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ABSTRACT

The ejection of high energy protons from various materials by 322 Mev bremsstrahlung has been investigated using a detector telescope consisting of three liquid scintillators. Protons, above a minimum energy of 65 Mev, were distinguished from other particles by their dE/dx at a fixed range. At 70 Mev the angular distribution appears to be independent of nuclear complexity; the relative distributions from Li, C, and Ta have about the same shape. Distributions from C at 77, 127, and 174 Mev were measured between 11° and 45°. The data do not fit the predictions of a quasi-deuteron model but adequate calculations require more knowledge of the deuteron photodissociation process. The yields at 45° for 72 and 142 Mev protons from various materials was found to be directly proportional to Z. The energy spectra of photoprotons from C have been measured at 45° and 90°. The absolute differential cross section for production of 72 Mev protons from C at 90° has been measured.

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A study has been made of the high energy photoprotons emitted from various targets when bombarded with the 322 Mev bremsstrahlung beam of the Berkeley synchrotron. The object was to extend to higher proton energies an earlier investigation made by Levinthal and Silverman[1] with the same beam. Recently somewhat similar high energy measurements have been reported by Keck.[2]

Protons above a minimum energy of 65 Mev were detected with a counter telescope consisting of three liquid scintillators (terphenyl in toluene) viewed by RCA 1P21 photomultiplier tubes. This counter was constructed in cooperation with W. S. Gilbert and is described in a report of an investigation of the photodisintegration of the deuteron at high energies.[3] A particle's range was specified by demanding that it pass through the first counter and stop in the second. The protons were then distinguished from less heavily ionizing particles (e.g. mesons and electrons) by requiring a certain minimum pulse height in the first counter. By this method a deuteron would be recorded as a proton, but at the high energies investigated (corresponding to deuteron energies > 90 Mev) it is doubtful that the deuteron contribution was appreciable. To vary the mean energy of the protons detected, copper absorbers were placed in front of the first counter.

By adjusting the rf accelerating voltage of the synchrotron the so-called long beam pulse was obtained in which the electrons are made to spill into the internal 0.020 inch platinum target over a period of about 3000 μ sec. Since the magnetic field is varying as a 30-cycle sine wave during the beam pulse the electrons strike the target at various energies, ranging from 298 to 324 Mev.

The bremsstrahlung beam was collimated by a 3/4 inch diameter hole in a 9 inch thick lead wall, the various targets employed being placed in the beam about 50 inches beyond this wall. To monitor the beam use was made of two ionization chambers which were part of the standard synchrotron installation and which had been calibrated absolutely by Blocker and Kenney.[4] The counter telescope was installed in a lead house with 3 inch thick walls, a 1-1/2 inch diameter hole in the front wall of the house defining the effective solid angle subtended by the detector. The lead house was mounted on a carriage that could be revolved about the center of the x-ray target.

The angular distributions of protons of energy near 70 Mev from lithium, carbon, and tantalum were measured in the range from 30° to 150°. The results are given in Fig. 1, plotted taking $d\sigma/Q\text{-}d\Omega\text{-}dE = 1$ at 90°. Each point represents a total angular interval of 6°. For measurements made with $\theta \lesssim 90^{\circ}$ the targets were along the line at $\theta = 135^{\circ}$; for $\theta > 90^{\circ}$ the targets were along the line at $\theta = 45^{\circ}$. The data were adjusted (< 5 percent correction) to take into account variation of proton energy losses in the target due to variation with angle of emission and the use of various target thicknesses.

Apparently the differences in complexity between the heavy tantalum nucleus and the light lithium and carbon nuclei have little effect upon the angular distribution. The observed distributions are within the precision of the measurements identical for all three elements. In Fig. 2 the carbon data have been plotted separately for comparison with the carbon data of Levinthal and Silverman at a lower proton energy (40 Mev) and those of Keck at a higher proton energy (100 Mev), all obtained at a synchrotron energy of about 300 Mev. The comparison indicates the distributions in this angular range become steeper with energy. Also plotted in Fig. 2 is the curve calculated by Levinger[5] for 70 Mev photo-protons from carbon using a quasi-deuteron model. Actually this curve is for a synchrotron emergy of 200 Mev, but the curve for 300 Mev synchrotron energy would be the same except at the largest angles where it would be somewhat higher. The position of the peak in the calculated distribution is in obvious disagreement with the data. Levinger's calculations, which considered the photodisintegration of a two-nucleon substructure (quasi-deuteron) moving inside the nucleus, utilized an extrapolation of the Schiff[6] and the Marshall and Guth[7] calculations of the electric dipole and quadrupole photodisintegration of the deuteron. This extrapolation has been found, however, to disagree with recent experiments.[3,8]

