Experimental Limits on the Mass and Lifetime of ν_μ*

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Based on a scan for converted e^+e^- pairs in a large neutrino exposure of the Argonne National Laboratory twelve-foot bubble chamber, we report an upper limit of $m_{\nu_\mu}\Gamma_{\nu_\mu} < 4.6\times10^{-4}$ MeV/sec for the process $\nu_\mu \to \gamma + X$, where X satisfies appropriate conservation laws.

It is possible in principle that one or both of the electron-type and the muon-type neutrinos has a finite rest mass, and might therefore be capable of decaying into still lighter particles.[1-3] From published results the present directly measured experimental uppler limits on the masses are[4] $m_{\nu_e} < 60$ eV and $m_{\nu_\mu} < 0.65$ MeV. Thus the electromagnetic decay

$$\nu_\mu \to \gamma + X \tag{1a}$$

where X satisfies appropriate conservation laws is a possibility. In terms of known particles, the only two-body decay mode is

$$\nu_\mu \to \nu_e + \gamma. \tag{1b}$$

Here muon-type and electron-type lepton numbers are not separately conserved. There has recently been considerable experimental interest in another lepton-number-nonconserving process

$$\mu \to e + \gamma. \tag{2}$$

The published experimental upper limit on process (2) is[5]

$$R_\mu \equiv \frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\nu)} < 2.2\times10^{-8} \tag{3}$$

so that $\mu \to e\nu\nu$ is highly dominant. There are, on the other hand, no known modes of ν_μ to compete with Reaction (1b). Theories which deal with process (2) are likely also to deal with process (1b),[2,6] and experimental information about process (1b) could be helpful in choosing between such theories.

Independently of any theory, the observable laboratory decay rate of process (1) is $\Gamma^{1ab} = m_{\nu_\mu}\Gamma_{\nu_\mu}/E_{\nu_\mu}$ where Γ_{ν_μ} is the intrinsic, center-of-mass rate for process (1). If the neutrino-beam energy spectrum is reasonably well known, one can in general establish a value or limit for the quantity $m_{\nu_\mu}\Gamma_{\nu_\mu}$.

We have searched for Reaction (1) in 592 000 photographs of the Argonne National Laboratory twelve-foot diameter bubble chamber filled with deuterium exposed to a neutrino beam. This film sample corresponds to 8.3×10^{17} protons on the primary target and a path length of muon-type neutrinos in the bubble chamber of 2.3 light years. The neutrino-flux spectrum[7] peaks at about 600 MeV and is known to an absolute normalization of ± 15%. The photon conversion efficiency into observable e^+e^- pairs depends on photon energy but is typically ~ 4% in the bubble-chamber liquid. As described by Barnes,[8] most of the photons from Reaction (1) in this experiment will have laboratory energy greater than 100 MeV and laboratory angle less than 1° with respecto to the incident neutrino direction (which is itself known to within ± 1°).

A search was made for possible e^+e^- pairs with energy $\gtrsim 10$ MeV and pointing within about 20° of the neutrino beam direction, and not clearly pointing to some interaction vertex. Candidates were measured three times and reconstructed in space using the computer program TVGP. Using the program SQUAW a one-constraint kinematic fit was attempted to the process

$$\gamma + d \to e^+ + e^- + d. \tag{4}$$

Nineteen events make acceptable fits to Reaction (4). Figure 1 is a scatter plot of their dip and azimuth about a vertical axis in the bubble chamber. The neutrino beam enters horizontally in the direction (0 ± 1°, 0 ± 1°). Accuracy of measuring the photon directions is typically a few degrees or better. Only two events have $E_\gamma > 100$ MeV and lie within 10° of the forward direction. Their characteristics are listed in Table I. For photons of about 300-MeV energy the maximum

