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NEW MEASUREMENTS OF STAR PRODUCTION IN NUCLEAR EMULSIONS AND APPLICATIONS TO HIGH-ENERGY NEUTRON SPECTROSCOPY

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ABSTRACT

When stars are produced in nuclear emulsions by high-energy neutrons there is a strong dependence of the average number of grey prongs per star on the incident neutron energy. This dependence has been measured by exposing emulsion stacks to 27-MeV, 105-MeV, and 230-MeV neutrons produced by deuteron stripping, and to 4-GeV neutrons produced by 6.2-GeV protons incident on a copper target. These results are used to obtain information on the energy distribution of an unknown neutron spectrum from the measurement of the average number of grey prongs per star. We assume a parametric representation of the neutron spectrum, defined by the maximum energy and by the slope of the spectrum on a logarithmic scale, and calculate the average number of grey prongs for a wide range of these parameters. These results are expressed on a single graph which is used to relate the measured average number of grey prongs to a simple exponential spectral shape. The results obtained for a number of accelerator and cosmic-ray spectra are in good agreement with results obtained with threshold detector methods.

1. INTRODUCTION

Nuclear emulsions have been used extensively as tools of fast-neutron spectroscopy. These techniques are mostly based on the study of recoil protons scattered elastically by the incident neutrons. Such methods, however, have a fairly limited useful energy range, extending only from about 1 to about 20 MeV. At lower energies the tracks are too short to be counted efficiently, and at higher energies the length of the recoil proton track becomes so great that the beginning and the end of the track seldom occur in the same emulsion plate. In this paper we discuss the extension of the useful energy of nuclear emulsions to much higher energies through the study of stars produced by high-energy neutrons.

A star is a cluster of prongs originating from the same point in the emulsion. It is caused by an inelastic collision between an incident nucleon and a nucleus--such as C, N, O, Ag, or Br--in the emulsion. It is generally assumed that both cascade and evaporation processes may give rise to stars in emulsion. A detailed discussion of the star production processes is to be found in the report of an earlier study at Lawrence Radiation Laboratory by Remy.[1]

It was also reported by Remy that when stars are produced in nuclear emulsions by high-energy neutrons there is a unique relationship between the incident neutron energy and the average number of grey prongs per star, abbreviated as ANGP in the following. Furthermore, this relationship was found to be strongly dependent on the neutron energy in the range from 20 to 300 MeV. Measurements of star production were made by Remy by exposing thick (600 μ) nuclear emulsions to

20-, 100-, 160-, and 220-MeV neutrons from deuteron stripping reactions, and 300-MeV neutrons produced by 360-MeV protons incident on beryllium targets. The interpretation of these results was complicated by large numbers of prongs which did not end in the emulsion, so that their range could not be measured. Remy's method of estimating the greyness was based on grain counting. This is not an absolute method, being dependent on the development of the emulsion and also on fading. To overcome these difficulties we have used stacks of emulsion, which allows us to define greyness in terms of range, which we measure by following each track to its end; a grey track is one with range $\geqslant 2$ mm. We have re-exposed emulsion stacks to 27-, 105-, and 230-MeV neutrons produced by deuteron stripping. We have also extended the energy range of the star method by exposing emulsion in the forward direction from a copper target bombarded by 6.2-GeV protons. These measurements are discussed in Section 2.

We also discuss the use of stars in emulsion in high-energy neutron spectroscopy. The unique relationship obtained between the monoenergetic incident neutron energy and the measured ANGP is used to compute the ANGP values for a wide range of neutron spectra characterized by the maximum energy of the neutron spectrum and its slope on a logarithmic scale. These results, discussed in Section 3, are expressed in a graphical form which uniquely relates the ANGP and the slope of the spectrum for a given maximum energy. We use these same results in Section 4 to evaluate neutron spectra from ANGP values obtained at high-energy accelerators and with cosmic rays. The results agree well with those obtained with threshold detector techniques, as well as with preliminary results obtained through a more complicated computation by Omberg and Patterson.[2]

2. MEASUREMENTS OF STAR PRODUCTION

Stacks of emulsion were exposed to neutrons produced by deuteron-stripping reactions at the Berkeley 184-inch cyclotron. The mean energies of the neutrons were 27.5, 105, and 230 MeV. The energy spread of stripping neutrons can be computed by using Serber's theory;[3] however, no correction due to this energy spread is applied here. We also exposed stacks of emulsion in the forward direction from a copper target bombarded by 6.2-GeV protons at the Berkeley Bevatron. The peak energy of the neutrons produced is taken to be 4 GeV.