The distributions measured at 70 Mev, as shown in Figs. 1 and 2, may represent contributions from more than one process. Meson production from a static free nucleon by 300 Mev photons will lead to 70 Mev recoil nucleons at 30°. The motion of a nucleon inside the nucleus will make it possible to have some 70 Mev recoil protons at angles greater than 30°. Also, the reabsorption of a meson inside the nucleus in which it is produced could lead to some high energy protons. The forward angular distribution of the protons shows this latter, which would give an isotropic distribution, cannot be a primary process.

The angular distributions of photoprotons from carbon at smaller angles were measured at three proton energies. The results are shown in Fig. 3, all plotted to the same scale of relative cross section. In order to get to small angles the detector system was moved to a distance of 40 inches from the target; at all points the counter telescope aperture subtended an angle of 2°. Precautions were taken to operate at a beam intensity which was low enough to eliminate pile-up of pulses in the electronics.

The solid curves given in Fig. 3 are those calculated by Levinger for 130 Mev and 175 Mev protons produced from carbon by 300 Mev bremsstrahlung (taken from Keck's article). The normalization of the curves is arbitrary. As for the case of 70 Mev protons the distributions calculated by Levinger underestimate the small angle contributions.

The dotted curves represent calculations of the yield of protons from the disintegration of a static deuteron under the assumption of a cross section for deuteron dissociation that above 180 Mev is constant and isotropic. Such an assumption perhaps more closely approximates recent findings[3,8] than the theoretical values used by Levinger, and the slightly better fit (in spite of the disagreement for 174 Mev protons) suggests that Levinger's fundamental quasi-deuteron model, corrected by more accurate data for the high-energy photodisintegration of the deuteron, may yet prove fruitful.

An investigation of the Z dependence was made at an angle of 45° by measuring the yields of 72 Mev protons from eleven elements, from lithium to zinc, and of 142 Mev protons from six elements, from beryllium to lead. The results are shown in Fig. 4. For both energies the yield was approximately directly proportional to Z; the curves in Fig. 4 are proportional to $Z^{1.06}$. The same data, plotted with the abcissae (NZ/A) and ($NZ/A^{7/6}$) (the former suggested by Levinger, the latter by Keck), show a greater deviation from proportionality than when plotted against Z. For both energies the yield was approximately proportional to $(NZ/A)^{1.09}$ or to $(NZ/A^{7/6})^{1.32}$.

The energy spectra of the photoprotons ejected from carbon by the 322 Mev bremsstrahlung were measured at 45° and 90° for energies above about 70 Mev. The results, shown in Fig. 5, have been corrected for nuclear absorption of the protons in the copper absorber used to vary the mean energy of the protons detected. A cross section equal to the geometrical area was used, giving a mean free path in copper of 112 gm/cm^2. The results seem to be a smooth continuation of the $E^{-1.7}$ spectrum observed at 90° by Levinthal and Silverman at energies below 70 Mev. Keck found a break in the spectrum that he observed from carbon at 67.5°, and interpreted the fact that it occurred at half the energy of the upper limit of the bremsstrahlung distribution as confirmation of a deuteron model for the dissociation process. A proton recoiling from a neutron would carry off about half the energy for angles near 90°.

Under such an interpretation the energy of this break should depend on angle, as determined by the kinematics of deuteron disintegration. A 300 Mev photon would give a 123 Mev proton at 90° and a 197 Mev proton at 45°. However, what might be called breaks in the curves in Fig. 5 both occur near 140 Mev, which suggests that an interpretation cannot be so easily made.

The absolute differential cross section for the production of 72 Mev protons from carbon at 90° was measured to be 0.72 ± 0.29 μb/Q-Mev-Ster, which is in good agreement with the value 0.74 ± 0.22 found by Keck at approximately the same proton and bremsstrahlung energies, but is considerably higher than the value 0.15 (± factor of 2) measured by Levinthal and Silverman. Levinger gives 0.29 μb/Q-Mev-Ster as the result of his calculations.

