

$C^{12}(p, pn)C^{11}$ Cross Section from 3 to 6 Bev

NAHMIN HORWITZ* AND JOSEPH J. MURRAY

Lawrence Radiation Laboratory, University of California, Berkeley, California

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The $C^{12}(p, pn)C^{11}$ cross section has been measured at proton energies of 3.0, 4.5, and 6.0 Bev. The measured values are 29.8 ± 1.6 , 27.7 ± 1.7 , and 29.8 ± 1.6 mb, respectively.

I. INTRODUCTION

THE $C^{12}(p, pn)C^{11}$ reaction can be used to monitor proton fluxes once its cross section is known. Measurements of this cross section have been made for proton energies from 0 to 3 Bev.¹⁻⁴ This experiment extends these measurements to 6 Bev.

II. PROCEDURE

A. General Remarks

Targets consisting of three plastic scintillators mounted behind a nuclear emulsion (see Fig. 1) were

exposed to a spatially dispersed internal proton beam at the Bevatron. They were bombarded by a time-integrated flux of approximately 2×10^6 protons/cm². The number of induced $C^{12}(p, pn)C^{11}$ reactions was measured by placing the scintillators on a photomultiplier and counting the positrons from the decay $C^{11} \rightarrow \beta^+ + B^{11} + \nu$. This technique of using a thick plastic scintillator to serve the dual purpose of both the carbon target and the scintillating medium in which to count the β activity was suggested to us by Crandall.⁵ The proton flux was measured by counting tracks in the emulsions.

The $C^{12}(p, pn)C^{11}$ cross section is given by the formula

$$\sigma = [\text{number of } C^{11} \text{ atoms produced}] [\text{protons/cm}^2 \text{ incident on target}]^{-1} [\text{number of } C^{12} \text{ nuclei in target}]^{-1}$$

$$= \left[\frac{(C - bT_3)}{\epsilon_\beta} \alpha_1 \left\{ F \frac{(1 - e^{-T_1/\tau})}{T_1/\tau} e^{-T_2/\tau} (1 - e^{-T_3/\tau}) \right\}^{-1} \right] [N\alpha_2]^{-1} \left[\frac{m\alpha_3 N_0}{12} \right]^{-1},$$

where T_1 = time interval from start of proton bombardment to end of proton bombardment, T_2 = time interval from end of proton bombardment to start of β^+ counting, T_3 = time interval from start of β^+ counting to end of β^+ counting, τ = mean life of C^{11} = 29.36 min, C = number of counts recorded during T_3 , b = background counting rate, ϵ_β = efficiency of detecting a C^{11} disintegration with the scintillation counter, α_1 = transition-effect correction factor, F = correction factor for fluctuations in proton-bombardment intensity during T_1 , N = average number of protons/cm² counted in the emulsion, α_2 = correction factor for nonuniformity of proton spatial distribution, m = mass of plastic scintillator, α_3 = fraction of plastic scintillator, by weight, which is C^{12} , and N_0 = Avogadro's number.

Subsection B deals with the measurements of C , b , ϵ_β , α_1 , and F , which are needed to determine the number of $C^{12}(p, pn)C^{11}$ reactions. Subsection C deals with the measurements of N and α_2 , which are needed to determine the incident proton flux.

B. Measurements of C , b , ϵ_β , α_1 , and F

C , the number of counts recorded during T_3 , was obtained with conventional scintillation-counter techniques. To provide an internal consistency check, two similar but completely independent channels were set up. The same scintillator could then be counted with each of two different photomultipliers, each feeding its own electronic circuit. The number of activated C^{11} atoms in a given scintillator as determined independently in each of these two channels agreed to $\pm 1\%$. In order to establish long-term stability, an artificial γ -ray source was used and the counting rate in each channel was monitored over a 1-week period. Each

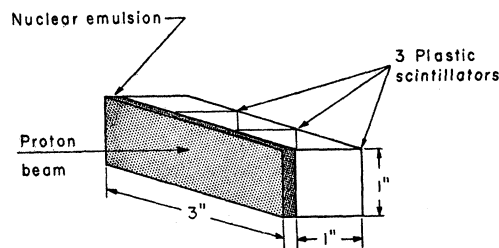


FIG. 1. Three plastic scintillators behind a nuclear emulsion were exposed to a spatially dispersed internal proton beam at the Bevatron.

* Present address: Department of Physics, Syracuse University, Syracuse, New York.

¹ Crandall, Millburn, Pyle, and Birnbaum, Phys. Rev. **101**, 329 (1956).

² Rosenfeld, Swanson, and Warshaw, Phys. Rev. **103**, 413 (1956).

³ Cumming, Friedlander, and Swartz, Phys. Rev. **111**, 1386 (1958).

