Cross Section for $C^{12}(p,pn)C^{11}$†

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The cross section for the reaction $C^{12}(p,pn)C^{11}$ has been measured at a proton energy of 461 Mev; the result is $\sigma=31$ mb with an associated error of 3 percent. Because of some disagreement among earlier experiments by several laboratories, a detailed discussion of the errors involved in those measurements is given, and in particular, a discussion of the techniques used for positron counting in a 4π proportional counter. A summary of the present state of knowledge of this reaction is presented.

I. INTRODUCTION

THE reaction $C^{12}(p,pn)C^{11}$ has been studied by several investigators because of its use as a monitor for proton beams at energies above the 19.5-Mev threshold. There has been some lack of agreement between the several groups that have reported values for this cross section, especially in the energy region about 350 Mev.[1] We, too, have contributed to the confusion by reporting cross sections at 300 and 400 Mev which we now believe to be too large. This does not affect our conclusion that the "dip" reported by Aamodt *et al.* does not exist; we doubt only the absolute values. We have therefore repeated the measurement with more conventional techniques made possible by the availability of a much more intense external proton beam at The University of Chicago synchrocyclotron[2] and we wish to withdraw the previously reported value.[3]

In addition to describing our own work, we will discuss in this article the reasons for the discrepant results. The errors that seem to have plagued the earlier experiments are of two kinds. (1) C^{11} activity was produced by secondaries originating in absorbers stacked in front of the target foil. Aamodt *et al.* in particular used this stacked foil technique to obtain the excitation curve for the reaction, getting points at several energies in the same run. This resulted in the dip mentioned above, which we eliminated by keeping several feet between our absorber and our target foil in the earlier measurement.[1] (2) The absolute beta counting has been subject to significant errors in the self-absorption correction. It apparently has not been realized that there may be a different self-absorption for positrons and electrons of the same maximum energy. Beta-counting techniques have improved since the earlier experiments, and it seemed desirable to use this advance to better the accuracy of the cross-section measurement.

At about the same time that we measured our single point, Crandall *et al.* used the proton beam at Berkeley to investigate a series of reactions of the type $C^{12}(x,xn)C^{11}$ and $Al^{27}(x,x2pn)Na^{24}$ from 350 Mev down to 170 Mev. Because of their careful measurements we saw no point in reducing the energy of our beam to verify the excitation curve. However, a discrepancy in the absolute value of the cross section of up to 10 percent may still exist because of some disagreement on the self-absorption correction.

In the following discussion, we will emphasize the techniques for beam calibration that we developed for this measurement, but are so satisfactory and relatively simple that we hope they will find wider application in other accelerator work. Again, the positron counting technique will be discussed in detail because this was where most of the earlier experiments seem most questionable, because it is interesting and useful in its own right, and because there is still some disagreement between the Chicago and the Berkeley groups.

Sections II and III of this paper concern our own work; Sec. IV will be a critical discussion of errors in older experiments, and a short summary of the present experimental situation.

II. METHOD

A. General

The external (spill-out) proton beam[2] at Chicago has an intensity of about 5×10^6 protons/cm²/sec and an energy of 461 ± 3 Mev estimated from the impact parameter of the escape orbit and from the range in copper. With this beam we can activate thin (4 mg/cm²) polyethylene foils to an easily countable level. The beam, after collimation carefully designed to minimize the neutron background produced when stray protons strike collimating material,[4] was allowed to pass through

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[1] Aamodt, Peterson, and Phillips, Phys. Rev. **88**, 739 (1952); Warshaw, Swanson, and Rosenfeld, Phys. Rev. **95**, 649 (1954); R. L. Wolfgang and G. Friedlander, Phys. Rev. **96**, 190 (1954); Birnbaum, Crandall, Millburn, and Pyle, University of California Radiation Laboratory Report UCRL-2756 (unpublished); Crandall, Millburn, Pyle, and Birnbaum, Phys. Rev. **101**, 329 (1956); earlier references are given in the above papers.

[2] A. H. Rosenfeld and S. D. Warshaw (unpublished); S. D. Warshaw and S. C. Wright, Rev. Sci. Instr. (to be published).

[3] A. H. Rosenfeld, Phys. Rev. **96**, 1714 (1954).

