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$C^{12}(p,pn)C^{11}$ CROSS SECTION FROM THRESHOLD TO 340 MEV

R. Lee Aamodt, Vincent Peterson, and Robert Phillips

September 14, 1951

Berkeley, California

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ABSTRACT

The excitation function for the reaction $C^{12}(p,pn)C^{11}$ has been measured from threshold to 340 Mev using the Berkeley 40 ft. linear accelerator and 184-inch cyclotron. Absolute cross section measurements were made at various energies, using a Faraday cup and calibrated beta-counter. The threshold occurs at (18.5 ± 0.3 Mev). The cross section has a broad maximum of 100 millibarns near 45 Mev and decreases to 43 millibarns at 340 Mev.

I. INTRODUCTION

The formation of radioactive C^{11} from C^{12} by high energy particles (protons, neutrons, deuterons, and alpha-particles) has been widely used at this laboratory as a monitor and detector.[1-6] These reactions have threshold near 20 Mev and therefore discriminate against low energy background. The positron activity of

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1. A. C. Helmholz, E. M. McMillan, and D. C. Sewell, Phys. Rev. 72, 1003 (1947)
2. W. W. Chupp, E. Gardner, and T. B. Taylor, Phys. Rev. 73, 742 (1948)
3. L. Cook, E. M. McMillan, V. Peterson, and D. C. Sewell, Phys. Rev. 75, 7 (1949)
4. A. Bratenahl, S. Fernbach, R. Hildebrand, C. Leith, and B. Moyer, Phys. Rev. 77, 597 (1950)
5. S. B. Jones and R. S. White, Phys. Rev. 78, 12 (1950)
6. W. J. Knox, Phys. Rev. 81, 687 (1951)

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C^{11} (0.97 Mev, 20.5 min.)[7] is convenient for short activation and counting periods. Carbon targets are readily available in the form of graphite or polystyrene.

Knowledge of the variation of the cross section with energy and the absolute value of the cross section is important to the extensive use of such reactions. The $C^{12}(p,pn)C^{11}$ reaction is of particular interest because of the number of existing proton accelerators. A considerable amount of work, both experimental and theoretical, has already been done at the Radiation Laboratory on this reaction. Before the 184-inch cyclotron was converted from deuteron to proton acceleration, Chupp and McMillan[8] measured the relative excitation curve up to 140 Mev using protons "stripped" from 190 Mev deuterons inside the cyclotron vacuum tank. Using this proton source, McMillan and Miller[9] determined the absolute cross section at 62 Mev. More recently Panofsky and Phillips,[10] working with the Berkeley 32 Mev proton linear accelerator, established the excitation curve up to 27 Mev. In particular they studied the region just above the threshold in detail where the reaction was shown to be $C^{12}(p,d)C^{11}$. Heckrotte and Wolff[11] have calculated the excitation curve to be expected for both the (p,pn) and (n,2n) reactions up to 100 Mev using a model of the nucleus proposed by R. Serber.

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7. E. Siegbahn and E. Born, Arkiv, Mat. Astron. Fysik 30 B, No. 3.
8. W. W. Chupp and E. M. McMillan, Phys. Rev. 72, 873 (1947).
9. E. M. McMillan and R. D. Miller, Phys. Rev. 73, 80 (1948)
10. W. K. H. Panofsky and R. Phillips, Phys. Rev. 74, 1732 (1948)
11. W. Heckrotte, P. Wolff, Phys. Rev. 73, 264, 265 (1948)

The new experimental work described here was performed mainly after an external deflected beam of 340 Mev protons became available from the 184-inch cyclotron. Absolute measurements of the (p,pn) cross section at proton energies of 340 Mev and below were then possible with a well-collimated beam. Additional work with the linear accelerator has extended the previous excitation curve up to 32 Mev, and an absolute determination of the cross section at 32 Mev has been made with improved accuracy. Considerable effort has been spent in the preparation and calibration of a beta-ray standard in order to establish the absolute values of the cross section over the entire energy range. Preliminary results of this work have been published.[12] Experiments using these early values have been described in the literature.[13]

II. EXPERIMENTS USING 340 MEV PROTONS

A. Deflected Proton Beam

Experiments requiring a well-collimated beam of high energy charged particles have been made possible by the electrostatically deflected beam of the 184-inch cyclotron. The deflected beam is bent through about 20 degrees by an auxiliary magnet after emerging from the cyclotron tank. The beam may be collimated at two positions, one just before entering the auxiliary "bending" magnet and the other at the exit end ("snout") of the 22-foot long tube passing through the concrete shielding. The "snout" collimator is a 48-inch long brass column with an axial 2-inch diameter cylindrical opening into which collimating tubes of smaller apertures may be fitted. During most of the runs described

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12. L. Aamodt, V. Peterson, and R. Phillips, Phys. Rev. 78, 87(A) (1950); and L. Aamodt, V. Peterson, and R. Phillips, UCRL-526 (1949)

13. O. A. Towler and C. L. Oxley, Phys. Rev. 78, 326 (A) (1950); R. Birge, U. E. Kruse, and N. F. Ramsey, UCRL-1097 (1951); R. B. Holt and J. W. Meadows, Bull. APS 26, 17 (1951); N. M. Hintz, Bull. APS 26, 17 (1951)

here the exit collimator hole was 1 inch in diameter. The beam emerges to the air directly after collimation through a 0.010 inch thick aluminum window.

Under normal conditions a 340 Mev proton beam of intensity varying from 10^{-12} to 10^{-10} amperes, depending on collimation conditions, is available. The pre-magnet collimator is adjusted until the size of the beam striking the exit collimator is nearly the size of the exit hole. Neutrons and low energy protons produced at the pre-magnet collimator are eliminated from the final beam by the bending magnet. Neutrons formed by protons striking the 48 inch brass column are greatly attenuated in intensity. Using a 1 inch hole, the angular spread of protons emerging into the air is about 0.004 radian.

B. Inadequacy of "Stack" Technique

Measurement of the relative activity of foils interleaved with absorbing material gives a relative excitation curve, provided the bombarding flux throughout the stack is constant. For 340 Mev protons the range in the absorber is so great that nuclear absorption removes more than half the protons by the end of the range. For this reason, separate absolute measurements of the (p,pn) cross section were made at various energies from 340 to 93 Mev by bombarding a polystyrene foil directly in front of the Faraday cup used to measure the proton current. The acceptance angle of the Faraday cup is large enough ($\sim 60^{\circ}$) that nuclear elastic scattering does not result in loss of protons at the cup after they have passed through the foil.

Foils placed beyond the end of the proton range gave activities of about 0.8 per cent of the initial activity. This indicates that the background of neutrons (>20 Mev) is negligible despite the absorptions of protons in slowing down. The expected neutron activity can be estimated from independent

measurements of yields* and angular distribution[14] of neutrons produced by high energy protons, and from the known $C^{12}(n,2n)C^{11}$ cross section.[15] It agrees within a factor of two with the measured activity.

C. Description of Apparatus

The experimental arrangement used in most of the absolute cross section determinations is shown in Fig. 1. The 340 Mev collimated proton beam emerges from the "snout" window, travels a short distance in air and then impinges upon a copper absorber placed on the beam axis directly in front of the Faraday cup. The absorbers are 3 inches in diameter and the thickness is varied to reduce the proton energy to the desired value. Polystyrene foils of the same diameter are placed directly behind the absorber. The Faraday cup is placed as close as possible to the foil and absorbers, and all three are carefully aligned on the beam axis by exposing films.

The Faraday cup is a solid cylinder of brass, 6 inches in diameter and 6 inches long. (The range of 340 Mev protons in copper is 4.1 inches.) On the incident surface a projecting collar helps to prevent the loss of secondary electrons from the cup. A 0.001 inch aluminum foil is mounted directly in front of the collar. Various potentials can be applied to the foil to study the effect of secondary electron emission. The brass cup and electron suppressing foil are insulated from the vacuum chamber body by polystyrene standoffs and a guard ring between the cup and foil prevents leakage currents to the cup. The electrical

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* See reference 6. The neutron detectors were Bi fission chambers having a 50 Mev threshold.

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14. R. D. Miller, D. C. Sewell, and R. W. Wright, Phys. Rev. 81, 374 (1951)

15. E. M. McMillan and H. F. York, Phys. Rev. 73, 262 (1948); and R. L. Mather and H. F. York (private communication). The (n,2n) cross section is 20± 4 millibarns for neutrons of mean energy of 90 Mev.

connections to the cup and foil are made through the chamber wall by means of Teflon insulated coaxial plugs.