Since we use stacks of emulsion rather than a single plate, we can base the criteria for a grey prong on proton range. In accordance with Remy we define a grey prong as one whose range in emulsion is 2 mm or more, corresponding to a proton energy of 20 MeV or more. By using a microscope with a large precision stage and fixing 10 individual pellicles from the stack on a rotating superstage, it was easy for our scanners to follow a track through several emulsion layers if necessary. More than 500 stars were analyzed at the lower three energies and about 280 at 4 GeV.

The results of our measurements are summarized in Table I and II. The number of grey prongs per star, extrapolated up to 50 GeV, is also shown in Fig. 1 together with the results from Remy's work. The results of this work are similar to those reported by Remy; however, we believe that they are more accurate because of an objectively defined technique for prong selection and better statistics. The extrapolation to higher energies is in good agreement with results with cosmic-ray spectra, as discussed in Section 4. The angular distributions given in Table II show less forward peaking for the higher energy. This is probably due to the fact that at the lower energy essentially all of the incoming neutron's momentum must be transferred to form a grey track.

3. RELATING NEUTRON SPECTRUM SHAPES AND MEASURED NUMBER OF GREY PRONGS

Ömberg and Patterson[2] reported a way to determine the logarithmic slope of a neutron spectrum from the measured value of ANGP. We have incorporated the new measurements into similar calculations and report the results in a form which enables us to conveniently, without any further computations, relate the shape of the neutron spectrum and the ANGP.

For a source of monoenergetic neutrons of energy E_0 the ANGP is expressed as

$$A(E_0) = \frac{\sum_{i=1}^{N} \sigma_i(E_0) A_i(E_0)}{\sum_{i=1}^{N} \sigma_i(E_0)} , \qquad (1)$$

where the summation over i is done for different elements in the emulsion material, $\sigma_i(E_0)$ is the probability of producing a star, and $E_i(E_0)$ is the corresponding ANGP. The $A(E_0)$ is the quantity which we have measured for several energies, E_0, as discussed in Section 2.

For a neutron spectrum $\phi(E)$ extending over the energy range from E_{min} to E_{max} the ANGP is given by

$$\bar{A} = \frac{\int_{E_{\min}}^{E_{\max}} \phi(E)\left[\sum_{i=1}^{N} \sigma_i(E)\, A_i(E)\right] dE}{\int_{E_{\min}}^{E_{\max}} \phi(E)\left[\sum_{i=1}^{N} \sigma_i(E)\right] dE} . \qquad (2)$$

Using the expression of A(E) in Eq. (1) yields

$$\bar{A} = \frac{\int_{E_{\min}}^{E_{\max}} \phi(E)\, A(E)\left[\sum_{i=1}^{N} \sigma_i(E)\right] dE}{\int_{E_{\min}}^{E_{\max}} \phi(E)\left[\sum_{i=1}^{N} \sigma_i(E)\right] dE} . \qquad (3)$$

The cross section for producing stars, which is proportional to the inelastic scattering cross section, we assume to be independent of energy. This simplifies the expression of ANGP to

$$\bar{A} = \frac{\int_{E_{\min}}^{E_{\max}} \phi(E)\, A(E)\, dE}{\int_{E_{\min}}^{E_{\max}} \phi(E)\, dE} . \qquad (4)$$

The above equation can be used to compute $\bar{A}$ for any given neutron spectrum. But if we want to determine $\phi(E)$ from a measured value of $\bar{A}$, then we are limited to determining a single parameter in a representation of $\phi(E)$. This limits the spectral shapes to a family of curves. Thus we do not expect such a method to reveal any detailed structure that may exist in the real spectrum, but rather to give only the general shape of it.