[4] A check with a liquid-scintillator neutron counter gave less than one neutron in 10 000 beam protons capable of making C^{11}.

a thin ionization chamber. This consisted of $1\frac{1}{2}$ inches of air at atmospheric conditions, enclosed between the collector and polarizing plates, each a $\frac{1}{16}$-inch-thick Lucite sheet made conducting with Aquadag. Just in front of the chamber, mounted to a rigid, machined fixture, was the foil or, alternatively, an Ilford G5 plate to calibrate the chamber. Both foil and emulsion were normal to the beam direction. After exposure to the beam, with the total charge produced in the chamber recorded, the foil was counted in a 4π counter. Then the cross section is given by

$$\sigma=\frac{T_1\exp(T_2/T)}{T[1-\exp(-T_2/T)][1-\exp(-T_3/T)]}\cdot\frac{N}{\eta s\alpha\gamma Vx}\equiv\frac{\beta N}{\eta s\alpha\gamma Vx},$$

in which T_1 is the exposure time, T_2 is the interval between the end of the exposure and the beginning of the count, and T_3 is the total counting time; $T=29.6$ minutes is the mean life of C^{11}; N is the total number of events counted in the 4π counter with efficiency η and self-absorption coefficient s; α is a correction for fluctuation of beam intensity during the run; s, η, α, are of order unity; γ (protons through foil/volt) is the calibration factor for the ionization chamber-electrometer combination, which gives a deflection of V volts at the end of a run; and x is the number of carbon atoms/cm^2 in the foil. We have ignored the presence of 1.1 percent C^{13} in natural carbon.

An auxiliary ionization chamber was placed in the beam behind the experiment and its signal (ν) fed to a recording potentiometer. We used this record to compute numerically the fluctuation correction

$$\alpha=T_1\int_0^{T_1}\nu\exp(t/T)dt\Big/\int_0^{T_1}\nu dt\int_0^{T_1}\exp(t/T)dt.$$

In no case did this correction differ from unity by more than 8 percent.

In actual practice, the beam passed through a "guard foil" first, in contact with the foil which was counted. The guard served as a source of recoil C^{11} nuclei, to compensate for recoils lost through the back of the counted foil.

We used a 4π counter designed to take foils of diameter not more than 2 cm; in the experiment, the foils were, in fact 1.8 cm in diameter, and (see below) cut off about 30 percent of the beam. Of course, for this purpose it would have been simpler to collimate the beam to, say, 1 cm, but we were trying to measure the $Al^{27}(p,3pn)Na^{24}$ reaction at the same time; a 1 cm beam would have resulted in an inconveniently small Na^{24} activity. Unfortunately, difficulties with the chemical separation of the Na^{24} prevent us from reporting that cross section.

B. Ionization Chamber Calibration

An Ilford G5 nuclear track plate was placed in front of the chamber in exactly the same position as the foil to be activated. The plate was then exposed to about 10^6 protons/cm^2, and the electrometer deflection noted. After processing, the appropriate area of the plate (the same diameter as the foil) was scanned for proton tracks. We obtained a statistical accuracy of 2 percent for each plate by scanning at 100 positions and finding about 25 tracks passing through a known area of the field of view at each position. For scanning, a reciprocating arm driven by a motor was tied to the fine focus control of the microscope, so as to rack the stage rapidly up and down. Under such conditions, the background (consisting of electrons, star products and scattered protons) blurs and it is very easy to identify the beam tracks normal to the plane of the emulsion. In this way, one can count[5] about one proton per second with an efficiency greater than 99 percent.[6]

This technique has, of course, the disadvantage that there is some delay while the emulsion is processed. The best compromise between scanning convenience and processing time is reached with 200-μ plates, which take one day to process; for quicker checks, however, we used 50-μ plates and these were ready to scan in less than an hour after exposure. A secondary advantage of this method (other than its accuracy, simplicity, and economy of cyclotron time) is that it gives as a by-product some information on the spatial and angular distribution of the beam. Any track making an angle of as much as 1° with the beam direction, stands out clearly, and this excellent angular resolution eliminates any worries about counting knock-on electrons made by the beam as it passes through the emulsion.[7]

The ionization current was integrated in a low-loss polystyrene capacitor placed in the feed-back loop of an Applied Physics Corporation vibrating reed electrometer. By using an extended range recorder, the voltage V, developed across the capacitor at the end of the run, could be read to better than one percent, even for the short calibration runs, and including the small drift in the electrometer. We used about 10^6 protons/cm^2 when irradiating the G5 plate, whereas we wanted about 10^9 protons/cm^2 to activate the foils. The well-calibrated range switch and the extended range recorder of the electrometer allowed us to handle this factor of 1000 in charge with ease. However, if we were to repeat the measurement, we would use thicker foils for some

[5] We would like to thank Mr. W. Slater for rigging up the microscope drive and for doing a large part of the scanning.

