$C^{12}(p,pn)C^{11}$ Cross Section at 2 and 3 Bev*

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Absolute measurements of the $C^{12}(p,pn)C^{11}$ cross sections were carried out in the external pencil beam of the Cosmotron at 2 and 3 Bev. The proton flux was measured with a counter telescope, and the C^{11} activity induced in 1-inch-thick plastic scintillators was determined by internal scintillation counting. Corrections for the formation of C^{11} by secondary particles produced in the thick targets were determined in separate experiments in which thin- and thick-target cross sections were compared directly. Other corrections for scattering and absorption effects and for deadtime losses in counters are discussed. Measurements were carried out both at proton fluxes sufficiently low to permit direct counting with the primary telescope and at higher fluxes which required scaling procedures with secondary telescopes. The measured cross sections for the $C^{12}(p,pn)C^{11}$ reaction are 26.0±0.9 and 26.6±1.0 mb at 2.0 and 3.0 Bev, respectively. From these data and from previously published cross-section ratios, the cross section of the $Al^{27}(p,3pn)Na^{24}$ reaction is found to be 10.4±0.6 and 10.0±0.6 mb at 2.0 and 3.0 Bev, respectively.

INTRODUCTION

THE production of C^{11} activity from carbon has been used as a monitor of high-energy proton beams and, in view of this use, the $C^{12}(p,pn)C^{11}$ cross section[1] has been the subject of numerous investigations.[2] The early work has been shown to contain substantial systematic errors, and only recently have data become available which are accurate to the order of 5% for proton energies up to 461 Mev.

Crandall *et al.*[3] have measured the absolute cross section of the $C^{12}(p,pn)C^{11}$ reaction at several proton energies from 170 to 350 Mev using a Faraday cup to determine the proton flux and 4π counting to obtain the disintegration rates of C^{11} produced in polystyrene foils. Their result of 36.0 mb at 350 Mev was also checked by an experiment in which a plastic scintillator was activated and the proton flux was measured with nuclear emulsions.

Rosenfeld *et al.*[4] have obtained a cross section of 31.1 mb at 461 Mev, also using 4π counting of foils to measure C^{11}, but determining the proton flux by means of an ion chamber calibrated with nuclear emulsions. This method of flux measurement was also checked by a counter telescope technique.

At higher energies the behavior of the $C^{12}(p,pn)C^{11}$ cross section is less well known. The available data are summarized in Table I. The errors assigned to the cross sections in this table are the original authors' estimates of their errors; where separate statistical and systematic errors were originally reported, the over-all values have been calculated by root-mean-square combination of the two. Wolfgang and Friedlander[5] have measured the ratio of the $C^{12}(p,pn)C^{11}$ cross section to that of the $Al^{27}(p,3pn)Na^{24}$ reaction at energies from 0.4 to 3 Bev. From these ratios and the absolute values reported for the latter cross section in this energy region,[6,7] $C^{12}(p,pn)C^{11}$ cross sections are obtained which agree with the directly measured values in the vicinity of 420 Mev and which then decrease monotonically to a value of 22 mb at 3 Bev. These results reflect any systematic errors in the $Al^{27}(p,3pn)Na^{24}$ cross-section determination which, due to the indirect procedure used, are small at the low energies but may be as large as 30% at 3 Bev.[7]

Burcham *et al.*[8,9] have used a procedure similar to that of Rosenfeld and co-workers to obtain absolute cross sections up to 1 Bev. Their results (obtained in a proton beam having a substantial neutron contamination) in general confirm the results of Wolfgang and Friedlander but have been interpreted as showing a possible deviation from a monotonic decrease in this region.

Prokoshkin and Tiapkin[10] have recently reported relative measurements of the $C^{12}(p,pn)C^{11}$ cross section as a function of energy from 150 to 660 Mev. They used a thermopile to measure proton fluxes. When normalized to Crandall's value at 350 Mev these data fail to show any fine structure and indicate that the cross section decreases very slowly from 450 to 660 Mev.

The present paper reports a series of absolute

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

[2] The early results are discussed in detail in references 3 and 4.

[3] Crandall, Millburn, Pyle, and Birnbaum, Phys. Rev. **101**, 329 (1956).

[4] Rosenfeld, Swanson, and Warshaw, Phys. Rev. **103**, 413 (1956).

[5] R. L. Wolfgang and G. Friedlander, Phys. Rev. **96**, 190 (1954); **98**, 1871 (1955).

[6] A. Turkevich, Phys. Rev. **94**, 775 (1954).

[7] Friedlander, Hudis, and Wolfgang, Phys. Rev. **99**, 263 (1955).

[8] Burcham, Symonds, and Young, Proc. Phys. Soc. (London) **A68**, 1001 (1955).

[9] Symonds, Warren, and Young, Proc. Phys. Soc. (London) **A70**, 824 (1957).

[10] Ja. D. Prokoshkin and A. A. Tiapkin, J. Exptl. Theoret. Phys. U.S.S.R. **32**, 177 (1957) [translation: Soviet Phys. JETP **5**, 148 (1957)].

measurements of the $C^{12}(p,pn)C^{11}$ cross section at 2 and 3 Bev. A preliminary value of 30.5 mb at 4.1 Bev reported by Horwitz *et al.*[11] supports our conclusion that the cross section for this reaction is larger in the Bev region than that previously reported.[5]

EXPERIMENTAL

A. General

The measurement of a cross section for an activation reaction such as the $C^{12}(p,pn)C^{11}$ reaction requires absolute measurement of two quantities: the incident proton flux and the number of C^{11} atoms produced. Of the possible methods of measuring the proton flux, beam current measurement with a Faraday cup was rejected because of the small flux and large range of the 2- and 3-Bev protons. Calorimetric techniques also were considered impractical. The remaining methods depend on the counting of individual protons in a beam by means of either nuclear emulsions or counter telescopes. For the present experiment, a procedure using a three-element counter telescope as the primary instrument for flux measurements was adopted because the direct availability of the output data was thought to make it preferable to an emulsion technique which always requires development and scanning after exposure.

