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C12 (p,pn)C11 CROSS SECTION FROM 3 TO 6 Bev

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ABSTRACT

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  $29.8 \pm 1.6$ ,  $27.7 \pm 1.7$ , and  $29.8 \pm 1.6$  mb respectively.

$C^{12}(p, pn)C^{11}$  CROSS SECTION FROM 3 TO 6 Bev

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## 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.<sup>1, 2, 3, 4</sup> 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  $2 \times 10^6$  protons/cm<sup>2</sup>. 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  $\beta$  activity was suggested to us by Dr. Walter Crandall.<sup>5</sup> 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

$$\sigma = \left[ \frac{\text{number of } C^{11} \text{ atoms produced}}{\text{protons/cm}^2 \text{ incident on target}} \right]^{-1} \left[ \frac{\text{number of } C^{12} \text{ nuclei in target}}{\text{cm}^2} \right]^{-1} \\ = \left[ \frac{1}{F} \cdot \frac{(C - bT_3)}{\epsilon \beta} \cdot \left\{ \left( 1 - \frac{1}{2} e^{-T_1/\tau} \right) \left( 1 - e^{-T_3/\tau} \right) e^{-T_2/\tau} \right\} \right]^{-1} \left[ \frac{m \alpha_3 N_0}{12} \right]^{-1}$$

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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  $\beta^+$  counting,

$T_3$  = time interval from start of  $\beta^+$  counting to end of  $\beta^+$  counting,

$\tau$  = mean life of  $C^{11}$  = 29.36 min,

$C$  = number of  $C^{11}$  disintegrations counted during  $T_3$ ,

$b$  = background counting rate,

$\epsilon_\beta$  = efficiency of detecting a  $C^{11}$  disintegration with the scintillation counter,

$a_1$  = transition-effect correction factor,

$F$  = correction factor for fluctuations in proton-bombardment intensity during  $T_1$ ,

$N$  = average number of protons/cm<sup>2</sup> counted in the emulsion,

$a_2$  = correction factor for nonuniformity of proton spatial distribution,

$m$  = mass of plastic scintillator,

$a_3$  = fraction of plastic scintillator, by weight, which is  $C^{12}$ ,

$N_0$  = Avogadro's number.

Subsection B deals with the measurements of  $C$ ,  $b$ ,  $\epsilon_\beta$ ,  $a_1$ , 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  $a_2$ , which are needed to determine the incident proton flux.

#### B. Measurements of $C$ , $b$ , $\epsilon_\beta$ , $a_1$ , and $F$

$C$ , the number of detected  $C^{11}$  disintegrations, 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  $\gamma$ -ray source was used and the counting rate in each channel was monitored over a 1-week period. Each 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  $\beta^+$  particles from  $C^{11}$  were flatter than the plateaus for  $\gamma$  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  $50 \pm 5$  cpm.

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

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

The efficiency  $\epsilon_\beta$  was measured for each channel three times during the experiment. 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  $a_1$  is intended to correct for this transition effect. Its value is measured as follows. Stacks of  $1 \times 1 \times 1/8$ -in. scintillators arranged as shown in Fig. 2 were exposed to the proton beam. From scintillator No. 1 to No. 8 there was a steady increase of 9.4% in. in the induced activity. The activity in scintillator No. 9 was 1% lower than in scintillator No. 1. On the basis of these data, the value  $0.945 \pm .03$  was used for  $a_2$ .

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 the most extreme fluctuations would require only a 1% correction. Therefore,  $F$  was set equal to 1.00.

### C. Measurements of $N$ and $a_2$

$N$  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  $a_2$  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 steered 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 substituting a mosaic of  $1/2 \times 1/2$ -in. scintillators for the emulsion. The spatial distribution of induced activity in these scintillators provides a "map" of the beam distribution. It was possible to produce a beam for which the maximum variation in intensity over the entire area of the emulsion was 14%. The correction  $a_2$  for this beam was less than 1% and therefore the value  $a_2 = 1.00$  was used.

