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Author

Thomas, Ralph H.

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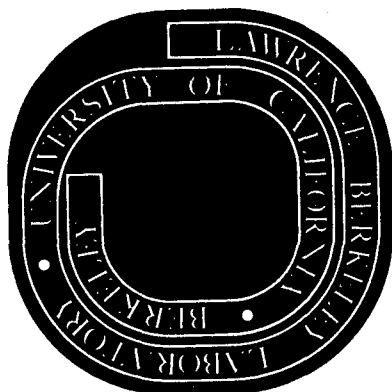
Ralph H. Thomas

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NEUTRON DOSIMETRY AT HIGH ENERGY PARTICLE ACCELERATORS—A REVIEW*

Ralph H. Thomas
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

INTRODUCTION

High Energy particle accelerators are primarily research instruments whose radiation environments are initially unknown and often complex. The dosimetry of their radiation fields therefore presents a great challenge to the health physicist. It is extremely dangerous, under these conditions, to assume that techniques of radiation measurement familiar in other applications will give reliable data. Before one begins to measure he must know what he is measuring! Under such conditions the use of "Rem-meters" is inappropriate because the design and construction of practical rem-meters requires some prior information of the radiation environment in which they are to be used.

The truly universal "rem-meter"—an instrument that determines dose-equivalent in any radiation field with good accuracy—is not theoretically feasible but even granted it were, there are still strong arguments for pursuing fundamental studies of accelerator radiation environments.

At the Lawrence Berkeley Laboratory we have always held that the phrase "radiation protection," which appears in the title of this symposium, means more than the mere measurement of radiation environments. To us it means the control of the interaction of people (and sometimes instruments) with radiation. "Control of radiation hazards involves (a) their anticipation and prior estimation; (b) their measurement or field evaluation and (c) the devising of shielding and procedures which insure adequate safeguards, yet allow experimental freedom." [1]

*Work done under the auspices of the U. S. Atomic Energy Commission.

To achieve this goal the activity of radiation protection at the Lawrence Berkeley Laboratory encompasses:

- (a) Knowledge of the primary radiation produced by the accelerator, under all possible modes of operation, and understanding of the interactions of this primary radiation with targets, collimators, and other accelerator components.
- (b) Understanding of the transmission of this primary radiation (and its interaction products) through shielding materials.
- (c) Development of techniques to measure the great variety of radiation environments produced.

It is this fundamental approach to accelerator radiation protection that will be stressed here.

Such a program permits:

- 1) The prediction of the response of personal dosimeters in accelerator radiation environments.
- 2) The design of accelerator-radiation survey instruments.
- 3) The modification of accelerator radiation fields by shielding.

The lessons learned in the development of techniques of measurement in mixed radiation fields for accelerators and the interpretation of these measurements are of general interest to the health physicist because they bear directly on the problem of developing a general, self-consistent, and practical scheme of dosimetry in radiation protection. [2-6] It is therefore hoped that, while the cognoscenti of accelerator health physics will find little that is new, this review will be of general interest.

HISTORICAL BACKGROUND, 1945-1966

"Begin at the beginning" the King said gravely "and go on till you come to the end: then stop." [7] The command of the King of Hearts to the White Rabbit is sound enough advice to anyone attempting a review. Fortunately the beginning of accelerator health physics is not too long ago!

Rotblat [8] has described our fundamental ignorance of accelerator radiation protection in the late forties and early fifties. Consequently many of the early synchrocyclotrons were buried underground [9], avoiding, but inhibiting any fundamental understanding of, radiation problems. [10, 11] This solution was short-term and could not be adopted indefinitely. As accelerators grew in physical size, energy, and intensity and as they became more widely applied to the problems of medicine, industry, and research it became vital to put accelerator radiation studies on a rational basis.

A more urgent stimulus came toward the end of 1948 when it became known that several nuclear physicists in France and the United States who had been exposed to radiation produced by a cyclotron had manifested incipient cataract. [12] In discussing the dose estimates of the American victims, Ham [12] emphasized that they "represented little more than an educated guess by physicists who were well qualified to estimate their exposures but who were handicapped by . . . faulty instrumentation so far as neutron dosimetry was concerned." In view of the potential hazard resulting from neutron exposure, extensive efforts to improve dosimetric

techniques began at some cyclotron laboratories. Thus, for example, by early 1953 the composition of the neutron radiation field of the 184 inch synchrocyclotron at Berkeley was broadly understood. [13] In 1954 Moyer [14] listed the then-available techniques of neutron measurement as follows:

- (1) For the determination of the flux density and spectrum of uni-directional fast neutrons: proportional counters, scintillation counters, photographic emulsions.
- (2) For the determination of thermal neutron flux densities, regardless of direction: counting techniques based on neutron capture in boron, activation foils.
- (3) For the approximately absolute determination of energy flux density delivered by fast neutrons, independent of energy spectrum or angular direction: polyethylene-lined proportional counter.
- (4) For the contribution to energy absorption in tissue due to neutrons, where the effects due to γ -rays are known and may be corrected for: cavity chambers or tissue equivalent chambers.

Such a list if written today would look much the same. Sullivan [15] in reviewing dosimetric techniques used at particle accelerators up to 1969 showed that, although there has been a steady improvement over the past 18 years in the techniques listed by Moyer [14], few basically new ideas have arisen. Perhaps the two most important new techniques absent from Moyer's list and mentioned by Sullivan were the use of ionization chambers to estimate the quality factors for mixed radiation fields and the development of activation detectors capable of yielding neutron spectra adequate for health physics purposes. It is this latter development with which this review is primarily concerned.

In the early fifties, following the successful operation of several accelerators in the GeV energy region, interest in accelerator radiation problems had become widespread. A conference held in New York in 1957 indicated the concern of several laboratories in the United States [16], and by 1962 an international meeting was organized in Paris. [17]

Experience at the 184 inch synchrocyclotron at Berkeley and the early proton synchrotrons — the Cosmotron and Bevatron—rapidly established the qualitative nature of their radiation environments outside thick shielding. [18-20] A general rule emerged showing that neutrons between 0.1 and 10 MeV contributed more than 50% to the dose-equivalent contribution of the radiation field; γ -rays and low energy neutrons contributed about 10-20%, and the balance made up by neutrons greater than 10 MeV in energy.

In order to quantify the high energy neutron contribution to dose-equivalent more precisely, Patterson et al. [21] suggested that the equilibrium neutron spectrum low down in the atmosphere produced by the interaction of the primary galactic cosmic radiation (mainly protons) must be very similar to that generated in the shield of a high energy proton accelerator. The cosmic ray neutron spectrum had previously been measured at several altitudes by Hess et al. [22] and was shown to reach equilibrium rapidly (at depths greater than 200 g/cm²). Using the Hess spectrum and fluence to dose-equivalent conversions given in NBS Hand-

book 63 [23], Patterson et al. concluded that "by far the largest contribution to total neutron dose comes from neutrons in the energy interval from 0.10 to 30 MeV." [21] Somewhat later Tardy-Joubert [24] pointed out that, at energies above 50 MeV, the Hess spectrum was consistent with that deduced from an analysis of the prong-number distribution of stars produced in nuclear emulsion exposed at different altitudes. [25]

These similarities to the cosmic ray spectrum also explain the relative unimportance of protons in contributing to the dose-equivalent. [26] At energies greater than a few hundred MeV, protons are present in numbers comparable with neutrons. At lower energies, however, protons are depleted by ionization losses. Puppi and Dallaporta [27] have suggested that the neutron/proton ratio in an equilibrium spectrum is of the form:

$$\frac{N}{P} = \frac{W^2}{W^2 - (m_0 C^2)^2} \quad (1)$$

where

W is the nucleon total energy,
 $m_0 C^2$ is the nucleon rest mass.

