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ENERGY SPECTRUM OF GEOMAGNETICALLY TRAPPED PROTONS

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INTRODUCTION

Nuclear emulsion detectors were flown through the lower part of the inner Van Allen radiation belt in the nose cone of an Atlas missile on October 13, 1960. The trajectory, from Cape Canaveral to Ascension Island, was nearly identical to that of a flight on July 21, 1959, the results of which have been reported (Armstrong, Harrison, Heckman, and Rosen, 1961). The maximum altitude attained was 1185 kilometers, 60 kilometers higher than in the earlier flight. The purpose of irradiating the emulsion detectors under similar flight conditions was to extend the spectrum to lower energies than had been possible in the previous experiment and to investigate the stability of the radiation in the inner belt.

GEOMETRY

For this flight a 4X4 inch section was removed from the aft ring of the nose cone and replaced by a thin-windowed canister containing the emulsions. With this geometry the only materials traversed by the incident radiation, before entering the emulsion detectors, were the windows sealing the canister and its contents, and a small amount of low-density insulating material.

The various emulsion stacks were designed and positioned in the canister to provide different areas of information. Figure 1 is a schematic drawing of their arrangement. For study of the lowest energies, four brass-walled cassettes were placed in a watertight compartment. Each cassette contained a stack of 13 K.2 emulsions, 30×13 mm, with their planes parallel to the 1-mil Ti window which sealed each cassette. The two upper pellicles of each stack were 200 μ thick, the remainder, 400 μ thick. The cassettes were placed at different depths in the well, covered by various thicknesses of styrofoam and microquartz, and sealed by a 2-mil Ta foil. The low-energy data were obtained from the emulsion stacks 1 and 2. The minimum energy of a proton that could reach the surfaces of stacks 1 and 2 was 10.6 Mev and 9.9 Mev, respectively.

Section A was occupied by a 3-3/4×3-1/4 inch emulsion stack, denoted as stack A, consisting of forty-eight 600 μ G.5 emulsion pellicles. Here the plane of the emulsions was normal to the entrance window. The absorbing material set a minimum proton energy of 24 Mev at the entrance edge of the stack. The stack in section B consisted of twelve 600 μ glass-backed G.5 emulsions, 2×3 inches, arranged in pairs with the emulsion surfaces in contact. This stack was to be used for investigating the high-energy protons in the Van Allen radiation in case stack A incurred serious distortions during processing.

Although the aft ring of the nose cone sustained excessive heating during re-entry, the heating caused little damage to the contents of the canister. The top emulsion pellicle in each of the two small stacks analyzed (1 and 2) had been overheated to such an extent that they were unusable. It was for just such a contingency that the two upper pellicles were only 200 μ thick; it was hoped that if heat damage should occur, only this thickness might be lost. Such, indeed, proved to be the case. The minimum proton energies for the analyzed stacks 1 and 2 were therefore actually 12.6 and 11.9 Mev, respectively. The large stack in section A suffered no detectable damage.

MEASUREMENTS AND ANALYSIS

A. Low-Energy Stacks: The low-energy part of the spectrum was obtained by counting the number of track endings vs. the depth of penetration into stacks 1 and 2. Since the particles selected for measurement entered nearly normal to the emulsion surfaces, each pellicle in the stacks recorded proton endings of a well-defined energy interval. A central and unshielded area of each pellicle of the stacks was scanned throughout its thickness for track endings. A track was accepted only if it entered the emulsion surface within a cone with a half angle of 20° to the normal and its ending was not less than 50μ from the top surface. The latter criterion was invoked because of the low efficiency for finding endings of steep tracks $0\text{-}50\mu$ below the surface and because of the large uncertainties in the measurements of the entrance angle of the tracks. Stacks 1 and 2 were analyzed independently in Berkeley and Los Alamos. Since the energy intervals for corresponding plates are different, the two sets of data are shown separately.

B. High-Energy Stack: The analysis of stack A followed closely the pattern used for the previous flight. The emulsions were calibrated for ionization vs. γ-1, the kinetic energy in rest mass units, by measuring the ionization vs. residual range along the path of π mesons whose residual ranges were at least 5 to 6 cm. Positrons in the π-μ-e decay chain were used to establish the plateau of the ionization vs. γ-1 curve.

The maximum energy of protons brought to rest in the emulsion was 190 Mev. Energies above this value were determined by ionization measurements. Two methods of scanning were used: (a) "along-the-track," and (b) "area." In method (a) the emulsion was scanned along a line 1.5 mm (E_{min} = 31 Mev) or 3.0 mm (37 Mev) from the entrance edge. All tracks that entered the emulsion within a projected angle of $\pm 15^{\circ}$ normal to the emulsion edge and a dip angle of

$\pm 10^{\circ}$ were accepted, and an ionization measurement made. For those with an ionization corresponding to protons of energy greater than 190 Mev, estimates of kinetic energy were made from the blob density of the tracks. For those of lower energy, the ionization was determined from the gap-length coefficient or percent transparency of the track. The energies of these latter particles were accurately determined from their ranges. The curves of ionization vs. residual range which were developed in the course of the analysis then served for identification of particles heavier than protons.

