$^{12}C(p,pn)^{11}C$ cross section at 300 GeV†

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The absolute cross section for the $^{12}C(p,pn)^{11}C$ reaction has been measured in the *M*2 diffracted proton beam of the Fermi National Accelerator Laboratory at an energy of 300 GeV. Proton intensities were measured with a scintillation counter telescope, and the 20.4-min ^{11}C activity induced in 3.2-mm thick plastic scintillator targets was determined both by internal scintillation (β) counting and by annihilation radiation counting with a NaI well crystal. A correction for the formation of ^{11}C by secondary particles was determined by measuring the activity in individual targets in a stack. The corrected value for the $^{12}C(p,pn)^{11}C$ cross section at 300 GeV is 24.6 ± 1.6 mb.

[NUCLEAR REACTIONS $^{12}C(p,pn)$, $E = 300$ GeV; measured absolute cross section.]

I. INTRODUCTION

The cross section of the $^{12}C(p,pn)^{11}C$ reaction[1] has been used as the primary standard for the determination of a large number of cross sections for high-energy proton interactions. This is because of the convenience of determining the ^{11}C disintegration rate induced in a plastic scintillator target by using internal β counting after the irradiation. With the availability of proton energies of 200–400 GeV at the Fermi National Accelerator Laboratory (Fermilab) a number of activation cross sections are being measured at these energies, but only relative cross sections have been reported until now. The present paper reports the results of measurements of the absolute cross section for the reaction $^{12}C(p,pn)^{11}C$ at 300 GeV.

II. EXPERIMENTAL PROCEDURE

The apparatus and experimental procedure used were the same as those used previously[2] in the measurement of this cross section at 7.6 GeV. The proton intensity was measured by direct counting with a scintillation counter telescope, and the induced ^{11}C activity was measured in two ways: internally in a plastic scintillator target and with an NaI well crystal by means of annihilation radiation counting.

A. Beam intensity

The diffracted proton beam in the *M*2 beam line of the Meson Laboratory at Fermilab was used for the measurements. The dimensions of the beam at the target location were approximately 2 mm × 5 mm, as compared to the 16-mm diameter of the targets. The counter telescope consisted of three elements, the first one of which was the same diameter as the target. The second and third elements were 25.4 mm in diameter, and all three were 3.2 mm thick. They were optically coupled via light pipes to RCA-8575 photomultipliers, which provided a fast (rise time ~1 nsec) pulse of about 2 V for a minimum ionizing particle at the operating voltage of 1800 V. These signals were fed through fast discriminators (which produced output pulses 4 nsec wide) to overlap coincidence circuits, yielding a total resolving time of 8 nsec. The rf structure of the beam was completely preserved in the diffracted beam, with a 20-nsec spacing between bunches. A delayed coincidence curve confirmed this structure and demonstrated that the apparatus could completely resolve pulses separated by 20 nsec.

Voltage plateaus established that the beam particles were being counted with 100% efficiency, and the equality (within 1%) of the singles counting rates of the three counters confirmed this. Moreover, the prompt coincidence rate between counters 1 and 2 was 99.3% of the singles rate in counter 1, confirming the correct operation of the electronics. The outputs of the discriminators and the coincidence circuits were counted with 100-MHz pulse counters. In order to measure the number of protons not counted because of two or more particles being in the same rf bunch, a delayed-coincidence technique was used. One output of the coincidence circuit was delayed by 20 nsec relative to a second output, and the delayed coincidences were counted. These measured the number of occupied pairs of rf bunches, which, for small probabilities, is just twice the number of rf bunches with two particles. The ratio of delayed to prompt coincidences was always less than 0.04. The beam intensity was varied between 0.16×10^6 and 1.6×10^6 protons/pulse for different runs, and no correlation between the measured cross section and the intensity was found.

