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SOME ENERGY SPECTRA OF STRAY NEUTRONS FROM THE BEVATRON

Berkeley, California

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Submitted to Nucleonics

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Abstract

Recent improvements in the speed of track scanning, in track sampling, and in the analysis of random track-energy distributions have extended the use of nuclear track emulsion to include the measurement of stray neutron spectra. The value of these improvements has been tested in the measurement of fluxes and spectra of stray fast neutrons at eight locations in the vicinity of the Bevatron.

The general form of the stray-neutron spectra measured between 0.7 and 20 MeV was a broad peak in the region 0.5 to 2 MeV followed by a smooth 100-fold drop in value between the peak and 12 MeV. Local departures from this pattern, arising from the influence of nearby smaller accelerators, were measured.

Those emulsions exposed in the direct stray field through the open (SW quadrant) roof measured a fast-neutron source strength of 0.14 to 0.21 neutron per accelerated proton. The values for the better-shielded locations were between 0.028 and 0.066 neutron per accelerated proton. The thermal neutron "source strength" was between 0.31 and 0.66 neutron per accelerated proton at all locations. At the better-shielded locations, the thermal neutron flux was about 10 times the fast neutron flux.

I. Introduction

The principal health hazard to workers in the vicinity of shielded high-energy particle accelerators is from stray fast neutrons of mean energy between 0.1 and 2 MeV (1, 2). Knowledge of the intensity and energy spectrum of these neutrons is important in the evaluation of the radiation dose they produce. Various counting, activation, and attenuation measurements have given precise values for the intensity, but only rough ideas about the energy distribution of such stray neutrons (3-7).

Until recently, the use of the most reliable instrument for measuring fast neutron spectra--nuclear track emulsion--has been restricted to neutron beams and point sources where the direction of incidence is known. Now, however, improvements in the speed of proton track scanning, in the track sample corrections, and in the analysis of random-track energy distributions have extended the use of nuclear track emulsion to include measurement of stray-neutron spectra (8-10). This work tests the value of these improvements through determination of some energy spectra of stray neutrons, by use of nuclear track emulsions exposed in the vicinity of the Bevatron.

II. Experimental Method

The emulsions

The nuclear track emulsion was from Ilford Inc., Ilford Essex, England, Type L.4, batch Z2147, manufactured on October 20, 1960. It was immediately shipped to Berkeley, California as 1 × 3-in. unmounted pellicles, 600 μ thick. The pellicles were stored 4 months, then cut into 1 × 1-in. pieces (each of which was wrapped with a single fold of black paper

and a single fold of black tape). The exposure period was between 4 and 10 weeks. They were developed on the day following the end of the exposure. Emulsion history charts (11) were kept for each piece.

Their location during exposure

Eight wrapped pieces of emulsion were taped to the inside of windows or to the sides of desks in rooms of buildings that stand within a 260-m radius from the Bevatron. The precise locations and exposure periods are presented in Fig. 1 and in Table 1. During the exposure period the Bevatron operated on a normal 24-hour daily schedule, and accelerated to high energy about 1.4×10^{16} protons per week. These protons struck internal targets at 82.99° in quadrant three and south end of west tangent tank. At the same time, the 184-inch synchrocyclotron was accelerating beams during approximately 50% of the exposure time. More than 90% of these beams were protons of several hundred MeV that were used in producing mesons.

The Bevatron shielding

The shielding of the Bevatron consisted of a 12-ft-thick cylindrical ring of concrete blocks lying just outside the magnet ring. Additional 2-ft slabs of concrete covered the straight (tangent) tanks, which unite the four curved quadrant sections. The top of the magnet ring was largely open and unshielded.

Emulsion processing

The exposed unmounted 1×1-in. pieces of emulsion were developed and fixed by a modified cold-cycle process (11). The processed emulsions were soaked for 24 h in a concentrated solution of wood rosin in ethanol. This treatment reduced the average thickness shrinkage to 27%. Prior to scanning, the emulsion pieces were mounted on 1×3-in. glass microslides by use of a clear epoxy cement.

Scanning

Track samples were selected with the help of a microcoordinate readout microscope: that track was measured next which lay with its end nearest the end point of the track just previously selected and measured (10). (However, only those tracks that had both end points within the emulsion volume were measured.) Thus track samples were selected along a microscopic "random walk" through the emulsion. The track density in each emulsion was measured independently by counting the tracks within a known volume. The hydrogen atoms in the protein matrix of the emulsion were the sole source of tracks from proton recoils. The only tracks measured were those of proton recoils.

Analysis

An IBM-650 computer, directed by the program "RECOIL I", computed the length of each measured track and assigned it to one of 86 proton track-length energy intervals (11). Several thousand tracks generated the points of a raw proton energy distribution. This distribution was corrected by a factor (based on the geometric probability that a track of a given energy will end outside the emulsion) that assumes an isotropic neutron exposure (9). This was reasonable, since the factor is relatively insensitive to departures from isotropic exposure.

There is a serious scanning bias against the very short tracks. Corrections for this bias have been derived from analyses of track-length distributions obtained by scanning from emulsions exposed to single-energy neutrons (10). In the figures corrected values are given as Δ's.

Track-energy distributions corrected as above contain two peaks that distort the basic proton recoil spectrum. One, at 0.60 MeV, arises from

the nuclear $N^{14}(n,p)C^{14}$ reaction with thermal neutrons. The other, at 1.25 MeV, is from α-particle tracks that are the major component in the background track density of the emulsions. Natural alpha emitters "built into" the emulsions during manufacture are the source of these tracks. The 1.25-MeV peak vanishes when the background track distribution is subtracted. The 0.60-MeV peak was bypassed by means of a smooth curve that joins the "anchor" point at 0.47 MeV with those at 0.86 and 0.96 MeV. At greater energies the curve was drawn in a monotonically decreasing form as the smoothest curve consistent with the statistical error of the points making up the track-energy distribution.

Points along the smooth curve (at 0.1-MeV intervals from 0.4 to 1 MeV, at 0.2-MeV intervals from 1 to 3 MeV, at 0.3-MeV intervals from 3 to 6 MeV, and at 0.4-MeV intervals beyond 6 MeV) were used by a second computer program "RECOIL DD" to find the points of the neutron spectrum. RECOIL DD determines these latter points by successively fitting a second-order polynomial curve to three adjacent input values, and differentiating the curve at the point of interest. For instance, if $f(E) = a + bE + cE^2$ is the polynomial curve based on the input points at 0.4, 0.5, and 0.6 MeV, then $f'(0.5)[0.5/\sigma(0.5)]$ is the relative value of the neutron spectrum at 0.5 MeV, if $\sigma(0.5)$ is the elastic-scattering cross section for hydrogen at 0.5 MeV.

III. Results

The distributions of track-length energy in nuclear emulsions exposed for a number of weeks at eight locations in the vicinity of the Bevatron are presented in Figs. 2 through 9. The points are corrected for the geometric probability of escape, and for short-track sampling bias (Δ). The smooth curve in each figure represents the basic recoil proton distribution after subtracting the background track distribution and after bypassing the

thermal-neutron interaction peak at 0.61 MeV. The neutron-energy curve that was derived from the smooth proton-energy curve by the RECOIL DD method is also given in each figure.

Background track-energy distributions from unexposed emulsions may be seen in Figs. 10 and 11. Their "lifetimes" were respectively 6 weeks and 10 months between manufacture and development. Comparison of the two reveals that the 1.25-MeV peak from alpha tracks grows at a rate greater than the proton recoil-track background (smooth lines). There was no evidence of a 0.6-MeV peak in the background emulsions.

The raw density of tracks and the density corrected for scanning bias against the 5- to 8-μ tracks are presented in Table 2. (All densities are those in the preprocessed emulsion; they refer to tracks with length 5 μ or greater.) The estimates of the densities of the corrected N(n, p)C track and the α track are based on the areas A and B in the figures. The densities per proton accelerated by the Bevatron during the exposure period are also given.

The thermal neutron flux, and the fast neutron (0.7 to 20 MeV) flux per 10^{12} accelerated protons have been computed from the track densities. The latter is based on a $\langle\sigma\rangle$ of 3.3 barns for the elastic collision of the fast neutrons with hydrogen. These values, plus their product with $4\pi r^2$ (r is the slant distance from the emulsion location to the center of the Bevatron) are presented in Table 3.

