Cross sections for the $^{12}C(\pi^{\pm}, \pi N)^{11}C$ reactions from 30 to 100 MeV

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Cross sections for the primary pion beam monitor reactions $^{12}C(\pi^{\pm}, \pi N)^{11}C$ (20.4 min) have been measured between 30 and 100 MeV by activation techniques. These cross sections are consistently lower, but within the uncertainties of our previously determined values. The experimental uncertainties of these new measurements are considerably smaller.

[NUCLEAR REACTIONS $^{12}C(\pi^{\pm}, \pi N)^{11}C$ measured cross sections by activation, $T_{\pi}=30-100$ MeV. Plastic scintillator targets; pion flux determined with scintillator telescope.]

The cross sections for the primary pion beam monitor reactions $^{12}C(\pi^{\pm}, \pi N)^{11}C$ (20.4 min) at energies of 30 to 100 MeV were measured by activation techniques at TRIUMF. The excitation functions for these reactions had previously been determined over the energy range from 40 to 600 MeV at LAMPF.[1] However, the low energy cross sections in that work had large relative uncertainties associated with them because of difficulties in reliably measuring the electron and muon contamination in the pion beam at these energies. The much more favorable duty factor (DF) and the shorter pion channel at TRIUMF (100% DF, micropulses 43-ns apart, 8-m channel), compared to LAMPF (6.5% DF, micropulses 5-ns apart, 14-m channel), made it advantageous to remeasure these cross sections at that facility.

The irradiations were performed at the TRIUMF Biomedical channel[2,3] $M8$, where the maximum momentum is 220 MeV/c (120 MeV). The momentum spread ($\Delta p/p$), was set as low as possible consistent with the beam intensity desired; this spread ranged from ± 2 to $\pm 4\%$. Because of its short length, adequate pion fluxes are available even at the lowest energies. Control of the channel is via a dedicated computer which makes energy selection and stabilization semiautomatic.[4] The experimental techniques were essentially the same as those used in the earlier LAMPF study.[1] A two-element, plastic-scintillator telescope was employed to measure the flux of charged particles that passed through the carbon target during an irradiation. The targets were 3.2-mm-thick by 38-mm-diam disks of Pilots B and F plastic scintillator[5] containing 91.6% carbon by weight. These disks were the same diameter as the first scintillator of the counter telescope and were mounted to its upstream face during the irradiations. No correction was made for the 1.11% ^{13}C content of the carbon; that is, the results reported here technically apply to natural carbon.

Upon tuning the channel to the desired pion charge and energy a measurement of the composition of the beam was made. The pion beams contain muons that come from both the decay of the pions and directly from the pion production target and electrons produced mainly in the target. The production target was 10 cm of Be, selected to minimize electron production. Protons present in the π^+ beam were removed by absorption and differential momentum degradation. The scintillator telescope counted all three particles (π, μ, and e) and, in addition, was used to obtain a time-of-flight (TOF) spectrum which provided the abundance of each component in the beam. Although the pions are almost completely responsible for the production of ^{11}C over most of the energy range covered in this study, we have evidence for electro-production and photoproduction at the lowest energies where e/π ratios are very large (see below). Targets placed just outside the pion beam to test for ^{11}C production by fast neutrons and high-energy photons yielded negative results.

The beam composition was determined from time-of-flight spectra recorded at each pion energy and charge. Delayed pulses from the accelerator's radio frequency signal provided the time-of-amplitude (TAC) stop signal while twofold logic output from the scintillator telescope provided the TAC start pulse. The TAC output was recorded in a pulse height analyzer. At 60 MeV and below the pion and muon peaks were clearly resolved. At 70 to 100 MeV, the 5 to 10% muon contribution to the $\pi+\mu$ peak was determined by extrapolation of a curve drawn through the μ/π data that were determined between 20 and 60 MeV.

The targets were irradiated for 20 to 40 min (one to two half-lives of the ^{11}C) and were then transported to a counting area where the target scintillator disk was optically coupled to the face of a photomultiplier tube. This assembly was then placed in contact with the face of a 75-mm-thick × 75-mm-diam NaI(Tl) scintillator inside a lead shield. The ^{11}C positrons were self-detected by the plastic scintillator, and the annihilation quanta were detected in the NaI(Tl) scintillator which had an electronic window set to include only the 511-keV photopeak pulses. Each sample was counted for at least three half-lives with standard β-γ coincidence circuity. The ^{11}C disintegration rate was calculated from the net β^+, γ, and β^+-γ coincidence rates.