B. Targets and ^{11}C counting

The targets and counter telescope elements were circular disks of the pilot B plastic scintillator[3] of thickness 0.310 $g\,cm^{-2}$ and containing 91.55% carbon by weight. For each irradiation the target (or target stack) was taped to the first element of the counter telescope. The integrated beam intensity, as measured by the triple coincidence counts, was recorded at frequent intervals during the irradiation to allow corrections to be made for variations in beam intensity. In several runs there was a substantial amount of variation, due to various accelerator troubles, and this was taken into account in estimating the error of those measurements. The delayed coincidences were likewise recorded during the irradiation.

After the beam was turned off the target was transported to the Nuclear Counting Laboratory, about 5 km from the irradiation station. Two methods of counting were used: internal scintillation counting and annihilation radiation counting in an NaI well counter. In the former method, the target was optically coupled to a photomultiplier tube, covered with an aluminum cap to ensure uniform annihilation of the positrons, and made light tight. The assembly was placed inside a lead shield, with the target close to a 7.6- $\times$7.6-cm NaI scintillator. A narrow window around 511 keV was used for the NaI crystal and the singles rates and coincidence rate of the two detectors were recorded as a function of time. The efficiency of the internal β counting could then be calculated from the ratio of the coincidence counts to the γ counts.[4] With the β discriminator set just above the noise, the efficiency of detecting ^{11}C radiation was measured as (94.4± 0.3%). These measurements were confirmed by using a calibration scintillator of much greater specific activity, prepared by irradiating one of the targets with 3×10^{12} protons in a single pulse in the external proton beam of the Fermilab.

In order to be able to count more than one target at a time, a 5.1- $\times$5.1-cm NaI well crystal was used with a window set on the 511-keV peak. By rotating a single target between the well counter and the β-γ coincidence counter, the counting efficiency of the well counter was determined to be (21.7± 0.3%).

The counting of individual targets continued for at least five half-lives of ^{11}C ($T_{1/2}$ = 20.4 min), and the data were analyzed by a least-squares computer program. No activity other than a 20.4-min component and a nondecaying background was observed.

The vicinity of the beam was checked for halo or stray radiation by exposing several targets about 10 cm from the beam line during an irradiation. No detectable activity was observed, and an upper limit of 0.5% was set on the amount of activity induced by particles other than 300-GeV protons.

In order to estimate the amount of ^{11}C produced by secondary particles from nuclear interactions in the relatively thick targets and in the first counter telescope element adjacent to the target, two irradiations were performed with target stacks of two and three targets, respectively. The individual targets in the stack were counted separately in the two counting systems described above.

III. RESULTS

The integrated beam intensity for each irradiation was corrected for the number of protons not counted because of two protons being in the same rf bunch by adding one-half the number of delayed coincidences, and for any variation of intensity during the irradiation. The cross section was calculated from this number and the ^{11}C disintegration rate (corrected for the finite length of irradiation) and the target thickness and composition.[1]

The results are presented in Table I. Listed for each irradiation are the counter used to measure the ^{11}C activity, the average beam intensity in protons/pulse (7.5-sec repetition rate), the measured ratio of delayed to prompt coincidences, and the measured cross section. The error listed is made up of the standard deviation of the end-of-bombardment count rate (given by the least-squares analysis program), the uncertainty in absolute counting efficiency, and the estimated error in the correction for varying beam intensity in the case of those runs in which the variation was large. The weighted mean of these measurements is 27.0 ± 0.8 mb. This value must be corrected for the effect of secondary particles which produce ^{11}C in the relatively thick targets.

Table II summarizes the results of the two experiments done to measure the secondary effects. It can be seen from the data in Table II that the observed cross section of the first target in the stack is increased by the presence of additional material downstream. This effect is due to secondary particles produced in the downstream targets which are emitted in the backward direction and interact in the first target to form ^{11}C. In addition to these "backward" secondaries there is clearly a "forward" effect, as seen by the increase in observed cross section as one proceeds downstream in the target stack. Both backward and forward effects were assumed to be linear in target thickness and the data in Table II, together

TABLE I. Experimental ^{12}C (p, pn) ^{11}C cross sections.