Given Eq. (1) it is trivial to show that protons contribute little to the dose-equivalent in an equilibrium cascade spectrum.

By early 1965 there was sufficient experience at high energy accelerators at Berkeley [18-20], CERN [28], the Rutherford Laboratory [26,29], Saclay [24], and elsewhere [30] to confirm that the cosmic ray and accelerator produced neutron spectra were indeed quite similar. Thus, for example, at the 1966 Vienna meeting Perry [26] summarized experience at the British 7 GeV proton synchrotron thus:

"... the energy spectrum varies from place to place but always falls off rapidly with increasing energy. Most of the neutron flux and dose equivalent is due to neutrons with energies between 0.1 and 10 MeV. The dose contributions from thermal and very high energy neutrons are both very small."

Table I shows a summary of data given by Perry showing the composition of the radiation field outside the shielding of a 7 GeV proton beam.

The increased confidence this experience with accelerators in the GeV energy region gave strength to the earlier arguments of Patterson et al. [21] concerning the probable shape of the neutron equilibrium spectrum and led to the use of the Hess spectrum in the design of the shields of several high energy accelerators in the early sixties. [31-35] For this assumption to be valid it was necessary that the equilibrium spectrum be determined by the character of the interaction mechanisms of the nuclear cascade and essentially independent of the energy of the incident proton. [36] Some theoretical cascade calculations by Riddell [37] lent support to this assumption but the extrapolation from experience in the GeV energy region to hundreds of GeV could not be made without reservation. Patterson [20] indicated the need for more detailed information of the neutron spectrum between 1 and 10 MeV where "there may or may not be a flattening due to the production and scattering of evaporation neutrons." Nevertheless by early 1965 there was a

good quantitative understanding of the radiation environments outside particle accelerator shielding. About this time, however, some clouds of doubt appeared on the horizon when it was independently reported at the CERN PS [38, 39] and the Brookhaven AGS [40] that high energy neutrons contributed an unexpectedly high fraction of the dose-equivalent outside earth shields. This may be seen from Table II where two sets of data reported from CERN are summarised. Both give the relative composition of dose-equivalent measured through thick shielding, above an accelerator target. In the first case the shield material was concrete, in the second case earth.

Because the data in Table II was not placed on an absolute basis it was not possible to deduce whether the high fraction of dose-equivalent contributed by high energy particles was due to a deficit of low energy neutrons or a surfeit of high energy neutrons. At the time the latter assumption was generally accepted—wrongly as it was later to be shown—presumably because of the higher energy of the AGS and CPS than the other accelerators then in operation. Somewhat later this uncertainty was accentuated by the publication of the results of radiation surveys around several high energy accelerators with Bonner spheres and nuclear emulsions by the USAEC Health and Safety Laboratory (HASL). [42-44] Several spectra indicated a plateau in the energy range from about 5 to 40 MeV (Fig. 3). Two of these spectra were obtained at the Bevatron and contrasted with measurements of Lehmann and Fekula [45]: "The general form of the stray neutron spectra (measured between 0.7 and 20 MeV) at eight locations near the Bevatron is a broad peak in the 0.5 - 2 MeV region, followed by a smooth 100-fold drop in value between the peak and 12 MeV." (See Fig. 4.) Furthermore the HASL measurements were not supported by measurements with threshold detectors at the Bevatron [46] or at Saturne. [47]

Smith [46] demonstrated this simply, but convincingly, by calculating the ratios $R(i, j, k \dots ; a, b, c \dots)$ of detectors i, j, k, \dots in spectra designated by the subscripts a, b, c, \dots , to the response of the same detectors obtained at the Bevatron (Bev). For example, $R(i, a)$ is defined by

$$R(i, a) = \frac{\int_{E_i}^{E_{\max}} r_i(E) \phi_a(E) dE}{\int_{E_i}^{E_{\max}} r_i(E) \phi_{\text{Bev}}(E) dE} \quad (2)$$

$$= \frac{\int_{E_i}^{E_{\max}} r_i(E) \phi_a(E) dE}{C_{\text{BeV}}(i)} \quad (2a)$$

where $r_i(E)$ is the response function of the i^{th} detector,

$\phi_a(E)dE$, $\phi_{\text{Bev}}(E)dE$ is the flux density in the energy interval between E and $E+dE$ in the a^{th} spectrum and the Bevatron spectrum respectively,

E_i is the threshold energy of the i^{th} detector,

E_{max} is the maximum neutron energy in the spectrum,

$C_{\text{Bev}}(i)$ is the measured response of the i^{th} detector in the Bevatron spectrum.

Figure 5 shows values of such ratios calculated for several neutron spectra compared with measurements made at the Bevatron with a moderated BF_3 counter and threshold detectors utilizing the $^{27}\text{Al}(n, \alpha)^{24}\text{Na}$, $^{12}\text{C}(n, 2n)^{11}\text{C}$ and bismuth fission reactions. Figure 5 indicates that in the energy region from 1-100 MeV the shape of the neutron spectrum fitting the Bevatron data is intermediate between that of the Hess spectrum and a $1/E$ spectrum. One important feature of such a technique is that no special computing facilities are necessary to evaluate these relative response ratios, which may be calculated with adequate accuracy very quickly by elementary numerical techniques.

Similar conclusions to those of Smith [46] were reported by Tardy-Joubert [24] as a result of studies at Saturne. Using threshold detectors, he reported a neutron spectrum of the form $E^{-4/3}$ in the region from a few MeV up to about 100 MeV.

Thus by the middle of 1966 there were conflicting data concerning the shape of the equilibrium neutron spectrum above a few MeV. It was desirable that these discrepancies be resolved before completion of the design studies of the large proton accelerators in the hundreds-of-GeV energy region. [48]

PROGRESS IN OUR UNDERSTANDING OF RADIATION ENVIRONMENT, 1966-1972

During the past six years the apparent anomalies in the spectra derived from emulsion data and the dose-equivalent composition data from emulsion data and the dose-equivalent composition data from different laboratories have been resolved. In the case of the emulsion data this proved relatively easy, but resolution of the apparent discrepancies between the AGS [40] and CPS [38, 39] data (Table II) and data at other accelerators was more protracted, requiring a fuller understanding of accelerator radiation environments. This was brought about primarily by:

- (a) the application of threshold detectors to the measurement of radiation fields,
- (b) the determination of neutron spectra from these threshold detector measurements,
- (c) increases in operational experience at several accelerators around the world,
- (d) a better understanding of particle spectra to dose-equivalent conversion,

- (e) theoretical studies of the nuclear cascades generated in dose matter by high energy particles.

Each of these areas will be briefly described.

NUCLEAR EMULSIONS

On the basis of a systematic comparison of the reduction of experimental and synthetic recoil proton spectra to neutron spectra by both the HASL and Berkeley data analysis programs, Patterson [49] has attributed the apparent plateau reported by McLaughlin et al. [44] to an artifact of the HASL routine. Neutron spectra derived from proton recoil data in the energy range 0.5 to 20 MeV by the Berkeley programs were subsequently shown to be in good agreement with spectra derived from threshold detector measurements [2] as may be seen in Fig. 6.

Awschalom [50] made similar arguments when he drew attention to discrepancies between the HASL Bonner sphere and emulsion data, and suggested the use of "an unfortunate smoothing function" as a probable cause.

It is clear, however, that whatever the accuracy of these spectra, extreme caution must be exercised in extrapolating proton recoil data to energies above about 20 MeV when track loss corrections become unreliable.