The emulsions were area-scanned for track endings between 0.8 and 30 mm from the leading edge of the stack, a range interval corresponding to proton energies 27.8 to 102 Mev. A stopping particle was counted if its direction 1 mm from its end was within a projected angle $\pm 20^{\circ}$ normal to the entrance edge and a dip angle of $\pm 10^{\circ}$. The purpose of the area scan was to obtain a statistically independent measurement of the spectrum in this energy interval.

Several corrections were applied to the raw data. In the area scan the number of track endings recorded was reduced by 4% to eliminate star prongs which satisfied the selection criteria. An estimate of this background was obtained by tracing a sample of 100 stopping tracks to their point of entrance or star origin. In the along-the-track scan the direction of a proton of energy in excess of 200 Mev at the scan line was unknown; therefore, corrections were made for particles traveling in the backward direction. The calculated fractions of backward-traveling particles, appropriate to the experimental geometry and the observed energy spectrum, for the energy intervals 200-300 Mev, 300-500 Mev, and 500-650 Mev are 0.135, 0.15, and 0.17, respectively.

RESULTS AND DISCUSSION

Energy Spectrum

The complete proton energy spectrum is shown in Fig. 2. The excellent agreement between the two low-energy stacks supports the reliability of these results. Data from 32 to 190 Mev, obtained from stack A by following tracks to their endings, are augmented by data obtained by area-scanning for track endings between the energies 28 and 102 Mev. Above 190 Mev the energy spectrum is based upon ionization measurements, and for proton energies above 500 Mev, upon multiple scattering in addition to ionization measurements.

The spectrum below 80 Mev exhibits a quite different character from that expected from the albedo hypothesis (Singer, 1958 ab; Hess, 1959; Freden and White, 1960; and Lenchek and Singer, 1961). Instead of a monotonically decreasing spectrum with increasing energy, there is observed a broad, flat maximum centered at about 35 Mev and a minimum near 20 Mev, with an indication of a rise toward lower energies. Above 80 Mev the spectrum steepens with increasing energy, consistent with the prediction of the albedo-neutron theory. Few, if any, protons in excess of 660 Mev, i.e., $\gamma - 1 \geq 0.7$, were detected in the experiment. This is in agreement with the results of the July, 1959 experiment, in which the most energetic proton detected was 610 ± 100 Mev.

The results of this experiment are compared with the proton-energy spectrum obtained from our previous (July, 1959) flight in Fig. 3. The July, 1959 spectrum is normalized to the present (October, 1960) data in the region of 100 Mev. Also shown are the theoretical curves of the equilibrium-proton-energy spectrum as given by Freden and White (1960) and Lenchek and Singer (1961), each normalized to the data at 100 Mev.

Above 80 Mev both measurements of the spectrum are in good agreement, showing little evidence for changes in the shape of the spectrum with time. As

Freden and White (1961) have also observed, the measured spectrum falls significantly below their theoretical curve for energies $E > 300$ Mev. The theoretical energy spectra to which the data are compared are based upon the hypothesis that the source of geomagnetically trapped protons is the decay of cosmic-ray albedo neutrons. The Freden and White spectrum results from the approximations that the injection coefficient, i.e., trapping probability, is independent of neutron energy, and that protons are lost from the trapped radiation by ionization and nuclear collisions. Lenchek and Singer have extended Freden and White's theoretical treatment by: (1) taking into account the anisotropy of energetic albedo neutrons (above 50 Mev)--an effect which decreases the injection coefficient with increasing energy; and (2) assuming that protons above a critical energy, E_c, are lost from the belt owing to the breakdown of the adiabatic invariance of the magnetic moment. The introduction of these loss mechanisms into the theory increases the slope of the spectrum, particularly for energies above ~ 300 Mev--where the spectrum becomes sensitive to the cut-off energy E_c. Such a modification is in accord with experiment. Lenchek and Singer were able to obtain a good fit to the July, 1959 spectrum for energies $E > 80$ Mev with $E_c = 1000$ Mev. The results of the present experiment indicate a cut-off energy that is between 500 and 1000 Mev. Because no protons in excess of about 650 Mev have been detected in either experiment, we show the energy spectrum for $E_c = 650$ Mev. An excellent agreement between observation and theory is thereby attained for $E > 80$ Mev.