### 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.<sup>3</sup> and the preliminary results from Horwitz et al.,<sup>5</sup> are plotted in Fig. 4.

### IV. ACKNOWLEDGMENTS

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### REFERENCES

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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. Amer. Phys. Soc. Ser. II*, 1, 225 (1956).

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		

## FIGURE LEGENDS

- Fig. 1. Three plastic scintillators behind a nuclear emulsion were exposed to a spatially dispersed internal proton beam at the Bevatron.
- Fig. 2. Arrangement of scintillators used to determine transition-effect correction factor  $a_2$ .
- Fig. 3. Arrangement for producing a beam of uniform spatial intensity at the emulsion-scintillator target.
- Fig. 4. Measured values of the  $C^{12}(p, pn)C^{11}$  cross section.

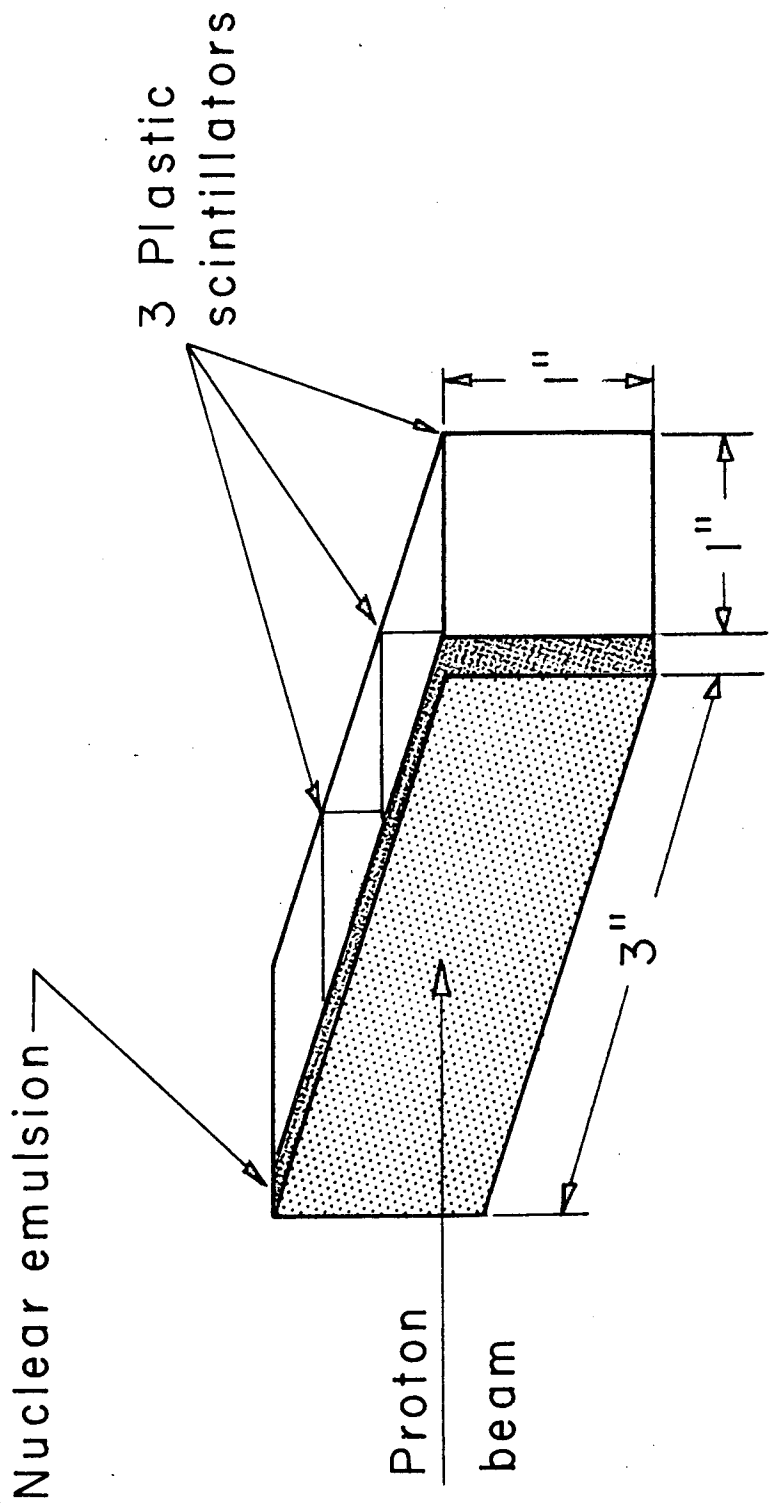
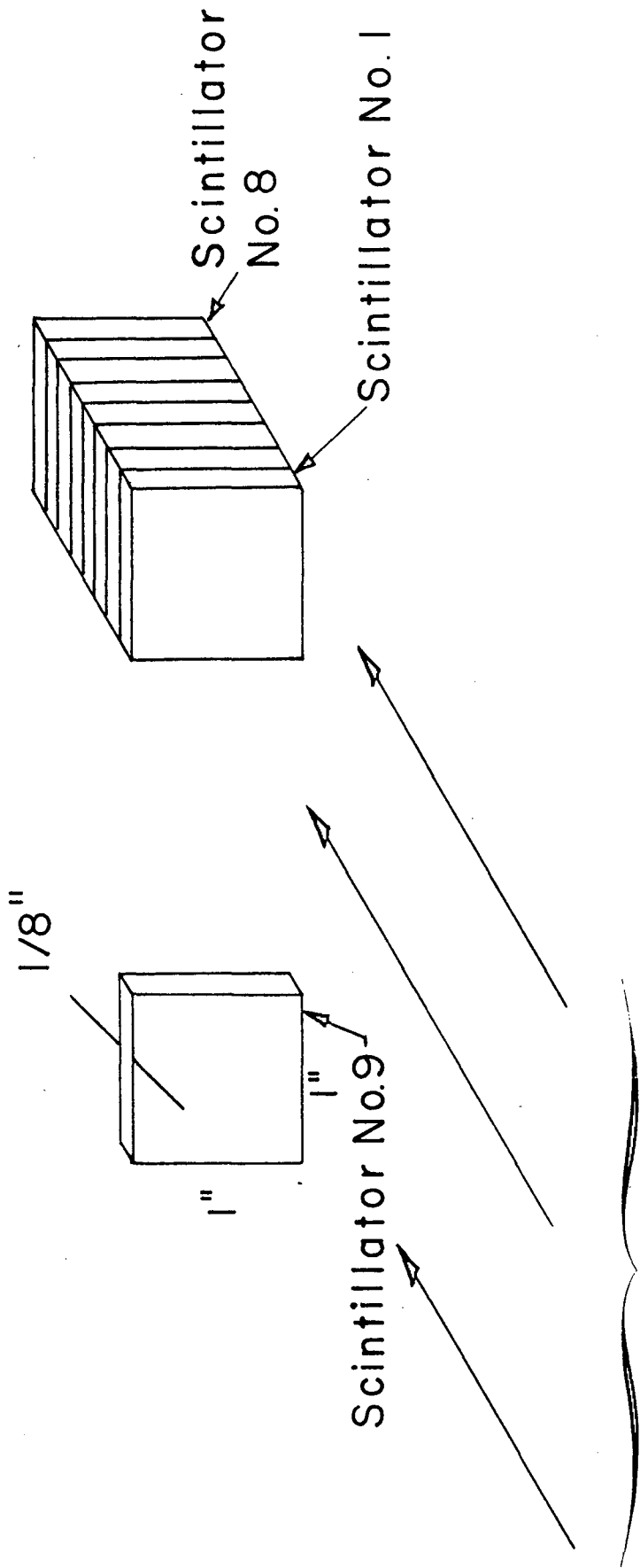