An order-of-magnitude calculation is of interest to show the problems involved in the experiment. The Cosmotron accelerates protons to a maximum energy of 3 Bev in a 1-sec cycle which may be repeated every 5 sec. The beam may be extracted from the machine during a period of ~10 milliseconds at the end of the acceleration cycle with a temporal distribution dependent on the rate of turnoff of the rf voltage. Scaling circuits that are routinely available have deadtimes of ~0.1 microsecond. If we wish to avoid large losses due to the circuit deadtimes, we are limited to rates of a few thousand protons per pulse. Thick targets must be used to obtain reasonable C^{11} counting rates from such an irradiation. For example, a flux of 2000 protons/pulse for which the deadtime correction is ~2% will give a C^{11} disintegration rate of about 40 disintegrations per minute (dpm) at the end of a 20-min irradiation of a 1-inch-thick polystyrene target. By use of plastic scintillator targets, high detection efficiency for the C^{11} in the thick targets can be achieved, and with anticoincidence procedures the counter backgrounds can be reduced so that these low activity levels can be measured accurately.

Direct counting of protons was always the primary standard; however, in some experiments secondary monitors were placed in scattered beams. These were calibrated in terms of the direct beam monitor at low proton fluxes and then used at rates were the primary

TABLE I. Previously reported $C^{12}(p,pn)C^{11}$ cross sections (in mb).

Proton energy Bev	Crandall *et al.*[a]	Rosenfeld *et al.*[b]	Wolfgang and Friedlander[c]	Burcham *et al.*[d]	Prokoshkin and Tiapkin[e]	Horwitz *et al.*[f]
0.35	36.0±1.8				36.0[g]	
0.42			33.5±1.7	32.3±2.9		
0.46		31.1±1.0			32.0±1.7	
0.52				33.2±1.6		
0.56					30.4±1.6	
0.60			27.5±1.5			
0.66				25.5±3.0	31.0±1.7	
0.84				30.0±1.7		
1.0			26.1±2.1	23.4±1.3		
1.4			24.1±3.0			
1.8			22.6±3.8			
2.2			23.3±5.0			
3.0			22.0±6.6			
4.1						30.5±4.1

[a] See reference 3.
[b] See reference 4.
[c] See reference 5.
[d] See references 8 and 9.
[e] See reference 10.
[f] See reference 11.
[g] Normalized to the value of Crandall *et al.* at this energy.

counters have very large losses. This removes the necessity for low-level counting of C^{11} and reduces the corrections needed for deadtime losses in the proton counters. Both procedures were used during the present experiment. In the series of runs described below, Series I was a first attempt at direct proton counting and required relatively large corrections for counter deadtimes, Series II and III represent development of the alternate high-level procedure, and Series IV was a return to direct proton counting.

B. The Pencil Beam

The present experiment was made possible by the availability of a well-collimated beam of protons. The external "pencil beam" of the Brookhaven Cosmotron has been previously described.[12,13] It delivers to a convenient experimental area outside the main shielding wall a nearly parallel beam $\sim\frac{1}{2}$ inch in diameter which contains about 0.1% of the circulating proton flux. The beam emerges from a collimator at the Cosmotron, passes through a strong focusing magnet, then a deflecting magnet and finally through a channel in the shield wall as shown in Fig. 1. The distance from the exit of the focusing magnet to the primary counter and target location is about 35 feet. Air along the beam path is replaced by helium to reduce scattering.

The purity of this beam was checked in several experiments. For example, when the deflecting magnet was energized and the beam bent so as not to emerge through the shield wall, polystyrene targets on the undeflected beam line outside the shield showed C^{11} activity levels less than 0.03% of those found at the same position when the beam was not deflected. This confirms that neutrons produced in the collimators and

[11] Horwitz, Murray, and Crandall, Bull. Am. Phys. Soc. Ser. II, 1, 225 (1956).

[12] Cool, Morris, Rau, Thorndike, and Whittemore, Phys. Rev. 108, 1048 (1957).

[13] Cool, Friedlander, Piccioni, Ridgway, and Sternheimer, Brookhaven National Laboratory Report BNL-498I24, 1958 (unpublished).