The parametric representation chosen is the same as used by Omberg and Patterson. The neutron spectrum is defined by an $E^{-\gamma}$ function up to a given junction energy, E_c, of the spectrum. The high-energy end is represented by a parabola which joins the low-energy part smoothly and goes to zero at the maximum energy, E_{max}. Thus we have

$$\begin{aligned} \phi_1(E) &= \phi_0\, E^{-\gamma}, && \text{for} \quad E_{min} \leq E \leq E_c, \\ \phi_2(E) &= c_0 + c_1\, E + c_2\, E^2, && \text{for} \quad E_c < E < E_{max}. \end{aligned} \tag{5}$$

The constants c_0, c_1, and c_2 are determined from the conditions

$$\begin{aligned} &\phi_1(E_c) = \phi_2(E_c), \\ &\left.\frac{d\,\phi_1(E)}{dE}\right|_{E=E_c} = \left.\frac{d\,\phi_2(E)}{dE}\right|_{E=E_c}, \\ &\phi_2(E_{max}) = 0, \end{aligned} \tag{6}$$

which yields

$$\begin{aligned} c_2 &= \phi_0\, \frac{(\gamma+1)\,E_c^{-\gamma} - \gamma\, E_{max}\, E_c^{-\gamma-1}}{-(E_c - E_{max})^2}, \\ c_1 &= -\gamma\,\phi_0\, E^{-\gamma-1} - 2\, c_2 E_c \\ c_0 &= -c_1\, E_{max} - c_2\, E_{max}^2 . \end{aligned} \tag{7}$$

In this representation the maximum energy and the junction energy are specified, the normalizing factor ϕ_0 does not affect the measured ANGP, and the only free parameter is the logarithmic slope, γ, of the lower-energy part of the spectrum. We find that such a representation can closely describe both accelerator and cosmic-ray spectra measured by other techniques.

In the subsequent calculations we assume $E_{min} = 20$ MeV and $E_c = 2/3\ E_{max}$, in accordance with Omberg and Patterson. For a given maximum energy there exists, then, a unique relationship between the measured ANGP and the spectral index, γ. We have calculated $\overline{A}$ for a number of maximum energies and spectral indices. A Fortran program using an adaptive Simpson's rule algorithm was written and run on a CDC-6600 machine to numerically integrate the expressions in Eq. (4). These results are summarized by the family of curves shown in Fig. 2. These curves uniquely relate the measured $\overline{A}$ for a range of spectral indices ranging from 0 to 4 and a number of maximum energies, namely 50, 100, 200, 400, 730, 3000, 6200, 14 000, 28 000, and 50 000 MeV. These energies include the maximum energies of several accelerators, and values corresponding to other maximum energies can be easily determined by interpolation. The highest maximum energy is applicable to cosmic-ray spectra, although it includes some uncertainty arising from extrapolation of the A(E) curve up to 50 GeV.

4. NEUTRON SPECTRA DETERMINED FROM MEASURED STAR PRODUCTION

The results obtained above are used to analyze measurements made at high-energy accelerators and with cosmic rays. Thick nuclear emulsions were exposed to high-energy neutron fields in one location at the Berkeley 184-inch cyclotron with 730 MeV maximum energy; in three locations at the Bevatron, the 6.2-GeV Berkeley proton synchrotron; in three locations at the 28-GeV proton synchrotron of CERN; and at two altitudes at White Mountain in California. The emulsions were counted and the ANGP determined by using the techniques described in Section 2. These results, together with the spectral indices determined from Fig. 2, are summarized in Table III. It is important to note that the absolute magnitude of the neutron flux is not obtained from the ANGP; however, if one wishes, the recoil proton tracks in the emulsion can be used to determine that quantity as well.

Figure 3 shows the spectra obtained from measurements of ANGP at Berkeley accelerators and White Mountain together with two spectral shapes determined with threshold detector techniques.[4] The agreement between the results from the two methods is quite good, both in the Bevatron WTT spectrum and the cosmic-ray spectra. In all cases the spectral shapes appear reasonable and are consistent with our present understanding of high-energy neutron spectra at accelerators and in the atmosphere.[5]

Figure 4 shows typical neutron spectra obtained in the large CERN-LRL-RHEL experiment at the CERN proton synchrotron.[5] In this figure we also show a neutron spectrum determined from the proton track-length distribution in an emulsion exposed at the CERN PS together with an extension of the spectrum with an $E^{-1.8}$-shaped function. This extension is in good agreement with the results obtained from measured values of ANGP given in Table III. It is also in accordance with the other results shown, which are obtained from threshold detector measurements.[5]

5. CONCLUSIONS

Measurements of the average number of grey prongs per star produced by monoenergetic high-energy neutrons in nuclear emulsions have been improved. These results and their extrapolation to higher energies are used to compute the average number of grey prongs per star for a wide range of neutron spectra characterized by different energies and logarithmic slopes of the spectra. These results can be used to obtain information on the shape of an unknown neutron spectrum by using the measured values of average number of grey prongs. The results obtained at several accelerators and with cosmic-ray neutrons are in good agreement with results from threshold detector measurements.