Expt. No.	Counter	Average beam intensity (protons/pulse)	Delayed/prompt	Observed cross section (mb)
1	NaI	1.4×10^6	0.034	25.8 ± 1.0
2	internal	0.8×10^6	0.020	26.9 ± 0.4
3	internal	0.16×10^6	0.003	27.6 ± 0.6
4	NaI	1.6×10^6	0.030	27.2 ± 0.8
5	internal	0.44×10^6	0.009	26.4 ± 0.5
6	NaI	1.1×10^6	0.022	28.1 ± 0.8
Weighted mean				27.0 ± 0.8
Correction for secondary production of ^{11}C				-2.4 ± 1.4
Corrected cross section				24.6 ± 1.6

with the mean value of 27.0 mb from Table I, were fitted by a weighted least-squares procedure to the equation

$$\sigma = \sigma_0 + aF + bB. \quad (1)$$

In this equation σ is the observed cross section of a given target, σ_0 is the thin-target cross section, and F and B are the amounts of scintillator material forward and backward, respectively, of the center of the target. The first element of the counter telescope was included in B, but the second and third were neglected because of their much greater separation. Thus, for example, the values of F and B for the measurements in Table I are 0.5 and 1.5 target thicknesses, respectively.

The results of the least-squares fit were $\sigma_0 = 24.6 \pm 1.6$ mb, $a = 2.26 \pm 0.65$ mb/unit thickness, and $b = 0.85 \pm 0.50$ mb/unit thickness. The total correction for ^{11}C produced by secondary particles formed in the target and the first counter telescope element is thus 2.4 ± 1.4 mb. This is considerably larger than the value of 1.0 ± 0.3 mb estimated previously[2] at 7.6 GeV, for the same thickness of material. It seems likely that most of the increase is due to the forward secondary effect, caused by the increase in the number of pions and other particles formed in nucleon-nucleon collisions as the proton energy increases. Approximately 0.6% of the incident protons interact in traversing one scintillator thickness and the mean charged multiplicity in 300-GeV p-p collisions is 8.9,[6] so that the number of particles is increased by about 5% by each scintillator, assuming 0° particle production. The observed forward secondary effect is about 9% per unit thickness, indicating additional forward-directed particles are produced in proton-nucleus collisions, for example nucleons ejected by an intranuclear cascade.

In contrast, at a proton energy of 7.6 GeV the mean number of charged secondary particles in p-p collisions is less than 3, and these are much less forward directed than those produced at 300 GeV. Thus one expects a much smaller forward secondary effect at the lower energy.

Since such a large part of the error in the final cross section value is due to the uncertainty of the thickness correction, it would be desirable for future measurements to minimize the thickness of both targets and counter telescope elements, in order to minimize the magnitude of the correction.

The highest proton energy at which this cross section has been previously measured is 28 GeV,[5] at which energy a value of 25.9 ± 1.2 mb was found. The present measurement is consistent with the

TABLE II. Effect of target thickness on ^{11}C production.

No. of targets	Av. beam intensity (protons/pulse)	Delayed/prompt	Observed cross section (mb) 1st target	2nd target	3rd target
2	1.1×10^6	0.027	27.9 ± 0.9	29.5 ± 0.5	⋯
3	0.9×10^6	0.013	28.7 ± 0.6	30.4 ± 0.8	31.1 ± 1.4

hypothesis that this cross section is independent of energy above 28 GeV. However, in our previous measurement at 7.6 GeV,[2] in which the same apparatus and techniques were used, a value of 28.2 ± 0.6 mb was found. This is significantly higher than the values measured at 28 and 300 GeV, and indicates a decreasing cross section between 7.6 and 28 GeV.

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