At higher neutron energy, nuclear emulsions may still be used to give some indication of the slope of a smooth neutron spectrum if the average number of grey prongs per star is determined. As we have seen this was first done for cosmic rays [25], but the technique has been refined and used in accelerator radiation environments at Berkeley. [51-53] Figure 7 relates the average number of grey prongs per star, \bar{A} , to spectrum slope γ and maximum neutron energy in the spectrum.

Patterson et al. [53] have reported the use of this technique in several radiation environments, and their results are summarized in Table III. The values of the spectrum slope ranging from 1.5 to 1.8 for the proton synchrotrons is consistent with threshold detector data.

THRESHOLD DETECTORS

The use of threshold detectors in neutron dosimetry is a well understood and universally accepted technique in radiation physics. Their use has found widespread application at most high energy particle accelerators and has been described in several review articles. [2, 15, 24, 26, 46, 54]

Table IV summarizes some of the threshold reactions commonly used at accelerator laboratories. Column 5 indicates the typical sensitivity which may be readily achieved for these detectors. Sensitivity is, however, clearly a function of detector size and the precise experimental techniques employed, and the values indicated are intended only as a general guideline. They indicate the order of magnitude of minimum flux density that may be detected after a measurement lasting one hour. For precise details the reader is referred to the original sources. Furthermore Table V is not intended to be comprehensive but to indicate the reactions in common use. Particular laboratories may have their own preferred specialties that they have perfected.

It may be seen from Table V that threshold detectors are available of high sensitivity over the entire energy range normally of interest at

accelerators (0.1-100 MeV). No details of the shape of the neutron spectrum below about 1 MeV will be obtained using only one size of moderator with a thermal neutron detector. Fortunately this is not often required for two reasons: (1) because the dose-equivalent contribution is not large and (2) because below 10 keV the dose-equivalent per unit fluence is independent of neutron energy. In principle, should more detailed information of the spectrum be required in the energy region from $\sim 10^{-8}$ to 1 MeV, several moderators of different size could be used. [55]

At high radiation intensities (≥ 10 rem/h) several less sensitive reactions provide additional information. Figures 8 and 9 show the variation of sensitivity with energy for the reactions listed in Table V.

Although no significant "break through" in this technique of neutron dosimetry can be reported over the past five years, one is aware of some steady advances. In the autumn of 1966 an extensive set of measurements was made with threshold detectors over a wide range of locations, and under different operating conditions were made at the CPS. [2] Three accelerator laboratories collaborated in these measurements and it was possible to perform detailed absolute intercomparisons of neutron flux density determinations for most of the detectors listed in Table IV. These intercomparisons indicated good general agreement in flux density determinations. In addition there has been a steady program at Berkeley of cross-section determination for the threshold reactions utilized in neutron spectrometry. This work, much of it still unreported, has always confirmed the excitation functions shown in Figs. 8 and 9.

In the future we can confidently look forward to the refinement of the detection of ^{149}Tb produced in mercury so that unit flux density may be determined. The detection of spallation products in medium heavy targets offers interesting possibilities for a new type of threshold detector system. [56] For example, the γ -rays resulting from the decay of more than 20 radionuclides produced in copper may be detected in a copper target. Simultaneous observation of several of these reactions would permit the determination of the neutron spectrum by one threshold detector, if the excitation functions for the reactions utilized are adequately known. Unfortunately, because of the small cross sections of some of the reactions that would be utilized and the low detection efficiency, the technique will be limited to regions of high flux density.

SPECTRUM DETERMINATION

Measurements with several threshold detectors whose excitation functions are known provides information on the energy distribution of the neutron flux density.

One of the earliest successful attempts at spectrum determination was based on an extension of the idea, first proposed by Smith [46], of comparing the measured response of the threshold detectors with their anticipated response in hypothesized spectra. As we have already discussed, this technique does not require extensive computing facilities, but it is nevertheless greatly facilitated if they are available.

Specifically, a solution for the neutron spectrum $\phi(E)$ is sought from a set of activation equations of the form

$$A_j = C_i \int_{E_{\min}}^{E_{\max}} \sigma_j(E) \phi(E) dE \quad \text{for } j = 1, 2, \dots, m \quad (3)$$

where A_j is the saturation activity of the j^{th} detector,

$\sigma_j(E)$ is the cross section for the appropriate reaction at energy E ,

C_i is a normalizing constant between activity and flux density,

E_{\min} , E_{\max} are the minimum and maximum neutron energies in the spectrum.

Gilbert et al. [2] have described the use of an iterative technique that employs on-line facilities of a CDC-6600 computer for the determination of neutron spectra from a few threshold detectors—TELLY. The operator indicates to the computer his best estimate of the neutron spectrum which will match his experimental data. This is done by drawing the spectrum with a light pen on the screen of a CRT display. The computer then calculates the detector responses and presents them for comparison with the experimental data. The operator then systematically modifies his suggested spectra to the computer until, after a few iterations, the detector responses are matched with an accuracy reflecting the experimental errors. TELLY was found to work well, avoiding many of the pitfalls of more "sophisticated" methods of spectrum analysis. Its only drawback is that it is somewhat difficult to use in a systematic manner when many detectors with overlapping regions of sensitivity are used.

Equation (3) is a degenerate case of a Fredholm integral of the first kind. Formal methods of solution are not applicable when, as is the case with activation detectors, the A_j 's or σ_j 's are known only as a set of discrete points. [57]

Routti [57] has critically reviewed the numerical techniques commonly used for solution of such first-order Fredholm equations, and the interested reader is referred to his paper for a detailed account.

Early attempts to obtain neutron spectra from activation detector data were frustrated by difficulties such as non-uniqueness or an oscillatory (and even negative) character to the solutions to the Fredholm equations. Some of these problems arise from the mathematical characteristics of the equations to be solved, while others are related to the specific method of solution adopted.

Routti suggests that a suitable method of solution must be able to combine the information contained in the measured data with any already existing information of the neutron spectrum. Such prior information is almost always available on physical grounds. Thus, for example, the solution must be non-negative and zero beyond a given maximum energy. In addition the spectrum of radiation penetrating thick shields constructed of a complex material such as concrete may be assumed to be smooth. Some information on intensity or shape may be available from previous measurements. It is important that all this prior information be properly taken into account in the solution technique selected. However, care must be taken to ensure that the

consequent additional constraints imposed on the spectrum do not prevent it from matching the measured responses or from assuming any physically acceptable shape.

Any appropriate solution must fulfill two basic measurements:

- a. The neutron spectrum which is found to be a solution to the activation equations must accurately match the detector responses.
- b. If many solutions are found that fulfill condition (a) there should be a flexible way to apply physical prior information on the solution so that the most appropriate solution may be selected.

It is important that any solution method be tested to ensure that it meet all these requirements. This is most conveniently done by computing the response of the system to test spectra. The resolutions of the system and the influence of experimental errors or uncertainties in the detector response functions may then be systematically studied.

Routti has applied a generalized least-squares method to solve the activation equations. In his technique the solution is forced to be non-negative, and prior information on the spectrum can be incorporated in a very flexible way. The technique and the computer program LOUHI, written to perform the analysis have been subjected to the tests described in the previous paragraph. These tests show that the method meets the two basic requirements for an appropriate solution.

Considerable experience has now been obtained with LOUHI and it has been found to be extremely reliable and capable of calculating neutron spectra with adequate accuracy for radiation protection purposes.

A desirable feature of LOUHI is that, in addition to activation detector data, it may be used to determine neutron spectra from Bonner sphere or nuclear emulsion data.