The study of stars in nuclear emulsions extends the usefulness of emulsion methods in neutron spectroscopy to energies much higher than the upper limits of recoil proton techniques. Although it is not possible to reveal any detailed structure in the spectra, the information obtainable from stars is adequate in many applications of health physics and shielding design.

ACKNOWLEDGMENTS

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Table I. Measured values of number of grey prongs per star.

Neutron energy (MeV)	Average number of grey prongs per star	Relative abundance of different numbers of grey prongs per star						
		0	1	2	3	4	5	6
27.5	0.007	0.993	0.007					
105	0.23	0.770	0.214					
230	0.51	0.490	0.360	0.069	0.002			
4000	4.30	0.000	0.080	0.210	0.160	0.080	0.080	0.130
		7	8	9	10	11	12	13
		0.080	0.080	0.030	0.030	0.000	0.030	0.020

Table II. Measured angular distributions of grey prongs.

Angle to the beam direction (degrees)	Number of grey prongs	
	E_n = 105 MeV (Projected angle measured)	E_n = 4000 MeV (True angle measured)
0 - 20	39	38
20 - 40	35	55
40 - 60	19	51
60 - 80	11	38
80 - 100	0	40
100 - 120	3	30
120 - 140	8	11
140 - 160	5	10
160 - 180	5	8

Table III. Spectral indices obtained from measured values of the average number of grey prongs per star.

Location	E_{max} (MeV)	Measured ANGP	Spectral index γ
184-inch cyclotron between Bays 10 and 11	730	0.442	0.75
Bevatron west tangent tank shielding wall (WTT)	6200	0.500	1.50
Bevatron Col. 7, main floor	6200	0.321	1.68
Bevatron mezzanine	6200	0.272	1.78
CERN PS	14000	0.291	1.80
CERN PS	14000	0.214	1.95
CERN PS	28000	0.447	1.68
White Mountain, 12000 ft altitude	(50000)	1.071	1.32
White Mountain, 14000 ft altitude	(50000)	1.038	1.35