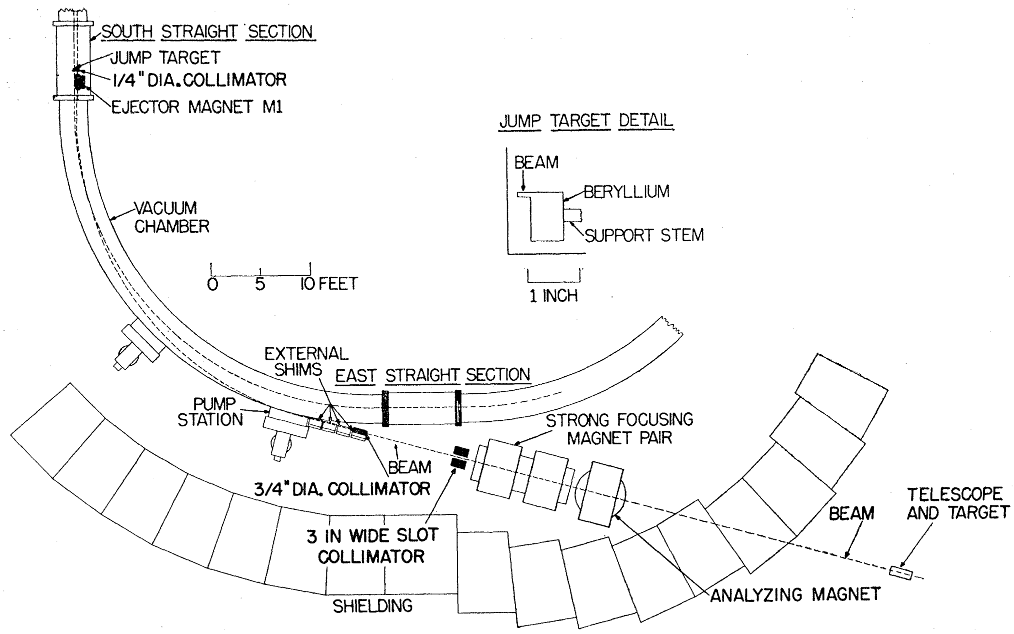

FIG. 1. Floor diagram showing experimental arrangement for the pencil beam at the Cosmotron.

scattered particles reaching the target position by paths other than through the channel were negligible in number. With the beam undeflected, a small residual flux (0.1–0.5%) could be detected 1.5 inches off the axis of the beam. Emulsion[14] and cloud chamber investigations[12] indicated that this was probably due to scattered protons. For the present experiment the undeflected beam was generally used.

The temporal distribution of the pencil beam was measured by means of a multichannel time analyzer and was observed to be nearly Gaussian with a peak ~25 milliseconds after the nominal rf turnoff and a full width at half maximum of ~12 milliseconds. These results depend on the particular rf turnoff conditions used, and the above figures are typical for those used during the present experiment. No protons of substantially lower energy than that determined by the rf turnoff time appeared in the pencil beam, even when a major portion of the circulating beam disappeared before that time. These observations confirm that the beam is monoenergetic within the few percent spread determined by the rf turnoff conditions.

C. Primary Proton Counters

A three-element scintillation counter telescope was used as the primary monitor of the proton flux for all series of this experiment. However, circuit improvements were made between Series II and III which reduced the deadtime of the system by a factor of two.

The particular type of proton counter system used in the later runs will now be described. A block diagram is shown in Fig. 2. The requirements for the coincidence circuit and discriminator-pulser were determined by the geometrical and temporal structure of the proton beam. Since the cross section of the beam was much smaller than that of the plastic scintillators, edge effects were negligible and pulses were very uniform in height. Background was sufficiently low that single counts over a wide range of discriminator settings were only slightly more plentiful than doubles. These factors eased the requirements on sharpness of discriminator cutoff and speed of coincidence circuit. However, since it was desired to count pulses at a rate of several thousand per 10-millisecond pulse in a beam that was time-wise badly bunched, it was necessary to have a discriminator-pulser-scaler system as fast as possible. In practice this meant a system operating at nearly 100% efficiency with a pulsing and recovery time of 1.0×10^{-7} second.

The standard set-up for primary detection consisted of three in-line counters spaced three inches apart. A single 1P21 photomultiplier in each viewed a plastic scintillator 0.5 inch thick and 1.84 inches in diameter. The negative signals from these were sent directly to the detection room and there amplified by single-stage distributed amplifiers with voltage gain of about 7. These amplifiers saturate at an output voltage of 10 volts across 185 ohms. Since the average input signal from the passage of a minimum-ionizing particle through the scintillator was 3 volts, all proton signals saturated the amplifiers by a wide margin. The output signals were fed to the grids of 6BN6 tubes where they were clipped with two-foot lengths of shorted cable.

Cable curves showed a resolution (2τ) of 6 millimicroseconds. The 6BN6 cathode follower output from

[14] The authors are indebted to G. T. Zorn of this laboratory for results of the emulsion investigation of the beam distribution.

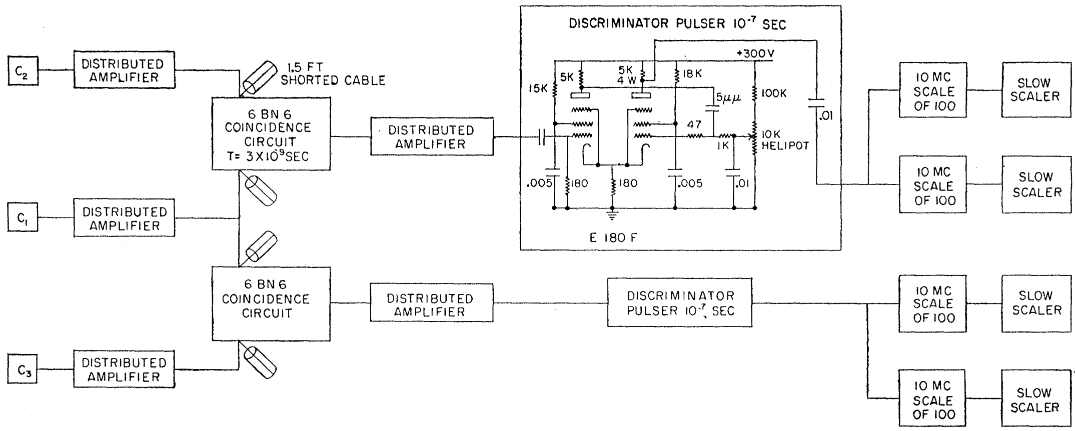

FIG. 2. Block diagram of primary proton counter circuits.

a doubles count was 0.7 volt, 10 times larger than that of a singles count. This negative pulse was amplified by another single-stage distributed amplifier which drove the discriminator-pulser shown in Fig. 2. It could be triggered by a positive pulse of from 1.4 to 2.5 volts depending on the helipot setting. The positive output pulse of 6 volts across 185 ohms drove a Hewlett-Packard 10-Mc scaler. Usually two such scalers were driven in parallel and data were accepted only when the two agreed.