[6] This efficiency determination is not based on statistical arguments of the sort that require checking 10 000 tracks to get 1 percent accuracy. A spot-checker merely scans the same 100 protons in a field of view that has just been tallied by another scanner; any discrepancies can then be individually discussed. Actually, hundreds of proton tracks were spot-checked and no discrepancy ever found.

[7] M. G. Meshcheryakov *et al.*, Doklady Akad. Nauk, U.S.S.R. 99, 995 (1954).

or all of the activations. For example, we would have needed only 10^8 protons/cm^2 for 40-mg/cm^2 foils (only a one-minute cyclotron bombardment) and the necessary electrometer range would only have been 100. The disadvantage of the thicker foils is that the self-absorption corrections become large (about 1.3 at 40 mg/cm^2) and we were reluctant to make such large corrections before we gained confidence in the positron counting.

Table I gives the data on the calibration and the result

$$\gamma = 3.30\ (\pm 1.9 \text{ percent}) \times 10^6 \text{ protons/millivolt},$$

where the error is the standard error of the mean.

An incidental measurement of the beam fraction that was contained within the foil circle was made separately by activating a large-area 60-mg/cm^2 polyethylene foil and counting the activity of the inside circle relative to the whole piece. An average of two runs gave the result that a fraction $f=0.323$ of the whole beam (which was collimated to $1\frac{1}{2}$ inches) was contained in the 0.72-inch circle. Using this fraction f we get, as a by-product, a chamber calibration for future use of 1.86×10^{10} protons/microcoulomb. (The integrating capacitor had a value of 0.55 microfarad.) The same f was obtained from the nuclear track plates used for ion chamber calibration. This ensures that the calibration is independent of beam intensity.

A misalignment error, i.e., from improperly placing the circle on the emulsion, was checked by counting the flux of tracks through a slightly displaced circle. This showed that we could get of the order of 2 percent change in the calibration constant per millimeter displacement (varying somewhat with the direction of displacement); since the plate, chamber, and foil holder were securely mounted in a reproducible way to a machined fixture, we feel satisfied that errors of this kind could not produce an effect of even as much as 1 percent.

C. Alternative Beam Calibration

It should be noted in passing that we also tried to monitor the beam with a purely electronic counting method. When the fastest available scaling equipment was used, however, the duty cycle of the cyclotron beam resulted in an effective dead-time of about 22 microseconds (i.e., a proton current of about 10^7 per second, at 60 pulses per second each 70 microseconds long). This meant that the beam intensity was about 10^4 times greater than it would have to be for, say, 1 percent counting losses. A "bootstrap" method was used to count the beam. First, the beam was passed through a small aperture in an 8-inch steel block which reduced the current to be counted by a factor of around 500; this count, made with a conventional large area plastic scintillator telescope, designate A. At the same time, a two-counter telescope was placed off-axis well upstream of the eventual foil position, and looked, at an angle of about 40°, at the scattered radiation from a polyethylene target 1 inch thick which had already been set permanently in place on the beam axis. Designate this count by T. With the cyclotron intensity set to give negligible losses in the telescope A, the ratio of counts T/A was obtained. Another counter telescope, B, had already been placed in position in the beam, but in *front* of the small aperture; during the T/A determination, this counter was not used. Now the ratio B/A was determined by reducing the cyclotron intensity by another large factor (500) to give negligible losses in B. The off-axis telescope was used as a monitor during a run: if C_T was this count, then the number of beam protons during a foil activation run was $C_T(A/T)(B/A)$, and when one uses the fraction f defined in Sec. IIB above as data, the number V in the expression for the cross section is to be replaced by $fC_T(A/T)(B/A)$. The appropriate checks on the counter voltage plateaus, and delay curves were made to ensure that they were counting with 100 percent efficiency.