The pressure within the Faraday cup is maintained below 10^{-4} mm Hg in order to prevent leakage of charge from cup due to ionization of the air. At pressures above 10^{-2} mm the electrons and negative ions are drawn by the positive potential of the cup in sufficient numbers to partially neutralize the charge on the cup. This is evident from Fig. 2, in which the relative charge collected by the Faraday cup (monitored by an ion chamber) is plotted against the Faraday cup pressure for a 340 Mev proton beam. At about 1/2 mm Hg the conduction of the ionized air inside the cup is so high that the potential of the cup remains zero despite a steady beam. At still higher pressures the cup begins to collect charge again, this being interpreted as due to the effects of recombination of the ion pairs formed before the negative ions can be drawn to the cup. The charge collected at atmospheric pressure fluctuates badly and is about 20 per cent of the charge measured at very low pressures.

The charge accumulated by the Faraday cup was collected on a low leakage polystyrene condenser.* The voltage across the condenser was determined using a "slide-back" voltmeter, i.e., a voltage of opposite sign to the collected charge is applied to the low impedance side of the condenser until it is exactly equal to the potential drop across the condenser. The adjustment is determined by the null indication of a high input impedance (10^{14} ohms) electronic voltmeter (using VX32 electrometer tubes) as shown in Fig. 3. In such an arrangement the capacity to ground of the Faraday cup and connecting cables does not enter into the charge determination since the final potential drop across it is

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* Polystyrene insulated condensers manufactured by the John E. Fast Co., Chicago, Illinois.

zero. The integration condensers were calibrated by comparison with standard condensers* by bridge methods both at 1000 cycles/sec and at low frequency (repeated d.c. impulses). The values obtained by the two methods agreed to within 0.3 per cent and this is taken to be the limit of error due to short-term dielectric absorption. Essentially the same capacity values were obtained by the d.c. bridge method for steady-state balance.

It is essential that the leakage resistance of the integration system be either very high or accurately known so that a negligible or known amount of charge leaks from the condenser during the course of the run. The time constant of the entire integrating system, including the Faraday cup, could be determined before or after each run by watching the decay of a potential induced across the condenser. Two methods of integration were used during the course of the experiments. At first a great deal of care was taken to preserve the high leakage resistance of the integration system, so that the RC time constant was very much greater than the period of integration (20 to 100 hours vs. 20 minutes). In this method it was necessary to read the voltage as a function of time to account for occasional fluctuations in the beam current. Later these requirements were made unnecessary by adjusting the RC to exactly equal the mean life of the C^{11} activity. Using Victoreen vacuum-sealed resistors of approximately 10^{12} ohms the RC could be matched within 1/2 per cent, and remained constant from one run to another. In this manner the amount of charge collected across the condenser is at all time directly proportional to the amount of C^{11} radioactivity present in the foil.**

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* General Radio Company mica condensers calibrated at 1000 cycles/sec to ± 0.1 per cent.

** This method was suggested to us by W. K. H. Panofsky

The emission of secondary electrons from metal surfaces traversed by the proton beam inside a Faraday cup may produce an error in the proton current determination. According to a simple classical picture of secondary electron emission[16] the production of secondary electrons varies approximately as 1/E, where E is the energy of the primary particle. Thus the magnitude of the effect may be expected to be about 1/10th as great for 340 Mev protons as compared to 32 Mev protons. A vertical stray magnetic field from the cyclotron of about 25 gauss at the Faraday cup prevents electrons of less than 1 kilovolt kinetic energy from escaping. Experimental determinations of the effect of secondary emission were made by varying the bias voltage on the suppressor foil, and by the use of additional magnetic fields. Fig. 4 shows the relative current to the Faraday cup for bias voltages of +500 to -500 volts. A slight effect is just discernible above experimental error (± 1 per cent) when only the stray magnetic field is present. With an auxiliary magnetic field of 100 gauss the current is independent of bias voltage. At zero bias, no effect was noted in removing the 100 gauss field. It is therefore concluded that the error in charge collection due to secondary electron emission is, for 340 Mev protons, less than 1 per cent for this geometry. A larger effect is noted for 32 Mev protons (see Section III).

The dimensions of a Faraday cup to contain 340 Mev protons must account not only for the range of these penetrating particles, but also for their lateral motion due to scattering. If the diameter of a cylindrical cup is too small, charge will be lost through the sides due to nuclear or multiple Coulomb scattering. The r.m.s. lateral displacement of 340 Mev

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16. For a classical treatment of secondary emission phenomena and reference to experimental work, see E. M. Baroody, Phys. Rev. 78, 780 (1950).

protons due to multiple Coulomb scattering in slowing down to the end of their range in copper, calculated using Foldy's formula,[17] is 0.45 cm. Assuming a Gaussian distribution in displacement, one may therefore estimate that the radius of the Faraday cup must be 2.25 cm greater than the radius of the beam in order to contain 99.9 per cent of the Coulomb scattered protons. Nuclear elastic scattering of protons in copper should not produce a measurable loss of charge since the diffraction pattern is relatively narrow (half-width at first minimum is 7.87°).[18] In order to test these conclusions experimentally, a series of copper Faraday cups of increasing diameter were used to stop a 1 inch diameter 340 Mev proton beam. The relative current retained by each cup as a function of its diameter is shown in Fig. 5. It can be seen that the cup diameter should be at least two inches greater than the maximum diameter of a full energy beam. The Faraday cup adopted for use in these experiments was 6 inches in diameter. A sensitive test to set an upper limit on the total charge lost by this cup was made by placing nuclear emulsions (Ilford C-2) at selected points around the sides and rear of the cup during a bombardment by full energy protons. Protons of energies below 50 Mev leave detectable tracks, even if passing normal to the 100 micron emulsion, and consideration of the total surface area of the cup leads to an upper limit of 0.02 per cent of the incident beam lost.

Considering all the sources of error in making an absolute measurement of charge collected by the Faraday cup, it is felt that the results are good to

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17. L. L. Foldy, Phys. Rev. 75, 311 (L) (1949)

18. Angular distribution of diffracted protons and variation with energy based on optical model of nucleus is given by S. Fernbach, R. Serber, and T. B. Taylor, Phys. Rev. 75, 1352 (1949).

± 2 per cent. In relation to the difficulties in determining the absolute number of beta particles emitted by the radioactive foils (discussed in Section IV), the charge measurement is a minor source of error in determination of the absolute cross section.

D. Absolute Cross Section Measurements

Direct measurements of the number of protons required to produce C^{11} activity in 0.005 inch polystyrene foils were made for proton energies down to 93 Mev using the general arrangement of Fig. 1. Bombardment periods of 10 to 20 minutes were used. The foils were counted on the lower shelves of an end-window Geiger counter and their counting rates compared with those of a standard beta source (see Section IV). If a polystyrene $(C_8H_8)_n$ foil $\underline{w}$ (mg/cm^2) thick is bombarded for a time $\underline{T}$ by a constant current $\underline{I}$ ($\mu\mu$ amps) of protons, the cross section (in millibarns) per carbon atom for producing C^{11} activity is:

$$\sigma(\text{mb}) = 3.44 \frac{N'(T)}{(1-e^{-\lambda T})\, wI} \qquad \text{(Method A)}$$

where $N'(T)$ is the number of C^{11} disintegrations/sec. at the end of bombardment. In actual practice the proton current from the cyclotron often varies abruptly by as much as a factor of two during the course of a run. The several contributions to the total activity time T must then be computed for each interval of constant current. This is a tedious task and inaccuracies may result from the determination of the slope of the voltage/time curve. A more desirable method is to adjust $RC = 1/\lambda$. In this case:

$$\sigma(\text{mb}) = 0.00612 \frac{N'(t)}{Q(t)} \cdot 1/w \qquad \text{(Method B)}$$

where $Q(t)$ is in micro coulombs, read at the same time that $N'(t)$ is determined.

The use of absorbers to reduce the proton beam energy introduces range straggling which limits the usefulness of this method to energies above 100 Mev if one wishes energy definition within ± 10 per cent. The r.m.s. straggling in range and energy of an initially monochromatic 340 Mev proton beam in copper is shown in Fig. 6, calculated from standard formulas.[19] An energy spread of 0.5 per cent in the primary proton beam[20] increases the observed energy inhomogeneity. The use of lower Z absorbers would not reduce the total straggling significantly since for copper the parts contributed by the primary beam energy spread and absorber are approximately equal. At 32 Mev mean energy the energy spread due to both sources is about ± 20 Mev, making it difficult to establish a direct connection between cyclotron and linear accelerator absolute measurements.