The detection efficiency of this system may be less than 100% even at low counting rates and will certainly decrease as counting rate increases. To determine these efficiencies and to provide a continual check on the system, the counter telescope consisted of three elements, C_1, C_2, and C_3, with coincidences taken between C_1 and C_2 and between C_1 and C_3 (henceforth to be referred to as C_1C_2 and C_1C_3, respectively). Since interactions took place in the plastic, the average counting rate in C_1C_3 was lower than that in C_1C_2 by 1.5%. If the C_1C_2 detection efficiency were less than 100%, one would expect to find an occasional C_1C_2/C_1C_3 ratio greater than unity when small numbers of counts are recorded. Such inversions of the ratio were indeed observed. Out of a total of 142 bursts where the C_1C_2 count was 300 or lower, there were 5 inversions, 4 of them in the region of 100 or less. An analysis of the probable frequency of these as a function of efficiency and total count shows that the efficiency of C_1C_2 at low counting rates was $99.6\pm0.3\%$. This analysis is based on the assumption that all C_1C_3 counts are correlated with an event that would have given a C_1C_2 count except for the C_1C_2 counter inefficiency. However, $\sim1.5\%$ of the incident beam interacts in C_1 and some of these events will fail to give a C_1C_2 count but may give a C_1C_3 count. For example, a proton scattered by C_1 so as to just miss C_2 may undergo a second scattering in the material near C_2 and be scattered back into C_3. This type of event may account for the observed inversions and the $99.6\pm0.3\%$ is considered significant only in setting a lower limit for the intrinsic efficiency of C_1C_2. The fraction of the incident 3-Bev beam producing counts in C_1C_2 is calculated to be 0.992. The loss of 0.008 is due to those interactions of protons in C_1 which fail to produce secondary particles registering in C_2; its magnitude has been computed from the data of Chen *et al.*[15]

To determine the detection efficiency as a function of counting rate, a ratio was taken between C_1C_2 counts and the counts from a two-element counter telescope also placed in the beam but behind an absorber with a transmission of ~0.1. A typical curve of the scale factor between the two telescopes (i.e., the ratio of their counting rates) as a function of counting rate is shown in Fig. 3. This ratio decreased with increasing C_1C_2 rate due to counting losses in C_1C_2. The curve

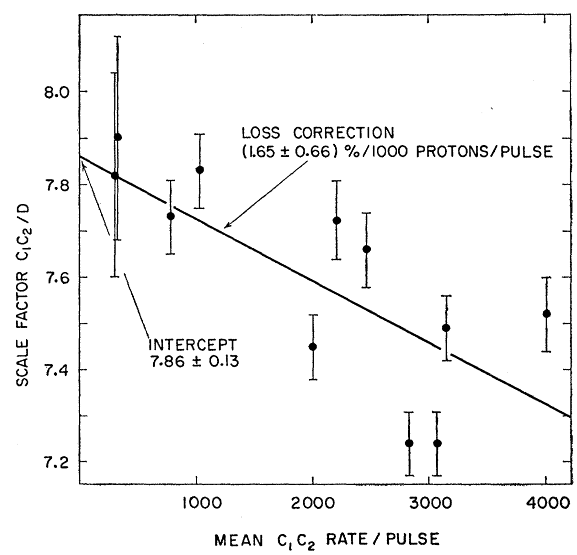

FIG. 3. Typical data for calculation of counting loss due to circuit deadtime.

[15] Chen, Leavitt, and Shapiro, Phys. Rev. **103**, 211 (1956), and additional unpublished data.

was least-square fitted to a straight line which is expected to be a good approximation in the region of small losses. This line was used to extrapolate the data to zero C_1C_2 rate, and from its slope the loss corrections at the C_1C_2 rates used for the activation were calculated. Since the counting losses displayed by such a curve are dependent on the temporal bunching of the proton beam, and this was apt to change from one run to the next, it was necessary to determine the amount of the effect frequently during each series of runs. The limiting element of the counter system due to this bunching was the discriminator-pulser-scaler combination. The discriminator shown in Fig. 2 was designed to be at least as fast as the scalers. Losses were of the order of 1% at 1000 counts per burst.

D. Targets and C^{11} Counting

Targets used in the present experiment consisted of cylindrical polystyrene-based plastic scintillators, 1 inch thick and from 1 to 1.84 inches in diameter. Both Pilot-*B*[16] and a plastic scintillator produced at the University of California Radiation Laboratory[17] were used. Chemical analyses confirmed that these scintillators contained carbon and hydrogen in the proportion expected for polystyrene with less than 0.5% of other elements present.

After irradiation the scintillators were mounted on Dumont 6292 photomultiplier tubes and the C^{11} was detected by conventional scintillation counter techniques. Starting 5 minutes after the end of irradiation, the decay curves of these targets showed only the 20.4-min half-life of C^{11}. The efficiency for detecting C^{11} in this system was experimentally measured by a beta-annihilation coincidence method[18] as a function of the lowest energy of pulses accepted by the counter. An efficiency of 97.5% was obtained at a nominal discriminator setting of 50 kev which was determined relative to the 625-kev internal conversion electrons of Cs^{137}.