In general over our ranges of energy and angle the absolute values calculated by Levinger appear to be roughly a factor of four too small. At energies above the meson threshold (~ 140 Mev) the extrapolation employed by Levinger of the calculations of Schiff and Marshall and Guth of the total cross section for photodisintegration of the deuteron disagrees with experiment.[3,8] The cross section near 200 Mev has been found to be five to ten times higher than predicted. Thus one might expect a closer agreement between experiment and predictions from the quasi-deuteron model of the nucleus after appropriate corrections are made in that theory for both the observed angular distribution and the excitation function for deuteron photodissociation above 140 Mev.

ACKNOWLEDGMENTS

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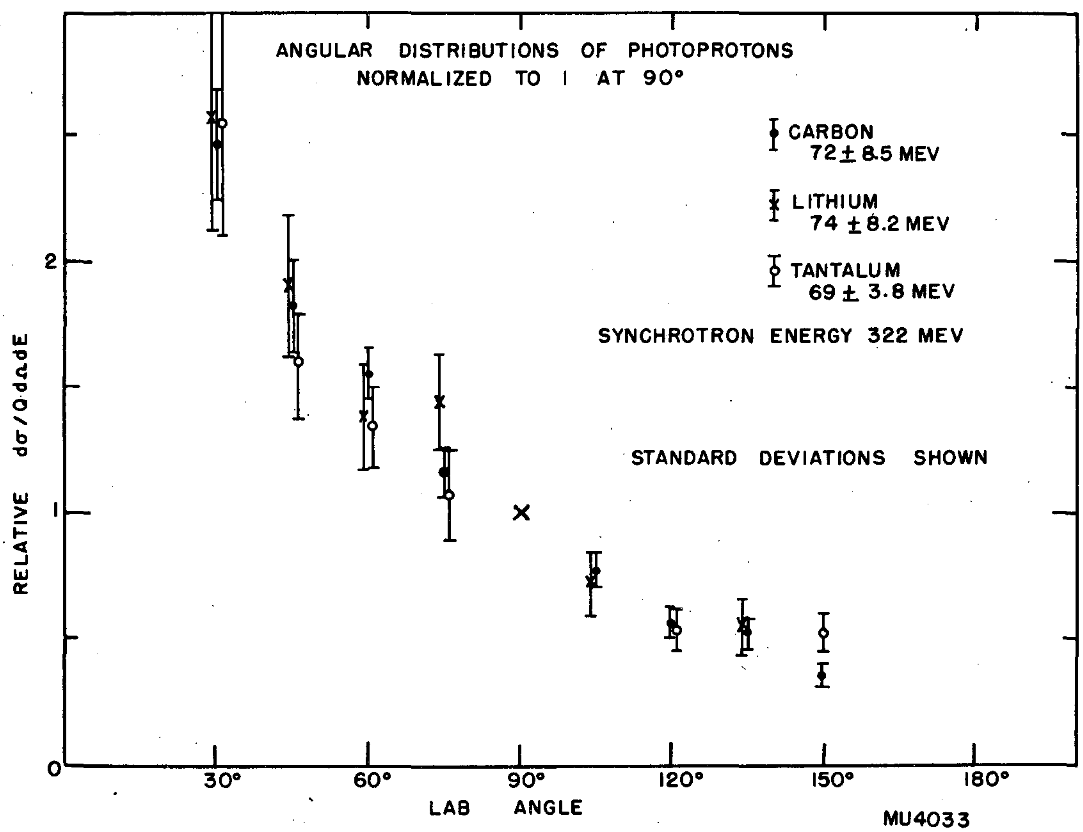
FIGURE CAPTIONS

1. Angular distributions of photoprotons near 70 Mev produced from Li, C, and Ta by 322 Mev bremsstrahlung.
2. Angular distributions of photoprotons from carbon.
3. Angular distributions of photoprotons from carbon at small angles. All experimental points are plotted to the same relative scale.
4. Z dependence of photoproton production. Curves shown are proportional to $Z^{1.06}$.
5. Energy spectra of photoprotons from carbon, arbitaray normalization.