Below 80 Mev, both the October, 1960 and July, 1959 measurements deviate from the calculated spectra. That the spectrum observed in July, 1959 departed from the Freden and White calculation below 80 Mev has been pointed out and discussed (Armstrong et al., 1961). Because the 1959 proton spectrum was measured 5-11 days after the 3+ solar flares on July 10-16, 1959 we were

led to propose that the peak or plateau in the region of 80 Mev, if transient in nature, might be attributed to the effects of solar protons. However, a comparison of our two measurements of the spectrum between 50 and 100 Mev reveals no major difference between them other than in intensity. This suggests that the departure of the measured spectrum from that of Freden and White noted in the July, 1959 experiment may not be a transient phenomenon attributable to solar protons, but rather may be a slight, but not negligible, systematic difference between their measurements of the proton-energy distribution and ours. We conclude from our 1959 and 1960 experiments (Fig. 3) that the spectrum of geomagnetically trapped protons for energies above 50 Mev in the lower regions of the inner belt has not varied significantly over a period of a year. Evidence that the spectrum below 50 Mev may not have had the same shape during the July, 1959 flight as it had on October, 1960 is provided by the data of Holly, Allen, and Johnson (1961). By counter techniques they obtained a measurement of the proton spectrum between 24 and 52 Mev during the same 1959 flight that carried our emulsion package. In the region of maximum counting rate, Holly et al. report that the differential spectrum varied as E^{-n}, where $n = 1.68 \pm 0.09$ in the interval 24 to 52 Mev. This value of n is at variance with $n \approx 0$ observed in the present experiment. Naugle and Kniffen (1961) have observed a proton spectrum that varies approximately as $E^{-1.5}$ between 15 and 100 Mev for protons which populate the central region of the inner belt. Thus, although our data do not substantiate evidence for a time variation of the spectrum of high-energy protons in the lower regions of the inner belt, they do not rule out the possibility that such effects may be present at low energies.

The question as to what extent solar flares can influence the proton spectrum of the inner belt is thus open for further investigations. For completeness we wish to cite that the period between July, 1959 and October, 1960 was a time of strong solar activity, culminating in the intense 3+ flare on September 3, 1960.

The experiment carried out by Naugle and Kniffen on September 19, 1960, sixteen days after the solar flare, has shown that the intensity and spectrum shape of trapped protons vary greatly with altitude and latitude. Such observations support the hypothesis that particles are contributed to the Van Allen belts by the interactions of solar protons with the atmosphere at high geomagnetic latitudes. As suggested by Armstrong et al. (1961), and discussed in more detail by Lenchek and Singer (1961), the generation of albedo neutrons by the interactions of solar protons in the atmosphere during strong solar activity, to as far south as 60° geomagnetic latitude, may contribute significantly as a source of geomagnetically trapped protons.

The current theories of the proton spectrum are less reliable below ~80 Mev due to the large uncertainty in the albedo-neutron spectrum. If one assumes that the observed proton spectrum represents an equilibrium distribution, it is possible to derive an albedo-neutron-energy distribution from it. Freden and White (1961) have derived from their (October, 1960) data such an effective albedo-neutron spectrum. To account for the minimum and maximum in the proton spectrum at ~20 and 35 Mev (Fig. 2), the derived neutron spectrum exhibits a minimum at about 20 Mev. This suggests that a maximum exists in the inelastic cross section for neutrons in nitrogen and oxygen at this energy. A maximum in the inelastic neutron cross section for carbon at 20 Mev is, in fact, known.

The absolute flux of protons—with $E \geqslant 45$ Mev—entering the leading edge of the emulsion within the selected angular criteria measured in the October, 1960 experiment is in good agreement with the flux measured by Freden and White (1961). These measurements are, however 5.0±0.2 times as great as the flux we observed in July, 1959. Because the maximum altitudes differed by only 60 km, an increase of about 2.5 might be reasonably expected if one takes into account the approximate variation of intensity with altitude, and the difference

between the flight times above 1000 km (690 and 590 sec for the 1960 and 1959 experiments, respectively). The similarity of the experimental geometries for the two flights permitted us to check whether or not this ratio was sustained for the volume density of particle tracks near the center of the emulsion stacks. It was not. The ratio of the total time-integrated flux of protons in excess of about 150-200 Mev, the minimum energy observable in the central regions of the stacks, was 2.0 ± 0.2. The observed ratio is close to the ratio expected for the omnidirectional flux. We conclude, therefore, that in these emulsion experiments the tumbling of the nose cones did not insure a random sampling of the anisotropically distributed particle flux over the flight trajectories. As a consequence, systematic errors as large as 200-300% may enter into estimates of absolute particle intensities in experiments of this type.