OPERATIONAL EXPERIENCE AT ACCELERATORS, 1966-1972

The simultaneous application of threshold detectors to accelerator radiation environments at several laboratories rapidly broadened our fundamental understanding of these environments, and made possible the confirmation of some speculation on the reasons for the apparent discrepancies in the dose-equivalent data.

Figure 6 shows several typical neutron spectra obtained at these proton synchrotrons. Because all accelerator spectra are steeply falling with energy and because the presence of water in earth or concrete shields imposes a "1/E" character on such spectra below a few MeV, the conventional representation of neutron differential spectra often masks some of the important differences in spectral character. Thus in Fig. 6 the spectra all look alike and it is difficult to discriminate between them. It is sometimes more revealing to plot the ratio $R(E)$, of neutrons/MeV in the actual spectrum to the number of neutrons/MeV in a 1/E spectrum. Thus:

$$R(E)dE = E\phi(E) dE \quad (4)$$

In such a plot a $1/E$ spectrum becomes a horizontal line (Fig. 10a). This representation of the Hess cosmic ray spectrum (Fig. 10b) clearly shows the large excess of neutrons in the MeV region (due to evaporation processes [22]) in comparison with a $1/E$ spectrum. At lower energies the spectrum is $1/E$ in character, but there is a noticeable dearth of thermal neutrons, due to the small quantity of hydrogen in the atmosphere.

Figure 10c shows the neutron spectrum obtained above the concrete shielding around targets at the CPS, where previous measurements had been reported (see Table II). The spectrum is seen to be $1/E$ in character from ~ 1 MeV down to thermal energies. This would be expected from neutron slowing-down theory in a homogeneous medium, such as concrete. [58] About 1 MeV the evaporation peak, also evident in the Hess spectrum, is clearly seen, and the spectrum shows a rapid decline at energies above about 50 MeV.

Figure 10d shows the neutron spectrum measured above the earth shield of the CPS. (Previous data summarized in Table II.) This spectrum is depleted of neutrons below ~ 1 MeV, but in other respects is similar to the spectrum shown in Fig. 10c. The water content of the earth shield through which the neutrons penetrated was very high ($\sim 15\%$ by weight [2]) compared to concrete (few percent by weight [59]), and this paucity of low energy neutrons is therefore to be expected. The resolution of the apparent discrepancy in the CERN data (Table 2) is not therefore an abundance of high energy neutrons, quite the contrary.

Figure 10e shows the neutron spectrum outside the Bevatron shielding which is intermediate in character between the two spectra measured at the CPS, suggesting that the hydrogen content of the concrete at Berkeley is higher than that at CERN. (To the author's knowledge this speculation has never been tested.)

Finally Fig. 10f shows the spectrum around a steel shielded proton beam of the British 7 GeV synchrotron. The expected buildup of neutrons in the kilovolt region and below is evident.

THEORETICAL STUDIES OF THE NUCLEAR CASCADE

No review on neutron dosimetry at high energy accelerators could fail to mention, albeit briefly, the significant advances in our theoretical understanding of the hadronic and electromagnetic cascade processes that occur in accelerator shields. Monte Carlo calculations of their cascade have been applied to a variety of radiation problems around high energy accelerators. Ranft [60] has recently reviewed such calculations and has concluded that good agreement with experimental data, in such diverse areas as induced radioactivity, radiation doses, radiation heating, and shielding, is possible.

Thus, for example, Goebel and Ranft [61] have reported a comparison between Monte Carlo calculations of particle spectra and measurements with threshold detectors around a steel backstop bombarded by 19.2 GeV protons. They report good agreement between calculated and measured flux densities. Spectrum comparisons are more difficult, but in the energy region where experimental and theoretical data overlap (~ 100 MeV) they find general agreement in the spectrum shapes, but unfortunately these authors did not have bismuth fission counter data, which defines the neutron spectrum shape fairly closely up to about 500 MeV. Neither was there

adequate flux intensity to use the mercury reaction with a 600 MeV threshold.

A more convincing example of the agreement between theoretical and experimental data is the recent calculation of the neutron spectrum in the earth's atmosphere by Armstrong et al. [62]. These workers used a Monte Carlo code to compute the production of protons, charged pions, and neutrons by the incident galactic protons, and the subsequent transport of these particles down to energies of 12 MeV. The calculated production of neutrons of energy ≤ 12 MeV calculated by the Monte Carlo code was used as input to a discrete-ordinates code to obtain the low energy neutron spectrum. Figure 11 shows the results of these calculations and an absolute comparison with the experimental data of Hess et al. [22] at atmospheric depths of 200 and 1033 g/cm². The calculated and measured spectra differ somewhat at lower energies but are in very good agreement at high energies.

The increasing number of such examples of good agreement between calculated and experimental data obtained with threshold detectors must lend confidence to the validity of the experimental technique.

NEUTRON SPECTRA TO DOSE-EQUIVALENT CONVERSION

Over the past five years neutron spectra to dose-equivalent conversion has become better understood. Fluence to dose equivalent conversion factors for monoenergetic neutrons up to several GeV have been derived [63, 64] from Monte Carlo calculations of nuclear cascades in tissue. Summaries of these calculations have recently been published. [64, 65] Comparisons between such calculations and experimental measurement are in general quite good. [66]

The assignment of conversion factors is to some extent an arbitrary matter. It is important to bear in mind, however, that the evaluation of dose-equivalent consists of two separable elements: a physical measurement capable of some precision (say, to within 10% or less for external radiation fields), and the conversion of this physical measurement to units appropriate to radiation protection. This conversion is limited by our basic lack of knowledge in radiobiology. It is important to recognize that the final expression of physical measurements in rem is in essence an administrative decision; there is no reason why the basic precision of the physical measurements should not be preserved in such a step. Provided general agreement may be reached on the steps to be taken during conversion, there seems to be no reason why all adequate techniques of radiation measurement will not give dose-equivalent estimates essentially in agreement.

There is some disagreement on the steps to be taken, however, in using conversion factors derived for monoenergetic neutrons in the neutron spectra at high energy accelerators which extend over a wide energy range. [67]

If only a table of conversion factors $g(E)$ is available as a function of particle energy, an average conversion factor may be specified for particle spectra defined by the equation

$$\frac{1}{\langle g \rangle} = \frac{\int_{E_{\min}}^{E_{\max}} \frac{\phi(E)}{g(E)} dE}{\int_{E_{\min}}^{E_{\max}} \phi(E) dE} \quad (5)$$

where $\langle g \rangle$ is the average conversion factor,

$\phi(E)dE$ is particle differential energy spectrum,

and E_{\min} , E_{\max} are appropriate energy limits.

The conversion factors, $g(E)$, for monoenergetic neutrons are estimated at the maximum dose-equivalent consequently, use of the expression

$$\dot{H} = \int_{E_{\min}}^{E_{\max}} \phi(E)dE/g(E) \quad (6)$$

to arrive at the dose-equivalent rate, \dot{H} , can lead to an overestimate. { Equation (6) expresses the sum of the maxima of the dose-equivalent depth curves at each energy rather than the maximum of the sum of the dose-equivalents from each component of the spectrum [10] . }

On occasion it may be necessary to evaluate dose-equivalent more precisely. Goebel et al. [68] have suggested an alternative procedure, influenced primarily by their measurement of absorbed dose, essentially at the body surface. If it is assumed that particle equilibrium is established in radiation shielding, then it is plausible that this equilibrium will be maintained in a body irradiated outside the shield: No dose buildup would then be detected. In general the true dose-equivalent rate, \dot{H} lies between the two limits:

$$\int_{E_{\min}}^{E_{\max}} \frac{\phi(E)dE}{g_{\text{surface}}(E)} \leq \dot{H} \leq \int_{E_{\min}}^{E_{\max}} \frac{\phi(E)dE}{g_{\text{MADE}}(E)} \quad (7)$$

where $\phi(E)dE$ is the flux spectrum incident on the body, and

$g(E)_{\text{surface}}$, $g(E)_{\text{MADE}}$ are conversion factors determined at the body surface and at the maximum dose equivalent respectively.