For high-level activations, the scintillator activity was measured in a 2-in. lead shield which was lined with a cadmium-copper graded shield to absorb x-rays from the lead. For the low-level activations further background reduction was necessary. To reduce cosmic-ray backgrounds, the C^{11} counter was placed inside a shield consisting of 12 inches of iron and 1 inch of mercury and was surrounded with a ring of Geiger counters connected in anticoincidence with the C^{11} scintillation counter. Under these conditions, backgrounds of 8 to 9 counts per min were obtained for the 1.5-inch diameter University of California Radiation Laboratory scintillators. These counting procedures are described in detail elsewhere.[18]

[16] Produced by Pilot Chemicals Inc., 47 Felton Street, Waltham 57, Massachusetts.

[17] L. F. Wouters, University of California Radiation Laboratory Report UCRL-4516, 1955 (unpublished).

[18] J. B. Cumming and R. Hoffmann (to be published).

E. Low-Level Activations

The experimental procedures used in each series of runs will now be described in detail. Series I measurements consisted of bombardments at energies of 2, 2.6, and 3 Bev of 1-in. diameter 1-in.-thick Pilot-*B* scintillators in a forerunner of the present pencil beam. The beam position was located and the focusing conditions were optimized with the help of x-ray and Polaroid Land film exposures. The three-element counter telescope ($C_1C_2C_3$) directly behind the target block was used to monitor the proton flux, and the C_1C_2 and C_1C_3 readings were recorded at 2-minute intervals during the 20-minute irradiations to allow correction for variations in beam intensity during the runs. The deadtime loss of the telescope counters was not directly measured in these experiments but was estimated from the known deadtime of the counter system measured for random pulses and from the time distribution of the beam observed on an oscilloscope. The irradiated targets were mounted on Dumont 6292 photomultipliers and the C^{11} activity was then determined in the low-level anticoincidence arrangement. Series I represents the data which have been reported previously,[19] but they have now been modified by application of revised scattering and counting corrections.

Series IV (3 Bev) represented a return to low-level C^{11} counting and direct counting of the proton flux after the intervening high-level series described below. The development of the faster discriminator-pulser combination described above, several improvements making the detection of C^{11} at low levels more reliable, and the difficulties encountered in the high-level procedure all combined to make the low-level technique the method of choice again. However, an individual activation using this method has a relatively large standard deviation, and many activations are necessary for a reasonably precise result. In this series, one scaling telescope as shown in Diagram *A* of Fig. 4 was used to measure the loss correction for C_1C_2 and C_1C_3 at frequent intervals as described in Sec. C. The length of activations in this series was increased to 30 minutes to increase the available C^{11} activities at a given proton rate. A typical activation of this series consisted of scale factor determinations at several rates to evaluate the counter loss correction, a 30-minute activation of a 1.5-inch diameter 1-inch-thick UCRL plastic scintillator placed in front of the C_1 counter, and then additional scale factor determinations. The proton flux was again recorded at 2-minute intervals to make corrections for nonuniform beam intensity and for counter deadtime possible.

F. High-Level Activations

Series II (3 Bev) and Series III (2 Bev) were carried out in conjunction with the elastic *p*-*p* scattering

[19] Cumming, Swartz, and Friedlander, Bull. Am. Phys. Soc. Ser. II, 1, 225 (1956).

measurements of Barge, Barton, and Smith.[20] In these runs flux monitoring at levels up to the full-intensity pencil beam was attempted by a series of scaling telescopes with circuitry similar to that of the primary telescope. The performance of all telescopes was initially checked in the direct beam and they were then placed as shown in Diagram *B* of Fig. 4. Telescopes C_1C_2 and C_1C_3 were the primary monitors of the beam and were located at the target position. M_2 was a secondary monitor used in absorption studies. The 14-inch copper absorber between M_2 and M_3 served to reduce the beam intensity by a factor of $\sim$50. It also was a source of secondary particles which was viewed by telescopes M_4 and M_5. Their positions were chosen such that their counting rates were lower than the M_3 rate by factors of $\sim$50 and $\sim$2500, respectively.

After the beam line had been accurately located by means of x-ray film exposures, and the counters checked and placed as described above, an absorption curve was determined by measurements of the M_2/C_1C_2 ratio as a function of thickness of plastic added just behind the C_1C_2 telescope. The absorption curves with both 2- and 3-Bev protons were exponential within experimental errors, and the observed transmissions agreed with those calculated from the data of Chen *et al.*[15] and Coor *et al.*[21]

Scale factors for each pair of telescopes were then determined as follows. The beam intensity was adjusted to give counting rates from several hundred to several thousand protons per pulse in C_1C_2. The scale factor C_1C_2/M_3 was then measured as a function of rate over this interval. The C_1C_2/M_3 data having been accumulated, the beam intensity was increased by a factor of $\sim$50 and a similar procedure carried out for M_3/M_4. Then after an additional increase in intensity, the ratio M_4/M_5 was measured. In this manner a known factor between C_1C_2 counts and counts observed in M_5 was established; the full-intensity pencil beam ($\sim 10^7$ protons per pulse) corresponded to a few hundred counts per pulse in M_5. The scale factor data were evaluated in the manner described in Sec. C.

In principle the accuracy of this procedure is limited only by the statistical effects in the counting. However, in practice more limitations appear. The data for a given scale factor determination generally showed deviations larger than expected on the basis of statistics alone. This effect appears to be due to changes in the time distribution of the beam which affect the loss corrections (slope of the curve in Fig. 3). Even more serious were the large changes in scale factors ($\sim$30%) which were correlated with shifts of $\sim\frac{1}{8}$ inch in the beam position. While these generally occurred when the Cosmotron was turned off, either intentionally or due to machine failure, it was not possible to rule out smaller gradual shifts during the runs. In practice

[20] Barge, Barton, and Smith (unpublished).
[21] Coor, Hill, Hornyak, Smith, and Snow, Phys. Rev. **98**, 1369 (1955).