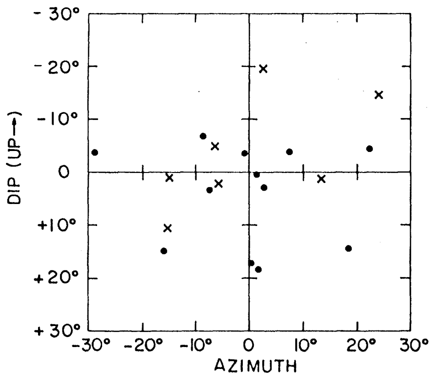

FIG. 1. Scatter plot of dip vs azimuth for the 19 fitted $\gamma \to e^+e^-$ pairs. Dots represent pairs with $E_\gamma < 100$ MeV; and crosses, $E_\gamma > 100$ MeV.

kinematically allowed value of $\theta_{\gamma,\nu}$ is 0.06°, even if m_{ν_μ} is as large as 0.65 MeV. The values of $\theta_{\gamma,\nu}$ for the two events lie, respectively, 4 and 5 standard deviations away from zero.

The energy spectrum of the pairs is shown in Fig. 2, and is seen to lie mainly below 100 MeV. The accumulation between 30 and 110 MeV is suggestive of background from π^0 decaying nearly at rest, perhaps produced from external π^-'s which stop in the bubble-chamber wall.

Cosmic-ray tracks occur in nearly all of the pictures, because of the large detector volume and the sensitive time of ~15 msec. Cosmic-ray-associated γ's giving e^+e^- pairs are seen and rejected about every 100 pictures.[9] Less than 3% of the bubble-chamber expansions have a cosmic-ray track with location and direction such as to have caused rejection at the scanning stage of one of the e^+e^- pairs shown in the figures.

A large fraction of the background is rejected by requiring that $E_{\nu_\mu} > 100$ MeV and that $\theta_{\gamma,\nu}$ be within a few degrees of zero. This rejection is effective for cosmic-ray-associated γ's unaccompanied by charged cosmic-ray tracks, and also for other small sources of background such as decaying π^0 from the reactions $\nu n \to \nu n \pi^0$, $nn \to nn\pi^0$,

TABLE I. Events with $E_\gamma > 100$ MeV and $\theta_{\gamma,\nu} < 10°$.

Roll-frame	Azimuth[a]	Dip[a]	E_γ (MeV)	$\theta_{\gamma,\nu}$[a]
750-5453	-5.8 ± 0.4	2.3 ± 0.5	273	6.2 ± 1.6
751-2753	-6.3 ± 0.4	-4.7 ± 0.6	304	7.9 ± 1.6

[a]Includes a conservative ±1.5° uncertainty in the neutrino beam direction.

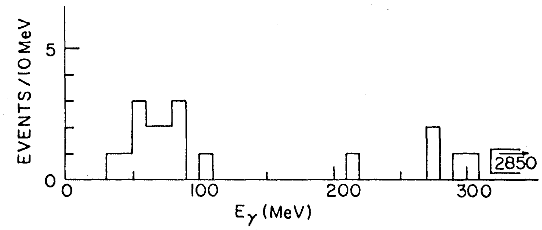

FIG. 2. E_γ spectrum for the 19 fitted $\gamma \to e^+e^-$ pairs.

and $K_L{}^0 \to 3\pi^0$. We have a direct estimate of the background level from the density of pairs shown in Fig. 1. Above 100 MeV, the average density is such that we would expect about one background event in the central ±10° by ±10° region compared with the two which actually occur there. In summary, there is no excess density of e^+e^- pairs anywhere near the forward direction. Since neither e^+e^- pair above 100 MeV is at all consistent in direction with the expected signal, we report a null result and a 90%-confidence-level upper limit $m_{\nu_\mu}\Gamma_{\nu_\mu} < 4.6 \times 10^{-4}$ MeV/sec. A preliminary upper limit equivalent to 3.3×10^{-4} MeV/sec at 90% confidence level has been found in the heavy liquid bubble chamber Gargamelle exposed to the CERN neutrino beam.[10] In that experiment, a shorter neutrino path length and a higher average neutrino energy are compensated by a greater photon conversion efficiency to give a result with a sensitivity comparable to ours.