ANGULAR DISTRIBUTIONS OF PHOTOPROTONS
NORMALIZED TO 1 AT 90°
CARBON
72 ± 8.5 MEV
LITHIUM
74 ± 8.2 MEV
TANTALUM
69 ± 3.8 MEV
SYNCHROTRON ENERGY 322 MEV
STANDARD DEVIATIONS SHOWN
RELATIVE dσ/Q·dΩ·dE
0
1
2
30°
60°
90°
120°
150°
180°
LAB ANGLE
MU4033

Fig. 1

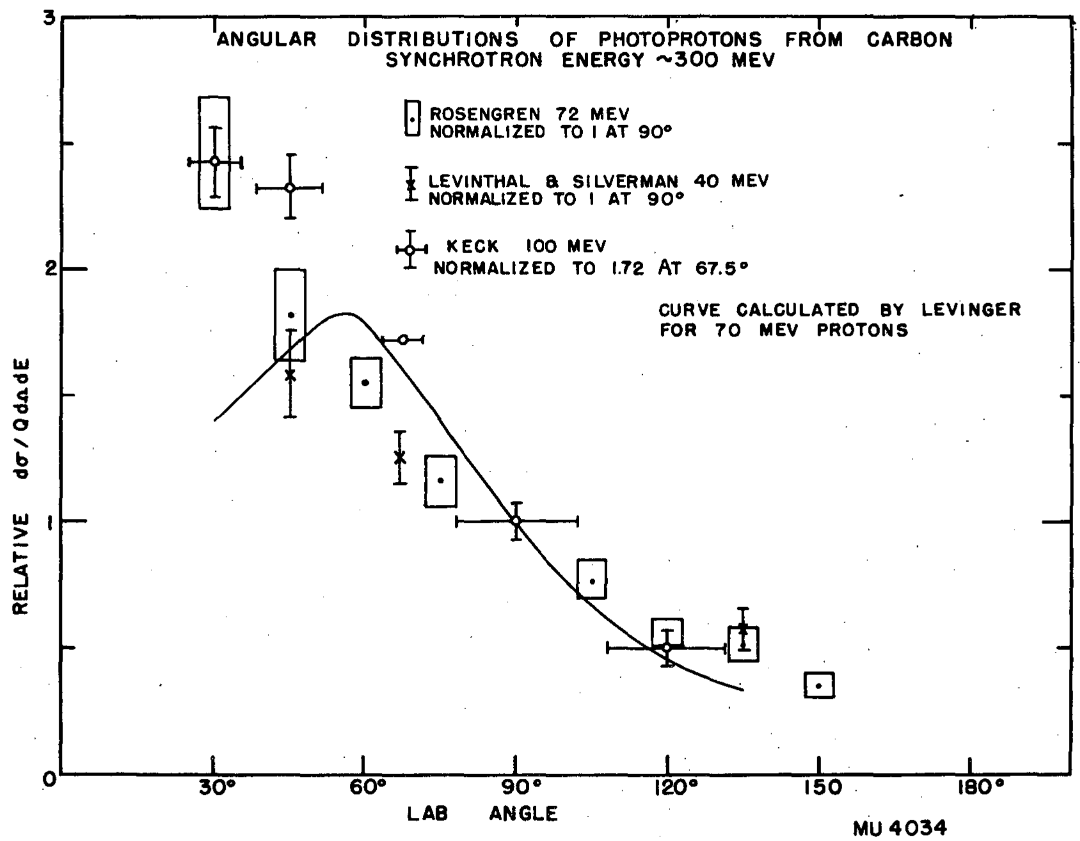

ANGULAR DISTRIBUTIONS OF PHOTOPROTONS FROM CARBON
SYNCHROTRON ENERGY ~300 MEV
ROSENGREN 72 MEV
NORMALIZED TO 1 AT 90°
LEVINTHAL & SILVERMAN 40 MEV
NORMALIZED TO 1 AT 90°
KECK 100 MEV
NORMALIZED TO 1.72 AT 67.5°
CURVE CALCULATED BY LEVINGER
FOR 70 MEV PROTONS
RELATIVE dσ/QdΩdE
0
1
2
3
30°
60°
90°
120°
150
180°
LAB ANGLE
MU 4034