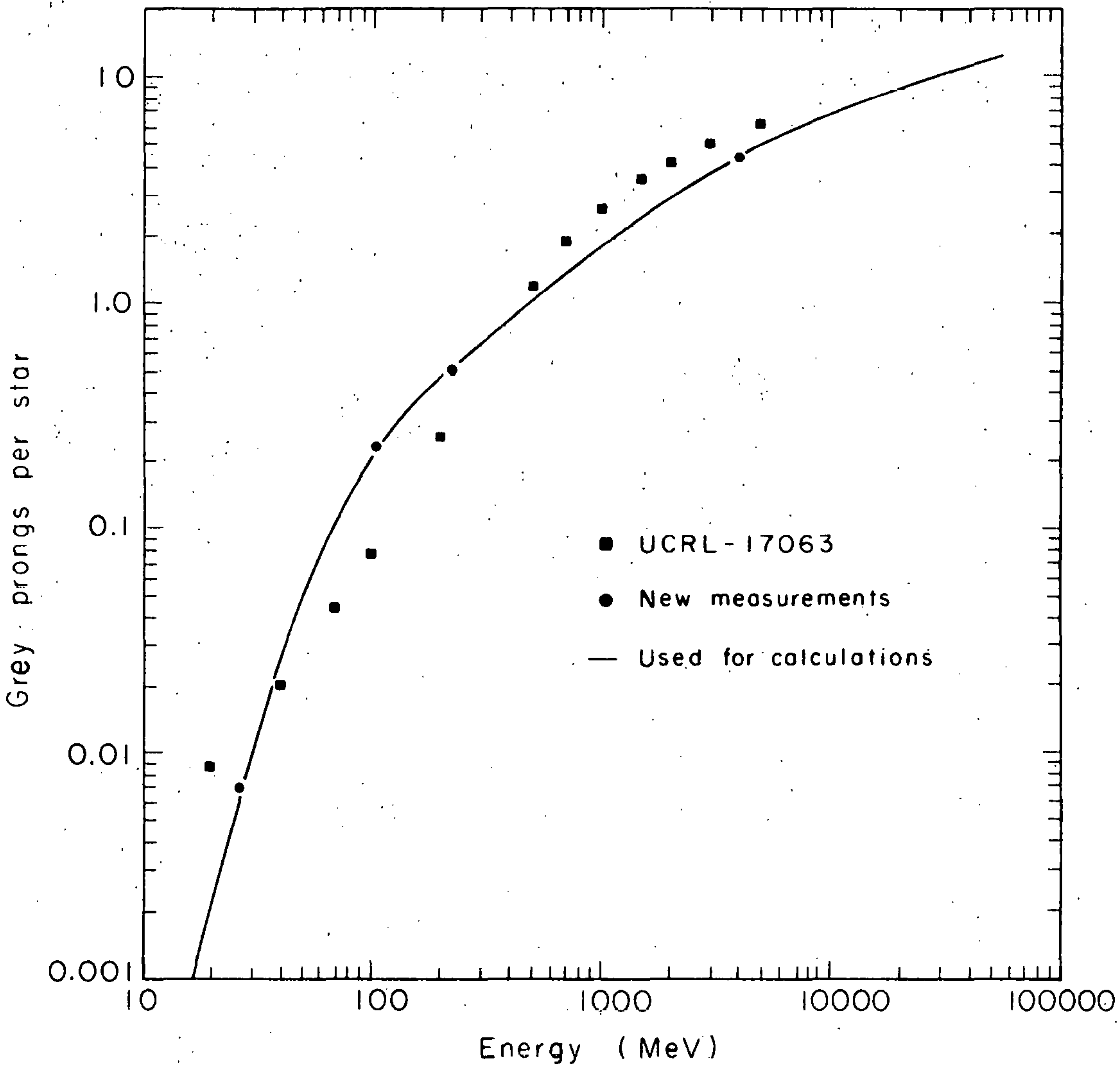
FIGURE CAPTIONS

Fig. 1. Average number of grey prongs per star as a function of neutron energy.

Fig. 2. A graph relating the average number of grey prongs per star and different shapes of neutron spectra characterized by