The above procedure, while yielding an ion chamber calibration equal to that obtained using nuclear track plates, was considered unsuitable for routine calibrations because (a) about 8 hours of cyclotron time were required per calibration, and (b) an additional measurement of the ratio of total beam to beam through the sample was required for each run. The procedure is of interest because it constitutes an independent check of our monitoring procedure.

TABLE I. Calibration of ion chamber with nuclear track plates.

Plate	Emulsion thickness in microns	Protons/millivolt[a] $\times 10^6$	Estimated error[b]
1	50	3.10	3.2%
2	50	3.31	1.8%
3	600[c]	3.26	2.9%
4	600	3.41	2.2%

[a] Through area (0.72 inch in diameter) corresponding to foil.
[b] Statistics of track count and reading error of electrometer.
[c] 600 μ plates were unnecessarily thick, but we ran out of 200 μ plates.

D. Positron Counting

1. The 4π Counter

The C^{11} activity was counted in a 4π proportional counter continuously flushed with methane at atmospheric pressure.[8] The samples were held in place between two pairs of 5-mil wires in a plane perpendicular to the plane of the two wire loops 1 cm in diameter which served as collecting electrodes. The plateau for this counter was 600 volts long and rose 1.2 percent from one end to the other.

We standardized this counter with P^{32} or Na^{24} sources. These were prepared by depositing a measured volume of the solutions on 0.7-mg/cm^2 rubber hydrochloride films,[9] evaporating to dryness, and then rendering

[8] We are indebted to V. L. Telegdi for the loan of this counter.
[9] R. C. Koch (to be published).

them conducting with Aquadag. The sources were then counted in our proportional counter and under an end-window counter whose calibration had been determined for sources of this thickness and energy to within 1 percent.[9] This method gave an efficiency of 0.984 ± 0.015, where the error comes from the end-window counter calibration and the estimate of absorption in the supporting film when counting in the 4π counter.[10] A calibration using P^{32} and Na^{24} sources standardized by the National Bureau of Standards, gave the same result with a slightly greater error.

We explored the relative efficiency in the median plane of the counter by moving a 1.2-mm^2 source (Na^{22}) along a radius. At 1.0 cm from the center, the efficiency was 0.988 ± 0.004 of that at the center; since the polyethylene foils used in the experiment were 0.91 cm in radius and about the same size as the calibration sources, the correction for source area was negligible. At larger radii the efficiency dropped—to 0.77 at a radius of 1.2 cm. The counter cathode is a cylinder of radius 1.3 cm, and this drop-off indicates that some electrons strike the counter wall before producing enough ion pairs to count. If one assumes that the shape of the radial sensitivity curve is entirely due to this effect, then the mean electron path needed to produce enough ion pairs to count is less than 0.20 cm; this leads us to believe that the efficiency for counting at the center is greater than 0.995 for C^{11} decay electrons. If one also notes that the absorption due to the foil supporting wires is less than 0.003, then the measured efficiency seems to be consistent with the efficiency estimated from plateau, relative radial efficiency, and support wire absorption.

2. *Self-Absorption*

Since the efficiency of the 4π counter was determined for weightless sources, it was necessary to determine the self-absorption correction for our nominally 3.7-mg/cm^2 foils. Foils of thickness 0.75 ± 0.05 mg/cm^2 were prepared by dropping an ethyl acetate solution of polystyrene onto a distilled water surface. One of these foils was activated in the internal beam of the cyclotron and counted in the 4π counter. The active foil was then placed in a stack with four identical but nonactive foils, and a count was made with the active foil in each of the five possible positions in the stack. All exposed surfaces were covered with thin Aquadag films; cohesion was sufficient to give a good representation of a single thicker foil. It should be noted that any gaps in the stack are regions from which ions cannot be collected; they also increase stack thickness which tends to produce a region of low electric field between the edge of the stack and the counter wall. Such regions of poor ion collection can make the "self-absorption" in a stack anomalously high.

After corrections for background and decay were made, the ratio of average stack count to single foil count was 0.994 ± 0.003; the error is counting statistics. Similar measurements with thicker foils were made up to a thickness of 29.2 mg/cm^2, resulting in the empirical curve of Fig. 1. Our correction is less than 1 percent up to 4 mg/cm^2 and then increases by about 0.8 percent/mg/cm^2. The nonlinear behavior at low thicknesses is thought to result from the shape of the positron spectrum and a tendency for electrons to scatter out before stopping. One expects much greater corrections for electron emitters of comparable maximum energy because of the markedly different spectral shape at low energy.