Estimates of the expected track densities in soft tissue from fast and thermal neutrons, and the derived tissue dose in μrads per 10^{12} accelerated protons, are given in Table 4. The values pertain to the expected dose at the location of the emulsions, based on the measured track density and energy distribution in the emulsions (11).

IV. Discussion

Methods of analysis

Several methods that are indifferent to the direction of neutron exposure are available for using proton recoil tracks in nuclear emulsion to measure fast neutron fluxes and energy spectra (12). These methods depend upon an accurate evaluation of the derivative of the proton recoil energy spectrum at the points of interest. Such an evaluation requires a precisely determined track-length energy spectrum, and a suitable method for differentiating it.

In practice, the best estimate of the proton-recoil spectrum is one based on a large random sample of tracks corrected for the escape probability, the scanning bias, the N(n, p)C contribution, and the background. Further, if necessary, the curve is bent to the theoretical requirement that it shall decrease in value monotonically with increasing energy.

Finding a suitable method for differentiating the recoil spectrum has proven as difficult as obtaining the spectrum itself. Attempts to generate analytical curves that closely fit recoil spectra, by use of various standard computer programs (including double precision matrix inversion), failed (13). Roberts has used successfully the difference between successive equally spaced points (12). Although this method has the advantage of giving a direct estimate of the error in the neutron spectrum, it can lead to oscillations in the neutron spectrum which are not real, but rather arise from the statistical uncertainties in the values of the points making up the proton spectrum.

In this work there was no reason to expect any but smooth and continuous stray neutron spectra. The point of view was therefore taken that any curving in the derived neutron spectra should reflect a local trend in the proton spectrum, not the random variations between adjacent points. For this

reason, the input points for RECOIL DD were taken from the smoothed proton recoil spectra.

Effect of synchrocyclotron operation

Film B-41 was located about 50 m from the relatively well-shielded synchrocyclotron and at approximately the same elevation. There is no evidence of a track contribution greater than about 25% of the total in this film (see Table 3). The neutron spectrum (Fig. 8) can be interpreted as a Bevatron stray neutron spectrum with a small superimposed peak from the synchrocyclotron at 6 MeV. There is no evidence that this accelerator contributed a measurable fraction of the tracks in the other films, which were located well below it and at considerable distances from it.

The neutron fluxes and spectra

The emulsions located where the direct stray-neutron field of the Bevatron reached them through the unshielded roof (B-28, B-31, and B-39) indicated the Bevatron stray fast neutron source strength to be 3 to 7 times as great as for the other positions. In April of 1959, before the roofs of the straight (tangent) sections were shielded, the fast neutron source strength was measured by use of indium foils in paraffin spheres inside cadmium boxes and and found to be 1.8 neutron per accelerated proton through the roof of the NE quadrant (19). The tenfold lower value measured by the emulsions reflects the effect of the partial roof shielding, the fact that the indium foils measured intermediate-energy neutrons to which the emulsions are insensitive, and anisotropic stray neutron emission stronger in the NE than in the SE or SW directions (15).

Every emulsion measured a thermal neutron flux that indicated a "source strength" of between 0.31 and 0.66 thermal neutron per accelerated proton.

The fast neutron flux from the emulsions not in line with the open roof of the Bevatron was in each case very close to 0.1 the thermal neutron flux.

The emulsions located at a distance from the Bevatron ring measured fast-neutron spectra composed of a broad peak between 0.5 and 2 MeV with a smooth drop of two orders of magnitude or more between 2 and 12 MeV. The spectra measured inside the building housing the Bevatron fall away rapidly beyond 1 MeV. The surprising peak at 11 MeV in film B-27 (Fig. 3) is completely unexplained. The data leave no doubt that it is real, however, and it may reflect a contribution to the stray-neutron field from the nearby 70-MeV linear accelerator, which injects protons into the Bevatron.

There is no simple analytical method for evaluating the local uncertainty in the neutron spectra. If it is assumed that the stray neutron spectra are smooth and not composed of many sharp peaks, then the local uncertainty is roughly equal to the statistical uncertainty in the corresponding points in the proton recoil distribution. This can be determined by allowing the proton spectrum points to vary randomly within their statistical uncertainty limits—then redrawing the smooth curve for differentiation several times.

Past and future measurements

The value of improvements in scanning and analysis of nuclear emulsions in the spectrometry and dosimetry of stray neutrons has been tested in measuring fields from a plutonium-beryllium source, from a bare pulsed reactor, and from the Bevatron (8, 11). It will be of interest to compare the spectra reported here with those derived from emulsions exposed in the same locations, now that the recent total-roof shielding of the Bevatron has been completed.

The local fast-neutron spectra at various locations in and around human phantoms exposed 10 to 200 m from a bare pulsed reactor have been derived, and will be reported soon, as also will some measurements of Be(α, n)C spectra.

V. Summary and Conclusions

Nuclear track emulsion has been used to measure the stray fast-neutron fluxes and spectra in the vicinity of the Bevatron. The recent improvements in the speed of track scanning, in track sampling, and in the analysis of random track-energy distributions have made such measurements possible on a semiroutine basis.

The general form of the stray neutron spectra measured between 0.7 and 20 MeV at eight locations near the Bevatron was a broad peak in the region 0.5 to 2 MeV followed by a smooth 100-fold drop in value between the peak and 12 MeV. Local departures from this pattern, arising from the influence of nearby smaller accelerators, were measured.

Those emulsions exposed in the direct stray field through the open roof (SW quadrant) measured a fast-neutron source strength of 0.14 to 0.21 neutron per accelerated proton. The values for the more shielded locations were between 0.028 and 0.066 neutron per accelerated proton. The thermal neutron "source strength" was measured and found to be between 0.31 and 0.66 neutrons per accelerated proton at all locations. At the more shielded locations the thermal neutron flux was about 10 times the fast neutron flux.

Acknowledgments

The authors wish to thank Mr. Carl Quong, who wrote the computer programs RECOIL I and RECOIL DD, Mr. John Wood, who developed the emulsions, and Mr. H. Wade Patterson and Dr. Roger Wallace, who have supported this work and contributed to it through suggestions and advice.

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Table 1. Details of film exposure.

Film No.	Dates of exposure (1961)	Exposure per lifetime (days)	Location (Bldg. and Room)	With respect to Bevatron center			Accelerator operation	
				Slant dist. (m)	Angular elev. (deg)	Azimuth (deg)	No. Accel. Beva protons ($\times 10^{-16}$)	184-inch cyclotron proton-beam-on time (days)
B-17	-	0/307	-	-	-	-	-	-
B-22	-	0/44	-	-	-	-	-	-
B-25	2-8 to 3-8	28/160	70-221	113	10.8	S40°W	5.77	15
B-27	2-8 to 3-8	28/160	51-ICR	32	0	N80°E	5.77	15
B-28	2-8 to 3-8	28/160	51-Mez	35	10.0	S40°W	5.77	15
B-31	2-8 to 3-8	28/160	50-239	120	8.7	S80°W	5.77	15
B-39	3-14 to 4-19	36/52	51-Mez	35	10.0	S40°W	6.73	19
B-40	2-8 to 4-19	70/197	29-201	180	11.7	S10°E	13.9	36
B-41	2-8 to 4-19	70/197	80-CR	260	12.4	S25°E	13.9	36
B-43	2-8 to 4-19	70/197	64-209	176	1.0	N13°W	13.9	36

Table 2. Track scanning details.

Film No.	Size of track sample	Track density[a] ($\times 10^{-6}$ cm^{-3})					Track density[a] per Beva proton ($\times 10^{12}$ cm^{-3})	
		measured	corrected	proton recoil	N(n,p)C	alpha	proton recoil	N(n, p)C
B-17	434	-	-	-	-	-	-	-
B-22	288	0.008	0.008	0.004	-	0.004	-	-
B-25	2493	0.165	0.19	0.105	0.067	0.019	1.82	1.15
B-27	4066	2.1	2.7	1.6	1.1	0.012	28	19
B-28	3715	5.6	7.25	5.7	1.5	0.015	99	26
B-31	4017	0.35	0.415	0.31	0.088	0.017	5.4	1.5
B-39	3853	9.0	11.0	9.9	1.1	(0.005)	147	16.5
B-40	4293	0.245	0.295	0.16	0.115	0.018	1.15	0.83
B-41	4040	0.175	0.205	0.13	0.060	0.016	0.95	0.43
B-43	3938	0.325	0.39	0.25	0.14	0.013	1.80	1.00

a. Refers to tracks 5 μ in length or greater.