Another difficulty inherent in using a degraded energy beam is multiple Coulomb scattering which produces broadening and angular divergence of the proton beam. Fig. 7 shows calculated curves for r.m.s. lateral displacement (y) and plane-projected scattering angle (θ_0) for 340 Mev protons in copper. The lateral spread of the beam has been measured experimentally by counting annular rings in a foil. These measurements agree with the calculated lateral distribution and show, for example, that 99 per cent of the activity will be contained within a circle whose diameter is 2 inches at 100 Mev. However, it is also important that all the proton flux passing through the foil should also enter the Faraday cup which has an angular acceptance of ± 30 degrees from beam axis. Assuming a

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19. M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. 9, 283 (1937)

20. C. J. Bakker and E. Segrè, Phys. Rev. 81, 492 (1951)

Gaussian angular distribution $P(\theta)\, d\Omega = \frac{1}{\theta_0^2} e^{-\frac{\theta^2}{2\theta_0^2}} \sin\theta d\theta$, 99 per cent of the beam will be contained within a cone whose half-angle is $3\theta_0$. Fig. 7 shows that $3\theta_0$ is appreciably less than 30 degrees except near the end of the range.

Absolute cross section measurements using absorber and foil placed close to the Faraday cup window were made for proton energies ranging from 3[illegible] Mev to 93 Mev, or for absorber thicknesses of 0 gm/cm^2 to 82 gm/cm^2. A summary of the results is given in Table I. The probable errors are due mainly to counting statistics but do <u>not</u> include the absolute errors of beta-standardization. Absolute measurements were not extended below 93 Mev because of the increasing energy spread, difficulties in counting and extended beta-sources, and possible loss of proton flux from the Faraday cup.

TABLE I

<u>Absolute Cross Section Measurements</u>

<u>Berkeley Cyclotron</u>

Proton Energy (Mev)	Number of Runs	Cross Section Mean Value (millibarns)	P.E. of Mean (millibarns)
340	12	41.2	0.6
313	1	47.6	2.1
293	5	47.7	1.0
263	1	50.5	2.6
245	4	49.8	1.2
194	3	52.0	1.5
144	3	56.5	1.5
93	1	70.5	3.6

E. Intermediate Energy Region - 32 Mev to 100 Mev

The energy spread of the proton beam from the Berkeley cyclotron rapidly increases at degraded energies so that only the general outlines of the excitation curve can be observed. Fortunately, Dr. N. M. Hintz has investigated the $C^{12}(p,pn)C^{11}$ reaction using magnetically focussed 110 Mev protons in the Harvard cyclotron. This proton energy is ideally suited to provide data in the region 32 to 100 Mev, and Dr. Hintz has kindly consented to allow us to include his results. The relative excitation curve, corrected for nuclear absorption in brass absorbers (1.1 barns) and then fitted to the Berkeley data, is shown in Fig. 12. For the fit, both curves were plotted using a semi-logarithmic scale for the cross section and a linear scale for the energy. Adjustment was made along both cross section and energy scales to achieve the best match of the shapes in the steeply rising region from 20 to 30 Mev. When this is done, the curve also agrees within the probable error with the Berkeley cyclotron data at 93 Mev.

III. EXPERIMENTS WITH 32 MEV PROTONS

A. Relative Excitation Curve

Previously reported measurements[10] include data on the relative excitation curve from threshold (18.5 ± 0.3 Mev) to 27 Mev using the Berkeley 32 Mev proton linear accelerator. Using the same stacked foil technique the excitation curve has now been extended up to full beam energy.

Stacks of 0.010 in. polystyrene foils were bombarded by the full energy beam, and the foils were then counted with an end-window Geiger counter. In order to obtain good counting statistics, only enough foils were counted to

obtain a sufficient overlap with the previously established curve. The curve of the run which yielded the highest activity, fitted to the data from threshold to 27 Mev is shown in Fig. 8. The probable errors shown are due to counting statistics. The two curves overlap for about 2-1/2 Mev in a region where a bend permits accurate activity and energy normalization. The fitting of the two curves does not permit a shift of more than ± 0.15 Mev, which introduces an uncertainty of only 2 millibarns at the full energy. Although the incident energy of the beam may vary downward as much as 1 Mev, the best fit results from assuming the incident energy to be the same as for the lower part of the curve (32.0 ± 0.1 Mev).

A foil placed beyond the proton range as a neutron monitor showed that error from this source could be considered negligible.

Due to the comparatively small thicknesses of absorbers used to slow down 32 Mev protons, no nuclear absorption correction has been applied to the activity curves. Furthermore due to the small beam diameter (1/4 inch) relative to foil diameter (1 inch), no scattering loss is expected.

B. Absolute Cross Section at 32 Mev

The absolute cross section measurements at 32 Mev previously reported[10] have been extended and improved, primarily as regards beta-standardization (Section IV) and determination of the effects of secondary electrons. Thin (0.010 inch) polystyrene foils were bombarded at full beam energy, and the current was collected in a Faraday cup. Due to high average beam intensity ($\sim 10^{-8}$ amps.) it is possible to use short bombardments (6 to 120 sec.) and therefore render negligible any error due to inconstancy of the beam current. The electrometer tubes and integration condensers are contained within the cup vacuum chamber. The methods of charge determination have been described in Section II-C.

A total of 34 separate runs were made on the absolute cross section

at full beam energy. Three different target-Faraday cup arrangements were used as shown in Fig. 9 in order to assess and eliminate the error due to secondary electron emission. In the early runs as illustrated in Fig. 9a a cylinder at high (8000 v) negative potential removed most low energy charged particles from the beam before it entered the Faraday cup. The cup aperture was only 3/4 inch diameter, with the target foil inside. Since the solid angle of this aperture to particles emitted from the target area is only 1-1/2 percent (of 4π), this geometry might be expected to trap nearly all of the secondary electrons. However, it does not readily provide a means of measuring the magnitude of the effect.

Intermediate runs as shown in Fig. 9b were made with the target foil outside the cup chamber and a secondary-suppressing cylinder before the cup. The cylinder bias was kept at 200 to 400 volts negative. A series of foils was bombarded with different voltages on the cylinder. The results indicate that secondary electron emission from the Faraday cup decreases by approximately 5 per cent as the bias is decreased from 0 to 400 volts. This figure agrees with the secondary emission check made by Cork[21] for 32 Mev protons.

The final runs as shown in Fig. 9c were made with a permanent magnet which produced a field of 400 gauss inside the Faraday cup. A variation of suppressor voltage from 0 to 400 volts produced no observable change in the cross section.

The average values of the measured cross section using the three methods of integration are shown in Table II. The agreement between methods, combined with the voltage effects noted above, indicates that most of the secondary electrons are of low energy and that the suppression measures employed were adequate. The estimated systematic error in cross section due to secondary electron effects is 3 per cent.

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21. B. Cork, Phys. Rev. 80, 321 (1950)

The finally adopted value at 32 Mev is

$$\sigma_{32\ Mev} = 89 \pm 4 \text{ millibarns.}$$

The uncertainty includes errors due to integration and counting statistics but does not include the probable error in beta-standard calibration.

TABLE II

Method	Number of Runs	Mean Value (millibarns)	P. E.* (millibarns)
A	23	88.1	1.5
B	4	84.0	4.6
C	7	92.6	1.6
Combined		88.5	1.0

* Probable error of mean from spread in measured values.

IV. ABSOLUTE BETA ACTIVITY DETERMINATION

The absolute values of the cross section are dependent on a knowledge of the number of C^{11} nuclei produced in the target foil, and therefore, the disintegration rate at a later time. This rate is found by comparing the counting rate of the target foils with the counting rate of various β emitters of known disintegration rate under identical geometrical conditions.

Ideally, foils used for absolute beta activity determination should be very thin to minimize self-absorption and scattering in the source. The necessity for sufficient activity in short bombardments sets a lower limit on foil thickness, however, and 0.005 inch (~13 mg/cm^2) and 0.010 inch polystyrene foils were used in the cyclotron and linear accelerator runs. The foils were counted on the lower shelves on an end-window Geiger-Mueller counter of 2 mg/cm^2 window thickness. The geometry is shown in Fig. 10.

Significant corrections for absorption and scattering of low energy beta particles in the source, air and counter window must be made if the geometry or beta spectrum of the target foil and standard are different. These corrections are difficult to assess and involve dubious extrapolations to zero thickness. Here such corrections have been avoided by choosing beta-standards of nearly the same energy as C^{11} and counting them in geometries as nearly like that of the C^{11} foil as possible. Half-thicknesses of polystyrene foils were placed above and below the active deposit in counting standards, and the same foil holders were used. Since the standards were effective point sources, a small geometrical correction for the finite extent of the active region of the cyclotron-bombarded foils had to be made. This correction was based on a series of measurements, as shown in Fig. 10, of counting rate as a function of lateral position off the counter axis, made by Mrs. Beverly Lee in this Laboratory. The counting rate of a uniform distribution of

activity over a one-inch diameter centered circle, as compared to a point source on the axis, is 6 per cent low on the 3rd shelf, and 3 per cent low on the 4th shelf.