Crandall *et al.*[1] have measured a 4π-counter self-absorption curve using a technique which simulates thick foils by successive foldings of a thin active foil. Their results are also plotted in Fig. 1 for comparison; neither we nor they understand the marked difference at small thicknesses. We have used their technique in the region 0.9 mg/cm^2 to 3.6 mg/cm^2 but only reproduce our original curve. On the other hand, their curve is supported by a beta-gamma coincidence calibration. The existence of a common self-absorption curve is not likely to change our results by more than 3 percent or the Berkeley results by more than 5 percent, the difference arising because the Berkeley group used 13-mg/cm^2 foils where we used 3.7-mg/cm^2 foils.

III. RESULTS

Data for each of the six separate runs are given in Table II. The mean of the six values for the cross section is 31.1 mb. From the internal consistency of these six runs, we can calculate the standard deviation to be 2.2 percent, in good agreement with the tabulated estimated error of each run computed from statistics and other known uncertainties. The standard deviation of the mean $= 2.2$ percent$/\sqrt{6} = 0.9$ percent. We believe that the uncertainty in the calibration of the 4π counter for "weightless" samples is about 1.5 percent. The

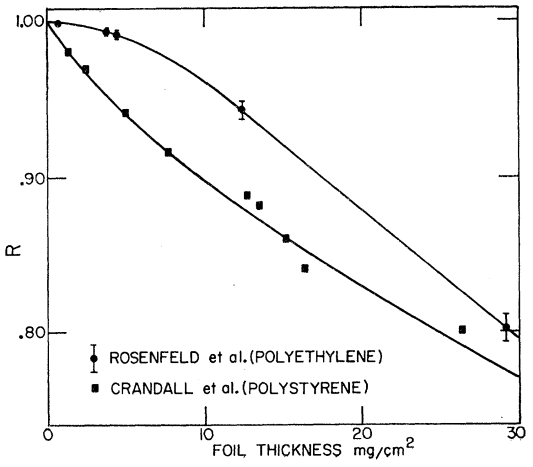

FIG. 1. Self-absorption curves for 4π counting of carbon foils.

[10] B. D. Pate and L. Yaffe, Can. J. Chem. **33**, 929 (1955).

calibration of the ion chamber has a standard deviation of about 2 percent (see Table I). Our estimate of the self-absorption error is 1 percent.

Our final result is then

$$\sigma(C^{11}) = 31.1 \pm 1 \text{ mb, at } 461 \pm 3 \text{ Mev.}$$

IV. OLDER EXPERIMENTS

A. Effect of Secondary Activity

Figure 2 is a sketch of the stacked-foil arrangement of Aamodt *et al.*[1]; the 0.01-inch polystyrene foils are shown being activated behind Cu absorber plates. The initial beam of 340-Mev protons passed through the first foil and then was moderated to 313 Mev in about 12 g/cm² of Cu before hitting the second foil. Now, in this much copper, about 10 percent of the protons undergo nuclear collisions, most of them producing a secondary proton and a secondary neutron of more than 30 Mev,[11] nearly half of them producing a secondary proton or neutron of more than 100 Mev.

TABLE II. $C^{12}(p,pn)C^{11}$ data. The notation is that of Eq. (1).

Run	Foil weight (mg)	γV = protons[a]	N' = C^{11} count[b]	α = Fluctuation correction	β	σ (mb)[c]
1	9.8	3.16×10^9	3604±2.2%	1.00	4.36	30.9±2.8%
2	9.9	5.53×10^9	7038±1.6%	0.985	3.80	30.2±2.4%
3	9.7	4.81×10^9	6471±1.7%	1.043	3.75	30.4±2.2%
4	9.7	3.76×10^9	4314±2.0%	0.922	4.07	31.7±2.2%
5	9.0	11.12×10^9	15 174±0.9%	1.05	3.56	31.2±2.0%
6	9.2	5.21×10^9	6773±1.4%	···	3.72	31.9±2.1%
						Mean 31.05

[a] Protons = $3.30\times10^6\times$(millivolts from electrometer).
[b] (Count − background)/s ± (standard error of counting).
[c] The uncertainty is the estimated error due to counting statistics combined with the assigned error of 1% to electrometer reading, foil weight, and α.