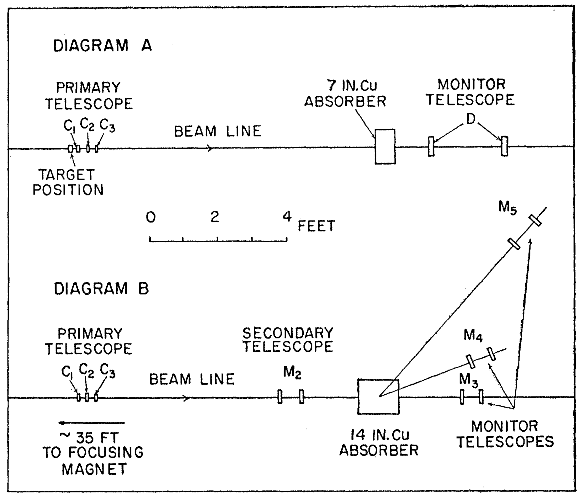

FIG. 4. Floor diagram showing location of target, counter telescopes, and absorbers in the experimental area.

each scale factor could be obtained no more accurately than $\sim$1%. For the present experiment, scale factor determinations and activations were interspersed as far as possible in order to avoid or at least detect systematic effects. Most of the activations in these series were carried out at such proton fluxes as could be monitored by the M_3 or M_4 counters to avoid the additional uncertainties of the M_4/M_5 ratio. During activations, the C_1C_2 counters were withdrawn from the beam and the targets put in their place. In this manner the total amount of absorber in the beam is nearly the same during calibration and activations, which removes the necessity for a correction for target absorption.

During the 3-Bev runs a large iron collimator was present about 3 feet ahead of the target position and this may have added some low-energy particles to the beam. This effect and the observed lack of scale factor reproducibility during Series II make the results of this series less reliable than those of Series III. In the latter series the extra collimator was removed and the Cosmotron was operating more stably. In both series, due to the higher flux levels, the C^{11} was detected without the low-level anticoincidence counting system.

G. Treatment of Data

Two sets of output data resulted from a given run, the flux monitoring data taken at 2-minute intervals during the activation and the decay data from the scintillator. The latter consisted generally of a continuous record of the decay for a period of about four C^{11} half-lives starting approximately 10 minutes after the end of the bombardment. These decay data were divided into 6-minute intervals, corrected for coincidence losses where necessary, and then resolved into a component decaying with a 20.4-minute half-life and a nondecaying background. This analysis was carried out by a weighted least-squares procedure on a Remington Rand 409/2R digital computer. The computer output gave the background rate and the C^{11} counting rate at the start of the counting period as well as the standard deviations assigned to each, calculated from the standard deviation of each input point. The standard F test[22] was applied to each decay curve to test the equality of the actual variance of the experimental points from the fitted curve with that variance expected from statistical fluctuations alone. This test is expected to show gross failures of the counting system. In only one case out of 28 activations of 1-in.-thick targets was the observed variance significantly larger than the statistically expected one (at the 95% confidence level). This case, a member of Series II, was discarded since there was independent evidence that the counter system was malfunctioning at that time.

The C^{11} activities were corrected first for decay from the end of bombardment and then for the inefficiency of the detector systems. In Series II and III the latter correction was due only to the intrinsic inefficiency of the 4π scintillation detector. This was experimentally measured as described in Sec. D by beta-annihilation radiation coincidence measurements as a function of discriminator setting and agrees within 1% with that calculated from the beta spectrum shape. In view of the possible systematic errors entering into the efficiency determination, a standard deviation of 1.0% has been assigned to the measured efficiency at any energy setting.

TABLE II. Experimental data.

(1) Series	(2) Target material and diameter in inches	(3) Proton energy in Bev	(4) Experimental thick-target cross section in mb	(5) Average thick-target cross section in mb	(6) Corrected thin-target cross section in mb
I	Pilot B	2.6	27.6±1.7	27.6±1.7	26.0±1.6
	scintillator	2.0	29.0±1.9	29.0±1.9	27.6±1.9
	1.0	3.0	27.9±2.6		
			26.7±1.9		
			28.3±1.7	27.6±1.2	25.8±1.1
II	Pilot B	3.0	31.0±1.6		
	scintillator		31.9±1.4		
	1.84		25.9±1.0		
			29.4±1.0	29.0±1.4	26.1±1.3
III	Pilot B	2.0	27.3±0.7		
	scintillator		27.8±0.7		
	1.84		28.1±0.7		
			28.5±0.7		
			28.2±0.6	28.0±0.4	25.9±0.5
IV	UCRL	3.0	33.6±1.9		
	scintillator		28.7±1.3		
	1.5		32.5±1.9		
			31.1±1.7		
			27.1±1.5		
			30.1±1.7		
			29.4±1.5	29.9±0.8	27.2±0.7

[22] W. J. Youden, *Statistical Methods for Chemists* (John Wiley and Sons, Inc., New York, 1951), p. 29.

For the low-level runs of Series I and IV an additional correction was necessary for a deadtime imposed by the anticoincidence circuit. To allow the Geiger counters to completely recover after the passage of an ionizing particle, a long deadtime is electronically imposed on the C^{11} counter. The magnitude of this correction is determined by the circuit parameters and the background rate in the GM ring. The correction was experimentally measured at several points during each series of runs and is known to 0.5%. Application of these corrections gave the disintegration rate of C^{11} in the target at the end of irradiation for each run.