⁴ Bibliographies of earlier work can be found in references 1 and 2.

⁵ Horwitz, Murray, and Crandall, Bull. Am. Phys. Soc. **1**, 225 (1956).

channel was stable to $\pm 2\%$ over a period comparable to that required for the experiment. It might be mentioned that the photomultiplier high-voltage plateaus for β^+ particles from C^{11} were flatter than the plateaus for γ rays from the artificial source. Therefore the stability for counting C^{11} activity was, if anything, better than $\pm 2\%$. The counting period T_3 was approximately 10 min, and C would typically be of the order of 10 000 counts.

To reduce the background counting rate, the scintillation counter was surrounded by a lead house with walls 8 in. thick. After each activation, the background counting rate b was measured by replacing the activated scintillator with an unactivated one of identical dimensions. These rates were of the order of (50 ± 5) counts/min.

Since C^{11} is a positron emitter and the positron produces two γ rays when it annihilates, the counter efficiency ϵ_β can be determined by a β - γ coincidence technique. A NaI scintillation counter was placed near the β counter and the number of β - γ coincidences as well as the number of γ counts was measured simultaneously. If $N_{\beta\gamma}$ and N_γ are the number of β coincidences and γ counts, respectively (suitably corrected for background and dead time), then

$$\epsilon_\beta = N_{\beta\gamma} / N_\gamma.$$

The efficiency ϵ_β was measured for each channel at the beginning, during, and at the end of the experiment. The results were consistent to $\pm 2\%$. The values for the two channels were $0.95 \pm .02$ and $0.96 \pm .02$.

As the proton beam passes through the 1-in. target, various reactions produce secondary protons and neutrons, which in turn produce $C^{12}(p, pn)C^{11}$ reactions. The factor α_1 is intended to correct for this transition effect. Its value is measured as follows. Stacks of $1 \times 1 \times \frac{1}{8}$ -in. scintillators arranged as shown in Fig. 2 were exposed to the proton beam. From scintillator No. 1 to No. 8 there was an increase of $9.4\% \pm 1\%$ per inch in the induced activity. After correction for the variation in the spatial distribution of the proton beam, the activity in scintillator No. 9 was $1\% \pm 1\%$ lower than in scintillator No. 1. Essentially the same results were obtained at 3, 4.5, and 6 Bev. The glass backing of the emulsion which precedes the scintillators was

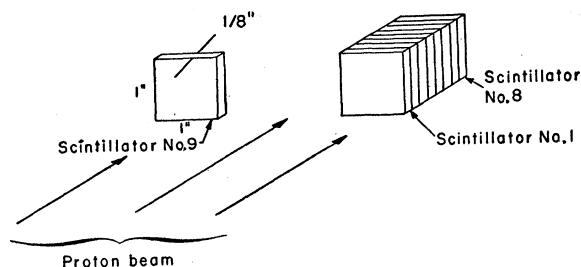


FIG. 2. Arrangement of scintillators used to determine transition-effect correction factor α_1 .

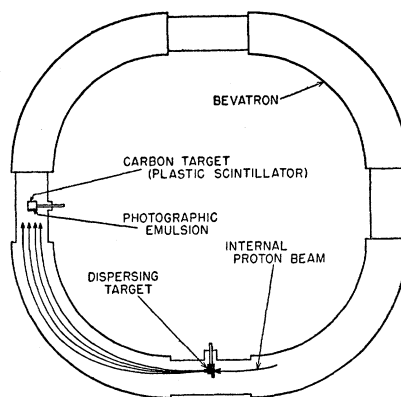


FIG. 3. Arrangement for producing a beam of uniform spatial intensity at the emulsion-scintillator target.

0.4 g/cm^2 thick. On the basis of these data, the value 0.93 ± 0.03 was used for α_1 at each energy.

The factor F is needed, in principle, to compensate for any temporal fluctuations in the proton intensity during T_1 . In practice, T_1 was only of the order of 1 min, and under these conditions any reasonable fluctuations would require only a 1% correction. Therefore, F was set equal to 1.00.

C. Measurements of N and α_2

N was measured by counting proton tracks in the nuclear emulsion. A reticle was used to define a field of view. The area thus defined was measured by using a standard ruled grating. The magnification was such that a field of view was approximately $9000 \mu^2$. We believe that the area was measured to an accuracy of $\pm 2\%$. Approximately 12 fields of view, each containing on the order of 200 protons, were counted at each energy. In all cases the *same* fields of view were studied independently by two people. Not only was the number of proton tracks counted, but also each viewer made a sketch showing the location of each track. Comparison of the two sketches then made it possible to detect any discrepancies and to restudy the emulsion. The discrepancies generally involved four or five tracks per field of view; these could usually be resolved and it is therefore assumed that the proton-detection efficiency was 100%.