Particles Heavier Than Protons

Deuterons and Tritons: In the course of analyzing the July, 1959 and October, 1960 experiments, a mass measurement was made for a total of 783 stopping particles. Tracks with ranges greater than 5 mm were selected for measurement. Figure 4 shows a typical graph of ionization vs. range, where the ionization parameter is the percent transparency of the track. The main locus is due to protons. Because the rate of energy loss, dE/dx, depends only upon the velocity for singly charged particles, the mass of an unknown particle in units of the proton mass is equal to R/R_p--the ratio of the residual range of the particle to that of the proton from points of equal ionization. Curves of range vs. ionization expected for deuterons and tritons are, therefore, determined relative to the proton curve. Whenever a mass measurement deviated more than 2σ (standard deviation) from the proton curve towards heavier mass, further ionization measurements were made at several points along the track. The results of these measurements, in addition to those by Freden and White (1960), are tabulated in Table I.

Table I: Observations of Deuterons and Tritons in Inner Belt

Date	No. of Tracks	No. of Deuterons	No. of Tritons
Oct. 1960	301	0	0
July 1959	482	5	0
May 1959 (F and W)	246	0	3

The first observation by Freden and White that particles heavier than protons exist in the inner belt led to the conclusion that these particles were products of nuclear collisions between the trapped radiation and the upper atmosphere. Within the limited statistics there is agreement that the abundance of particles heavier than protons in the inner belt is about 1%. Our data indicate that the heavy component is predominantly deuterons. The presence of deuterons alleviates the difficult problem of explaining their absence from the belt, as was indicated by the data of Freden and White. A conclusion--from the combined data--that the abundances of deuterons and tritons may be nearly equal is not inconsistent with the data of Bailey (1956), who has shown that $\sigma(p,t) \approx 0.2-0.5\ \sigma(p,d)$ for 190-Mev protons on various complex nuclei.

Helium Nuclei: No track which could be identified as a $z = 2$ particle was found during the ionization measurements described above. The selection of tracks greater than 5 mm range in emulsion corresponding to an initial alpha energy $\geq$ 185 Mev, biases against the detection of alpha particles. Subsequent scanning along the leading edge of the emulsion for alpha tracks between 1 and 5 mm range (E_{min} = 125 Mev) also failed to produce evidence for trapped alpha particles. An upper limit of the alpha flux is 0.1±0.05% of the proton flux in the interval 125 to 185 Mev. This limit is set by the alpha-particle background produced by nuclear interactions in the emulsion and surrounding matter.

ACKNOWLEDGMENTS

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FOOTNOTES AND REFERENCES

* This experiment was performed under the auspices of the U.S. Atomic Energy Commission.

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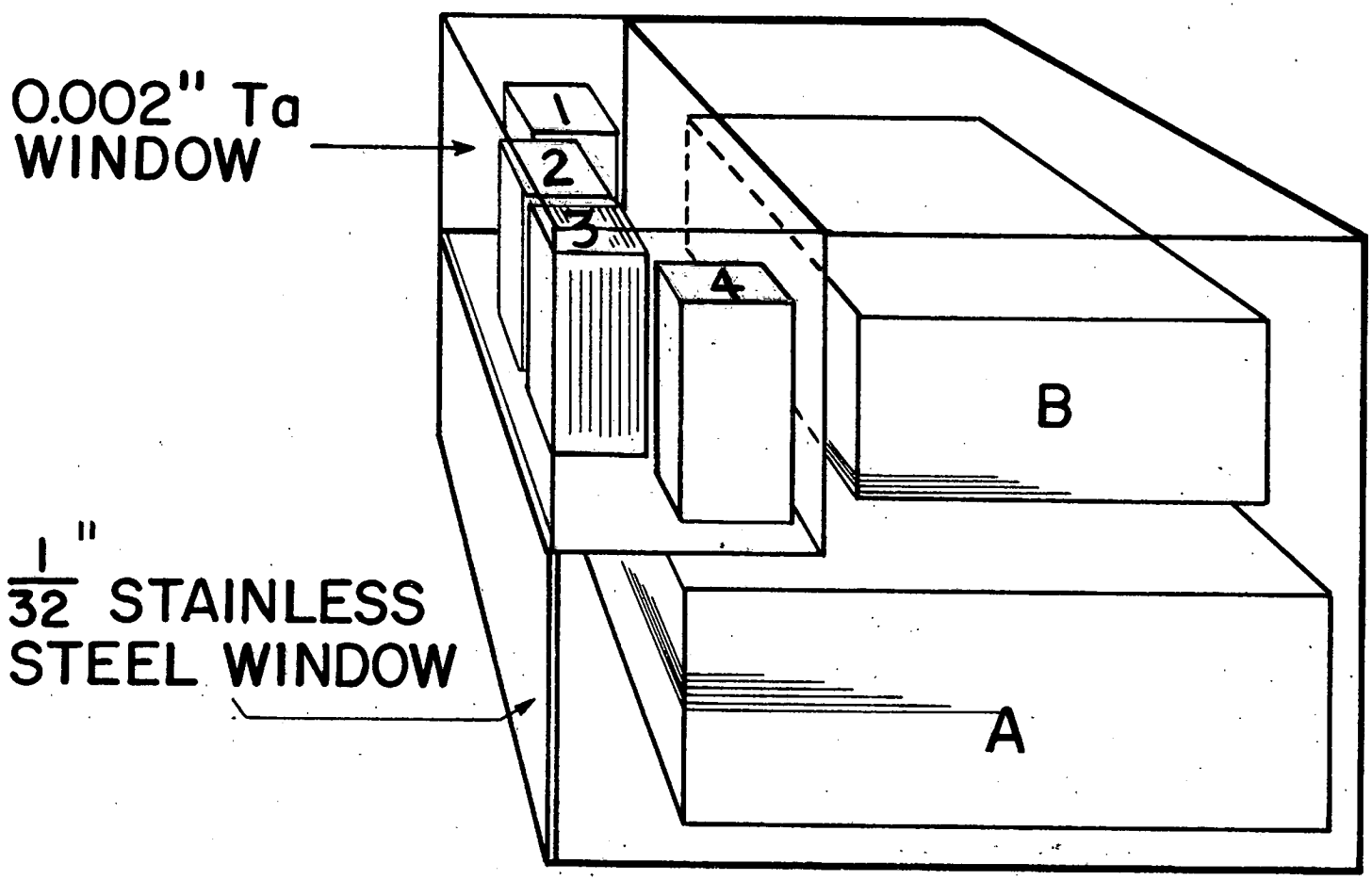
FIGURE CAPTIONS