Several beta-standards of energies bracketing that of C^{11} (0.97 Mev) were used: Au^{198} (0.92 Mev), RaE (1.17 Mev), and Na^{24} (1.4 Mev).[22] Both Au^{198} and Na^{24} have well-established simple decay schemes[23] which make them suitable for calibration by the beta-gamma coincidence method.[24] The RaE was calibrated by counting the alphas from the daughter RaF in a standard geometry alpha counter. The alpha count was made several times over a period of four half-lives to insure that the RaF was in equilibrium with the RaE. Each of these standards was then used to calibrate the beta-counter for C^{11} betas under specific conditions of geometry and foil thickness.

If the standard is calibrated at N_s disintegrations per minute, and counts at the rate of N_1 c/m, as compared with N_2 c/m for the C^{11} foil, then we say $(N_2/N_1)\ N_s = N_c$, the disintegration rate of the C^{11} foil. It is convenient to interpose a long lived secondary standard and assigning it a number of "equivalent" d/m. If it counts at a rate N_3 c/m we say this number $N_{eq.} = (N_3/N_1)N_s$. Then if at a later time the C^{11} is counted in the same geometry, it is satisfactory to say $N_c = (N_2/N_3)N_{eq.}$ since this equals $(N_2/N_3)\ (N_3/N_1)N_s = (N_2/N_1)N_s$ as before.

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22. G. T. Seaborg and I. Perlman, Rev. Mod. Phys. 20, 585 (1948)

23. C. L. Peacock and R. G. Wilkinson, Phys. Rev. 74, 297 (1948)
C. S. Cook, E. Jurney and L. M. Langer, Phys. Rev. 70, 985 (1946)

24. W. Siri, Isotopic Tracers and Nuclear Radiations (McGraw-Hill, 1949), Ch. 13. The Na^{24} sample was kindly made available by Dr. C. A. Tobias, as was the coincidence-counting equipment.

Obviously this number $N_{eq.}$ must be redetermined when the target thickness or the geometry is changed.

Values of $N_{eq.}$ for the various standards with geometry shown appear in Fig. 11, where the probable errors, including the standardization statistical probable error, are shown. It is assumed that the proper value of $N_{eq.}$ for a known C^{11} activity would lie somewhere in the shaded area (± 7.5 per cent probable error).

V. DISCUSSION OF RESULTS

The combined data from the Berkeley linear accelerator, Harvard cyclotron, and Berkeley cyclotron is plotted in the final curve of Fig. 12. The probable errors shown are those of absolute measurements but only relative to one another, i.e., they do not include the probable error of 7-1/2 per cent in beta-standard calibration.

An independent absolute measurement at 62 Mev by McMillan and Miller,[9] in which the present uranium "intermediate" beta-standard was used as the primary standard, may be corrected in view of a more accurate calibration of the equivalent C^{11} beta-activity of the uranium. The corrected value is 82 ± 11 millibarns and is plotted for comparison in Fig. 12.

The earlier experiments of Chupp and McMillan,[8] using stacks of graphite plates bombarded internally in the cyclotron with protons stripped from deuterons, indicated that the excitation curve was flat from 140 to 60 Mev. No correction for nuclear absorption was made in these earlier experiments. However, a correction based on a nuclear absorption cross section of 0.25 barns in carbon does not entirely account for the discrepancy apparently. The remaining discrepancy results from some other source of error, probably a

contamination of the proton beam inside the cyclotron tank from lower energy particles.

The shape of the excitation curve has several features of interest. As shown earlier by Panofsky and Phillips,[10] the low threshold energy provides definite evidence for the existence of a (p,d) reaction in this region. Evidence for the persistence of the (p,d) reaction with good probability for protons of 32 Mev occurs in the independent experiments of Levinthal, et. al.[25] In this energy range the (p,pn) and (p,d) reactions represent inelastic processes best described by the theory of the compound nucleus. The low energy excitation curve, Fig. 8, exhibits irregularities which are experimentally significant but difficult to analyze in terms of the capture process. The peak of the curve occurs at 45 Mev, in agreement with the calculations of Heckrotte and Wolff[11] but the width of the peak is considerably greater than their evaporation theory estimates.

At higher energies noncapture processes may be expected to become more important.[26] Heckrotte and Wolff[11] have considered the effects of (a) noncapture excitation or a (p,n) exchange, followed by evaporation of a single neutron or proton, and (b) direct "knockout" of a neutron. The resulting curve is nearly flat up to 140 Mev, the limit of the calculations. The experimental curve does not show this plateau but decreases with energy approximately as $E^{-1/2}$ above 60 Mev. This energy dependence is very similar to that of the neutron total cross section in carbon, and the C^{11} cross section is about one-sixth as large.[2,27]

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25. C. Levinthal, E. Martinelli, and A. Silverman, Phys. Rev. 78, 199 (1950)

26. R. Serber, Phys. Rev. 72, 1008 (1947)

27. J. DeJurén, Phys. Rev. 81, 919 (1951)

It is of interest to note that the (p,d) contribution to C^{11} production may be significant even at high energies. The experiments of Hadley and York[28] show that half as many deuterons as protons are knocked out of carbon by 90 Mev neutrons. If the deuterons are formed in a "pickup" process,[29] one would also expect them from proton bombardment. The total cross section for deuteron formation in carbon by 90 Mev neutrons was estimated at 20 millibarns.

The dip in the $C^{12}(p,pn)C^{11}$ cross section at 340 Mev represents a significant change from the gradual decrease in cross section at high energies. An estimate of the C^{11} background produced by secondary neutrons formed in the copper absorbers amounts to only 1/4 millibarn increase. The C^{11} activity in the foils showed no signs of contamination by radioactive recoil ions from the copper. The only known high energy reaction having a threshold in this region is meson production with a total cross section of about 6 millibarns, but it is not immediately obvious how this could directly compete with C^{11} formation.

VI. ACKNOWLEDGMENTS

We wish to thank Prof. W. K. H. Panofsky for his constant advice and encouragement throughout the history of this experiment. The generosity of Dr. N. M. Hintz in allowing us to incorporate his data is greatly appreciated. This work was sponsored by the Atomic Energy Commission.

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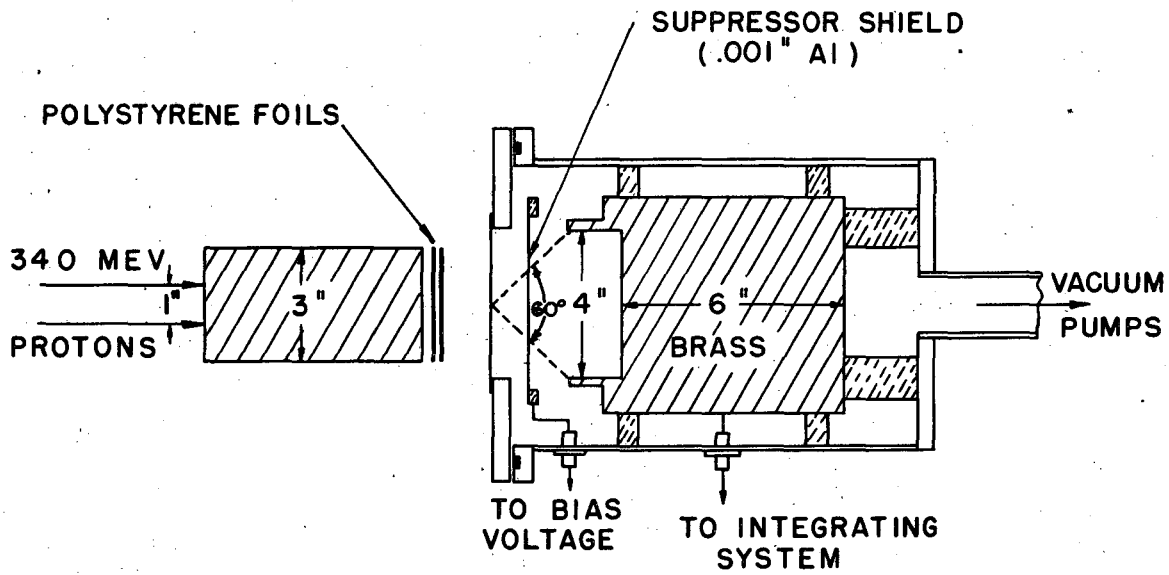
28. J. Hadley and H. York, Phys. Rev. 80, 345 (1950)