The fields of view were located symmetrically with respect to the center of each of the three scintillators. In general, unless the spatial variation of proton beam intensity is linear, the value of the proton flux as measured at a finite number of points does not equal the true average integrated over the entire emulsion. The factor α_2 corrects for any such effect. To obtain as uniform a distribution as possible, the internal beam was spatially dispersed by the arrangement shown in Fig. 3. The internal proton beam is first deflected into a wedge-shaped target located one quadrant upstream of the emulsion-scintillator sandwich. Variations in

energy loss in the dispersing target due to its wedge shape, plus multiple scattering, produce a spatially dispersed beam at the emulsion. The spatial distribution of the beam was measured in an auxiliary experiment by using as the target a mosaic of $\frac{1}{2}$ -in. \times $\frac{1}{2}$ -in. scintillators. The spatial distribution of induced activity in these scintillators provides a "map" of the beam distribution. Two maps were made at each energy. The dimensions of the mosaics used were 2 in. high and 3 in. wide in one case, and 4 in. high and 10 in. wide in the other. The spatial distributions were reasonably reproducible and indicated that the maximum variation of beam intensity over the region the emulsion would occupy was $(14 \pm 4)\%$. The correction α_2 for such a spatial distribution is less than 1% and, therefore, the value $\alpha_2 = 1.00$ was used throughout.

Finally, in regard to the measurement of N , there is the question of the nature of the flux at the target. Specifically one may ask whether the target was exposed to low-energy protons which "spill out" of the beam during the acceleration cycle, and further whether there is a general background flux of neutrons which produce C^{11} nuclei via the $C^{12}(n, 2n)C^{11}$ reaction and which, of course, would not be included in N . We feel there was negligible activation due to these causes for the following reasons: The target was kept in a retracted position until the energy of the proton beam was approximately 10% of the energy at which the bombardment was made. A duplicate scintillator placed at this retracted position exhibited an activity less than 1% of the activity of the scintillators exposed to the proton beam. In regard to a possible neutron back-

TABLE I. Cross sections obtained from the experimental data.

Proton energy (Bev)	Individual values of the $C^{12}(p, pn)C^{11}$ cross sections (mb)	Statistical uncertainty (mb)	Weighted mean value (mb)	Estimated total uncertainty in weighted mean value (mb)
3.0	29.8	1.8	29.8	1.6
	30.5	1.2		
	27.9	1.8		
4.5	30.1	1.8	27.7	1.7
	27.6	1.2		
	25.6	1.5		
	27.2	2.1		
6.0	29.3	2.1	29.8	1.6
	28.7	1.2		
	28.9	2.1		
	32.3	1.6		

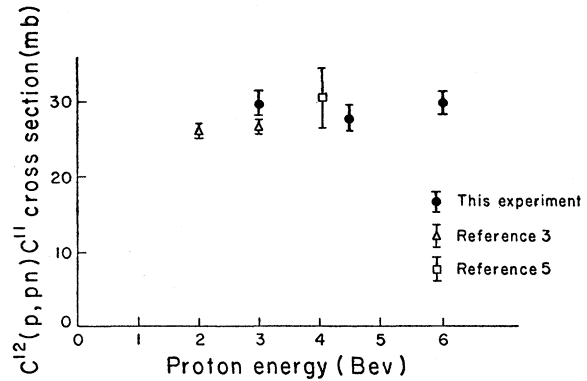


FIG. 4. Measured values of the $C^{12}(p, pn)C^{11}$ cross section.

ground, another scintillator, placed 7 inches above the point in the beam to which the target was plunged had an activity less than 1% of the activity of the scintillators exposed to the proton beam. Therefore, unless the neutron background has a spatial distribution which varies rapidly over 7 inches, its effect is negligible. The latter possibility cannot be ruled out but seems unlikely.

III. RESULTS

Since three scintillators are exposed with each emulsion, and since the emulsion is in effect divided into three areas corresponding to the locations of the three scintillators, each exposure gives us data for three separate cross-section calculations.

In addition, at 4.5 and 6.0 BeV a second exposure was made and the center scintillator and center portion of the emulsion were counted. Thus, at each of these energies, four values of the cross section were calculated. The results are given in Table I, along with their statistical uncertainties. A weighted mean value has been calculated for each energy and is also listed in Table I. The uncertainty due to systematic errors is estimated to be $\pm 5\%$. This uncertainty has been vectorially added to the statistical uncertainty in the mean value to give the total uncertainty listed in the last column.

These results, along with the results obtained by Cumming *et al.*³ and the preliminary results from Horwitz *et al.*,⁵ are plotted in Fig. 4.

IV. ACKNOWLEDGMENTS

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