Measurement of the Reaction $^{12}$C($\nu_\mu, \mu^-)$X Near Threshold

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Abstract

The reaction $^{12}\text{C}(\nu_\mu, \mu^-)X$ has been measured near threshold using a $\pi^+$ decay-in-flight $\nu_\mu$ beam from the Los Alamos Meson Physics Facility and a massive liquid scintillator neutrino detector (LSND). In the energy region $123.7 < E_\nu < 280\text{ MeV}$, the measured spectral shape is consistent with that expected from the Fermi Gas Model. However, the measured flux–averaged inclusive cross section ($\left(8.3 \pm 0.7_{\text{stat.}} \pm 1.6_{\text{syst.}}\right) \times 10^{-40}\text{cm}^2$) is more than a factor of 2 lower than that predicted by the Fermi Gas Model and by a recent random phase approximation calculation.
There has been little information to date on low energy neutrino–nucleus scattering despite its potential application to nuclear structure studies. This process principally involves axial–vector nuclear currents and consequently provides different information than low energy electron-nucleus scattering, which is sensitive only to polar–vector currents. While the coupling of the $W^\pm$ to a free nucleon is well understood at low $Q^2$ ($Q^2 < 1 \text{ GeV}^2$), calculation of the $(\nu, l^\pm)$ inclusive cross section from a nucleus is beyond the capabilities of present models. The Fermi Gas Model [1], for example, works well at higher $Q^2$ but is not expected to accurately reflect the behavior of nuclei probed at low momentum transfer. There are a variety of important strong–interaction dynamical effects that are not readily incorporated into models sufficiently global to reproduce inclusive cross sections. These inclusive charged–current processes, $A(\nu, l^\pm)X$, have taken on new importance in recent years as as they are central to the detection process in several active neutrino detectors.

We report here measurements of the salient features of the reaction $^{12}\text{C}(\nu_\mu, \mu^-)X$ from threshold (123.7 MeV) to 280 MeV neutrino energy. The data were obtained in the initial run of the Liquid Scintillator Neutrino Detector (LSND) at the Los Alamos Meson Physics Facility (LAMPF).

LSND is a cylindrical imaging Čerenkov detector 9 m long and 6 m in diameter with its axis horizontal. It consists of 197 m$^3$ of mineral oil viewed by 1220 20 cm φ photomultiplier tubes (PMTs), which cover 24.8% of the detector’s inner surface. A small amount of scintillator (0.031 g/l butyl-PBD) is dissolved in the mineral oil, so that both the scintillation and Čerenkov light produced by charged particles may be observed and resolved [2]. For a given amount of detected light, the ratio of light in the Čerenkov cone to isotropic light (which includes wave–shifted Čerenkov light) facilitates identification of particle type. For highly relativistic particles, this ratio is approximately 1:4. The spatial origin of the light associated with an event can be localized to within 25 cm rms using the photon arrival times at each hit PMT. For electrons, the relationship between the total detected PMT charge and particle energy is determined by the 52.8 MeV endpoint of electrons from the decay of stopping cosmic ray muons (the Michel spectrum). In this spectrum, 32 PE$^\text{e}$s per MeV are
detected, where a PE is defined as the peak of the PMT response to a single photoelectron. The energy resolution at the endpoint of the spectrum is 6%. The corresponding relationship between charge and energy for other particle types is determined by a GEANT-based Monte Carlo simulation of LSND [3] which reproduces the observed Michel spectrum and incorporates data from an exposure of a sample of LSND scintillator to protons and electrons of known energy [2].

The midpoint of the LSND detector is located 29 m downstream of the LAMPF A–6 proton beam dump at 12° from the axis of the proton beam. LSND is surrounded (except for the bottom) by a highly efficient cosmic ray veto counter [4], which is crucial for eliminating backgrounds that would otherwise arise from the 4kHz rate of cosmic muons in the detector.

The trigger requires signals above threshold in at least 100 of the detector PMTs, and fewer than 6 hit tubes in the veto counter. When this trigger is satisfied, the event is read out along with every other event that fired either the veto counter or at least 18 PMTs in the detector within the previous 50 µs. To remove the burden on the data acquisition system of recording decay electrons from stopping cosmic muons, the trigger is disabled for 7 muon lifetimes following each firing of the veto.