Fig. 1 - Schematic drawing of the experimental package showing the arrangement of the emulsion stacks.

Fig. 2 - Measured proton-energy spectrum (October, 1960). Data from stacks 1, 2, and A are shown separately. Standard errors are indicated.

Fig. 3 - Comparison of the normalized proton spectrum observed in July, 1959 with the results of this experiment. The theoretical curves of Freden and White, and Lenchek and Singer are normalized to the experimental data at 100 Mev. The spectra calculated by Lenchek and Singer are for cut-off energies of 650 and 1000 Mev.

Fig. 4 - Mass measurements by the ionization (percent transparency) vs. range method. Dashed curves are expected loci for deuterons and tritons as deduced from the proton calibration curve. Five tracks were identified as deuterons. Note that three measurements are shown for each deuteron. Kinetic energies of the deuterons were 93, 119, 126, 131, and 133 Mev.



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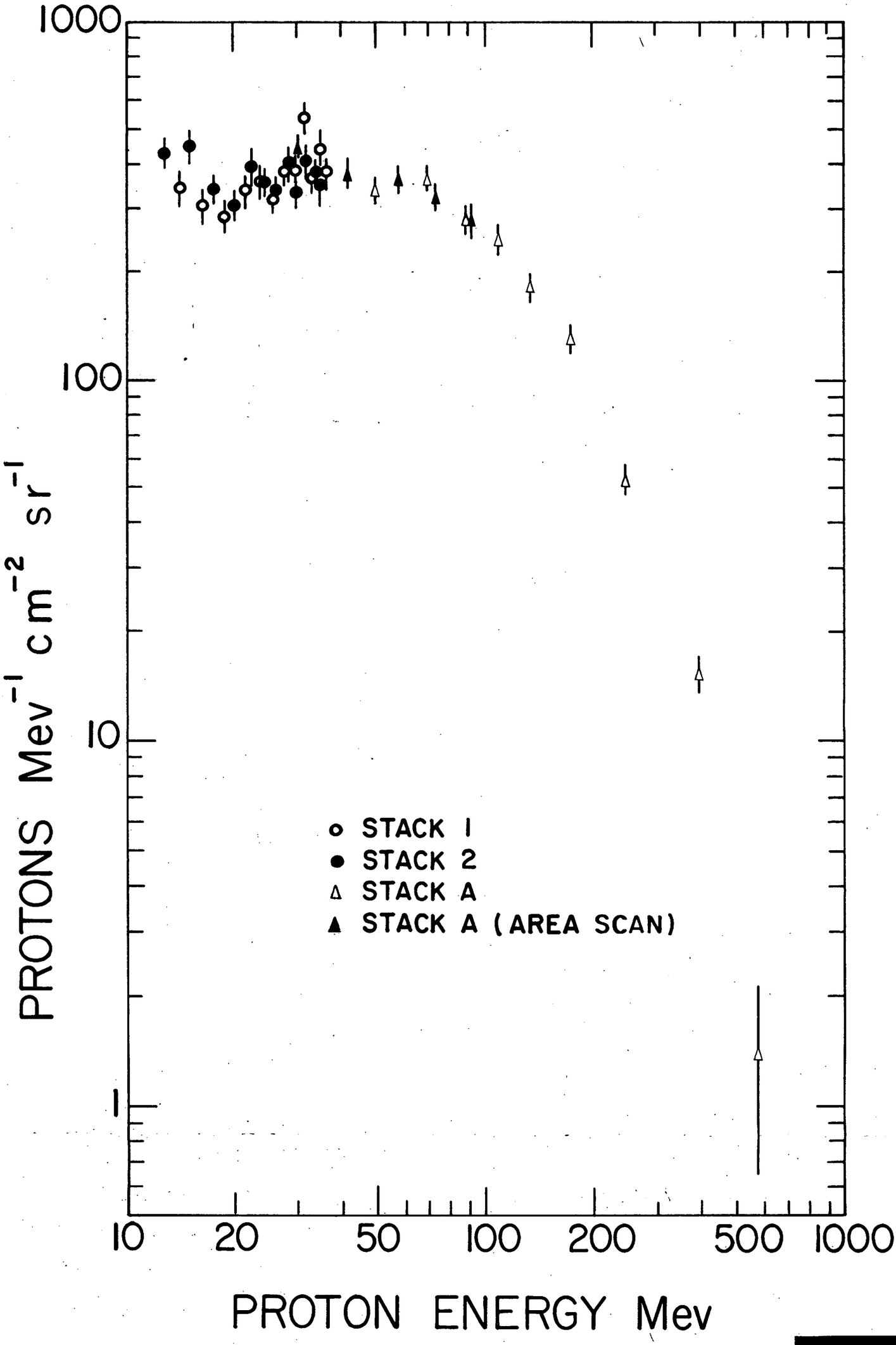

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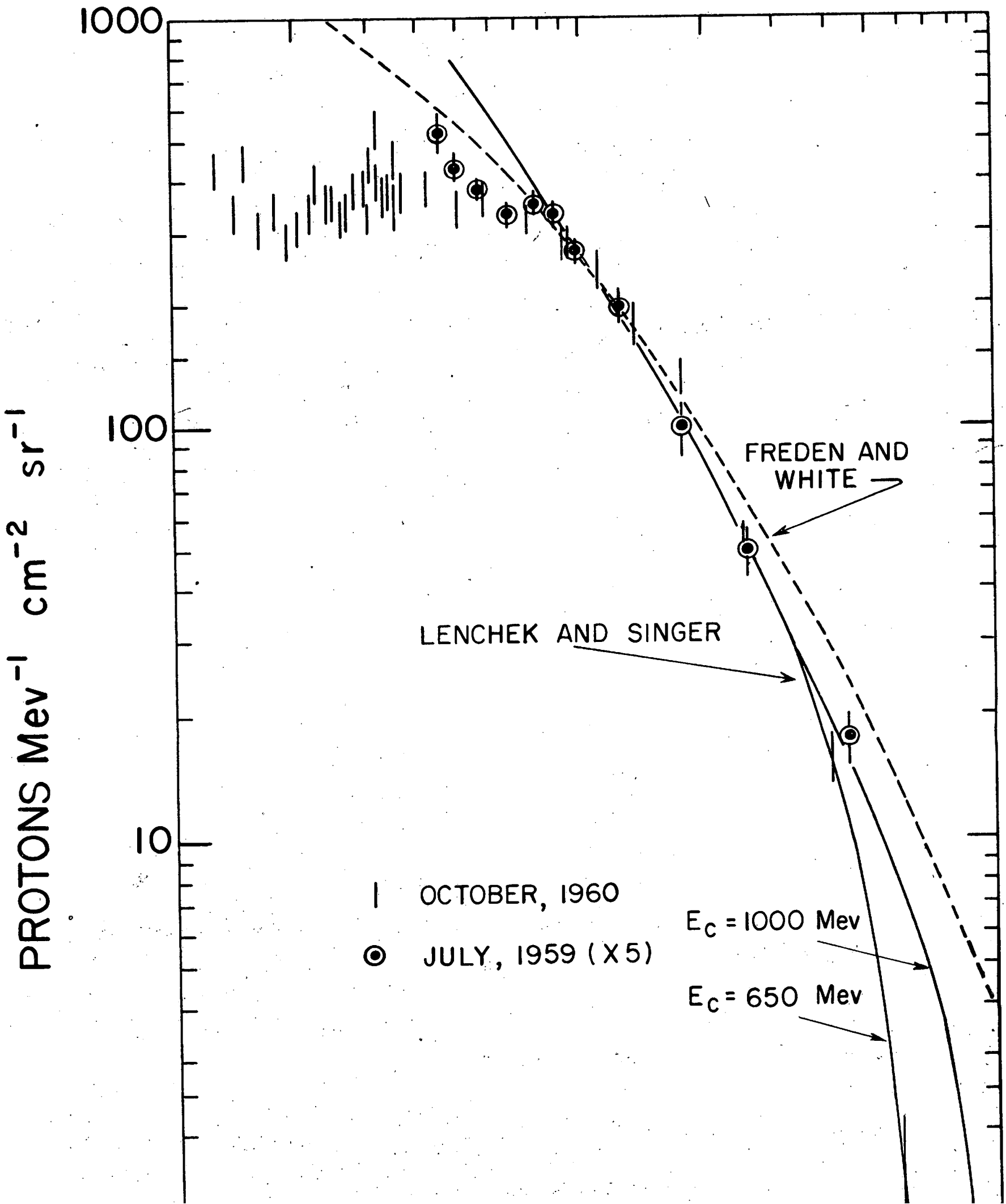
1000
100
10
PROTONS Mev^{-1} cm^{-2} sr^{-1}
FREDEN AND WHITE
LENCHEK AND SINGER
OCTOBER, 1960
JULY, 1959 (X5)
E_c = 1000 Mev
E_c = 650 Mev