Fig. 1



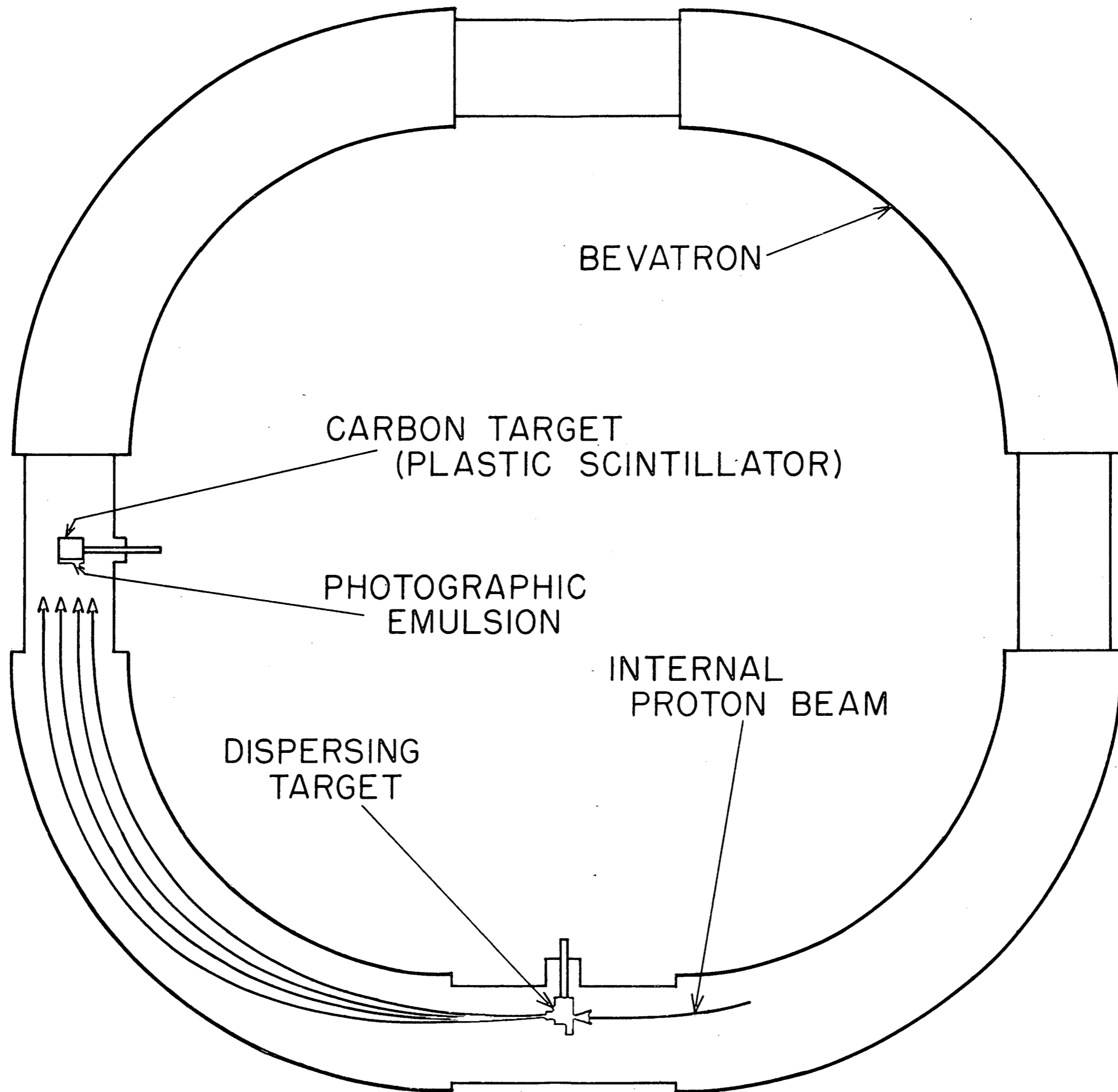


Fig 3