For the data reported here, a 780 MeV proton beam at 600–700 µA was delivered at a 7.1% duty factor to the A–6 proton beam dump. The integrated intensity was 1625 C. The beam dump configuration consisted of a 20 cm long water target, several inserts used for isotope production, and a copper proton beam stop. The water target serves as the main source of pions for both the decay–in–flight (DIF) and decay–at–rest (DAR) neutrino beams, with a smaller contribution to the DAR neutrinos arising from the beam stop directly. Because of the 123.7 MeV threshold for the $^{12}\text{C}(\nu_\mu, \mu^-)X$ reaction, only DIF neutrinos contribute.

The DIF neutrino flux is calculated by a Monte Carlo simulation of the beam dump [3], and includes the flux from the two thin targets well upstream of the beam dump, whose contributions are significant only at the highest neutrino energies. Because the decay chain $\pi^+ \rightarrow \mu^+ + \nu_\mu$ followed by $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ is dominant, the integrated neutrino flux
from $\pi^+$ DIF may be constrained by measurements of the neutrino flux from $\mu^+$ DAR. The Monte–Carlo–calculated flux from DAR has been verified in an independent measurement\cite{6} to an accuracy of $\pm 8\%$ and confirmed in an experiment that measured $\nu_e$ elastic scattering from electrons \cite{4} to an accuracy of $\pm 15\%(\text{stat.})$ $\pm 9\%(\text{syst.})$. We estimate a systematic uncertainty of $\pm 15\%$ in the DIF neutrino flux over the relevant energy interval of 123.7 to 280 MeV. This flux distribution is shown in Fig. 1.

The quasielastic process $^{12}\text{C}(\nu_\mu, \mu^-)X$ produces a muon in the interior of the detector, usually accompanied by a promptly ejected proton. The muon + proton signal is followed by an electron from the ($\tau = 2.03\mu$s) decay of that muon in mineral oil \cite{8}. Thus we select pairs of events occurring within 17$\mu$s of each other and reconstructing within 200 cm of each other. Requiring less than 4 hit tubes in the veto counter suppresses the cosmic ray muon contribution by a factor of $5 \times 10^{-5}$. The majority of the remaining cosmic–ray–induced events are eliminated by imposing the following additional criteria: First, the number of PEs detected for the first event (the $\mu^- + p$ candidate) is required to be less than the maximum expected from a $^{12}\text{C}(\nu_\mu, \mu^-)X$ event, given the flux shown in Fig. 1. Second, the energy associated with the electron candidate is required to be less than 60 MeV, and above the endpoint energy (13.6 MeV) of $^{12}\text{B}$ beta decay. ($^{12}\text{B}$ is formed in the detector by the capture of cosmic ray $\mu^-$ on $^{12}\text{C}$. This cut is accomplished by requiring the electron to fire more than 250 PMTs.) Finally, both events are required to have reconstructed positions within the central 108 m$^3$ fiducial volume. The efficiency of these selection criteria is $34 \pm 4\%$ (see Table I). Because of greater background for the lowest energy muons, tighter selection criteria (listed in Table I) were applied to these events, reducing the efficiency for those muons to $25 \pm 3\%$. (Less than 10$\%$ of the signal is in this lowest energy region.) A total of 270 events pass these selection criteria.

In this sample, the most important beam–related background is from $\pi^-$ DIF followed by $\overline{\nu_\mu} + p \rightarrow \mu^+ + n$. This process was calculated (using the cross section and form factors in ref. \cite{9}) to give $14 \pm 5$ events. Contributions from the two other neutrino–related backgrounds, $\overline{\nu_\mu} + ^{12}\text{C} \rightarrow \mu^+ + X$, and $\nu_\mu + ^{13}\text{C} \rightarrow \mu^- + X$ are closely related to the cross section being
measured, and were estimated to be less than 4% of the observed yield. From the number of events recorded with the beam off, we infer that $40 \pm 2$ of the 270 events are due to the cosmic–ray–induced background that passes the selection criteria. All histograms shown for this sample have this beam–off contribution subtracted on a bin–by–bin basis.