Fig. 2

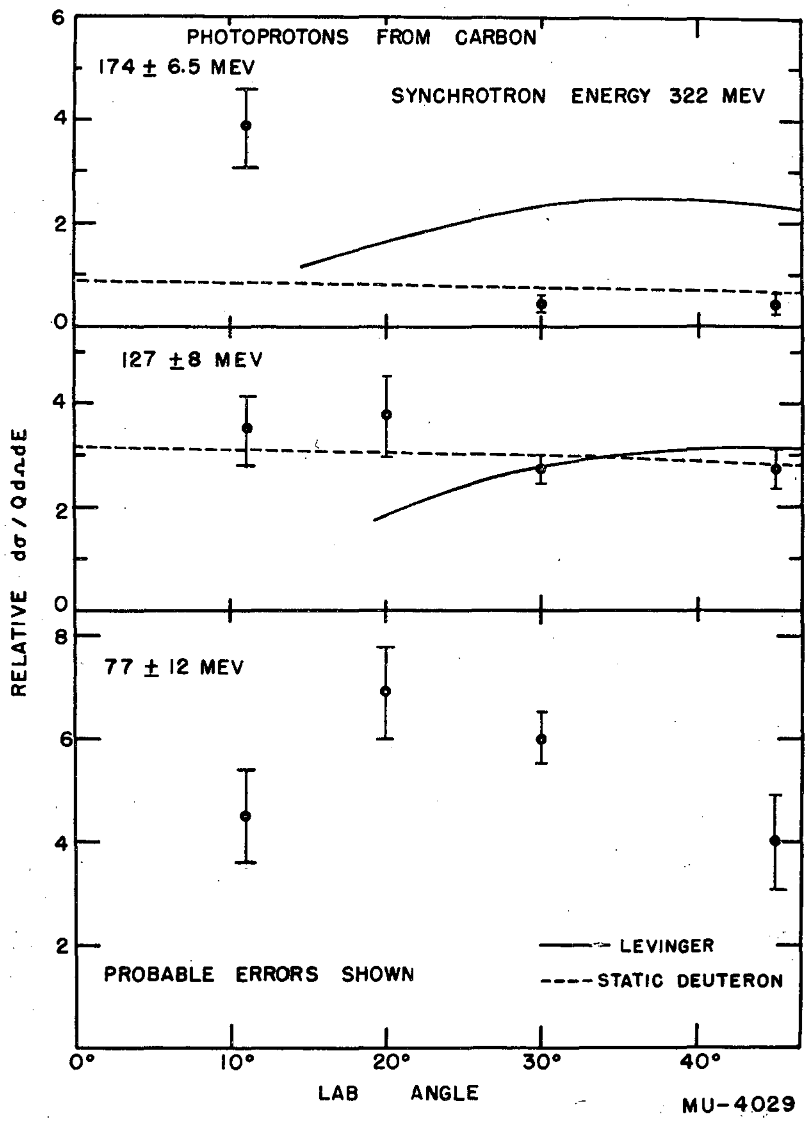
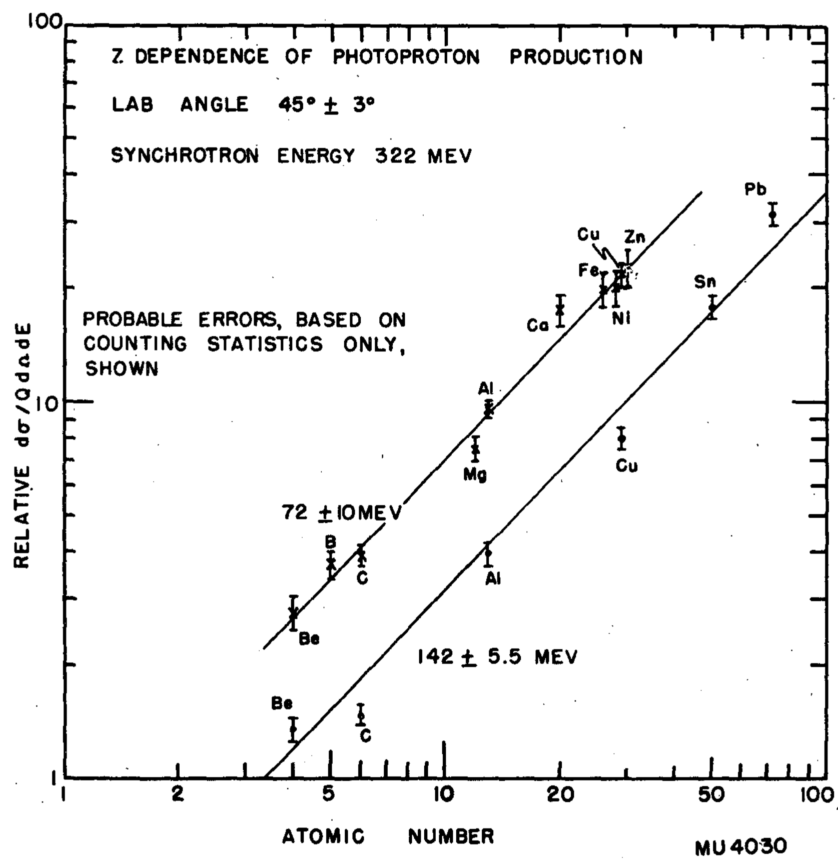