the logarithmic slope, γ, and the maximum energy of the spectra.

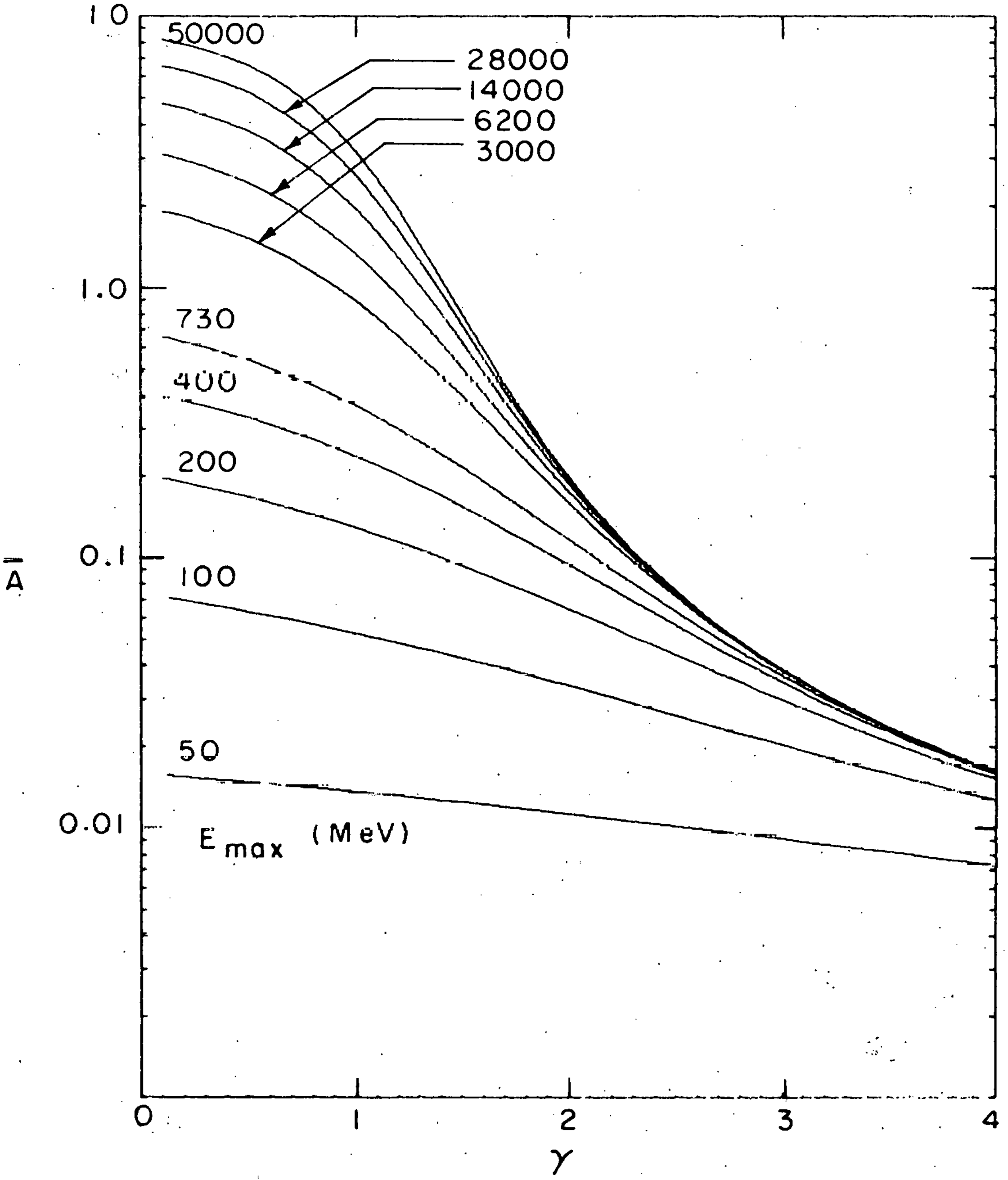
Fig. 3. Neutron spectra obtained from star measurements and threshold detector methods. The relative intensities of different spectra are not significant.

