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^{12}C(p, pn)^{11}C Cross Section at 7.6 GeV*

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The absolute cross section for the ^{12}C(p, pn)^{11}C reaction has been measured in an external beam of the Argonne zero gradient synchrotron at 8.5-GeV/c momentum (7.6-GeV protons). Proton fluxes were measured with a scintillation counter telescope, and the 20.4 min ^{11}C activity induced in $\frac{1}{8}$-in.-thick plastic scintillators was determined both by internal scintillation counting and by β^+-annihilation radiation counting with a NaI(Tl) well crystal. A correction for the formation of ^{11}C by secondary particles was determined and a correction was made for the small π^+ contamination of the proton beam. The ^{12}C(p, pn)^{11}C cross section at 7.6 GeV is 28.2 ± 0.6 mb.

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. (See Cumming[2] for a review of high-energy proton-beam-monitoring techniques.) The ^{12}C(p, pn)^{11}C cross section has been found to be relatively constant between 1 and 28 GeV.[3-6] Much higher proton energies will soon become available at the 200-GeV proton synchrotron at the National Accelerator Laboratory, and in order to establish absolute cross-section measurements with modern techniques and high accuracy, we have determined the ^{12}C(p, pn)^{11}C cross section at 7.6 GeV in an external beam of the Argonne Zero Gradient Synchrotron (ZGS).

II. EXPERIMENTAL

The determination of the ^{12}C(p, pn)^{11}C cross section by activation techniques requires the absolute measurement of two quantities: the incident proton flux and the number of ^{11}C atoms produced. For the present experiment, a three-element scintillation counter telescope was used to determine the proton flux incident on the target. The ^{11}C activity (20.4-min half-life) induced in plastic scintillator targets was measured both by internal scintillation counting and by positron-annihilation radiation counting.

A. Counter Telescope

A schematic diagram of the scintillation counter-telescope system is shown in Fig. 1. A Pilot B scintillator[7] disk $\frac{1}{8}$ in. thick and either $\frac{5}{8}$ or 1 in. diameter was optically coupled via a 6-in.-long by $\frac{1}{8}$-in.-thick Lucite light pipe to a RCA-8575 photomultiplier. The tube base put out a fast (rise time ~1 nsec) pulse of ~2-V amplitude for a minimum-ionizing particle with +1800 V on the photomultiplier. The three scintillation counters were aligned with their light pipes displaced 90° from each other in order to minimize coincidences caused by the Cerenkov radiation of protons passing through the light pipes.

The scintillation counter telescope was located downstream from a Be production target in a beam channel that was set for 8.5-GeV/c protons with a momentum spread of ±0.9%. The π^+ contamination of the beam was less than 4% and it was determined directly during the experiment with a Cerenkov counter-scintillation counter-telescope system that was immediately downstream from our equipment.[8]

Three pairs of twofold coincidences were monitored: C_1C_2, C_1C_3, and delayed C_1C_2 coincidences. A voltage-plateau curve was measured for each counter and a satisfactory voltage was found at which the beam particles were registered with 100% efficiency while electronic noise and room background was negligible above the fast discriminator threshold. The equality of the C_1C_2 and C_1C_3 rates established that the telescope was aligned with the beam and the electronics was performing satisfactorily. The C_1C_2 prompt coincidence delay curves had a flat top 4 nsec wide and a full width at $\frac{1}{10}$ maximum of 8 nsec.

The beam was defocused sufficiently to spread it over a larger area than that of the counters and hence lower the counting rate to 10^6 protons/pulse or less. In order to measure counting losses a delayed-coincidence rate between counters C_1 and C_2 was measured, using a delay of 100 nsec. The number of such chance coincidences is $2R\tau$, where R is the instantaneous rate and 2τ is the effective resolving time, and is just equal to the number of particles not registered because of the coincident arrival of two particles within the resolving time. This quantity varied from 1.3 to 1.9%, depending on the beam intensity.

B. Targets and ^{11}C Counting

Targets used in this experiment consisted of cylindrical Pilot B[7] plastic scintillators $\frac{1}{8}$ in. thick and $\frac{5}{8}$ in. diameter, containing 91.55% carbon by weight. It has been shown[9,10] that radioactive gas loss from $\frac{1}{8}$-in.-thick plastic scintillators is not significant.