To determine the pion reaction cross sections at our lowest energies special corrections were required. At these energies the cross sections for the pion-induced production of ^{11}C become small and low probability competing reactions must be considered because the electron-to-pion ratio becomes so large (~ 20 for 30-MeV π^-). Below 113 MeV/c (40 MeV) for π^- and 77 MeV/c (20 MeV) for π^+, the beams consist predominantly of electrons and positrons, respectively, and therefore ^{11}C resulting from electrodisintegration (via virtual photons) and photoneutron reactions (via bremsstrahlung) must be subtracted from the total ^{11}C yield.

We have determined the electrodisintegration cross sections by folding virtual photon spectra into a ^{12}C photonuclear excitation function[6]; the photon spectra were calculated with an analytical expression derived by Wolynec *et al.*[7] from plane wave considerations. This technique duplicates the $^{12}C(e,e'n)^{11}C$ measured cross sections[8] at 30 MeV, and it should reproduce the 77- to 113-MeV/c electron cross sections equally well. These corrections ranged from 2% for 30-MeV π^+ to 13% for 30-MeV π^-.

The larger photoneutron contribution to ^{11}C production due to bremsstrahlung is a difficult problem to resolve. One method we used to estimate an upper limit to this contribution was to measure the ^{11}C produced in a target with the 30-MeV $\pi^{\pm}$ "ranged out" with an absorber 0.5 m upstream of the target so that only electrons, bremsstrahlung, and a small number of muons passed through the target. The bremsstrahlung contribution was the net remaining after subtracting the electron contribution determined, as described above. This method provides an overestimate of the photoproduction of ^{11}C, due to the bremsstrahlung produced in the absorber; however, this enhancement was minimized due to the larger target-absorber separation. A second method was provided by a 10-MeV π^+ run (3 MeV below threshold). Assuming that all ^{11}C production at this energy is due to electron-induced reactions (53-MeV e^+), we applied this same correction factor (normalized for electron intensities) to our 30- and 40-MeV data, providing a lower limit for these pion reaction cross sections. Both methods gave essentially the same magnitude for the photoproduction of ^{11}C.

At 30 MeV the photonuclear contribution from bremsstrahlung is estimated to be 7% for π^+ and 45% for π^-. Because of the low pion reaction cross section and the large lepton contamination in the beam, no pion cross sections could be reliably determined below 30 MeV.

Cross sections for the $^{12}C(\pi^{\pm},\pi N)^{11}C$ reactions are listed in Table I along with the values determined earlier in LAMPF. While the cross sections determined in this study fall within the uncertainties associated with out earlier values, they are consistently lower. Over the energy range from 40 to 90 MeV, the new π^+ cross sections range from 26 to 5% lower and the π^- cross sections range from about 46 to 2% lower than our earlier cross sections. Hand-drawn curves starting from the thresholds for these reactions and passing through the new cross sections merged well with our previously recommended values in the 100- to 160-MeV range, as shown in Fig. 1. Thus we have obtained a set of recommended cross

TABLE I. Cross sections for the $^{12}C(\pi^{\pm},\pi N)^{11}C$ reactions.

Pion energy (MeV)	Cross sections (mb) This work	Previous work[a]
	π^+	
30	3.2 ± 0.4	
40	6.5 ± 0.4	8.8 ± 1.9
50	10.3 ± 0.6	13.7 ± 2.6
60	14.6 ± 0.8	19.0 ± 3.2
70	20.1 ± 1.0	23.6 ± 3.4
80	25.2 ± 1.3	27.6 ± 3.3
90	29.8 ± 1.5	31.5 ± 3.0
100	33.5 ± 1.7	35.0 ± 2.6
	π^-	
30	0.9 ± 0.8	
40	2.9 ± 0.4	5.7 ± 2.3
50	6.1 ± 0.5	8.1 ± 2.9
60	10.6 ± 0.6	11.6 ± 3.7
70	16.4 ± 0.8	17.5 ± 4.8
80	24.3 ± 2.0	23.8 ± 5.5
90	30.0 ± 1.5	30.6 ± 5.8

[a]Reference 1.