The average range of these secondary protons is about the thickness of the copper absorber. If the secondaries were no more effective than beam protons in producing C^{11}, then neither the foil nor the Faraday cup monitor could distinguish them from beam protons and no harm would be done. However, protons in the range 30–80 Mev are nearly twice as effective in producing C^{11} as the 200-Mev or more beam protons (Fig. 3). Secondary neutrons produce additional activation by the reaction $C^{12}(n,2n)C^{11}$ with a relatively constant cross section of about 20 mb.[12] Apparently, this secondary flux was sufficient to raise by 15 percent the activity of those foils of Aamodt that were embedded in the low-energy end of their stacks. In fact, Crandall *et al.*[1] have actually reproduced the "dip" of Aamodt using the arrangement

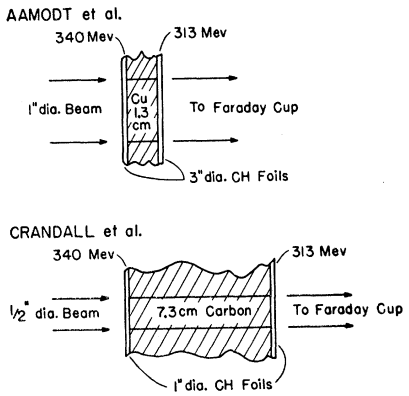

FIG. 2. Typical geometries for stacked foil measurement of C^{11} cross section.

sketched in Fig. 2. They used a different diameter for their beam and foils, and a lighter absorber (carbon). The sketches are drawn to scale and it is clear from them that a larger proportion of secondaries can escape from the stack of Crandall than from that of Aamodt. Even with this less compact stack, Crandall found that foils embedded in the stack were 7 percent more active than the front foil. Not only does the activation by secondaries depend on stack geometry, but it is also some unknown function of beam energy. Actually, for a beam energy initially below 100 Mev, the secondaries produced above the threshold no longer have a cross section much larger than that of the beam protons; at these energies the troubles from activation by secondaries should be small and due mainly to neutrons. It is not worthwhile to investigate the problem experimentally—the time would be better spent in measuring the cross section correctly with improved techniques. In making a first order correction to the published excitation function of Aamodt *et al.*, we have arbitrarily assumed that the secondary activity is directly proportional to the energy of the beam passing through the foil concerned. The error in doing this is probably not more than a factor of two in a correction which is 15 percent at 300 Mev.

It should be pointed out that a determination of the cross section of the other popular monitor reaction [$Al^{27}(p,3pn)Na^{24}$] is subject to troubles from a rela-

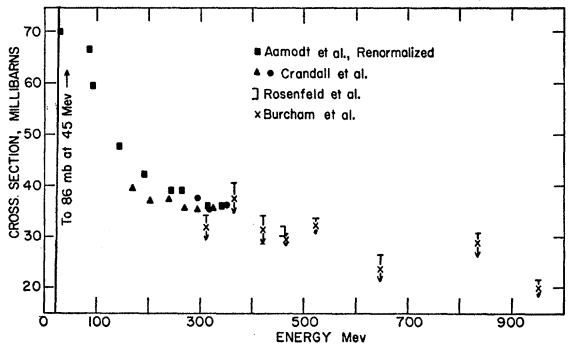

FIG. 3. Summary of cross sections for $C^{12}(p,pn)C^{11}$ below 1 Bev.

[11] Bernardini, Booth, and Lindenbaum, Phys. Rev. **85**, 826 (1952).

[12] R. L. Mather and H. F. York, quoted by Aamodt *et al.* (reference 1), using 90-Mev neutron spectrum; Warshaw *et al.* (reference 1) give 18 mb±1.4 mb for the spectrum peaked at 300 Mev, and maximum energy 430 Mev at Chicago; K. O. Oganesan, quoted by P. S. Baranov and V. I. Goldansky, J. Exptl. Theoret. Phys. U.S.S.R. **28**, 621 (1955) gives 21 mb for a 380-Mev neutron beam.

tively much more probable neutron-induced reaction: $Al^{27}(n,\alpha)Na^{24}$. This has an almost geometrical cross section for neutrons of only a few million volts. Crandall *et al.*[1] have demonstrated that the error attributable to the (n,α) reaction is less than 1 percent for a stack of CH and Al about $\frac{1}{2}$ g/cm^2 thick but thicker stacks should be used only with caution. Not only is the cross section for (n,α) large but the neutrons are produced almost isotropically so that the presence of spurious activity is not as easy to detect as it was in the $C^{12}(p,pn)C^{11}$ case.