For each irradiation a target was carefully aligned with and taped directly to the upstream side of scintillation counter C_1, which was the same size as the target. Each one of the targets was irradiated in the proton beam for approximately 20 min. The integrated beam intensity, as determined by C_1C_2 coincidences in the counter telescope, was recorded at 4-min intervals during the irradiations to allow corrections to be made for temporal variation of the beam intensity.

Starting about 10 min after the end of an irradiation, the ^{11}C activity was measured either by internal scintillation counting or by positron-annihilation radiation counting. For the internal scintillation counting, the target was optically cou-

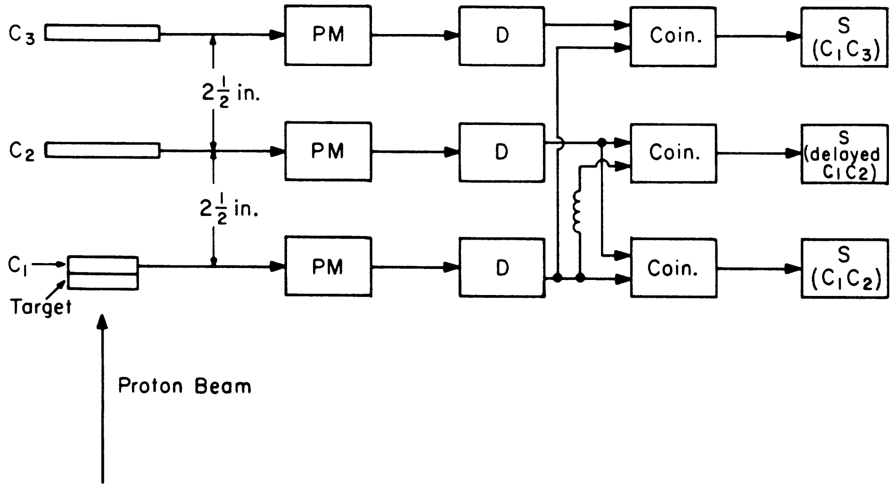

FIG. 1. Schematic diagram of the scintillation counter telescope system. The symbols have the following meanings: C = scintillation counter; PM = RCA-8575 photomultiplier tube and fast-tube base; D = EG & G leading-edge discriminator; Coin. = EG & G overlap, fast coincidence module; and S = 100-MHz scaler.

pled to a RCA 8575 photomultiplier tube and covered with a $\frac{1}{16}$-in.-thick aluminum annihilator (to reproduce calibration conditions). The system was then rendered light tight with aluminum foil and counted inside a steel shield. The efficiency for detecting ^{11}C with this system was experimentally measured by a positron-annihilation radiation coincidence technique[11] Three calibration sources were prepared by irradiating plastic scintillator targets with high-energy neutrons at the Argonne cyclotron [using the ^{9}Be$(\alpha, n)^{12}$C reaction at 45 MeV] to produce high activity ^{11}C sources via the ^{12}C$(n, 2n)^{11}$C reaction. A ^{11}C detection efficiency of (95.4 ± 0.2)% was obtained from these sources at a nominal discriminator setting of 50 keV, which was determined relative to the 624-keV internal conversion electrons from ^{137}Cs with the aid of a precision pulse generator.

The same ^{11}C sources whose disintegration rates were determined by the positron-annihilation radiation coincidence technique were also used to calibrate two 2 × 2-in. NaI(Tl) well crystals. With single-channel analyzer windows set around the 511-keV annihilation peak, these two detectors had efficiencies of (25.1 ± 0.1)% and (25.3 ± 0.1)% for detecting ^{11}C activity in a plastic scintillator target.

In all cases the counting measurements were continued for several ^{11}C half-lives and each decay curve was analyzed by a least-squares decay-curve program[12] into a 20.4-min component and a nondecaying background.

The vicinity of the beam was checked for stray radiation, such as neutrons, which could produce ^{11}C without registering in the counter telescope. This was accomplished by exposing a target 10 in. from the beam center line, but no detectable amount of ^{11}C was found.