Table 3. Neutron flux estimates.

Based on Film No.	Flux per 10^{12} Beva-protons ($n\ cm^{-2}$)		Source Strength ($4\pi r^2 \times$ Flux)	
	Thermal	Fast[a]	Thermal (n/Beva p)	Fast[a] (n/Beva p)
B-25	200	17	0.31	0.028
B-27	3250	260	0.40	0.034
B-28	4450	930	0.66	0.14
B-31	260	50	0.45	0.16
B-39	2800	1380	0.42	0.21
B-40	140	11	0.56	0.044
B-41	75	9	0.60	0.076
B-43	170	17	0.65	0.066

a. Refers to 0.7- to 20-MeV neutrons only--based on $\langle\sigma\rangle$ = 3.3 barns.

Table 4. Tissue dose estimates.[a]

Based on Film No.	Density of dose per 10^{12} Beva-protons						% n, p dose
	Proton recoil density (cm^{-3})	N(n, p)C density (cm^{-3})	Ave. E proton recoils (MeV)	Proton recoils (μrad)	N(n,p)C (μrad)	Total (μrad)	
B-25	3.4	0.47	1.75	0.095	0.0045	0.10	4
B-27	52	7.7	1.75	1.45	0.075	1.5	5
B-28	185	10.5	1.30	3.8	0.10	3.9	2.5
B-31	10	0.61	1.75	0.28	0.006	0.29	2.0
B-39	270	6.7	1.30	5.5	0.065	5.6	1.2
B-40	2.1	0.34	1.60	0.054	0.003	0.057	5
B-41	1.8	0.175	1.75	0.050	0.0015	0.052	3
B-43	3.4	0.41	1.45	0.079	0.004	0.083	5

a. Refers to the dose at the exposure location of the emulsions, from proton tracks with energy between 0.47 and 16 MeV.

Figure Captions

Fig. 1. Emulsion exposure locations. Hill Area, Lawrence Radiation Laboratory.

Fig. 2. Track-length energy distribution from emulsion B-25, exposed 28 days on a desk in Bldg. 70, Room 221, 113 m from the Bevatron.
A: peak from nuclear n,p protons; B: peak from alpha particles;
C: smoothed recoil proton spectrum corrected for background tracks and n,p protons; D: neutron spectrum derived from C.
●: output of RECOIL I; Δ: points corrected for scanning bias against short tracks.

Fig. 3. Track-length energy distribution from emulsion B-27, exposed 28 days on a desk in the Bevatron Injector control room, 32 m from the center of the Bevatron.
A: peak from nuclear n,p protons; B: peak from alpha particles;
C: smoothed recoil proton spectrum corrected for background tracks and n,p protons; D: neutron spectrum derived from C.
●: output of RECOIL I; Δ: points corrected for scanning bias against short tracks.

Fig. 4. Track-length energy distribution from emulsion B-28, exposed 28 days on a window in the Bevatron mezzanine, 35 m from the center of the Bevatron.
A: peak from nuclear n,p protons; B: peak from alpha particles;
C: smoothed recoil proton spectrum corrected for background tracks and n,p protons; D: neutron spectrum derived from C.
●: output of RECOIL I; Δ: points corrected for scanning bias against short tracks.

Fig. 5. Track-length energy distribution from emulsion B-31, exposed 28 days on a window in Bldg. 50, Room 239, 120 m from the Bevatron.

A: peak from nuclear n,p protons; B: peak from alpha particles; C: smoothed recoil proton spectrum corrected for background tracks and n,p protons; D: neutron spectrum derived from C.

●: output of RECOIL I; Δ: points corrected for scanning bias against short tracks.

Fig. 6. Track-length energy distribution from emulsion B-39, exposed 36 days on a window in the Bevatron mezzanine, 35 m from the center of the Bevatron.

A: peak from nuclear n,p protons; B: peak from alpha particles; C: smoothed recoil proton spectrum corrected for background tracks and n,p protons; D: neutron spectrum derived from C.

●: output of RECOIL I; Δ: points corrected for scanning bias against short tracks.

Fig. 7. Track-length energy distribution from emulsion B-40, exposed 70 days on a window in Bldg. 29, Room 201, 180 m from the Bevatron.

A: peak from nuclear n,p protons; B: peak from alpha particles; C: smoothed recoil proton spectrum corrected for background tracks and n,p protons; D: neutron spectrum derived from C.

●: output of RECOIL I; Δ: points corrected for scanning bias against short tracks.

Fig. 8. Track-length energy distribution from emulsion B-41, exposed 70 days on a desk in the Bldg. 80 control room, 260 m from the Bevatron.

A: peak from nuclear n,p protons; B: peak from alpha particles; C: smoothed recoil proton spectrum corrected for background tracks and n,p protons; D: neutron spectrum derived from C.

●: output of RECOIL I; Δ: points corrected for scanning bias against short tracks.

Fig. 9. Track-length energy distribution from emulsion B-43, exposed 70 days on a window in Bldg. 64, Room 209, 176 m from the Bevatron. A: peak from nuclear n,p protons; B: peak from alpha particles; C: smoothed recoil proton spectrum corrected for background tracks and n,p protons; D: neutron spectrum derived from C. ●: output of RECOIL I; Δ: points corrected for scanning bias against short tracks.

Fig. 10. Background track-length energy distribution from unexposed emulsion B-22. Developed 6 weeks after manufacture. B: peak from alpha particles.

Fig. 11. Background track-length energy distribution from unexposed emulsion B-17. Developed 10 months after manufacture. B: peak from alpha particles.