The proton beam monitor data were treated as follows. The observed number of counts accumulated in each 2-minute interval during an activation was used to calculate a mean number of counts per Cosmotron pulse. In cases where pulses of zero or very low intensity occurred during a particular interval, the average rate per pulse for the interval was corrected upwards appropriately. This corrected rate per pulse was then used to determine the loss due to deadtime of the telescope systems. In Series II, III, and IV these corrections were based on experimental measurements obtained under Cosmotron operating conditions closely approximating those of the activations. In Series I the loss corrections were approximated as described in Sec. E. The observed counts per 2-minute interval, corrected for the deadtime losses, were used to calculate an effective number of counts, C_{eff}, defined by the relationship

$$C_{\text{eff}}=\sum_i C_i e^{-\lambda(\Delta t_i)},$$

where C_i is the corrected number of counts in the ith interval and $e^{-\lambda(\Delta t_i)}$ is the decay factor for C^{11} calculated from the midpoint of the ith interval to the end of the bombardment. C_{eff} is that number of counts which would have been recorded if the same number of C^{11} atoms existing at the end of the bombardment had been produced by a flux delivered instantaneously at the end of the run instead of spread over 20 or 30 minutes. C_{eff} then includes the corrections for variation of beam intensity during the run and for the saturation of the C^{11} activity.

For Series II and III, multiplication of C_{eff} by the net scale factor for the telescope used converts C_{eff} into the effective number of C_1C_2 counts. This differs from the flux incident on the target only by the inefficiency of the C_1C_2 telescope. As discussed in Sec. C, the efficiency of C_1C_2 was calculated to be 0.992 at 3 Bev. Division of the C_1C_2 count by 0.992 gives ϕ_{eff}, the effective proton flux which bombarded the target. Since the target replaced C_1 and C_2 during the activation, no additional correction for scattering and absorption of the target is needed.

In Series I and IV, C_{eff} is the effective C_1C_2 count with a target in place ahead of the counters. Correction must be made both for the inefficiency of C_1C_2 and for the scattering and absorption of the target. Coor *et al.*[21] have measured the transmission of carbon and hydrogen for 1.4-Bev neutrons in an experiment to determine the absorption and total cross sections for these elements. Chen *et al.*[15] have carried out similar studies using 2.0- and 2.6-Bev protons. In both cases the transmission was measured as a function of the detector solid angle. We have used their data to calculate the transmission of a 1-in. polystyrene target and find that for detector half-angles from ~0° to ~6° the transmission increases from ~95% to ~97.3% with a maximum spread of ~0.5% between the results obtained for different bombarding particles. For larger angles, no further increase in transmission was observed by Coor *et al.* During the present experiment, one measurement was made using large detector geometry (~32° half-angle) which gave a transmission for 3-Bev protons of 99.3%. This increase is qualitatively expected since this detector had a low threshold (similar to that used by Chen *et al.*) and will efficiently detect secondary particles produced by interactions in the absorber, while the detector used by Coor *et al.* had a high threshold and detected only the primary particles which are peaked forward. From the data of Coor *et al.* one would conclude that the C_1C_2 count should be increased by 4.4% to obtain the flux incident on the target. The data of Chen *et al.* lead to a correction of only 3.2%. A correction of 3.8% has been used since the response of the C_1C_2 telescope lies somewhere between these two extremes.

After the C^{11} disintegration rates at the end of the bombardments (D^0) and the effective proton fluxes were obtained as described above, cross sections for the production of C^{11} from carbon were calculated from the relation:

$$\sigma = D^0/\lambda n \phi_{\text{eff}},$$

where σ is the cross section, λ the C^{11} decay constant, n the number of carbon atoms/cm^2 in the target, and ϕ_{eff} the effective proton flux.

RESULTS

Individual thick-target cross sections for each activation are presented in column (4) of Table II. Of a total of 25 measurements for which reliable flux data were available, 3 gave cross sections >55 mb. Two of these were activations of Series I at very low proton fluxes where counting difficulties would have marked effects. The other was a member of Series II for which no obvious explanation could be found. These have not been included in Table II. Also excluded is the one run of Series II showing the poor C^{11} decay curve, although the cross section calculated for this run was not grossly different from the average of the remaining runs of this series. On the basis of these difficulties, Series I and II must be considered less reliable than Series III and IV in which no such abnormalities were observed. The errors attached to each individual cross section are standard deviations calculated by root-mean-square combination of the standard deviations from the C^{11} decay curve resolution, from the statistical fluctuations in the production and decay of C^{11} prior to the start of counting, and from possible fluctuations of the deadtime correction and scale factors. The series averages in column (5) of Table II are weighted averages whose standard deviations are calculated from the standard deviations of the individual results in column (4). In the cases where the variance of the individual results from the mean indicated a precision less than that expected, the standard deviation of the mean has been multiplied by the $\sqrt{F}$. Here $\sqrt{F}$ is defined as the ratio σ/σ', where σ is the standard deviation of the mean calculated from the actual deviations of the individual observations from the mean and σ' is the standard deviation of the mean calculated from the standard deviations of the individual observations.[22] The above procedure serves to decrease the precision of the mean in cases where deviations of the observations from the mean are greater than those expected from the estimated precision of the individual results; this correction is significant only for Series II.