B. Positron Counting

The high-energy (340-Mev) point of Aamodt *et al.* was not affected by secondary activation; it was reported as 41.2 mb with an attached standard error of 11 percent because of uncertainty about the calibration of the end-window counter they used to count positrons. At the same energy, the newer work of Crandall *et al.* gives a cross section of 36 ± 0.7 mb. Thus, Aamodt's result is 1.3 standard deviations above that of Crandall.

Since, evidently, the discrepancy cannot all be put into the error of the counter calibration, we have given some thought to the problem of calibrating an end-window counter for C^{11} positrons. Standard sources are usually negative electron emitters and one is often tempted to assume that the counter calibration depends only on the geometry and maximum energy and not on the charge of the radiation. Aamodt *et al.*, for example, assumed in their calibration procedure that the efficiency for counting RaE in a polystyrene sandwich was the same as that for counting C^{11} in a uniformly irradiated foil of the same total thickness. We therefore prepared a 13-mg/cm^2 polyethylene foil of known activity (known by using the 4π counter and our measured self-absorption correction) and also a weightless RaDEF source of known activity sandwiched between two 6.5-mg/cm^2 polyethylene foils. When counted in the same geometry, the apparent counter efficiency was 7 percent higher for the positron emitter.

Since the geometry used was quite similar to that of Aamodt *et al.*, we feel that their cross sections should be reduced by of the order of 7 percent, although without changing the 11 percent calibration uncertainty, which was independent of positron-electron difference. This brings their 41 mb cross section down, and well within one standard deviation from Crandall's 36 mb.

In the above case, the ratio of negatron efficiency to positron efficiency is presumably due to the absorption of the greater number of low-energy electrons in a typical electron spectrum. For very thin samples placed on backing sheets, Seliger[13] has shown that backscattering is the predominant effect and has the effect of making a counter more efficient for negatrons than for positrons. In intermediate cases (say 5-mg/cm^2 samples on backscatterers) one can expect that the measured efficiency difference will have either sign; it is therefore evident that calibration of end-window counters should be done with sources of the same charge as the isotope of interest. Otherwise, errors of the order of 10 percent can be expected.

[13] H. H. Seliger, Phys. Rev. **88**, 408 (1952).

C. Other Experiments: Summary of Data

1. $C^{12}(p,pn)C^{11}$

Figure 3 gives a compilation of published and unpublished cross sections for $C^{12}(p,pn)C^{11}$.

The squares, between threshold and 341 Mev, are taken from Aamodt *et al.*,[1] who have in turn reproduced the data of Hintz and Ramsey.[14] These early results have been normalized to agree with Crandall *et al.* in the energy range 300–350 Mev and have been crudely corrected for secondary activity as explained in Sec. IVA. The triangles and circles are, respectively, the "poor" and "good" geometry results of Crandall *et al.* The error on the recent Berkeley points is about 1 mb, as is indicated by the consistency of the points. The fact that the "corrected" excitation curve of Aamodt does not agree with the new results of Crandall illustrates that the low-energy points should be remeasured. The Chicago contribution is plotted without a symbol at 461 Mev.

The crosses represent the cross sections of Burcham *et al.*[15] The main uncertainty in this experiment is that there was a large neutron flux around the Birmingham synchrotron. This may have led to an overestimate of the (p,pn) cross section, and is suggested by the arrow heads instead of tags at the bottom of the indicated errors.