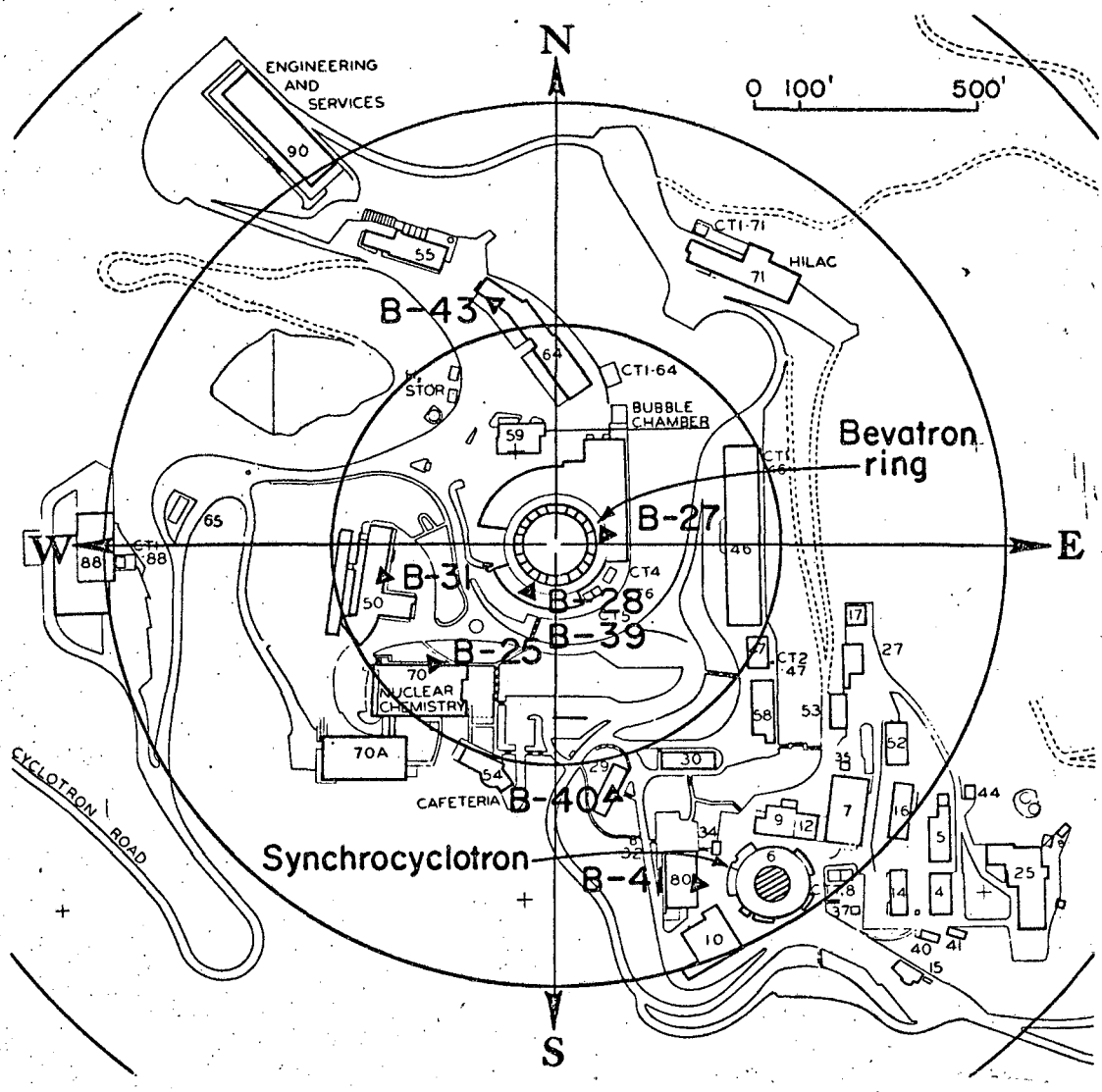


Fig. 1

MUB-3647

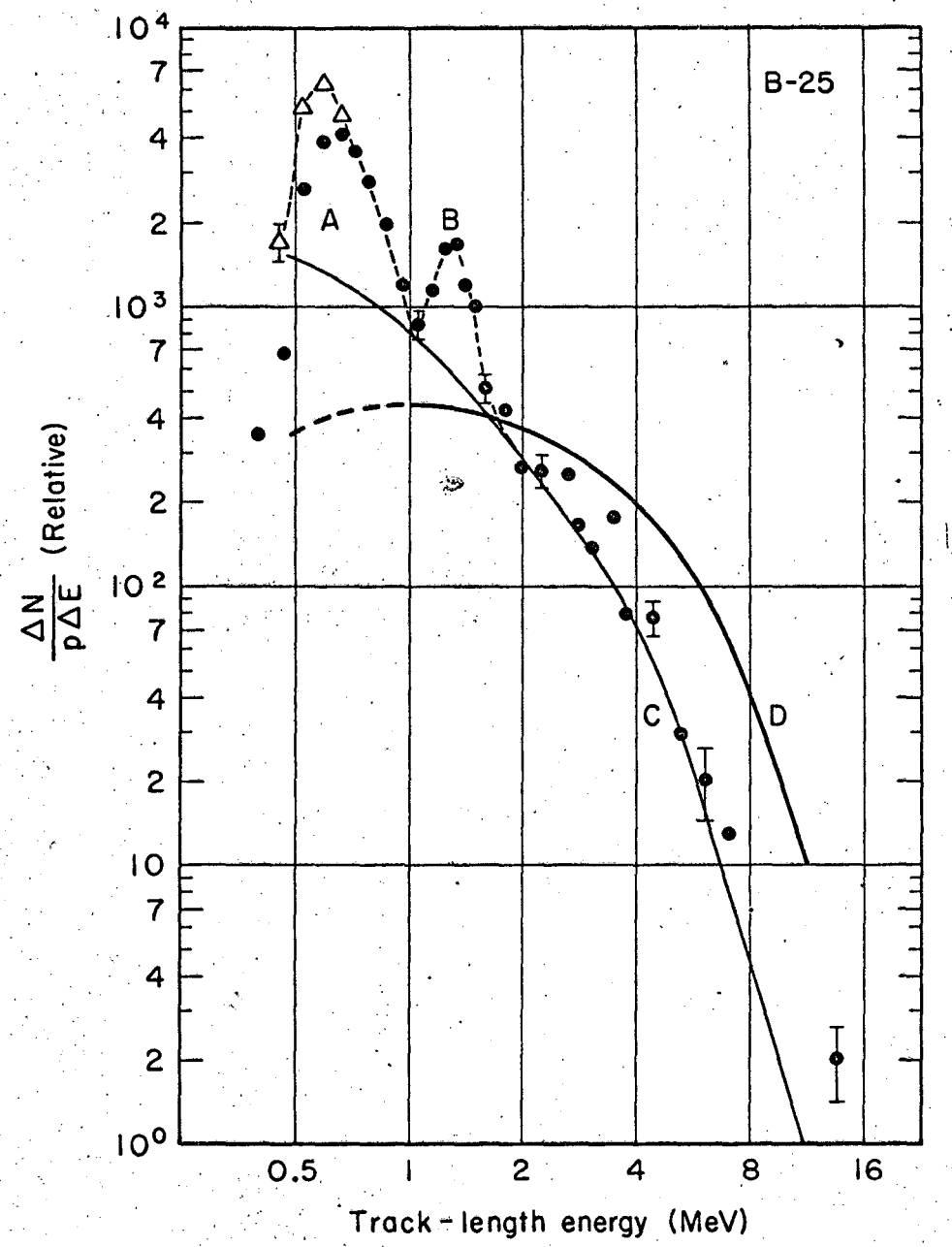

B-25
A
B
C
D
$\frac{\Delta N}{p\Delta E}$ (Relative)
Track - length energy (MeV)
10^4
7
4
2
10^3
7
4
2
10^2
7
4
2
10
7
4
2
10^0
0.5
1
2
4
8
16
MUB-3605