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

Sample No.	Counter	Cross section (mb)
1	Internal	28.3 ± 0.3
2	NaI No. 1	28.8 ± 0.5
3	NaI No. 2	29.0 ± 0.5
4	Internal	28.9 ± 0.3
5	NaI No. 1	29.0 ± 0.4
6	NaI No. 2	29.6 ± 0.5
Weighted mean		28.9 ± 0.2
Inclusion of 1.5% error in calibration method		28.9 ± 0.5
Correction for target thickness		−1.0 ± 0.3
Correction for π^+ contribution		+0.3 ± 0.1
Corrected cross section		28.2 ± 0.6

III. RESULTS

The experimental cross sections are listed in Table I. Two targets were counted internally with the photomultiplier, and two were counted in each of the two NaI(Tl) well crystals. Intensities corresponding to $2-3 \times 10^3$ disintegrations per minute of ^{11}C at the end of bombardment were observed. The The errors assigned to a measurement are made up of the standard deviation of the counting rate, as given by the decay curve program, the uncertainty in counting efficiency, and an estimated 1% error in aligning the target with the counter telescope. The weighted mean of these measurements is 28.9 ± 0.2 mb. In addition, an estimated error of 1.5% was assigned to represent the accuracy of the coincidence method of source calibration.[2]

The amount of ^{11}C formed by secondary particles, which are produced in the target and counter C_1 and interact before escaping, was measured by irradiating a "sandwich" of the usual target between two $\frac{1}{8}$-in.-thick disks of the same material. This measurement yielded a thick-target cross section of 30.2 ± 0.4 mb, where the error estimated is made on the same basis as in the other measurements. A secondary-effect correction was then calculated as a function of target thickness, and the thickness of the counter telescope scintillator on which the target was mounted, was included in the target thickness. A lower limit for this secondary effect can be set by assuming that the effect is linear with target thickness (i.e., by assuming that all the secondary particles which produce ^{11}C are strongly collimated forward), while an upper limit can be set by assuming the effect is isotropic. The actual secondary correction was taken to be the average of these two extremes.

After the target thickness correction was made,

TABLE II. Comparison with other data.

Proton energy (GeV)	Cross section (mb)	References
1.0	29.0 ± 1.3	3
2.0	26.2 ± 0.9	4
3.0	26.8 ± 1.0	4
3.0	29.5 ± 1.6	5
4.5	27.4 ± 1.7	5
6.0	29.5 ± 1.6	5
7.6	28.2 ± 0.6	Present work
9.0	26.2 ± 1.5	14
28	25.9 ± 1.2	6

the cross section was then corrected for the π^+ contamination of the beam by using the $^{12}C(\pi^-, \pi^-n)$-^{11}C cross section (19.4 ± 1.5 mb)[13] at 2.5 GeV/c and assuming that the π^+ cross section is the same as the π^- cross section and that the pion cross section is the same at 8.5 GeV/c. These assumptions are not critical because the π^+ contamination represents a small contribution which was constant at 3.7%. The final corrected cross section for the $^{12}C(p, pn)^{11}C$ reaction at 7.6 GeV is 28.2 ± 0.6 mb.

Experimental cross sections for the $^{12}C(p, pn)^{11}C$ reaction in the GeV region are listed in Table II. Except for the 1 and 9 GeV cross sections,[3, 14] the numbers were actually taken from Ref. 6. It is apparent that the cross section is essentially constant from 1 to 28 GeV. The error in the present experiment is significantly less than that quoted in any previous absolute cross section measurement for this reaction in the GeV region. This has been made possible through the use of modern, fast electronics for the proton beam intensity measurement at a level commensurate with the production of sufficient ^{11}C activity for higher statistical accuracy in the counting procedures.

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[1] Following the convention adopted in Ref. 6, the small but unknown contribution of ^{13}C (natural abundance 1.1%) to ^{11}C production is ignored, and the cross section for the formation of ^{11}C in proton irradiation of normal isotopic carbon is taken to be the $^{12}C(p, pn)^{11}C$ cross section. The notation $^{12}C(p, pn)^{11}C$ does not imply the emission of a proton and neutron, but is meant to include any other mechanism for ^{11}C formation, such as deuteron emission or processes involving pions, etc.

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