Shaw et al. [3] have suggested that the true dose-equivalent should be obtained by calculating the dose-equivalent depth curve in the body resulting from irradiation by a broad spectrum. The maximum dose equivalent in the body may then be evaluated. They have reported such calculations for several typical accelerator spectra and found the DE depth curves to be relatively uniform through the body. From these calculations conversion factors may be calculated for both unilateral and bilateral irradiation.

Table V summarizes values of average conversion factor $\langle g \rangle$ for several neutron spectra derived by Gilbert et al. [2], using an analytic form of the monoenergetic neutron conversion factors. Comparison with the more precise values obtained by Shaw et al. [3] shows that in all cases the routine system described by Gilbert et al. gives a comfortable, though

not excessive, overestimate of dose-equivalent. Thus in most practical situations a useful "cushion" in the control of personnel exposure is available. In special circumstances, however, such as moderate over-exposure, special analysis, appropriate to the particular case under review, is required.

SUMMARY AND CONCLUSIONS

The period under discussion, 1966 to 1972, began with the appearance of data from the newer proton synchrotrons that seemed, at first glance, to be at variance with our understanding of the radiation environments of the earlier high energy accelerators. Resolution of these apparent discrepancies had its own intrinsic interest but was given impetus by the design studies for the US 200 GeV and European 300 GeV accelerators.

Application of threshold detector techniques to the determination of neutron spectra at several different accelerators around the world, under different operating conditions and shielded in different ways, has proved illuminating. In general, the neutron spectra obtained confirm the earlier suggestions of Moyer and his colleagues [21]. Deviations from the cosmic ray produced neutron spectrum may be explained in general terms by the composition of the shield and maximum energy of the particle accelerated.

The apparent discrepancies in radiation survey data appearing in the middle sixties have been satisfactorily explained. Perhaps it is not too partisan to observe that this satisfactory explanation could not have been deduced solely from measurements of absorbed dose or estimates of dose equivalent and/or quality factor!

Perhaps the reader feels very much like Alice, who, after running hard for several minutes, exclaimed:

"Why, I do believe we've been under this tree all the time!
Everything's just as it was!
"Of course it is," said the Queen, "What would you have it?"
"Well, in our country," said Alice, still panting a little,
"you'd generally get to somewhere else—if you ran very
fast for a long time, as we've been doing."
"A slow sort of country!" said the Queen. "Now, here, you
see, it takes all the running you can do, to keep in the same
place. If you want to get somewhere else, you must run at
at least twice as fast as that." [69]

Actually, however, the last six years have resulted in solid, if not spectacular, achievement in neutron dosimetry with threshold detectors at accelerators. Given this depth of understanding of radiation environments, the response of any detector(s) used to monitor accelerator radiation may be correctly interpreted. Several authors have examined the errors involved in using a routine monitoring system based on a small number of activation detectors. [2, 3, 70]

For example, a moderated BF_3 counter, suitably calibrated, will almost always estimate dose-equivalent to about a factor of 2, in a wide range of accelerator spectra. If an additional measurement using the $^{12}\text{C}(n, 2n)^{11}\text{C}$ reaction is made, the accuracy can be improved to much better than 50% (usually 20% or better). Furthermore, since the measure-

ments and their evaluation take quite a short time (typically one hour or less) threshold detectors may be used as the basis of a very practical routine monitoring system.

This reviewer considers that neutron spectrometry can be considered to have "come-of-age" as a technique of neutron dosimetry at high energy accelerators. If this review is able to clarify some of the misunderstandings of the technique that one still finds in the literature it will have more than served its purpose. It would seem to be an appropriate time for a more general intercomparison of dosimetric techniques at accelerators to be undertaken.

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Table I. Radiation spectrum above Nimrod extracted proton beam shielding.
(From Perry, 1967.)

Type of radiation	Energy range	Estimated % of neutron flux density	Estimated % of total dose-equivalent
Neutrons	< 1 eV	< 7	< 1
Neutrons	1 eV - 0.7 MeV	70	20
Neutrons	0.7 - 3 MeV	15	35
Neutrons	3 - 7 MeV	7	25
Neutrons	7 - 20 MeV	1.5	5
Neutrons + protons	20 - 100 MeV	1	5
Neutrons + charged particles	> 100 MeV	0.5	4
Other particles + gammas	—	—	< 2

Table II. Composition of radiation fields above thick shields — CPS.

Radiation component	Percentage of dose-equivalent	
	Above CERN PS concrete shield bridge [41]	Above target through CERN PS earth shield [38,39]
Thermal neutrons	11 - 12%	< 1 - 3%
Fast neutrons (0.1 MeV < E < 20 MeV)	50 - 70%	10 - 37%
High energy particles (E > 20 MeV)	2 - 25%	52 - 89%
γ -rays and ionization from charged particles	2 - 19%	1 - 13%

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

Location	E_{\max} (MeV)	Spectral index, γ
184-inch cyclotron between Bays 10 and 11	730	0.75
Bevatron west tangent tank shielding wall (WTT)	6 200	1.50
Bevatron Col. 7, main floor	6 200	1.68
Bevatron mezzanine	6 200	1.78
CERN PS	14 000	1.80
CERN PS	14 000	1.95
CERN PS	28 000	1.68
White Mountain, 12 000 ft altitude	(50 000)	1.32
White Mountain, 14 000 ft altitude	(50 000)	1.35

Table IV. Properties of some commonly used threshold detectors.

Detector	Reaction	Half-life	Energy range	Typical minimum flux density measurable $n\text{ cm}^{-2}\text{ sec}^{-1}$ ^a	Remarks
BF ₃ proportional counter	$^{10}\text{B}(n,\alpha)^7\text{Li}$	—	Thermal		
Gold foil	$^{197}\text{Au}(n,\gamma)^{198}\text{Au}$	2.7 days	Thermal	10^2	
Indium foil	$^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$	54 min	Thermal	1	
Moderated BF ₃ counter	$^{10}\text{B}(n,\alpha)^7\text{Li}$	—	Thermal -15 MeV	10^{-2}	Energy range and sensitivity depends upon moderator size - 15 cm dia values quoted.
Moderated gold foil	$^{197}\text{Au}(n,\gamma)^{198}\text{Au}$	2.7 days	Thermal -15 MeV	10^2	
Moderated indium foil	$^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$	54 min	Thermal -15 MeV	1	
Thorium fission counter	Th(n,fiss.) fission products	—	> 2 MeV	1	
Sulphur	$^{32}\text{S}(n,p)^{32}\text{P}$	14.3 days	> 2.5 MeV	10^4	
Aluminium	$^{27}\text{Al}(n,\alpha)^{24}\text{Na}$	15 h	> 6 MeV	1	
Aluminium	$^{27}\text{Al}(n,\text{spall.})^{22}\text{Na}$	2.7 yr	> 25 MeV	10^4	
Polystyrene: plastic scintillator	$^{12}\text{C}(n,2n)^{11}\text{C}$	20.4 min	> 20 MeV	1	
	$^{12}\text{C}(n,\text{spall.})^7\text{Be}$	53.4 days	> 30 MeV	10^4	
Bismuth fission chamber	Bi(n,f) fission products	—	> 50 MeV	1	
Mercury	Hg(n,spall.) ^{149}Tl	4.1 h	> 600 MeV	10	

^a Based on 1 hr measurement.