Fig. 2

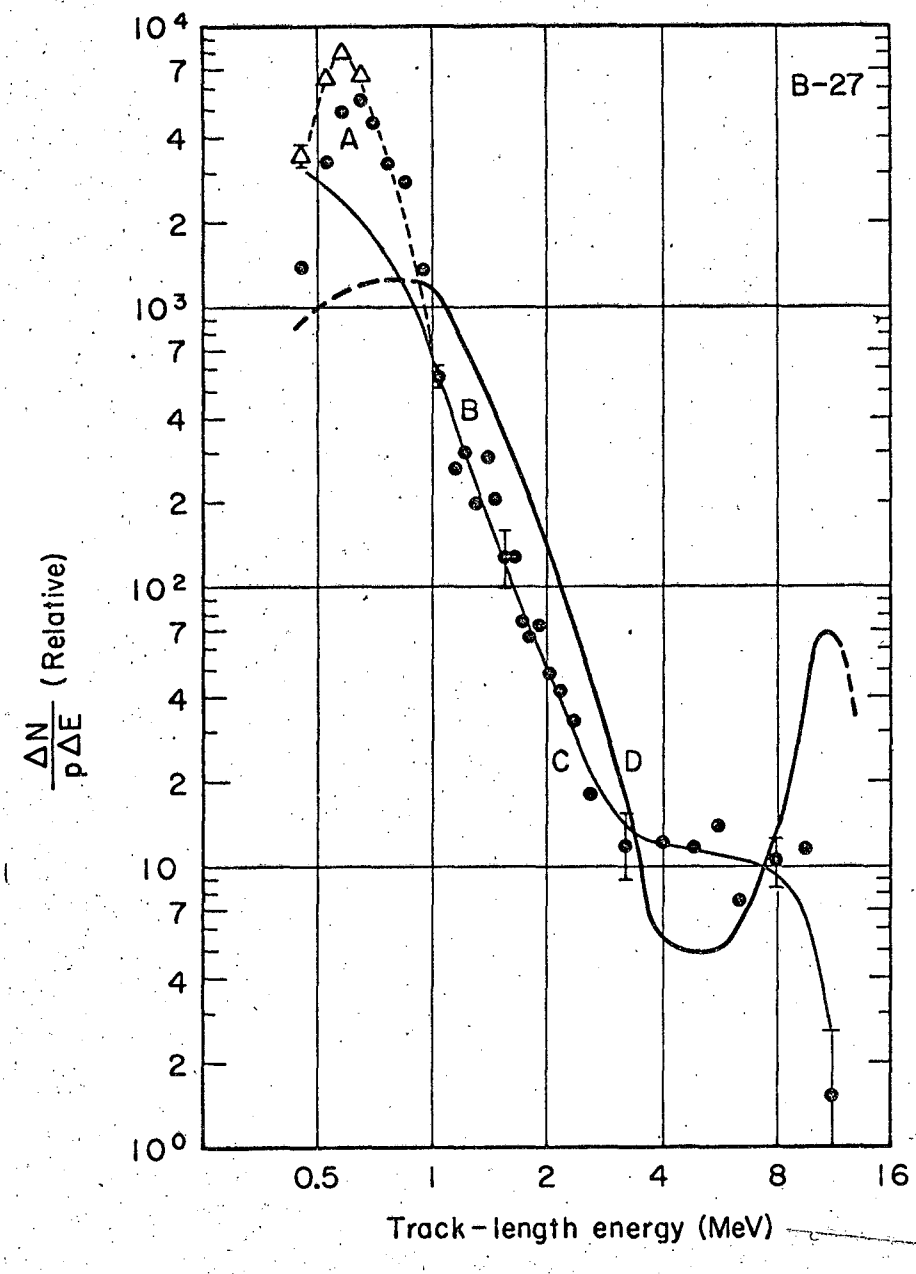

B-27
A
B
C
D
$\frac{\Delta N}{p\Delta E}$ (Relative)
Track-length energy (MeV)
0.5
1
2
4
8
16
10^4
10^3
10^2
10
10^0
MUB-3606

Fig. 3

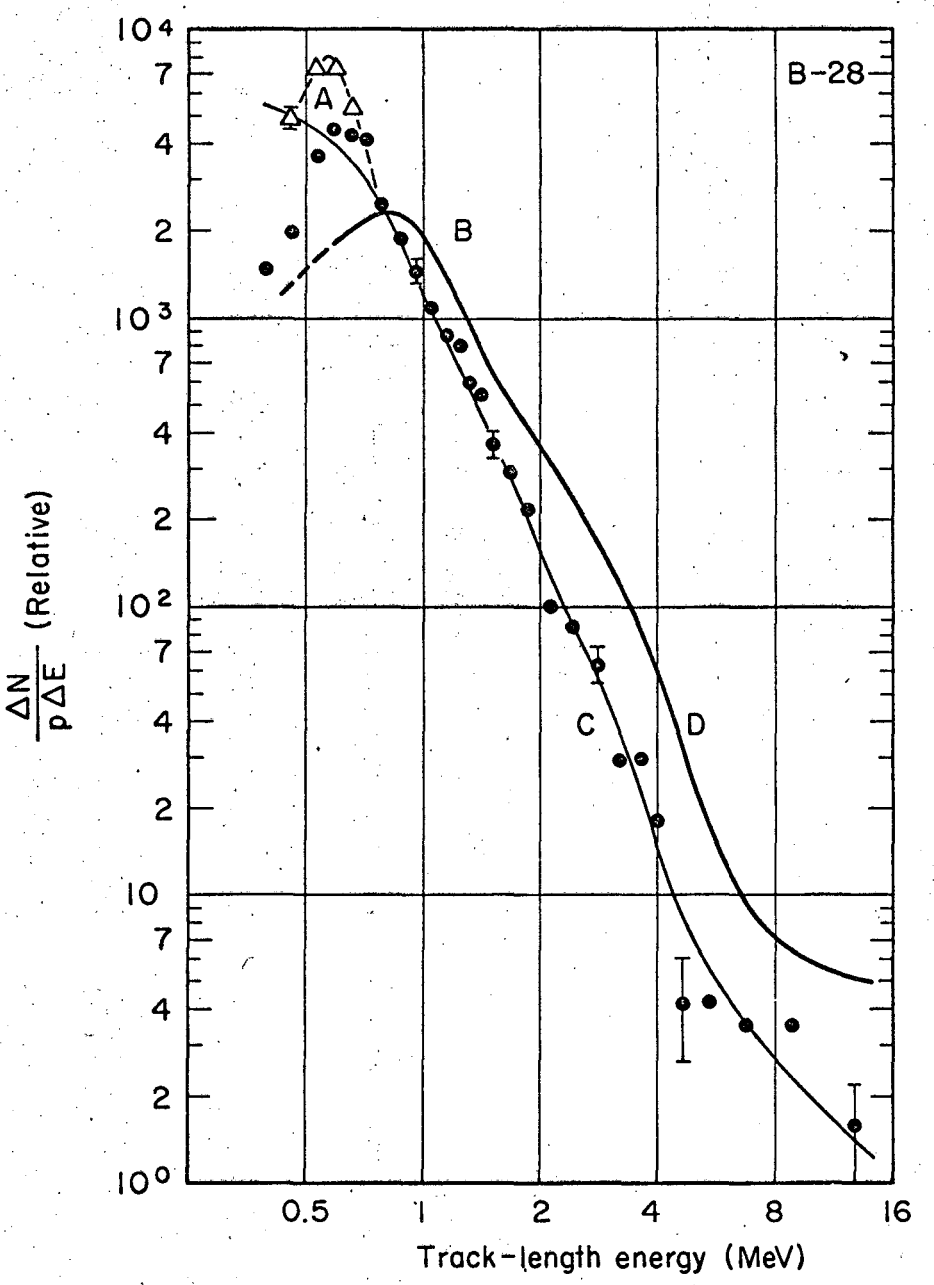

B-28
A
B
C
D
$\frac{\Delta N}{p\Delta E}$ (Relative)
