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# $C^{12}(p,pn)C^{11}$ Cross Section at 1.0 GeV*

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The cross section of the $C^{12}(p,pn)C^{11}$ reaction was measured at 1.0 GeV because the excitation function was not well known in this energy region. The cross section was found to be 29.0±1.3 mb.

## INTRODUCTION

In a paper by Cumming, Hudis, Poskanzer, and Kaufman[1] it was pointed out that there exists a region between 0.6 and 2 GeV where there are no reliable absolute cross section measurements for proton induced reactions. The $C^{12}(p,pn)C^{11}$ excitation function is changing slope in this region, making interpolation difficult. It is also just this region where some recently measured[2] $(p,p\pi^+)$ excitation functions exhibit interesting structure.

## EXPERIMENTAL

In this experiment the proton fluxes were determined by means of nuclear emulsions and the $C^{11}$ activity induced in plastic scintillators was measured by internal scintillation counting. The techniques were similar to those used for 28-GeV protons by Cumming, Friedlander, and Katcoff,[3] and only the differences will be discussed here. Of the four measurements to be described, the first was slightly different from the remaining three, having been performed almost two years earlier.

The irradiations were performed in the external proton beam of the Cosmotron and were all less than 2 min in duration. The energy was determined to be 1.0±0.05 GeV by measurements of the frequency and radius of the circulating beam. The external beam was partially defocused in an attempt to make the incident flux uniform across the target. The amount of defocusing was limited in order to prevent the beam from producing secondary particles in the beam pipe and magnets upstream. The targets consisted of plastic scintillator disks $\frac{1}{8}$ in. thick from which the $C^{11}$ gas loss is negligible.[4] In the first experiment the diameter was $1\frac{1}{2}$ in. and in the later experiments $\frac{3}{4}$ in. The carbon content of the scintillators was taken to be 92% and, as is customary, the cross sections were calculated on the basis of the total carbon content of the targets, not just the $C^{12}$ content. A 100-$\mu$-thick Ilford G-5 emulsion was mounted on the upstream side of each scintillator. The emulsions were perpendicular to the beam so that the plunging track method was used in scanning. In the later experiments pellicles were used instead of glass backed emulsions. These were supported on 0.01-in. Mylar foils, wrapped in black paper, and attached to the scintillators with double-sided Scotch tape. When the outline of the scintillators was traced with a pencil, an image was produced on the emulsion after development which located the position of the scintillators. To evaluate the contribution of stray secondary radiation in the beam cave, scintillators and emulsions were exposed at a distance of about 9 in. from the beam center. These scintillators had a mass 35 times that of the target scintillators and thus were a sensitive measure of the stray neutron flux. The effect found, when converted to the target mass, was less than 0.2%.

After irradiation, the $C^{11}$ counting system of Cumming and Hoffmann[5] was used with only slight modification. A more convenient method for setting the electronic discriminator was developed. After the scintillator was mounted and covered with Al foil, an $Am^{241}$ source which emits 59-keV $\gamma$ rays was placed on the scintillator in $2\pi$ geometry. By varying the phototube voltage, an integral discriminator curve was obtained. The point of inflection of this curve determines the center of the 59-keV photopeak, and this was taken as the standard discriminator setting. By noting the counting rate at this point, the discriminator setting for this size scintillator could be reproduced by adjusting the high voltage to obtain this counting rate from the standard $Am^{241}$ source. The sensitivity of the method is such that a factor of 1.5 change in $Am^{241}$ counting rate corresponded to only a 1% change in $C^{11}$ counting efficiency. The efficiency for the $\frac{3}{4}$-in.-diam scintillators was determined by ($\beta^+-511$-keV $\gamma$ ray) coincidence measurements[5] to be (93.2±2)% with a 59-keV discriminator. For the $1\frac{1}{2}$-in.-diam scintillator the $C^{11}$ counting efficiency measured previously[3] is also (93.2±2)% when corrected to the same discriminator setting. The initial $C^{11}$ activities were between 100 and 200 counts/min and were determined with a statistical error of about two percent. The effect of the secondary particles from the target stack on the production of $C^{11}$ activity was estimated from the measurements at 2 and 3 GeV.[6] For the target consisting of a glass backed emulsion and $\frac{1}{8}$-in. scintil-

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TABLE I. Cross section measurements for the $C^{12}(p,pn)C^{11}$ reaction at 1.0 GeV.

| Irradiation no. | Cross section in mb | Random error in % |
|---|---|---|
| 1059 | 30.1 | 3.7 |
| 1350 | 26.4 | 5.2 |
| 1352 | 29.7 | 5.3 |
| 1353 | 29.6 | 5.8 |
| Mean | 29.0 | 2.4 |

lator the effect was taken to be $(2\pm1)\%$, and for the targets consisting of a pellicle and $\frac{1}{8}$-in. scintillator, $(1\pm1)\%$.

The pellicles were mounted before development on treated glass plates with a cold 10%-alcohol solution so as to prevent distortion. Measurements indicated that distortion of the emulsions introduced less than a 2% error. Two modifications were made in the microscope used previously.[3] A Whipple recticle with a smaller size grid and an eyepiece with a factor of two more magnification were used. With this arrangement the area covered by the reticle was about $10^{-5}$ cm$^2$, measurable to an accuracy of two percent, thus allowing track densities up to $5\times10^6$/cm$^2$ to be measured. With a parallel beam of particles, the overlapping of tracks begins to become significant at this density. By independent checks of selected areas by two observers the scanning efficiency was estimated to be $(100\pm2)\%$. The image of the outline of the scintillator was first located under low power. Scanning was done under high power on a 25-point square array centered on this image. Usually a total of about 2500 tracks was counted. The data were then fitted with a least-squares program to a six-parameter quadratic surface and the total number of tracks over the area of the scintillator computed with a statistical uncertainty of about 5%. However, in the first measurement, because of greater flux nonuniformity, more areas were scanned and the number of tracks counted reached 10 000.

## RESULTS

The calculated cross sections are shown in Table I together with their random errors arising from $C^{11}$ counting and track counting. The sources of systematic errors which have been mentioned are: $C^{11}$ counting efficiency, secondary correction, scanning efficiency, and reticle area. The root-mean-square combination of these errors is 3.6%. Thus the total error is 4.4% and the final result for the cross section is $29.0\pm1.3$ mb. Burcham *et al.*[7] have reported a cross section at this energy which when corrected for gas loss,[1] is $24.4\pm1.5$ mb. Unfortunately, this number is subject to a large uncertainty due to neutron contamination of their proton beam. In a review article by Cumming,[8] our cross section is used to determine the $C^{12}(p,pn)C^{11}$ excitation function in this energy region.

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