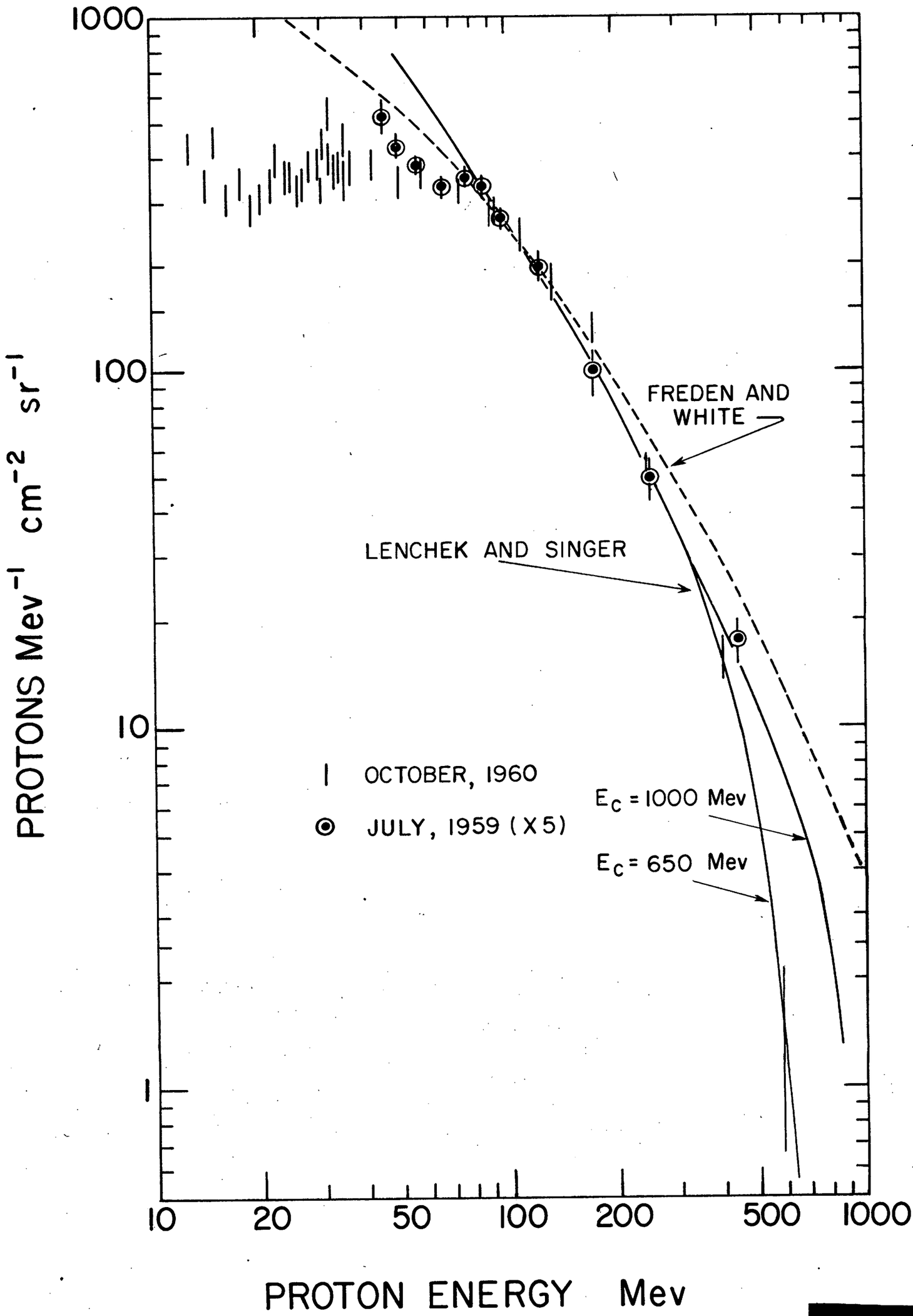

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Fig. 3

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