Quantitatively the uncertainty in the cross section reported by Burcham can be considered as follows: They monitored the neutron flux by exposing G5 nuclear track plates and comparing the number of stars with two or more prongs induced by beam protons with the number of similar stars induced by neutrons—the ratio turns out to be 2.4:1. The uncertainty enters in that protons are more likely to make such stars than are neutrons. In the absence of any information on this matter, Burcham *et al.* have to assume that this relative probability is unity. Secondly, Burcham *et al.* have assumed that the ratio of the (p,pn) to the $(n,2n)$ cross sections is 2.4:1, independent of energy. We doubt that the ratio is this large. Let us assume that at 400 Mev $\sigma(p,pn)$ is known to be about 34 mb. Then calling the $(n,2n)$ cross sections given in reference 12 equal to 20 mb, we compute a ratio of 1.7 or considerably smaller than 2.4. It seems plausible that this ratio should get even smaller at high energies. Burcham *et al.* used a self-absorption correction of 3 percent for 5-mg/cm foils counted in 4π geometry. This is half way between the corrections used by Crandall and by us, and the

[14] N. M. Hintz and N. F. Ramsey, Phys. Rev. **88**, 19 (1952).

[15] Burcham, Symonds, and Young, Proc. Roy. Soc. (to be published).

uncertainty seems small compared with the uncertainty in activation by neutrons.

2. $Al^{27}(p,3pn)Na^{24}$

An alternative monitoring reaction is $Al^{27}(p,3pn)Na^{24}$, whose cross section is usually determined relative to that of $C^{12}(p,pn)C^{11}$.

Figure 4 shows the results of measurements of the ratio of $\sigma[C^{12}(p,pn)C^{11}]/\sigma[Al^{27}(p,3pn)Na^{24}]$ below 1 Bev known to date.[16]

The Birmingham and Brookhaven points include a 12 percent correction for the difference in backscattering between electrons and positrons. There is no such correction for the Columbia ratio, where the counting was done on cardboard backings for which the difference was expected to be small, or for the Chicago ratio whose geometry was chosen to minimize the need for this correction. Since the errors in the measurement of this ratio come largely from the determination of the relative counter efficiency for electrons and positrons, the experimental data seem to indicate that these efficiencies are not measured properly for end-window counters. We thus are of the opinion that C^{11} is to be preferred as a monitor reaction for proton beams until this matter of relative counter efficiencies is better understood. This criticism does not apply to the absolute measurements of Marquez[17] and Crandall *et al.*[1]

V. CONCLUSIONS

We have measured the cross section for $C^{12}(p,pn)C^{11}$ at 461 ± 3 Mev and find $\sigma=31.1\pm1$ mb. The eventual resolution of a controversy (see Sec. IID2) on self-absorption corrections in 4π counting may raise this 3 percent, but at present, we see no reason to change our result.

The recent changes in the $C^{12}(p,pn)C^{11}$ cross section will, of course, affect those experiments in which C^{11} has been used as a monitor. Crandall *et al.*[1] have discussed these changes for p-p scattering and have given references for a number of other experiments with the exception of pion production, which will be covered in a paper on pion production by Hildebrand *et al.*[18]

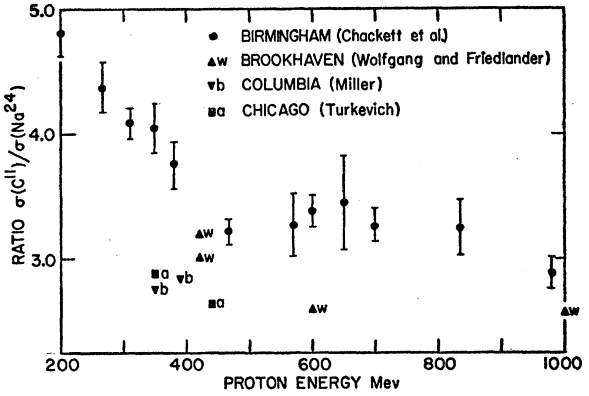

FIG. 4. Summary of cross sections for $Al^{27}(p,3pn)Na^{24}$ relative to $C^{12}(p,pn)C^{11}$ below 1 Bev.

We have found our technique of ion chamber calibration with nuclear track plates to be accurate and economical of accelerator time. Until the counting of C^{11} positrons is sufficiently well understood to permit carbon-monitoring, we prefer the track plate method to any other for accurate calibration. The commonly used Faraday cup becomes unduly cumbersome and expensive at high energy, in addition to being subject to uncertain corrections for secondary emission from the vacuum window and cup face.

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[16] R. L. Wolfgang and G. Friedlander, Phys. Rev. **96**, 190 (1954); Chackett, Chackett, Reasbeck, Symonds, and Warren (to be published).

[17] L. Marquez, Phys. Rev. **86**, 405 (1952).

[18] Hildebrand, Rosenfeld, and Solmitz (to be published).