PHOTOPROTONS FROM CARBON
SYNCHROTRON ENERGY 322 MEV
174 ± 6.5 MEV
127 ±8 MEV
77 ± 12 MEV
RELATIVE dσ/QdΩdE
PROBABLE ERRORS SHOWN
LEVINGER
STATIC DEUTERON
LAB ANGLE
0° 10° 20° 30° 40°
6 4 2 0
4 2 0
8 6 4 2
MU-4029

Fig. 3



Z DEPENDENCE OF PHOTOPROTON PRODUCTION
LAB ANGLE 45° ± 3°
SYNCHROTRON ENERGY 322 MEV
PROBABLE ERRORS, BASED ON COUNTING STATISTICS ONLY, SHOWN
72 ± 10 MEV
142 ± 5.5 MEV
RELATIVE dσ/QdΩdE
ATOMIC NUMBER
Be
B
C
Mg
Al
Ca
Fe
Cu
Zn
Ni
Sn
Pb
1
10
100
2
5
20
50
MU 4030

Fig. 4

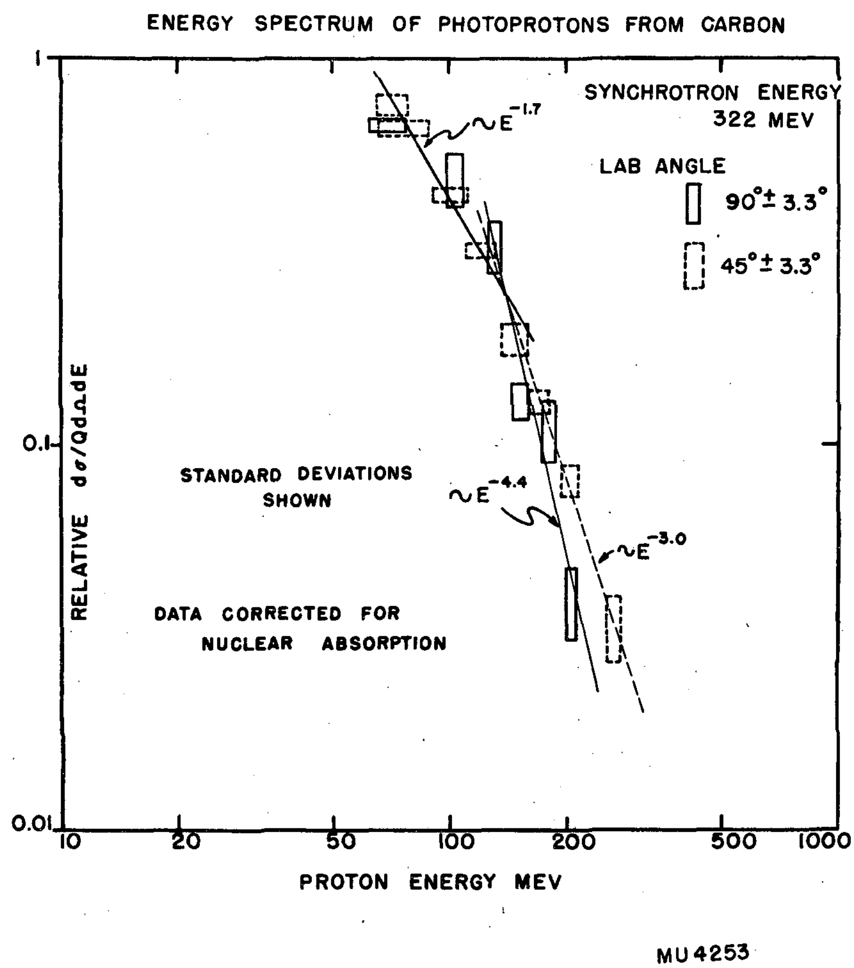

ENERGY SPECTRUM OF PHOTOPROTONS FROM CARBON
SYNCHROTRON ENERGY
322 MEV
LAB ANGLE
90° ± 3.3°
45° ± 3.3°
~E^-1.7
~E^-4.4
~E^-3.0
STANDARD DEVIATIONS SHOWN
DATA CORRECTED FOR NUCLEAR ABSORPTION
RELATIVE dσ/QdΩdE
1
0.1
0.01
10
20
50
100
200
500
1000
PROTON ENERGY MEV
MU 4253

Fig. 5