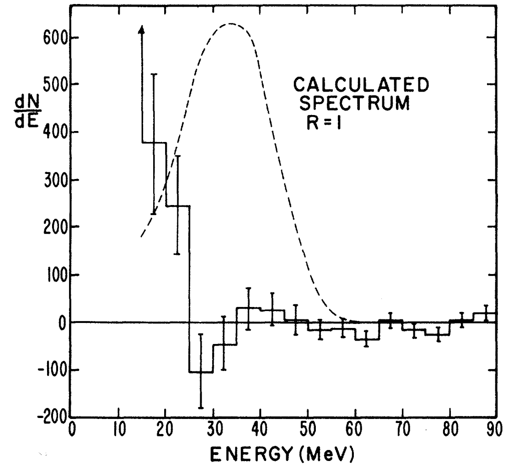

FIG. 3. Background-subtracted energy spectrum for H_2O data.

systematic errors as well.

After the error on R_D is increased for the 10% uncertainty in neutrino flux, the D_2O result translates to a spectrum-averaged cross section

$$\langle \sigma(\nu_e d \rightarrow ppe) \rangle = (0.52 \pm 0.18) \times 10^{-40}\ \mathrm{cm}^2,$$

in good agreement with O'Connell's predicted value[8] of $\langle \sigma \rangle = 0.48 \times 10^{-40}\ \mathrm{cm}^2$. This is the first measurement of inverse β decay by low-energy ν_e rather than $\bar{\nu}_e$. The reaction is the inverse of the reactions $pp \rightarrow de^+\nu_e$ and $ppe^- \rightarrow d\nu_e$, the primary energy sources in the sun.

For calculating the branching ratio (5) we eliminate the uncertainties of detector acceptance and neutrino flux by taking the ratio of the H_2O and D_2O results, $R = R_H/R_D$, with the errors added in quadrature, to obtain

$$R = -0.001 \pm 0.040.$$

We have excellent agreement with the additive law and see no evidence for a multiplicative one. The error includes systematic and statistical contributions. The result translates to an upper limit $R < 0.065$ (90% confidence level).

An upper limit on a $\bar{\nu}_e$ signal is also a limit on possible neutrino oscillations of the type $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$. For a maximal mixing parameter, we get a limit of $< 0.64\ \mathrm{eV}^2$ (90% confidence level) on the square of the mass difference between the neutrino eigenstates. This limit is consistent with other recent experiments.[9]

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