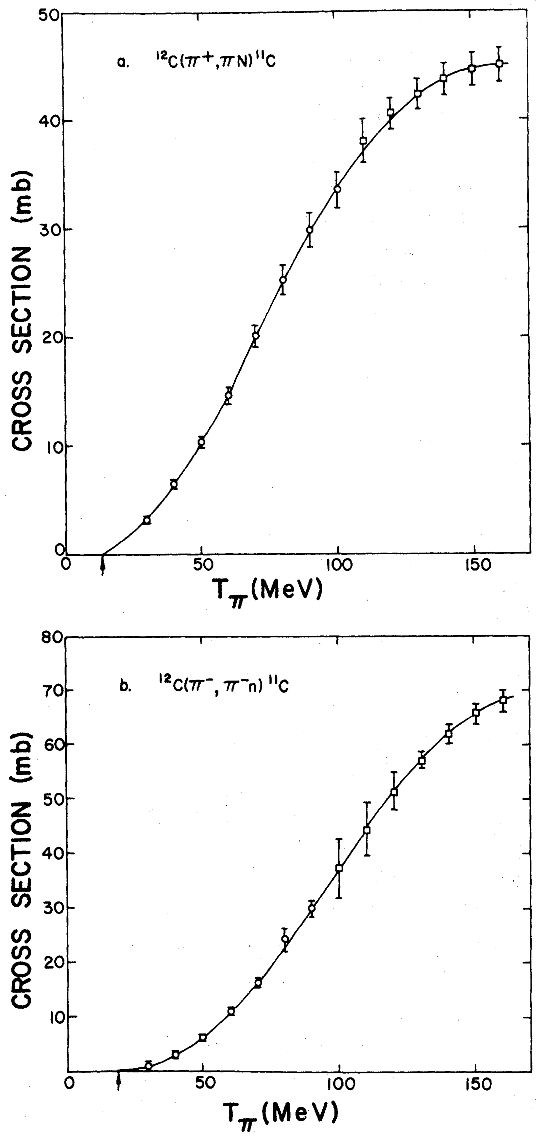

FIG. 1. Measured cross sections for the $^{12}C(\pi^+, \pi N)^{11}C$ reaction (a) and for the $^{12}C(\pi^-, \pi^- n)^{11}C$ reaction (b); ○ data points determined at TRIUMF, □ data points determined at LAMPF (Ref. 1).

TABLE II. Recommended cross sections for the $^{12}C(\pi^{\pm}, \pi N)^{11}C$ reactions.

Pion energy (MeV)	Cross sections (mb) σ_{π^+}	σ_{π^-}
30	3.2 ± 0.4	0.9 ± 0.8
40	6.5 ± 0.4	2.9 ± 0.4
50	10.3 ± 0.6	6.1 ± 0.5
60	14.6 ± 0.8	10.6 ± 0.6
70	20.1 ± 1.0	16.4 ± 0.8
80	25.2 ± 1.3	23.3 ± 1.2
90	29.8 ± 1.5	30.2 ± 1.5
100	33.5 ± 1.7	37.2 ± 2.0
110	37.0 ± 1.9	44.6 ± 2.3
120	39.8 ± 2.0	51.5 ± 2.6
130	42.0 ± 2.1	57.3 ± 2.9
140	43.7 ± 2.2	62.0 ± 3.1
150	44.6 ± 2.2	65.6 ± 3.3
160	45.1 ± 2.3	68.0 ± 3.4

sections, given in Table II, by reading the values from expanded plots of these excitation functions. This procedure resulted in some recommended values differing from the measurements, but within their uncertainties.

The threshold energies for the respective reactions were calculated from the mass differences between the products and reactants taking the kinetic energy of the center of mass into account. In the case of the $^{12}C(\pi^+, \pi N)^{11}C$ reaction, the pion charge exchange component $^{12}C(\pi^+, \pi^0 p)^{11}C$ provides the lower threshold (13 vs 19 MeV) and apparently is the primary contributor to the larger cross sections for the π^+ over the π^- reactions below about 90 MeV.

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