In general gauge theories,[6] the decay of a lepton as in Reactions (1) and (2) is proportional to $(m_{\text{lepton}})^5$. For example, in the theory of Marciano and Sanda[6] the ratio of the rates of Reactions (1b) and (2) is $0.36(m_{\nu_\mu}/m_\mu)^5$. The published limit on the decay rate for Reaction (2) corresponds to $\Gamma(\mu \to e\gamma) < 1.0 \times 10^{-2}$ sec^{-1}. Scaling this decay rate to Reaction (1b), using the published experimental upper limit of $m_{\nu_\mu} < 0.65$ MeV from muon-decay kinematics,[4] implies $m_{\nu_\mu}\Gamma_{\nu_\mu} < 2 \times 10^{-14}$ MeV/sec.

In any theory which gives Γ_{ν_μ} explicitly in terms of m_{ν_μ}, separate upper limits can be set on the mass and on the decay rate. For example, our upper limit coupled with the theory of Marciano and Sanda implies the nonrestrictive limit $m_{\nu_\mu} < 500$ MeV. If there are leptons heavier than the muon, this upper limit may be somewhat reduced. An experimental rate for process (1b) anywhere near our present upper limit would be in serious conflict with gauge theories such as those of Ref. 6, even with the inclusion of heavy leptons of reasonable mass, $m_L \ll m_W$, where W is the weak intermediate vector boson.

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[8]See Ref. 3. There is a typographical error in the printing of Eq. (5) of that paper; the corrected equation should read $\theta_\gamma \approx \theta_L \sin\theta^*/(1+\cos\theta^* - \theta_L^2/2)$.

[9]We reject at the scanning stage any obvious e^+e^- pair which points along the direction of a cosmic-ray shower or along the direction of a downgoing cosmic-ray muon, and is also within 20 cm of such a track.

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Longitudinal-Transverse Separation for Inclusive Electroproduction of Pions and Protons*

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We use new measurements of the inclusive electroproduction reactions $eN \to e'\pi^\pm X$ and $eN \to e'pX$ with ϵ values in the range $0.35 < \epsilon < 0.45$ together with earlier measurements with $0.85 < \epsilon < 0.95$ to determine the contributions to the cross section due to transversely and longitudinally polarized photons in the range $1.2\ \text{GeV}^2 < Q^2 < 3.3\ \text{GeV}^2$. The longitudinal component is small and consistent with that observed in the total virtual-photoproduction cross section.

The longitudinal polarization of virtual photons provides a powerful probe for determining the spin of the constituents of the nucleon. For electroproduction experiments in which only the scattered electron is observed, the total virtual-photoproduction cross section can be written in the form

$$\sigma_{\text{tot}} = \sigma_T + \epsilon\sigma_L. \tag{1}$$

Here σ_T is due to transversely polarized photons, σ_L is due to longitudinally polarized photons, and ϵ is the polarization parameter for the virtual photons. The Stanford Linear Accelerator Center–Massachusetts Institute of Technology data give the value 0.14 ± 0.07 for the ratio $R = \sigma_L/\sigma_T$.[1] This small value of R is interpreted in the parton model to mean that the constituents are predominately spin-$\frac{1}{2}$ particles. This supports the quark model for nucleon structure. The observed scaling of νW_2 and W_1 implies that R should be given by

$$R = Q^2/\nu^2 = 2M/\nu\omega, \tag{2}$$

where ν and $-Q^2$ are the energy and square of the mass of the virtual photon, respectively, and $\omega = 2M\nu/Q^2$. The available data are not sufficiently precise to distinguish between a constant R and a functional dependence of the form given by Eq. (2). There has been some speculation that the longitudinal component is due entirely to exclusive reactions such as $\gamma_v p \to \pi^+ n$ and that there is no longitudinal component in the inclusive reactions such as $\gamma_v p \to \pi^+ X$.[2]

In this Letter, we use new measurements made at low ϵ[3,4] of the inclusive electroproduction reac-