To convert the thick-target cross sections listed in column (5) of Table II to thin-target cross sections, the production of C^{11} in the thick targets by secondary particles originating in the targets themselves had to be determined. This effect was evaluated by means of the auxiliary experiments listed in Table III. In these experiments a $\frac{1}{32}$-inch scintillator was simultaneously irradiated upstream from a 1-inch scintillator in a high-intensity pencil beam. To compensate for recoil losses, the thin target was irradiated between sheets of 4-mil polyethylene and the C^{11} produced counted with the thin scintillator sandwiched between two $\frac{1}{2}$-inch-thick inactive scintillators. The observed variation of the secondary effect with target diameter is qualitatively in agreement with that calculated from simple models of the angular distribution of secondary particles, and the increase from 2 to 3 Bev is reasonable on the basis that, per interaction, a larger number of particles with energies above the $C^{12}(x,xn)C^{11}$ threshold is produced at the higher energy. The standard deviations attached

TABLE III. Correction for C^{11} production by secondary particles.

Target diameter in inches	Energy Bev	$\sigma_{\text{thick target}}/\sigma_{\text{thin target}}$ Experimental	Average or claculated
1.0	2.0	1.050±0.018	1.050±0.018
	2.6	···	1.063±0.011[a]
	3.0	1.072±0.008	1.072±0.008
1.5	3.0	1.094±0.008	
		1.104±0.008	1.099±0.006
1.84	2.0	1.062±0.012	
		1.090±0.009	1.080±0.013
	3.0	···	1.109±0.010[b]

[a] Interpolated value.
[b] Extrapolated value.

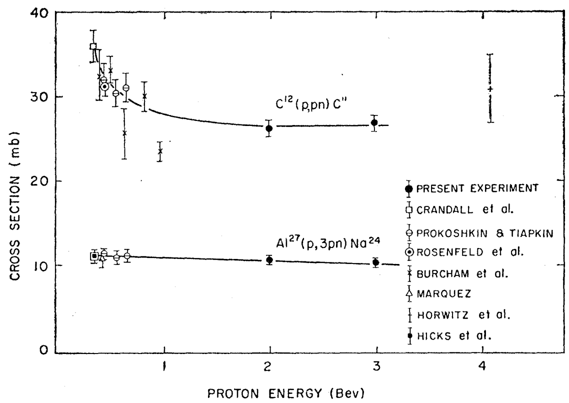

FIG. 5. Experimental cross sections for the $C^{12}(p,pn)C^{11}$ and $Al^{27}(p,3pn)Na^{24}$ reactions.

to the thin-target cross sections in column (6) of Table II are root-mean-square combinations of those attached to the mean thick-target cross sections and those due to the uncertainties in the ratios $\sigma_{\text{thick target}}/\sigma_{\text{thin target}}$. The corrected cross sections from all series lie in the range 25.8 to 27.6 mb.

The weighted average of the 3-Bev cross sections from Series I, II, and IV is 26.6 ± 0.6 mb; the average of the 2-Bev results from Series I and III is 26.0 ± 0.4 mb. The errors assigned to these cross sections are statistical standard deviations which are a measure of the precision of the experiments. The accuracy of the results is further decreased by systematic errors. The sum of the estimated possible systematic errors is $\sim5\%$; the result of root-mean-square addition of these systematic errors is $\sim3\%$. By combining the latter figure with the statistical errors, final values of 26.0 ± 0.9 mb and 26.6 ± 1.0 mb are obtained for the $C^{12}(p,pn)C^{11}$ cross section at 2 and 3 Bev, respectively. These results and other published measurements are plotted as a function of proton energy in Fig. 5. The curve of cross section *vs* energy shows a decrease of $\sim30\%$ from 0.3 to 2 Bev which is well outside of the experimental errors. The present results show no significant change from 2 to 3 Bev. The preliminary result of 30.5 ± 4.1 mb at 4.1 Bev[11] is higher than the cross section at 3 Bev only by the error on the point, and the apparent increase may not be significant. On the other hand, a monotonic increase in the cross section by as much as 25% between 1 and 4 Bev cannot be excluded.

The present data for the $C^{12}(p,pn)C^{11}$ cross sections may be used in conjunction with the ratios measured by Wolfgang and Friedlander[5] to obtain cross sections for the $Al^{27}(p,3pn)Na^{24}$ reaction. This reaction has been used extensively for beam monitoring because of the convenient half-life of Na^{24}(15.0 hr). For 420-Mev protons, Wolfgang and Friedlander have obtained a ratio of the $C^{12}(p,pn)C^{11}$ to the $Al^{27}(p,3pn)Na^{24}$ cross section of 3.10 ± 0.15 which may be compared with a ratio of 2.97 ± 0.20 calculated from the absolute values of the $C^{12}(p,pn)C^{11}$ cross section previously discussed[3,4,10] and the absolute measurements of the $Al^{27}(p,3pn)Na^{24}$ cross section[3,10,23,24] in this energy region. The agreement is taken to indicate that the Wolfgang and Friedlander ratios are reliable within the errors indicated. From the ratios and the $C^{12}(p,pn)C^{11}$ cross sections measured in this experiment, the $Al^{27}(p,3pn)Na^{24}$ cross sections are calculated to be 10.4 ± 0.6 mb and 10.0 ± 0.6 mb at 2 and 3 Bev, respectively. These values and the absolute values at lower energies are plotted in Fig. 5. The lack of dependence of the cross section on energy is striking. Although the line drawn through the points shows a decrease of $\sim10\%$ from 0.3 to 3 Bev, the results would also be consistent with a constant cross section of 10.7 ± 0.6 mb in this energy region.

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[23] L. Marquez, Phys. Rev. **86**, 405 (1952).
[24] Hicks, Stevenson, and Nervik, Phys. Rev. **102**, 1390 (1956).