29. G. F. Chew, and M. L. Goldberger, Phys. Rev. 77, 470 (1950)



DEFLECTED BEAM GEOMETRY

MU 2385

Fig. 1

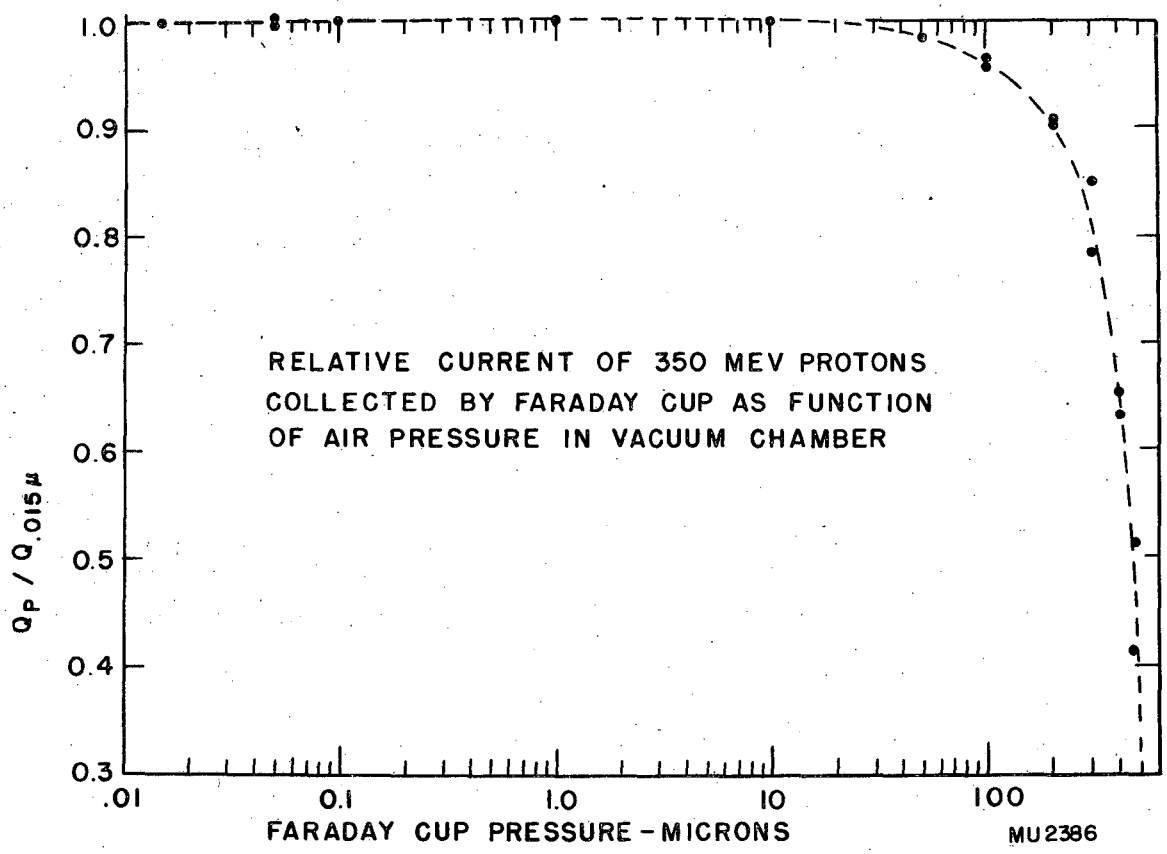
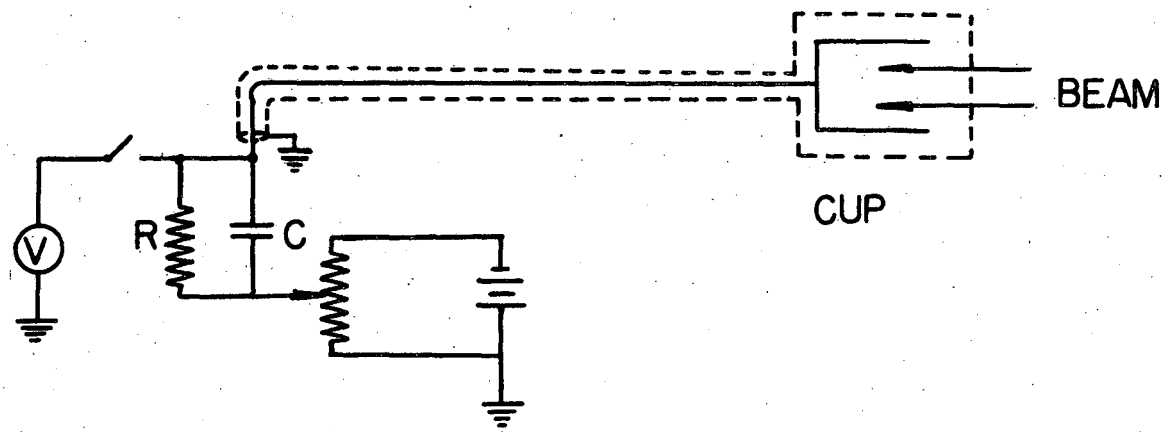

RELATIVE CURRENT OF 350 MEV PROTONS
COLLECTED BY FARADAY CUP AS FUNCTION
OF AIR PRESSURE IN VACUUM CHAMBER
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
$Q_P / Q_{.015\mu}$
.01
0.1
1.0
10
100
FARADAY CUP PRESSURE - MICRONS
MU2386

Fig. 2

"SLIDE - BACK" VOLTMETER



METHOD A: $R \sim 10^{14}\,\Omega$ $RC \gg 20$ MIN.

METHOD B: $RC = \frac{1}{\lambda} = 29.6$ MIN.

MU 2387

Fig. 3

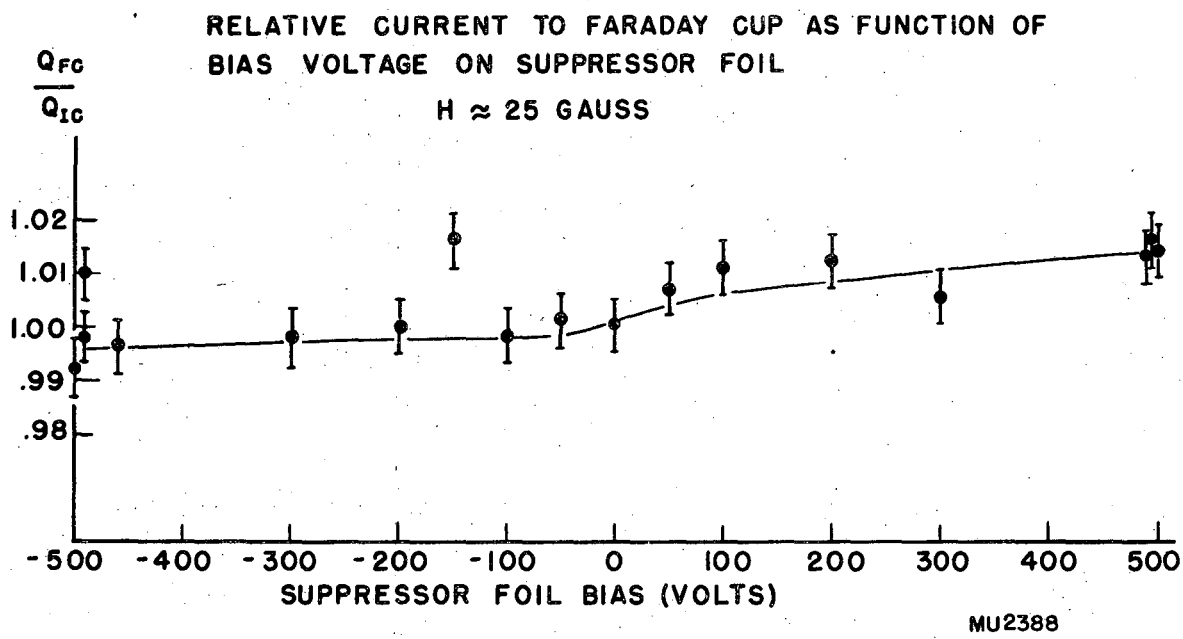

RELATIVE CURRENT TO FARADAY CUP AS FUNCTION OF
BIAS VOLTAGE ON SUPPRESSOR FOIL
H ≈ 25 GAUSS
Q_{FC} / Q_{IC}
1.02
1.01
1.00
.99
.98
-500
-400
-300
-200
-100
0
100
200
300
400
500
SUPPRESSOR FOIL BIAS (VOLTS)
MU2388