Fig. 4. Typical neutron spectra obtained from threshold detector measurements shown together with a spectrum obtained from the recoil protons and from the stars in an emulsion exposed at the CERN PS.



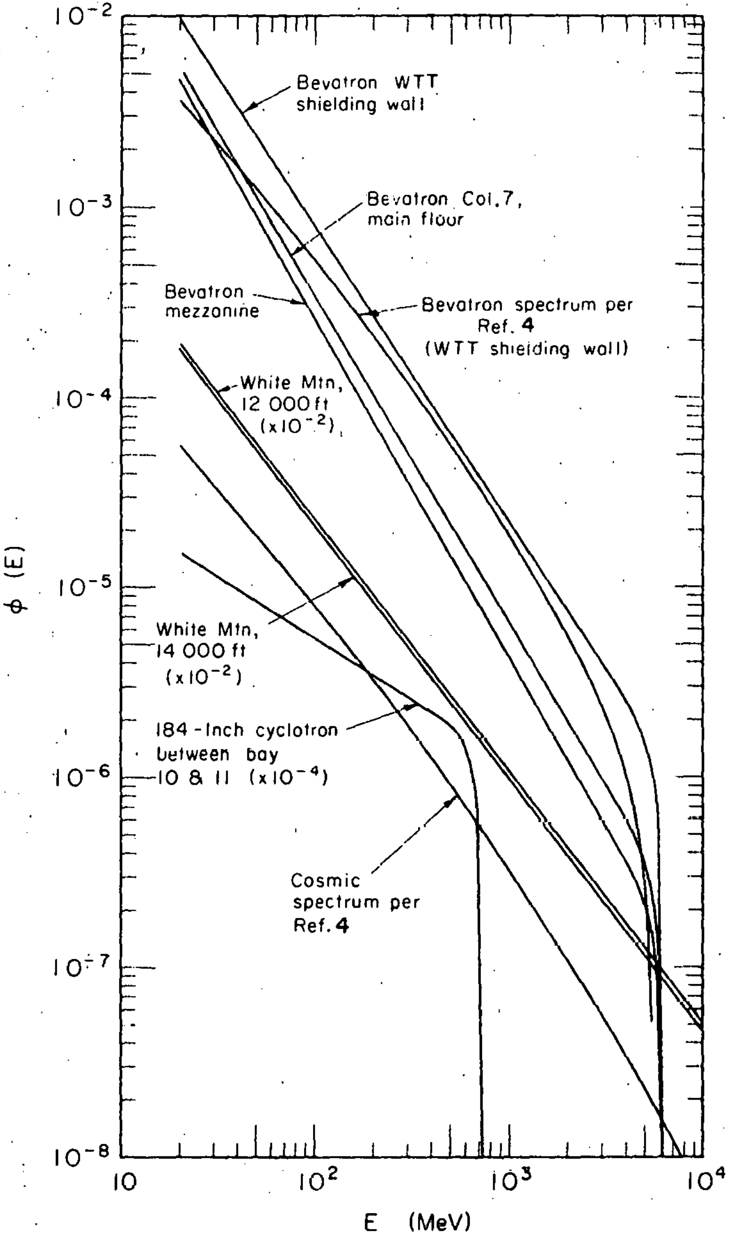
XBL6910-3966

Fig. 1



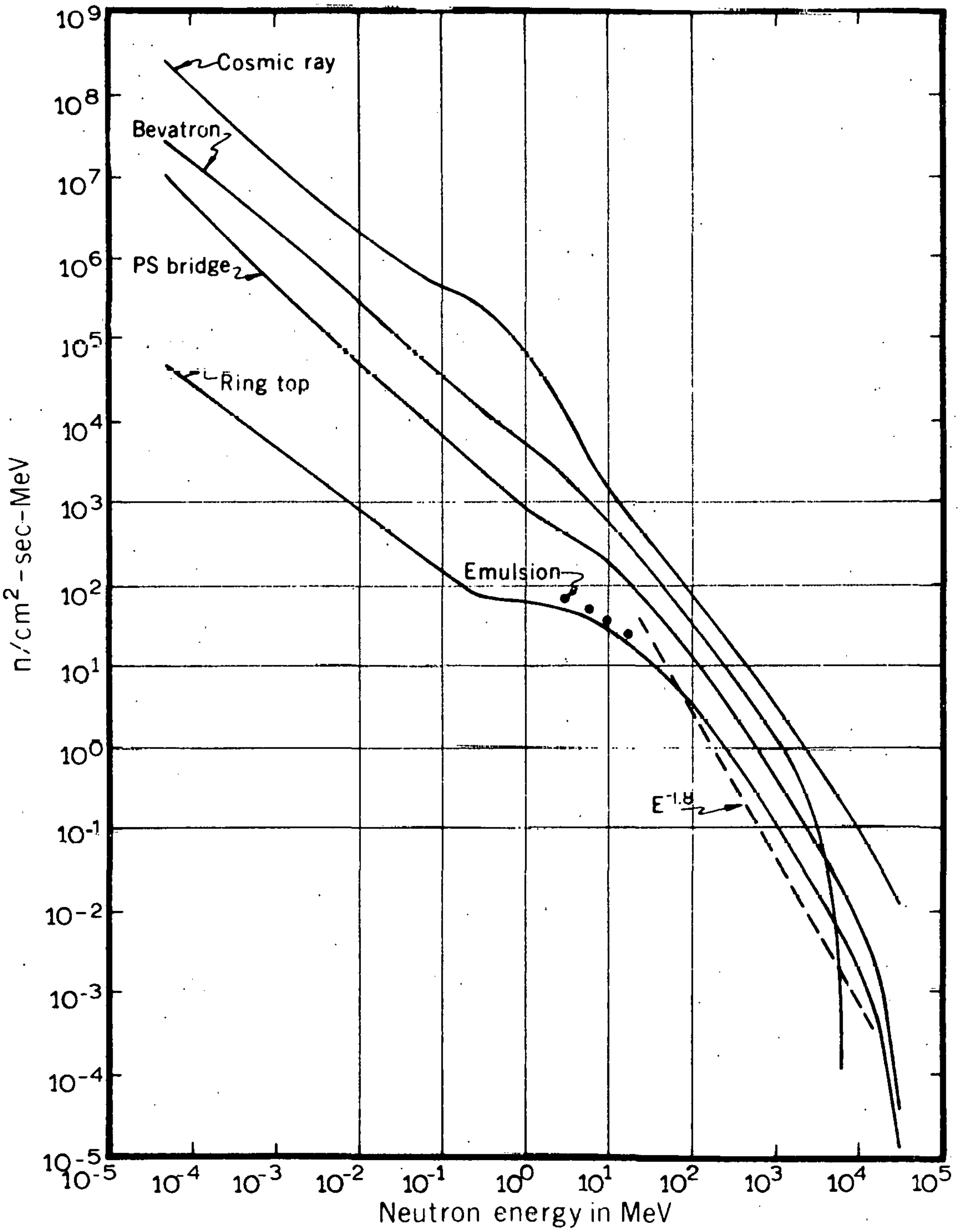
XBL6910-3964

Fig. 2



XBL674-2775

Fig. 3



XBL 682 4493

Fig. 4

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