Fig. 2a shows the spectrum of time differences between the muon and electron candidates in our final sample. This figure implies a mean muon lifetime of $2.1 \pm 0.2 \mu s$, consistent with expectation. The spatial separation between the $\mu$ and e candidates in each pair is shown in Fig. 2b. The muons are distributed uniformly throughout the fiducial volume. The energy spectrum of the decay electrons is shown in Fig. 2c. To demonstrate that this energy spectrum is representative of that produced by the decay of muons in LSND, the (normalized) energy spectrum of electrons from the decay of stopped cosmic muons is also shown.

The charge measured in LSND from $C(\nu_\mu, \mu^-)X$ events comes from both the $\mu^-$ and the (usually) ejected proton. The light output as a function of particle energy differs for the semi-relativistic muons and non-relativistic protons. A 180 MeV incident neutrino, for example, produces a quasielastic event with total PMT charge between 400 and 600 PEs, depending on the sharing of available kinetic energy between the final state $\mu^-$ and $p$ [2]. Events with summed PMT charge greater than 1500 PEs correspond to neutrino energies above 230 MeV. Because it is not possible to accurately recover the energy of the muon or the incident neutrino given only the total charge detected, we show in Fig. 3 the spectrum of collected charge for the quasielastic events, measured in terms of PEs. The collected charge spectrum predicted by a Coloumb-corrected Fermi Gas Model (FGM) [1], normalized to the total number of observed events, is superimposed on the data in Fig. 3. For additional comparison, the calculated [9] charge spectrum of $\nu_\mu$ on free neutrons, also normalized to the data, is shown in the same figure. (These calculated spectra have a systematic uncertainty in their charge scales, arising mostly from uncertainty in the amount of light produced by highly–ionizing low–energy protons. The scale uncertainty for 180 MeV neutrinos is $\pm 10\%$; the effect of any such rescaling factor increases at lower energies.) The shapes of
both calculated spectra agree with the shape of the experimental data. A similar level of agreement was also obtained with a low statistics sample of quasielastic events reported by the E645 collaboration at LAMPF \[10\]. The general agreement between the data and both the free neutron and FGM calculations in Fig. 3 indicates that the spectrum shape is not particularly sensitive to the nuclear dynamics which these models do not include.

The yield for the exclusive reaction to the ground state, $^{12}\text{C}(\nu_\mu, \mu^-)^{12}\text{N}$(g.s.), is well predicted, as it depends only on form factors measured in beta decay, muon capture, and electron scattering. Fortuitously, this yield can be measured because the $^{12}\text{N}$ ground state is the only $^{12}\text{N}$ level stable against strong decays, so its subsequent beta decay ($E_\nu = 16.3$ MeV, $\tau = 15.9\text{ms}$) serves to uniquely identify it. We presently observe six events for this reaction and the subsequent beta decay, while seven are expected from reliable calculations of this ground state transition \[11\]. This gives us some confidence that our calculation of fluxes and detection efficiencies are correct.

The net number of inclusive $^{12}\text{C}(\nu_\mu, \mu^-)X$ events detected (after subtracting the beam–off and three beam–related backgrounds) is $210 \pm 17$ events. This corresponds to a flux–averaged inclusive cross section of $(8.3 \pm 0.7_{\text{stat}} \pm 1.6_{\text{syst}}) \times 10^{-40}\text{cm}^2$ in the energy region $123.7 < E_\nu < 280$ MeV. The flux–weighted average neutrino energy is $< E_\nu > = 180$ MeV. This average cross section is lower than that obtained using the FGM ($24 \times 10^{-40}\text{cm}^2$) and a recent continuum random phase approximation (RPA) calculation \[11\] ($20 \times 10^{-40}\text{cm}^2$) evaluated with the flux shown in Fig 1. An earlier calculation \[12\] using the measured $\mu^-$ capture rates on $^{12}\text{C}$ along with a closure approximation gives a flux–averaged cross section of $11 \times 10^{-40}\text{cm}^2$, in agreement with our measurement; however, it is not clear if important contributions from partial waves with $l \geq 2$ were properly accounted for. Our measurement is substantially lower than the average cross section reported by an earlier experiment \[13\] involving a brief exposure of a less massive, segmented detector to a different (and slightly higher energy) neutrino beam at LAMPF. This previous measurement reported a visible energy spectrum significantly softer than that predicted by the FGM.