Track-length energy (MeV)
0.5
1
2
4
8
16
10^0
10
10^2
10^3
10^4
MUB-3607

Fig. 4

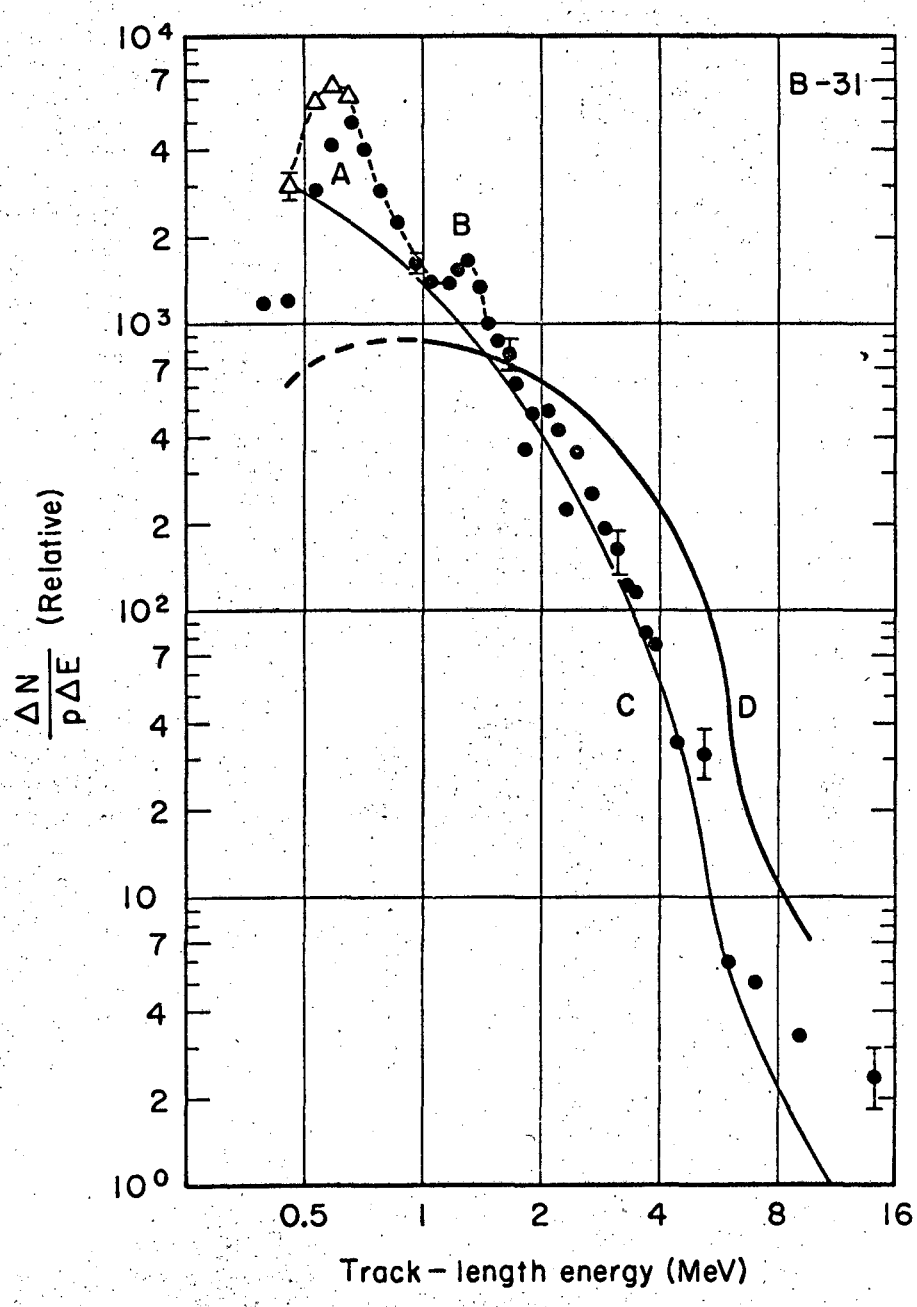

B-31
A
B
C
D
$\frac{\Delta N}{p\Delta E}$ (Relative)
Track – length energy (MeV)
0.5
1
2
4
8
16
10^0
10
10^2
10^3
10^4
MUB-3608