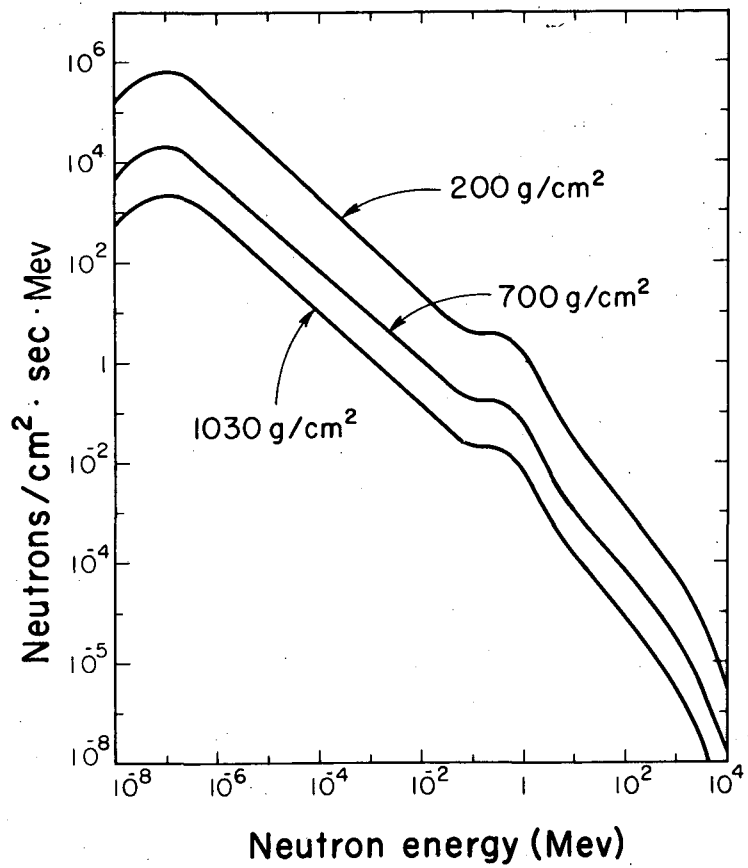
Table V. Effective conversion factors for neutron spectra (from Patterson and Thomas).

Spectrum	Effective neutron conversion factors		
	$\frac{\text{n/cm}^2 \text{ sec}}{\text{mrem/h}}$		
	Gilbert et al. (analytic)	Shaw et al. (unilateral irradiation)	Shaw et al. (bilateral irradiation)
Cosmic ray	12.1	14.1	21.9
Bevatron	8.8	11.9	14.9
CERN synchrotron bridge	7.3	12.1	12.5
CERN ringtop	4.3	5.1	5.3
1/E	4.7	6.4	7.0

FIGURE CAPTIONS

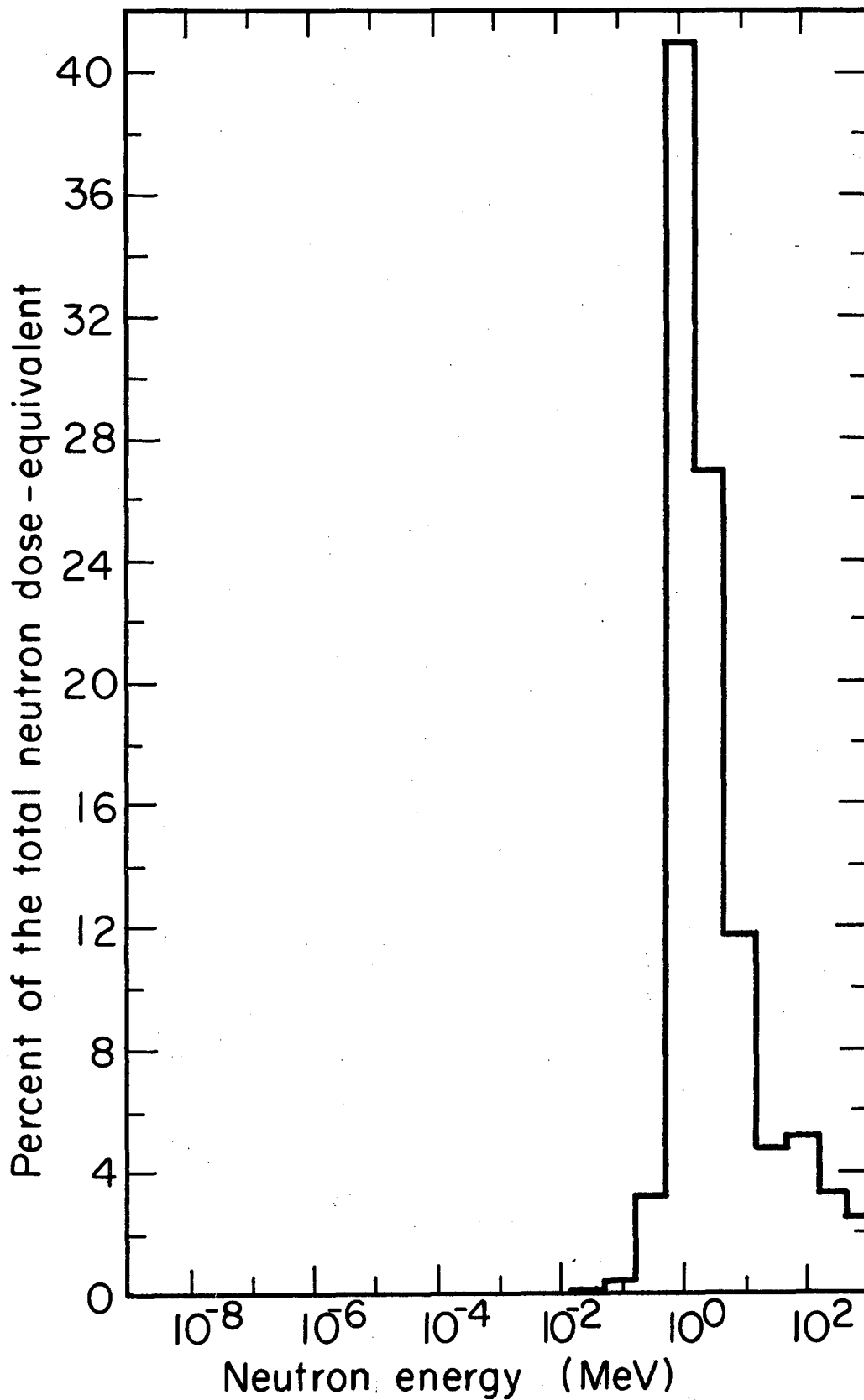
- Fig. 1. The cosmic ray produced neutron spectrum at various depths in the atmosphere (after Hess et al., 1959).
- Fig. 2. The percentage of neutron dose-equivalent contributed by neutrons of different energy groups in the Hess spectrum (from Patterson et al., 1959).
- Fig. 3. The neutron spectra outside the shields of several high-energy particle accelerators derived from nuclear emulsion measurements (after McLaughlin and O'Brien, 1967).
- Fig. 4. The neutron spectra derived from measurements of the recoil proton spectra in nuclear emulsions exposed at several locations around the Bevatron. In each diagram: (A) identifies the peak at 0.6 MeV due to the $^{14}\text{N}(n, p)^{14}\text{C}$ reaction of thermal neutrons; (B) identifies the 1.25 MeV peak due to α particles from the decay of the naturally radioactive constituents of the emulsion; the curve C shows the smoothed recoil proton spectrum corrected for background, and the curve D shows the derived neutron spectrum. The notations B-25, B-27, etc. identify location of the emulsion exposure (after Lehman and Fekula, 1964).
- Fig. 5. A comparison of the relative responses of several threshold detectors in a variety of neutron spectra with those measured at the Bevatron. The detectors used are a moderated BF_3 counter, and the $^{27}\text{Al}(n, \alpha)^{24}\text{Na}$, $^{12}\text{C}(n, 2n)^{11}\text{C}$, and $\text{Bi}(n, \text{fiss.})$ reactions.
- Fig. 6. Typical high energy accelerator neutron spectra obtained by threshold detectors. In the case of the "ring top" spectrum Ilford L4 emulsions were exposed. The experimental points labeled emulsion are derived from proton recoil track analysis while the line with negative slope 1.8 was obtained from star prong counting (for explanation of a location of measurement, see text).
- Fig. 7. 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. 8. Response functions for the four detectors used to determine neutron spectra at well-shielded locations.
- Fig. 9. Response functions for additional detectors used to determine neutron spectra in high radiation levels.
- Fig. 10. Typical high energy neutron spectra
- $1/E$ spectrum (for comparison).
 - CR—cosmic ray (Hess spectrum).
 - PSB—spectrum at concrete shielding bridge of CERN proton synchrotron.
 - RT—spectrum on earth shield of CERN PS.
 - BEV—spectrum outside Bevatron shielding.
 - PI—spectrum outside steel shielding of Nimrod external proton beam.