One may also compare the measurements of $^{12}\text{C}(\nu_\mu, e^-)X$ (made using $\nu_\mu$ from muon
DAR) to model predictions. Two measurements [14] [15] of the exclusive cross section to the ground state of \(^{12}\text{N}\) are in good agreement with one another and with various calculations of the expected yield [11] [12] [16]. Agreement between measured and predicted cross sections to excited states of \(^{12}\text{N}\) is less well established. The measured values \((3.6 \pm 2.7 \times 10^{-42}\text{cm}^2\) [14], and \(6.4 \pm 2.0 \times 10^{-42}\text{cm}^2\) [15]) span a factor of two, but agree within quoted errors. Predictions for this yield \((6.3 \times 10^{-42}\text{ (RPA)}, \text{ and } 3.7 \times 10^{-42} \text{ [16]) span the same factor of two.}\)

Thus at present there is agreement to \(\approx\) a factor two among simple FGM, continuum RPA calculations, and the inclusive cross sections observed in low energy neutrino reactions. However, the measurement reported here is significantly lower than model predictions, indicating the presence of nuclear effects important at low energy that are not accounted for in these models.

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FIGURES

FIG. 1. The calculated energy spectrum of muon neutrinos from the decay–in–flight beam.

FIG. 2. (a) Time difference between muon and electron candidates. An exponential fit yields a lifetime of $2.1 \pm 0.2 \mu s$. Muons that live less than $0.7 \mu s$ do not appear in the sample because of the time required for the trigger to reset. (b) Distance between the reconstructed positions of the muon and electron in quasielastic events. (c) Energy of the electron from muon decay. Data points show the electron energy spectrum from the decay of quasielastically produced muons. The histogram shows the spectrum obtained from a sample of stopping cosmic muons. Data points have beam-off contributions subtracted bin–by–bin in all three plots.

FIG. 3. Data points with error bars show the detected charge distribution of quasielastic events ($\overline{\nu}_\mu p$ and beam–off contributions subtracted bin–by–bin) compared with that predicted by the Fermi Gas Model[1] scaled to the data (solid line), and the predicted spectrum from scattering on free neutrons[9], scaled to the data (dashed line). The lowest energy events correspond to neutrinos at the threshold for $C(\nu_\mu, \mu^-)X$; the highest to neutrinos of 250 MeV and greater.
TABLE I. The efficiencies for selection of quasielastic events. As seen in Figure 2, the efficiencies for the spatial and temporal coincidences are essentially 100%.

| Source                      | Efficiency  |
|-----------------------------|-------------|
| veto counter inactive       | 0.77 ± 0.02 |
| computer ready              | 0.97 ± 0.01 |
| $\mu^-$ not captured        | 0.92 ± 0.01 |
| $\mu^-$ lives longer than 0.7 $\mu$s | 0.71 ± 0.04 |
| $\mu^-$ and $e^-$ in fiducial volume | 0.78 ± 0.08 |
| $e^-$ fires more than 250 PMTs | 0.90 ± 0.02 |
| Overall Efficiency for $E_{vis} \geq 140$ PE | 0.34 ± 0.04 |

Additional cuts for $E_{vis} < 140$ PE:

|                        | Efficiency  |
|------------------------|-------------|
| no cosmic muon in 51 $\mu$s prior to $e^-$ | 0.88 ± 0.01 |
| particle identification on electron $^a$ | 0.86 ± 0.03 |
| Overall Efficiency for $E_{vis} < 140$ PE | 0.25 ± 0.03 |

$^a$Efficiency for electron identification was determined using the electrons from the decay of muons produced in the higher energy quasielastic events.
\( \frac{dN_{\mu}}{dt_{\mu}} \) (events/0.4 \( \mu s \))

Time (\( \mu s \))