Fig. 5

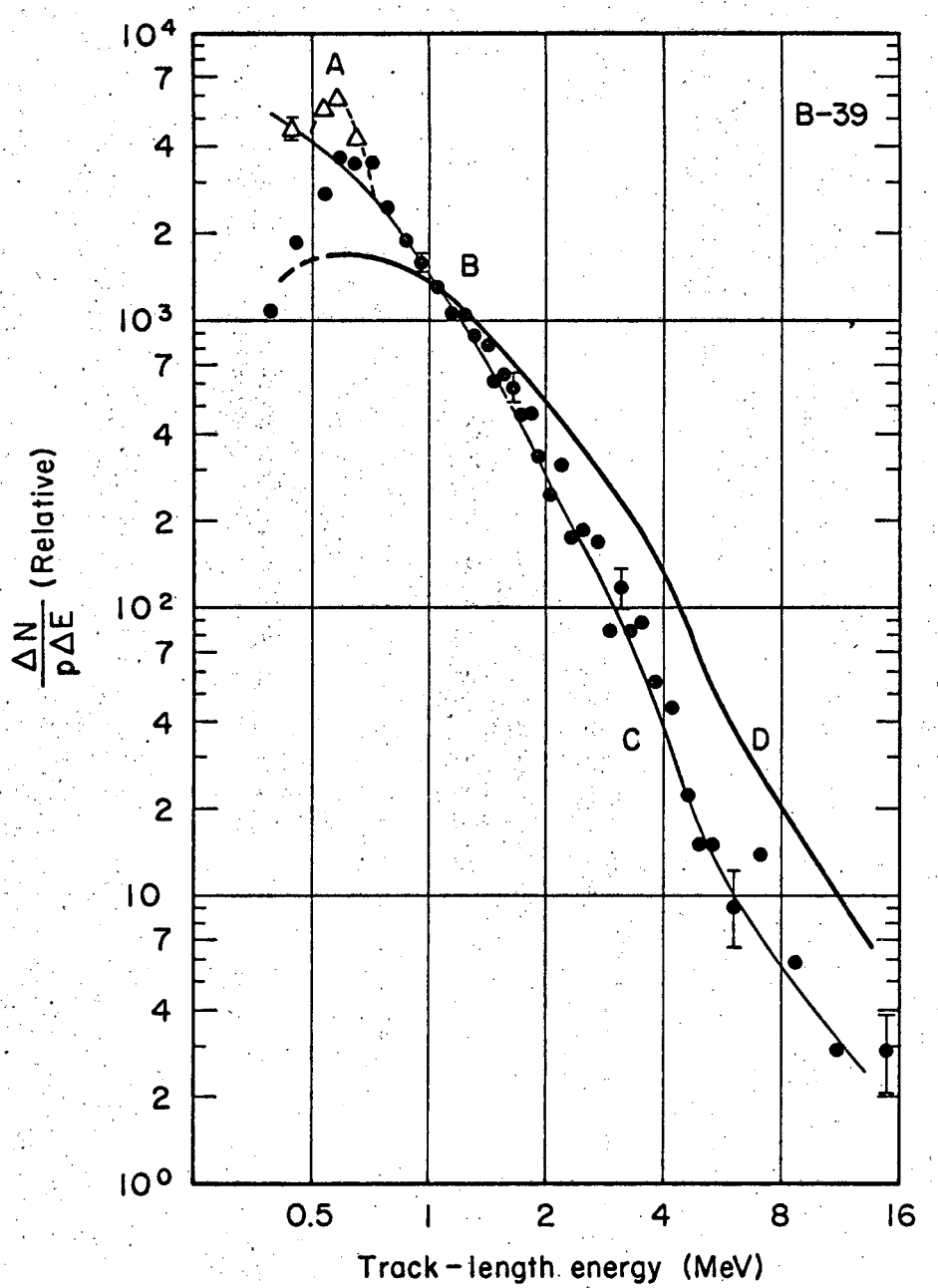
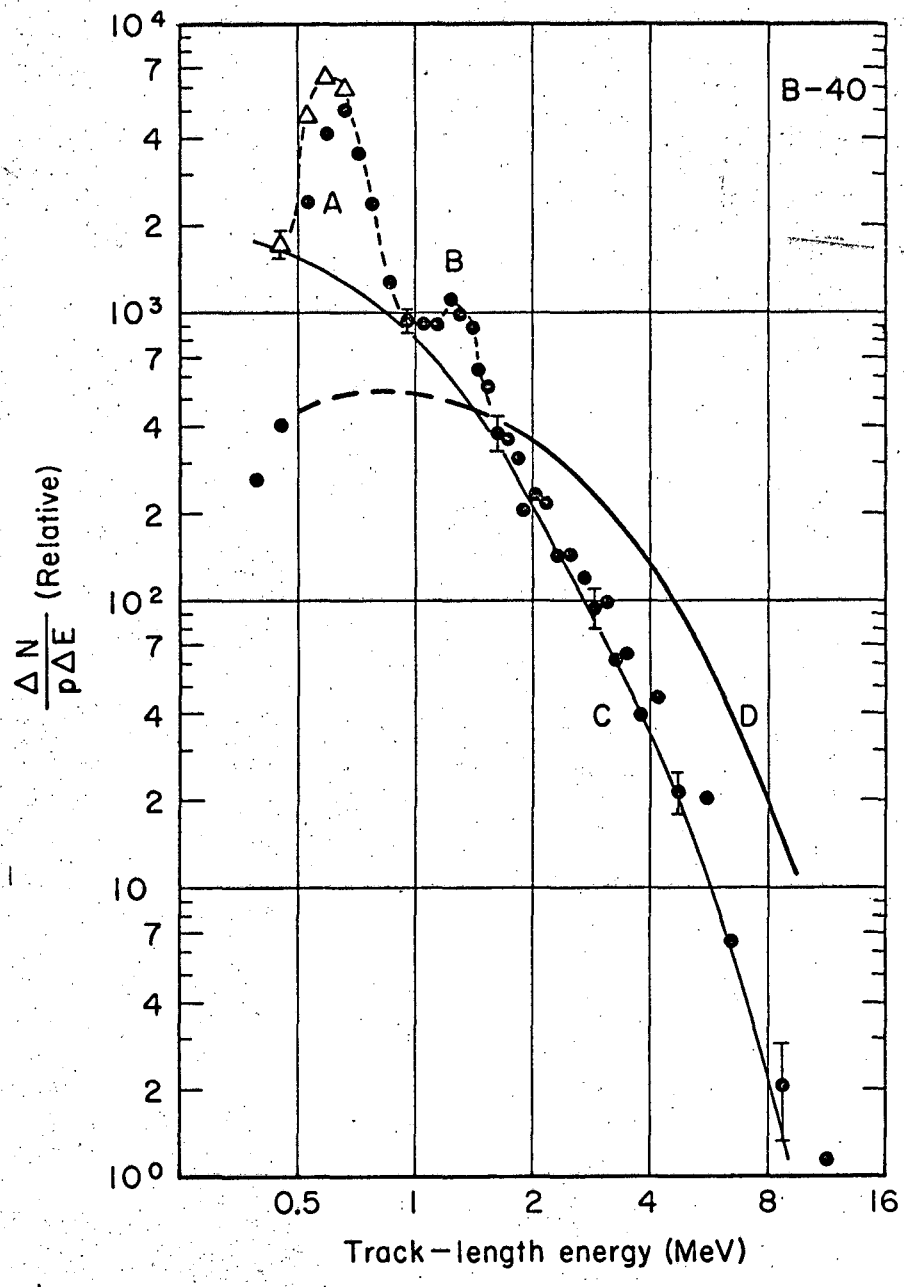
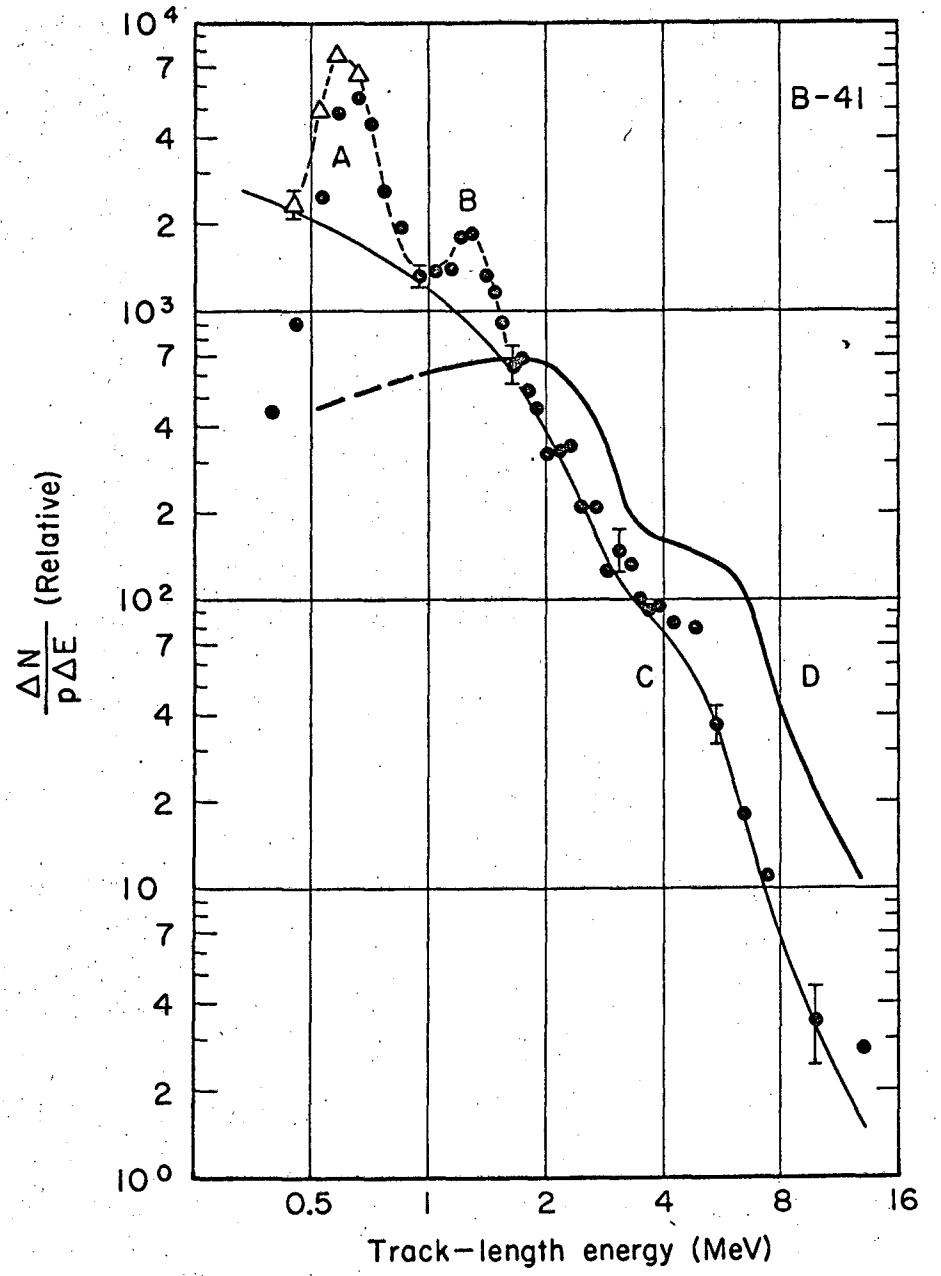