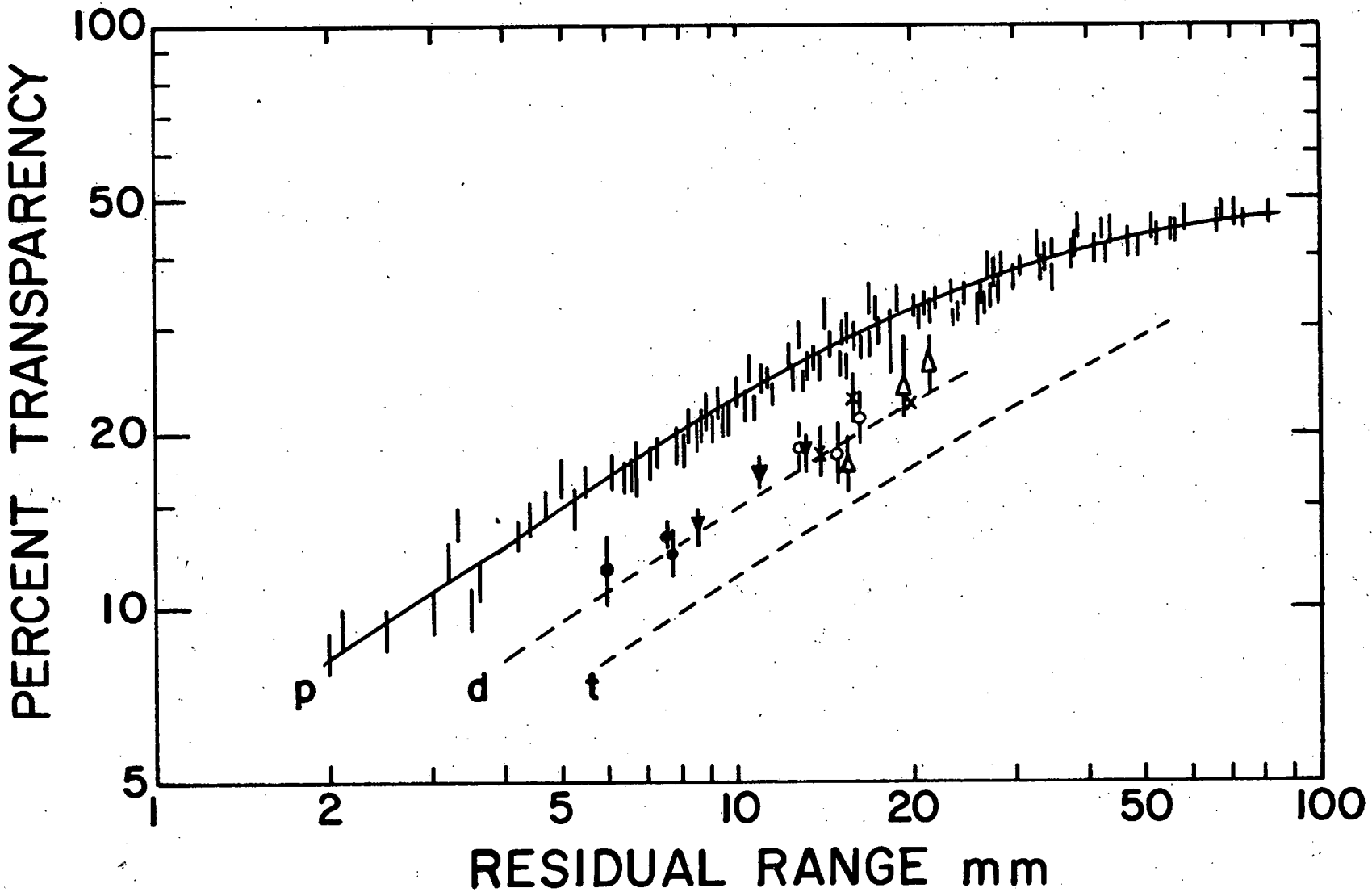

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Fig 4

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