Fig. 11. Neutron flux spectra at various depths in the earth's atmosphere produced by galactic protons near solar minimum. These calculations are compared with calculations of Lingenfelter and the measurements of Hess et al. (λ = geomagnetic latitude) (from Armstrong et al.).



MU-17054 A

Fig. 1



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Fig. 2

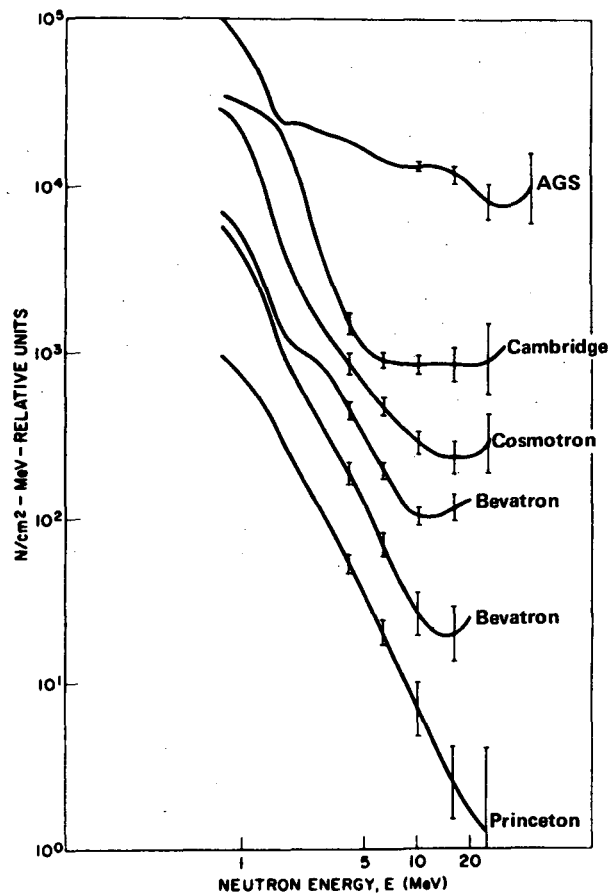
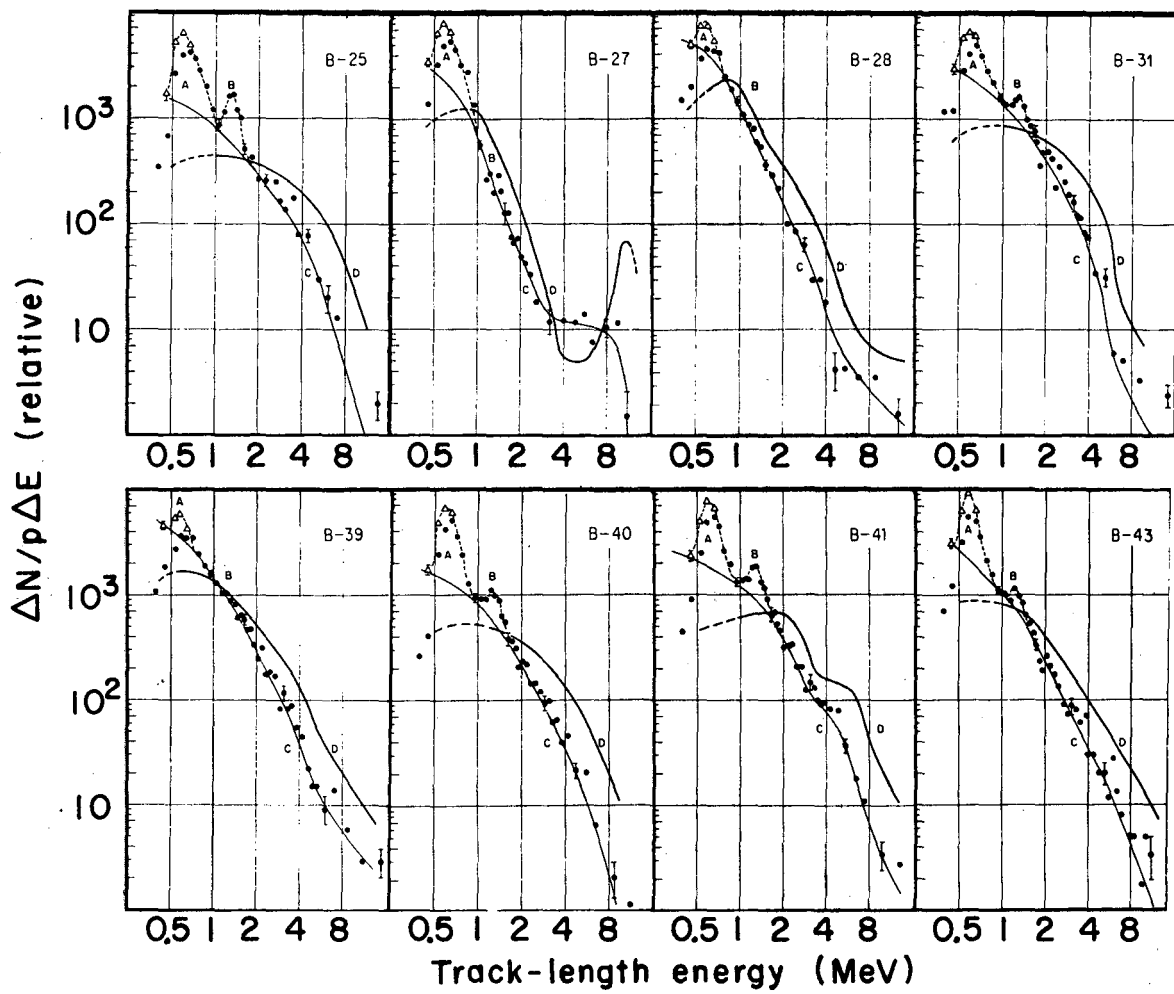