Fig. 4

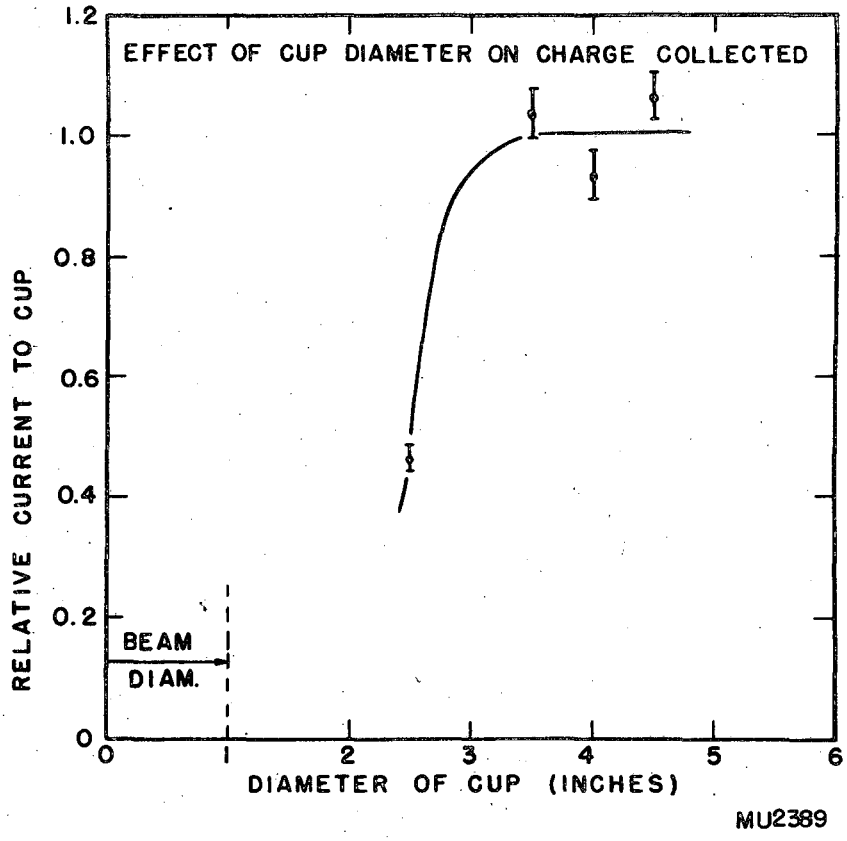

EFFECT OF CUP DIAMETER ON CHARGE COLLECTED
RELATIVE CURRENT TO CUP
1.2
1.0
0.8
0.6
0.4
0.2
0
BEAM
DIAM.
0
1
2
3
4
5
6
DIAMETER OF CUP (INCHES)
MU2389

Fig. 5

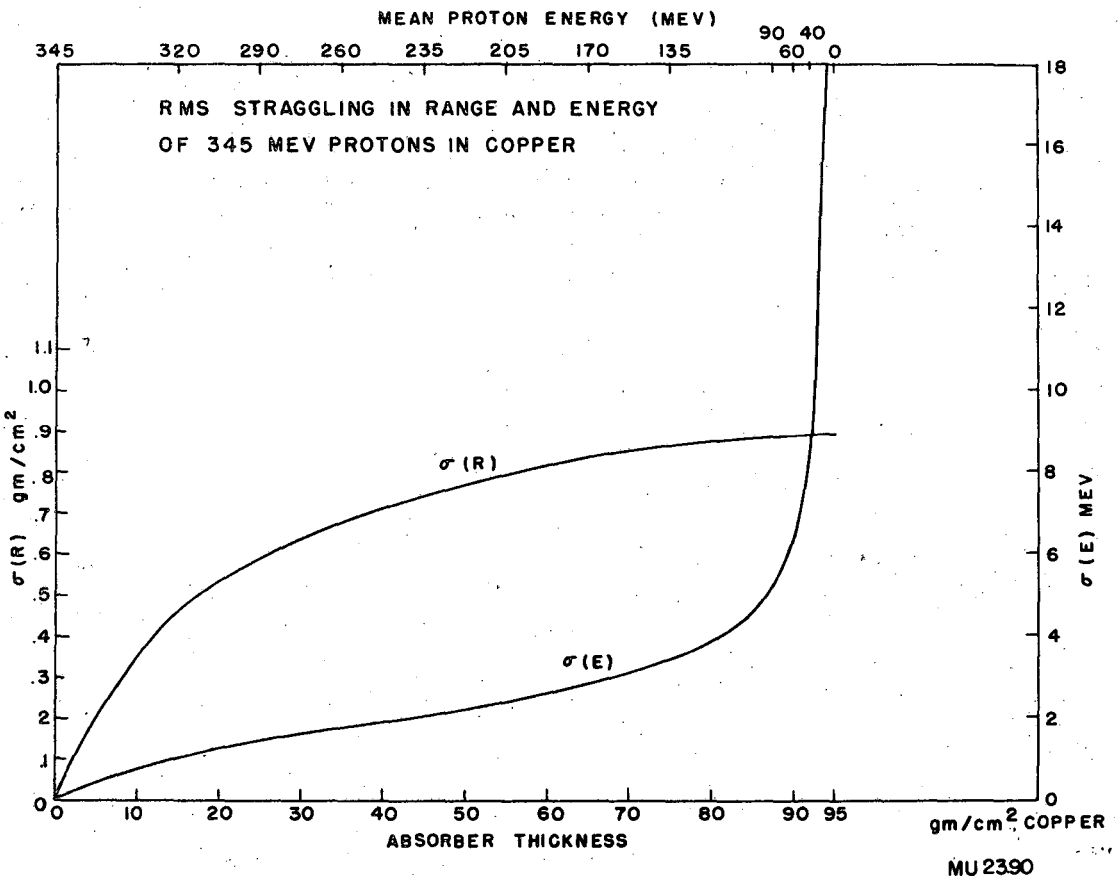

MEAN PROTON ENERGY (MEV)
345
320
290
260
235
205
170
135
90
40
60
0
RMS STRAGGLING IN RANGE AND ENERGY
OF 345 MEV PROTONS IN COPPER
σ (R)
σ (E)
σ (R) gm/cm²
σ (E) MEV
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
18
16
14
12
10
8
6
4
2
0
0
10
20
30
40
50
60
70
80
90
95
ABSORBER THICKNESS
gm/cm² COPPER
MU 2390

Fig. 6

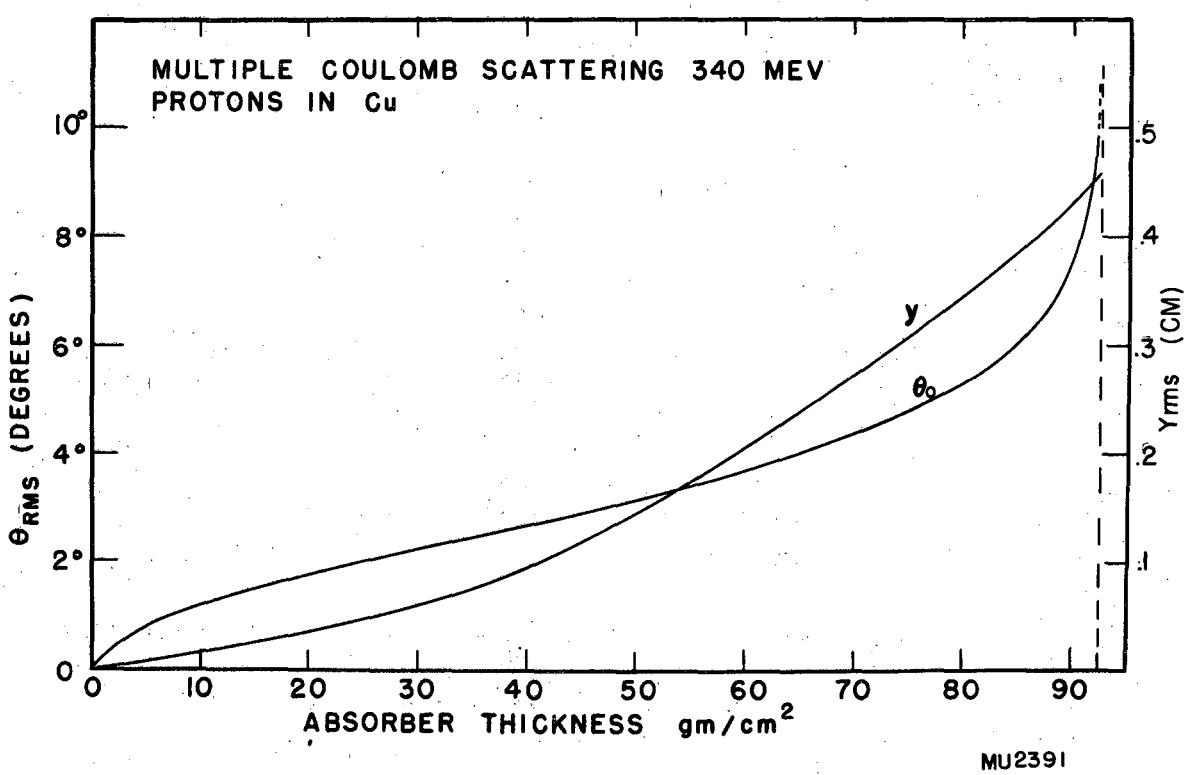

MULTIPLE COULOMB SCATTERING 340 MEV
PROTONS IN Cu
θ_{RMS} (DEGREES)
Yrms (CM)
y
θ_0
ABSORBER THICKNESS gm/cm^2
0
2°
4°
6°
8°
10°
.1
.2
.3
.4
.5
0
10
20
30
40
50
60
70
80
90
MU2391