A
B
C
D
B-39
$\frac{\Delta N}{p\Delta E}$ (Relative)
Track-length energy (MeV)
MUB-3609

Fig. 6



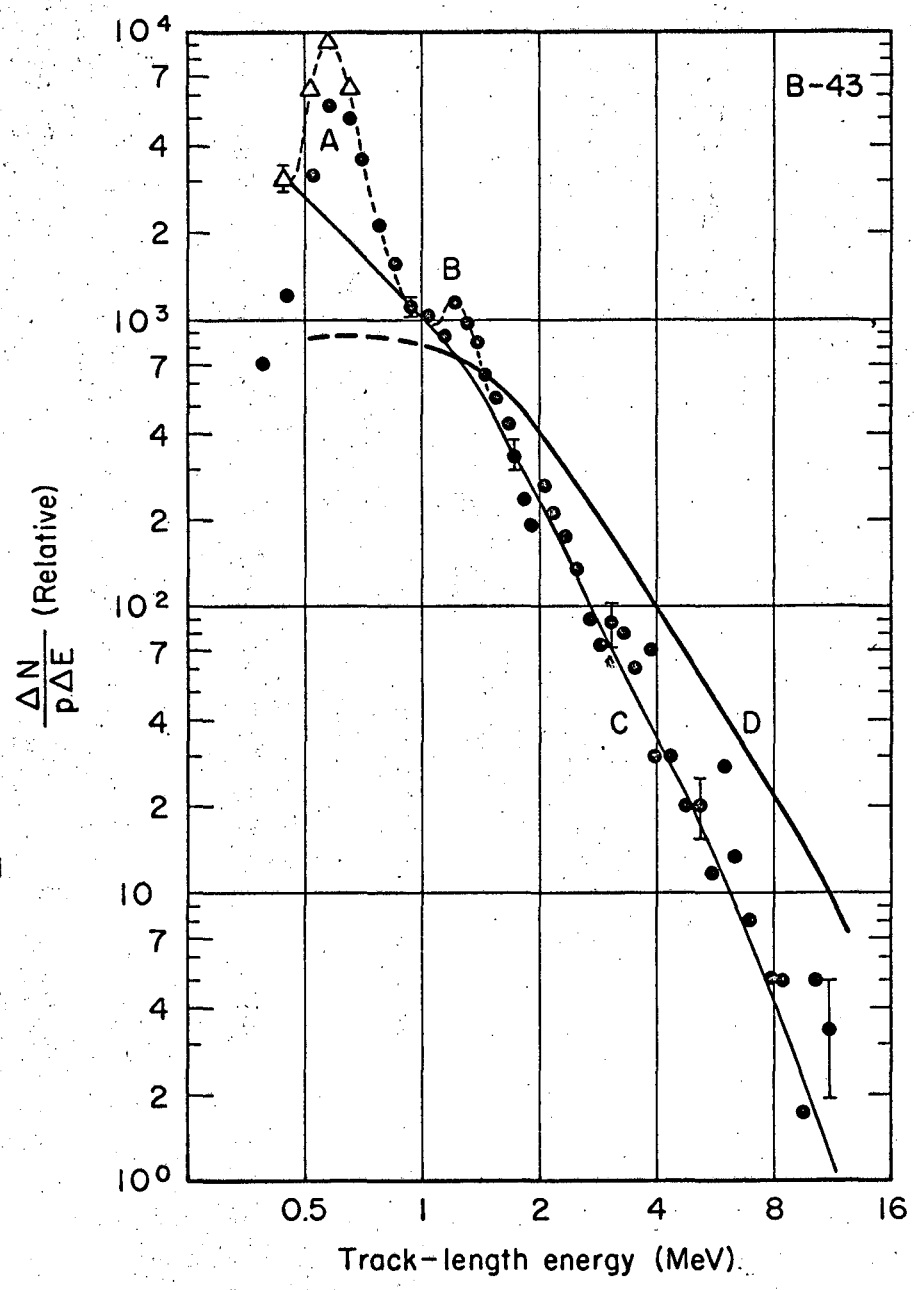
MUB-3610

Fig. 7



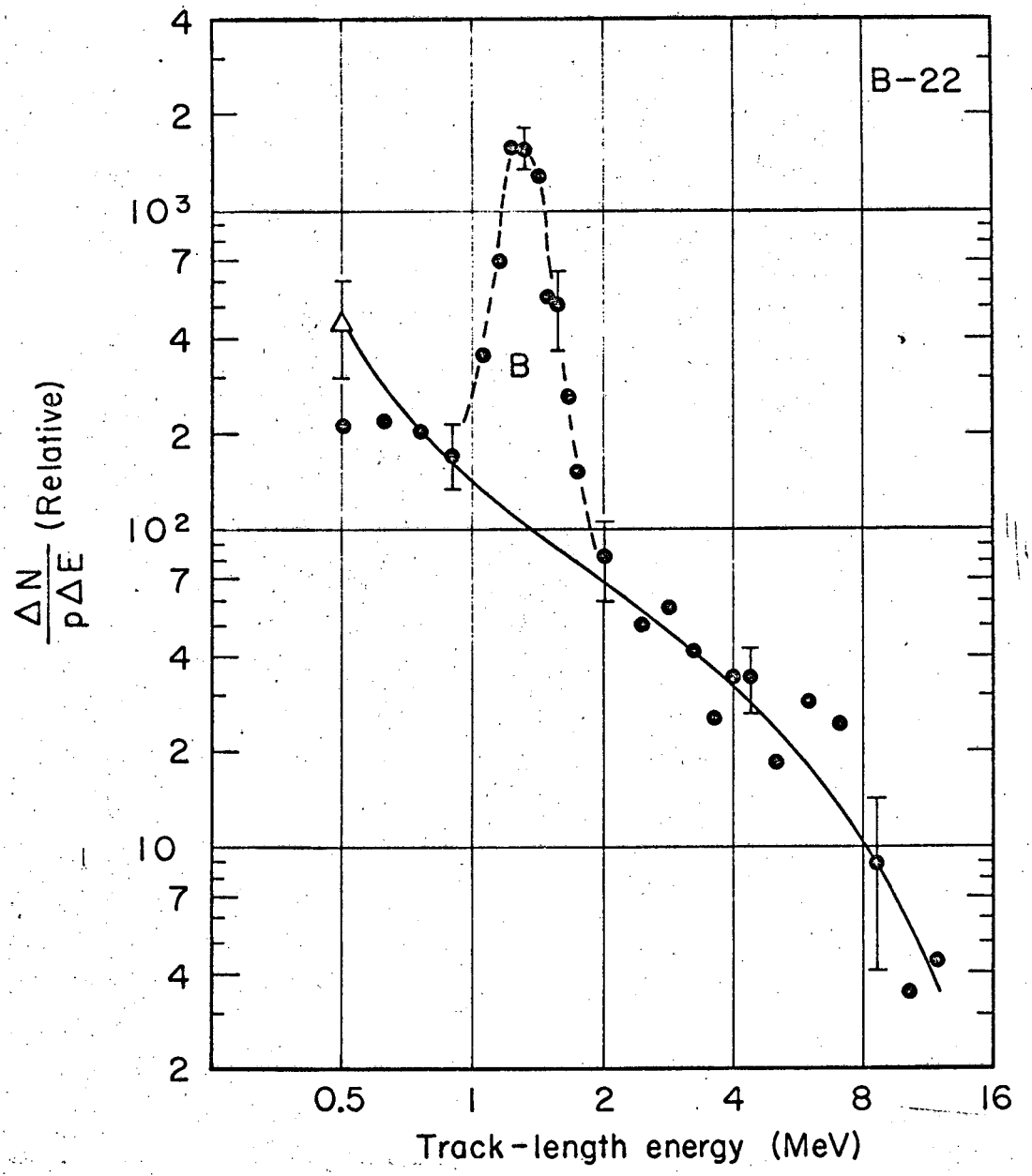
MUB-3611

Fig. 8



MUB-3612

Fig. 9



MUB-3613

Fig. 10

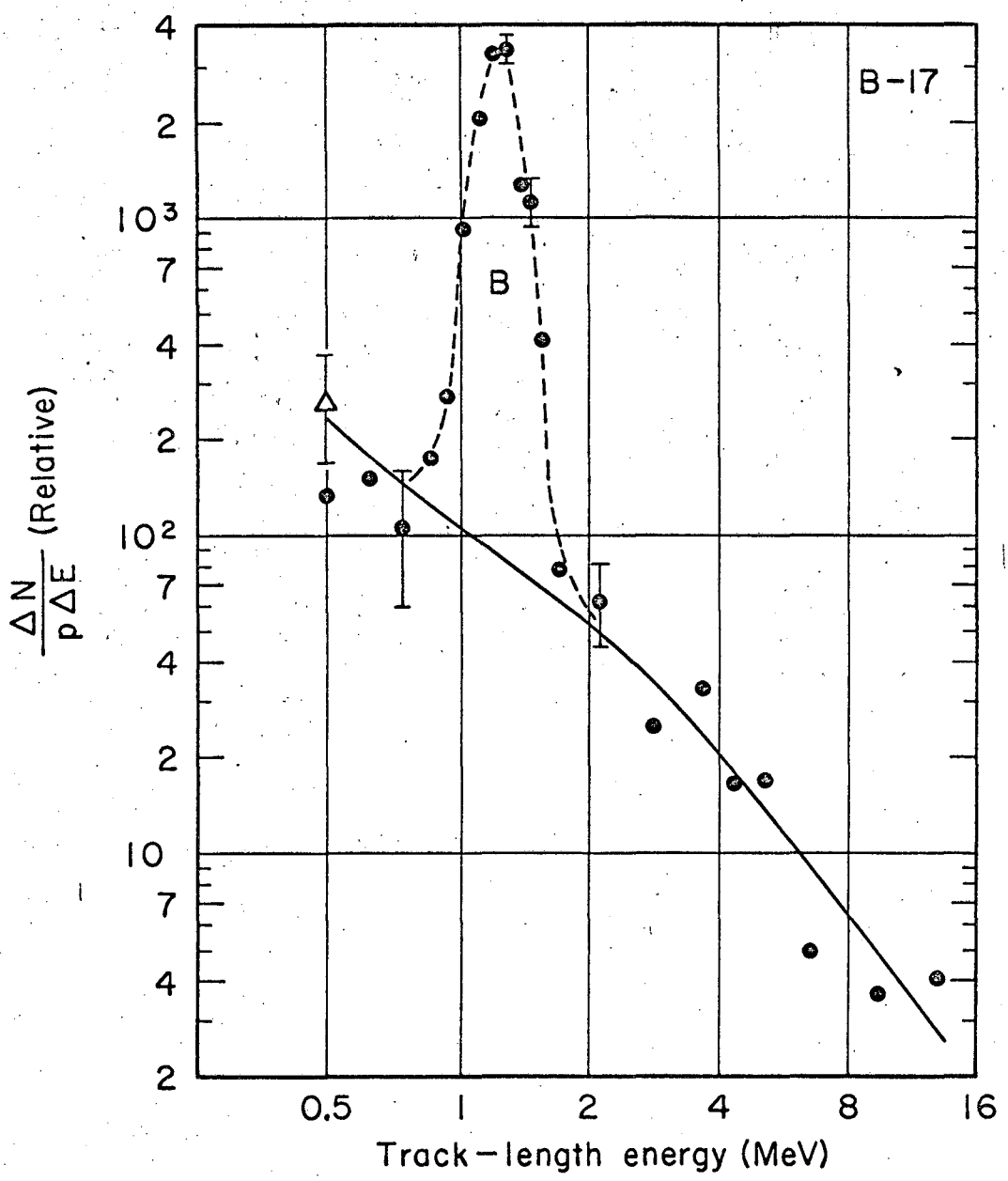

B-17
B
$\frac{\Delta N}{p\Delta E}$ (Relative)
Track-length energy (MeV)
0.5
1
2
4
8
16
10
10^2
10^3
MUB-3614

Fig. 11

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