Fig. 7

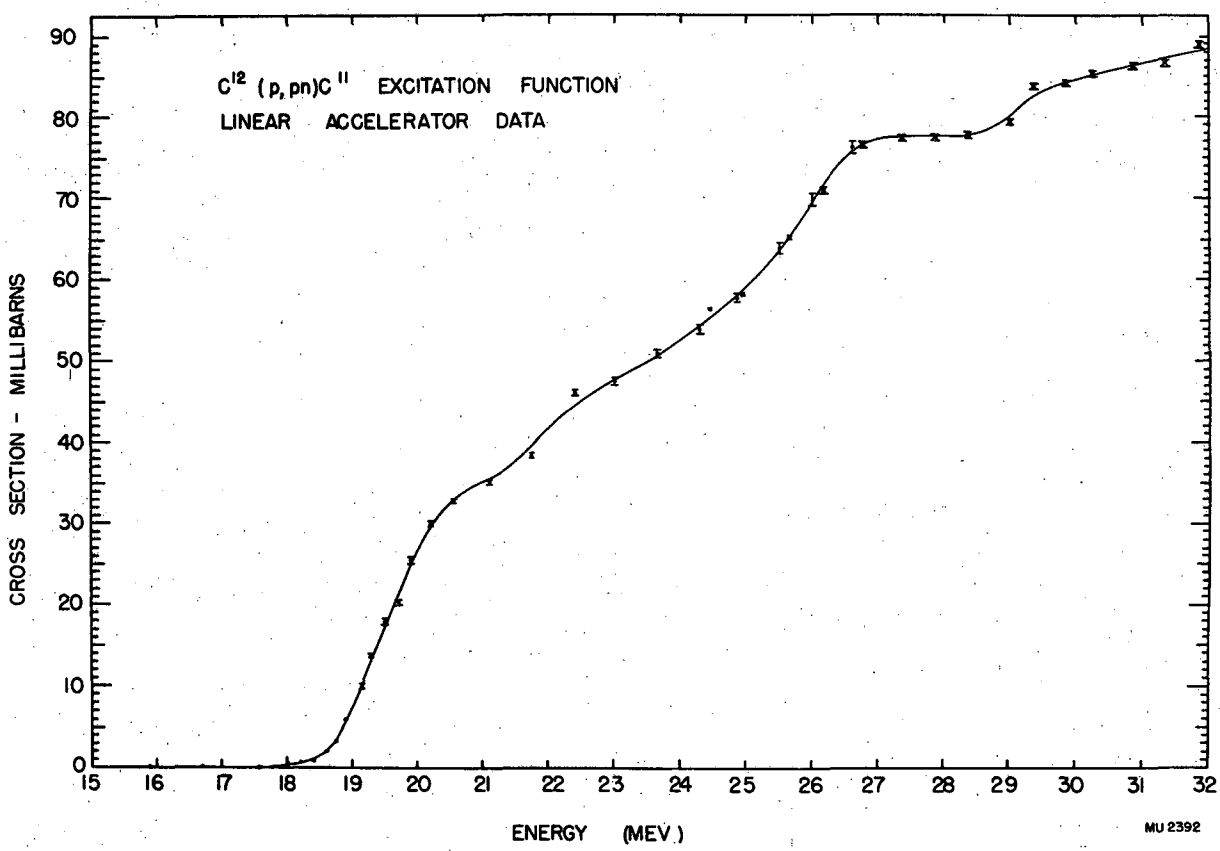

C12 (p, pn)C11 EXCITATION FUNCTION
LINEAR ACCELERATOR DATA
CROSS SECTION - MILLIBARNS
ENERGY (MEV)
MU 2392
0
10
20
30
40
50
60
70
80
90
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32

Fig. 8

FARADAY CUP GEOMETRY FOR MEASUREMENTS AT 32 MEV

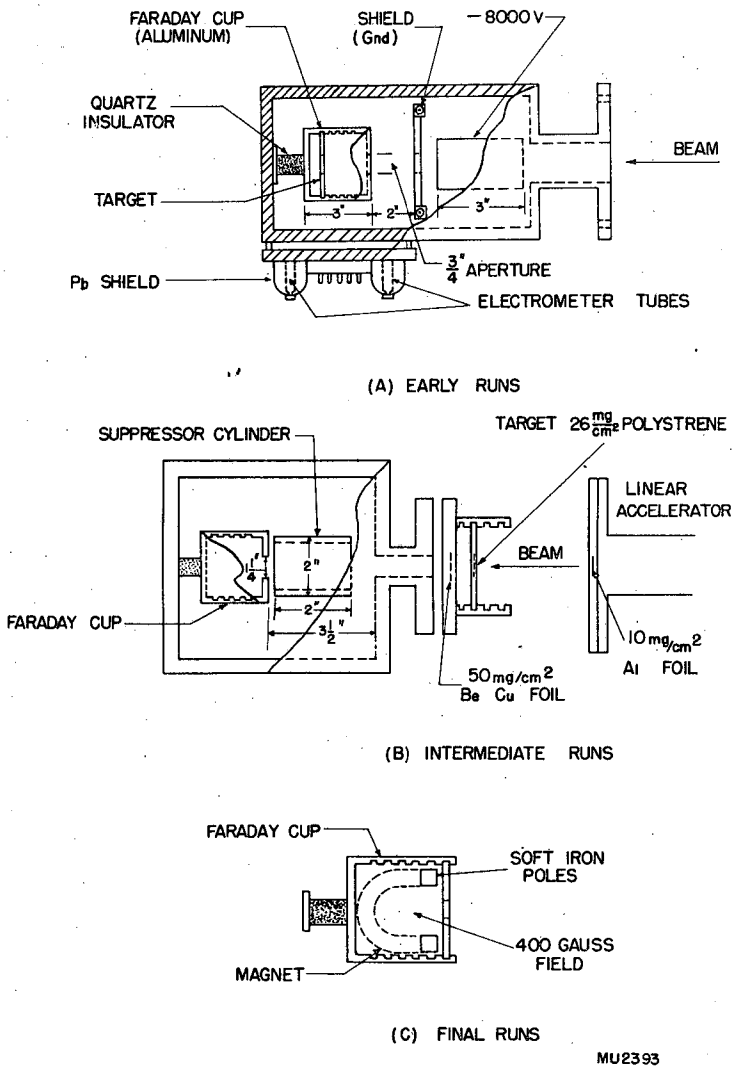


Fig. 9

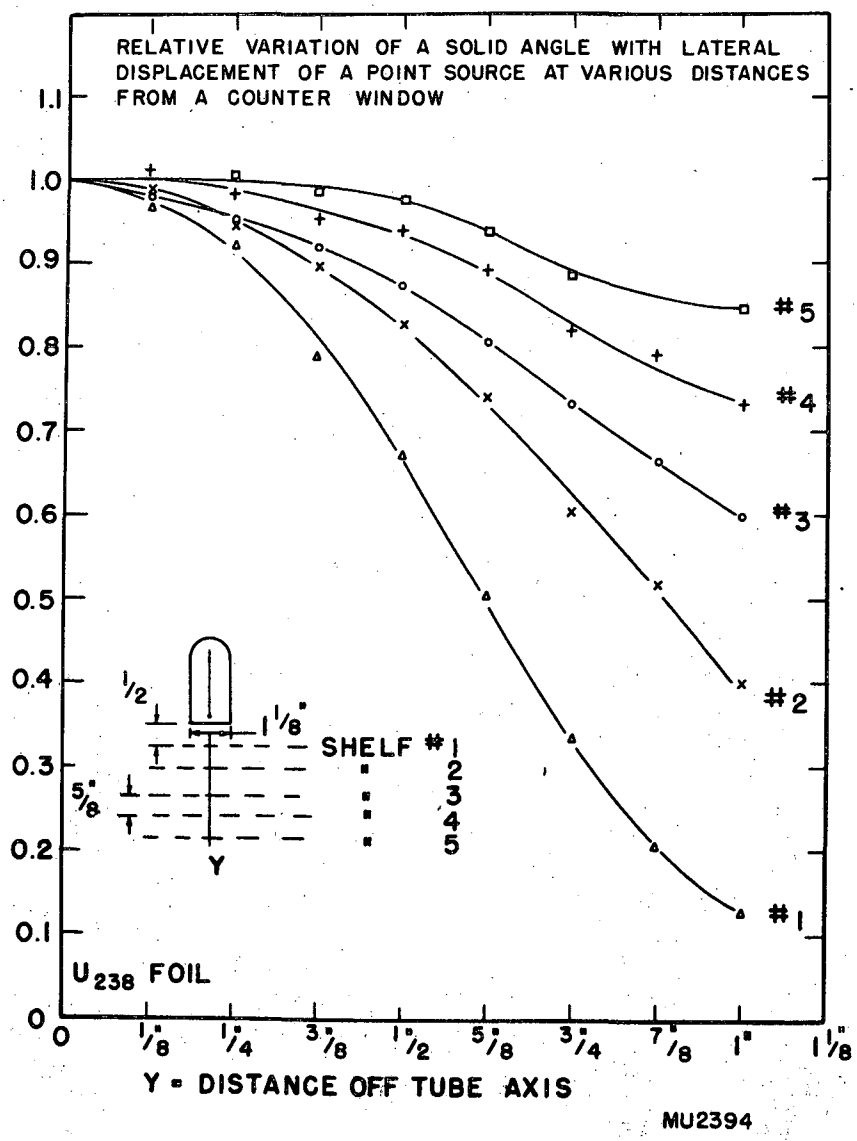

RELATIVE VARIATION OF A SOLID ANGLE WITH LATERAL DISPLACEMENT OF A POINT SOURCE AT VARIOUS DISTANCES FROM A COUNTER WINDOW
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
#5
#4
#3
#2
#1
1/2
1 1/8"
SHELF #1
" 2
" 3
" 4
" 5
5/8"
Y
U238 FOIL
0
1/8"
1/4"
3/8"
1/2"
5/8"
3/4"
7/8"
1"
1 1/8"
Y = DISTANCE OFF TUBE AXIS
MU2394

Fig. 10

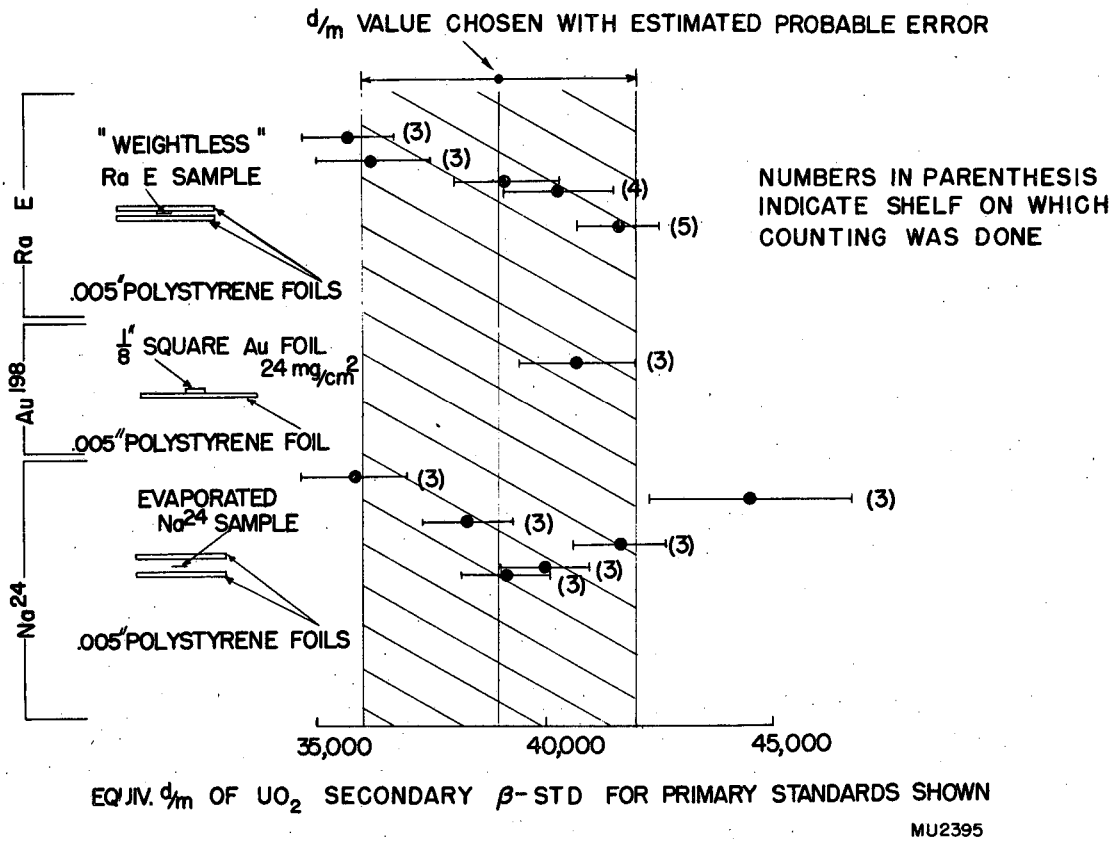

d/m VALUE CHOSEN WITH ESTIMATED PROBABLE ERROR
"WEIGHTLESS"
Ra E SAMPLE
.005" POLYSTYRENE FOILS
1/8" SQUARE Au FOIL
24 mg/cm²
.005" POLYSTYRENE FOIL
EVAPORATED
Na24 SAMPLE
.005" POLYSTYRENE FOILS
Ra E
Au 198
Na24
(3)
(3)
(4)
(5)
(3)
(3)
(3)
(3)
(3)
(3)
NUMBERS IN PARENTHESIS
INDICATE SHELF ON WHICH
COUNTING WAS DONE
35,000
40,000
45,000
EQUIV. d/m OF UO2 SECONDARY β-STD FOR PRIMARY STANDARDS SHOWN
MU2395

Fig. 11

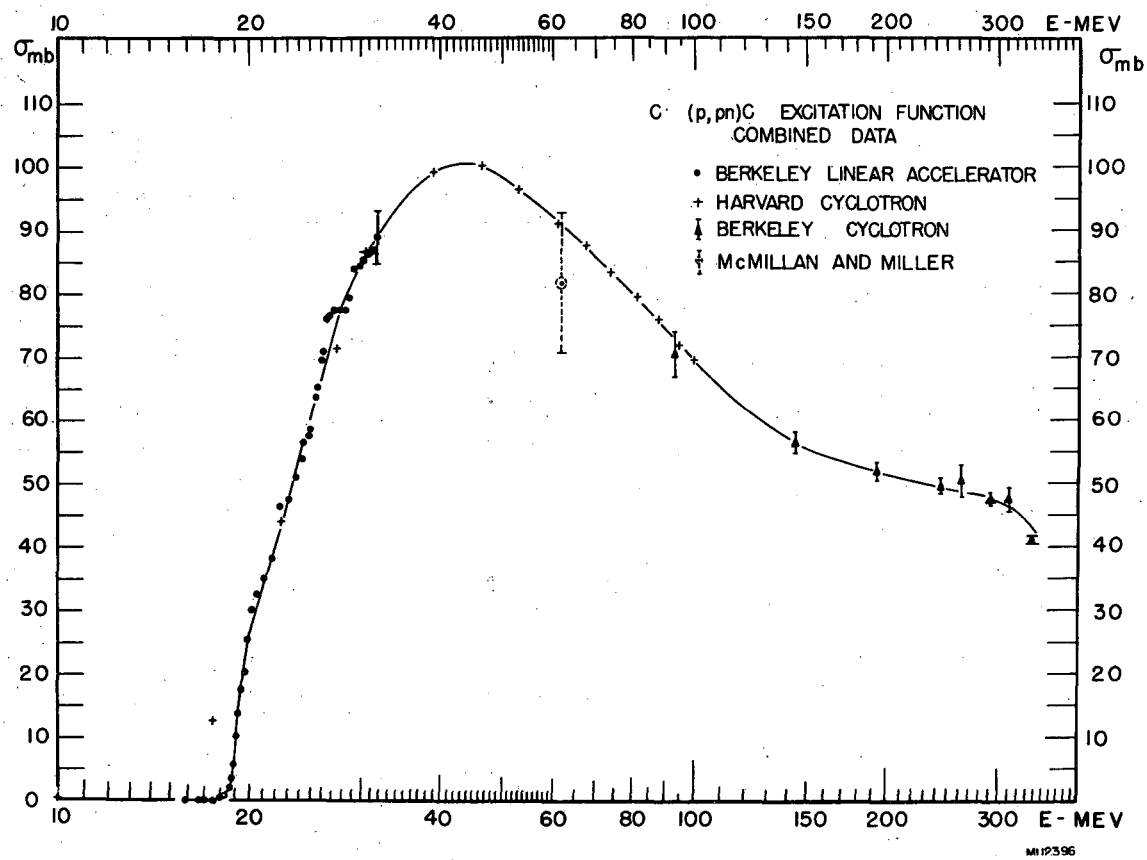

C (p,pn)C EXCITATION FUNCTION
COMBINED DATA
• BERKELEY LINEAR ACCELERATOR
+ HARVARD CYCLOTRON
BERKELEY CYCLOTRON
McMILLAN AND MILLER
σmb
E-MEV
MU12396

Fig. 12