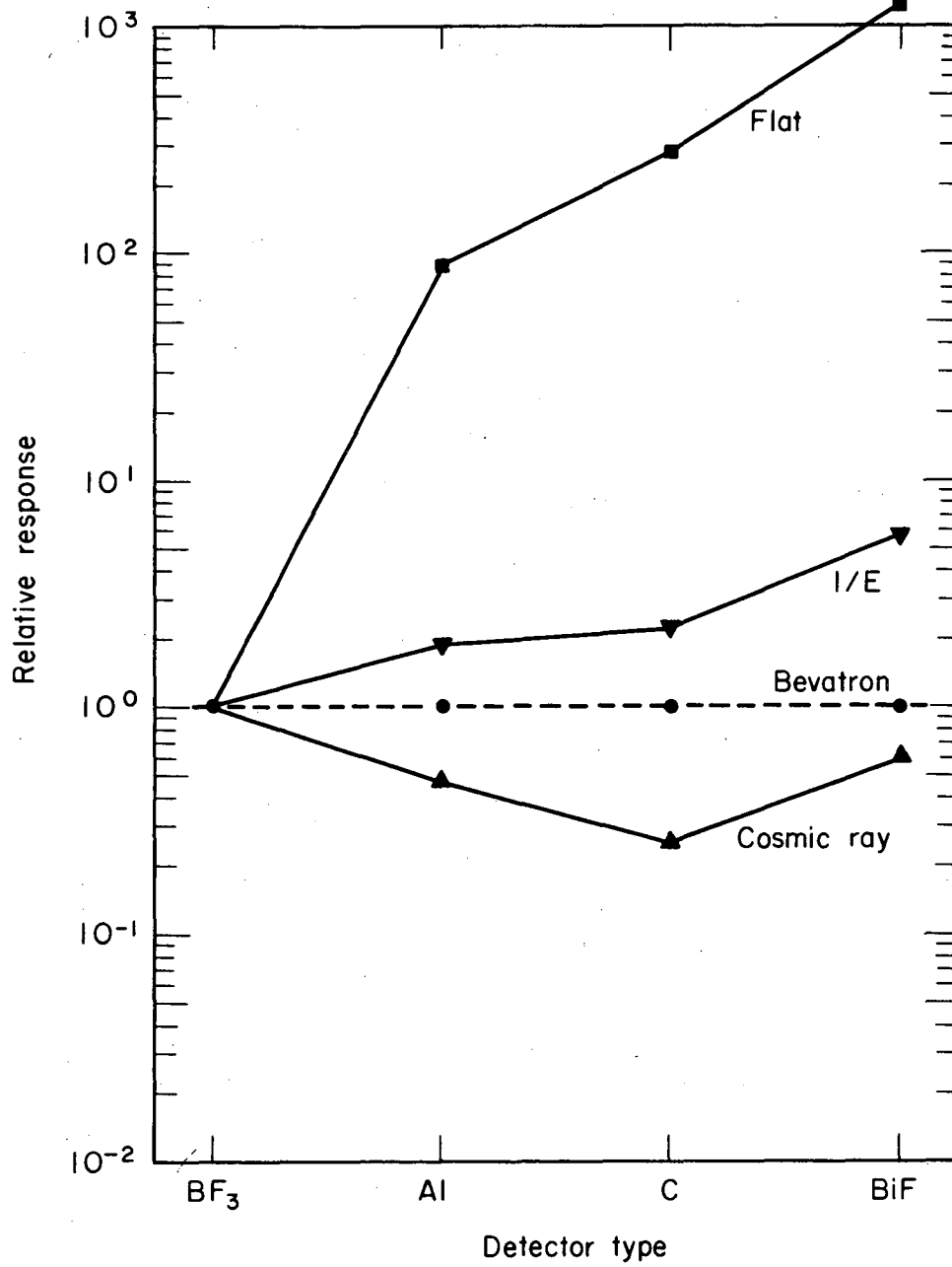
Fig. 3. Accelerator shield leakage spectra from emulsion measurements (After McLaughlin and O'Brien, 1967)

XBL 729-1913



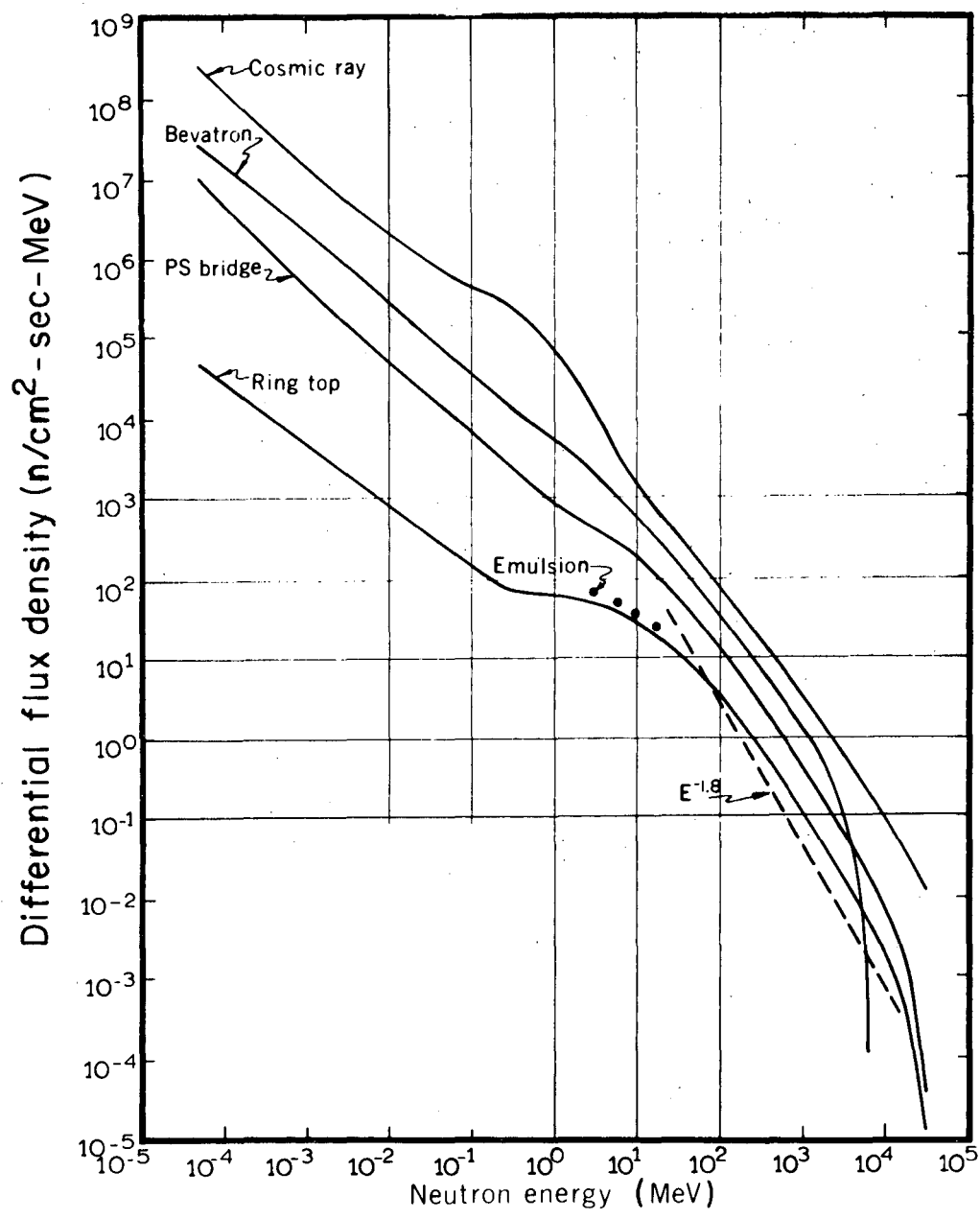
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Fig. 4



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Fig. 5



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Fig. 6

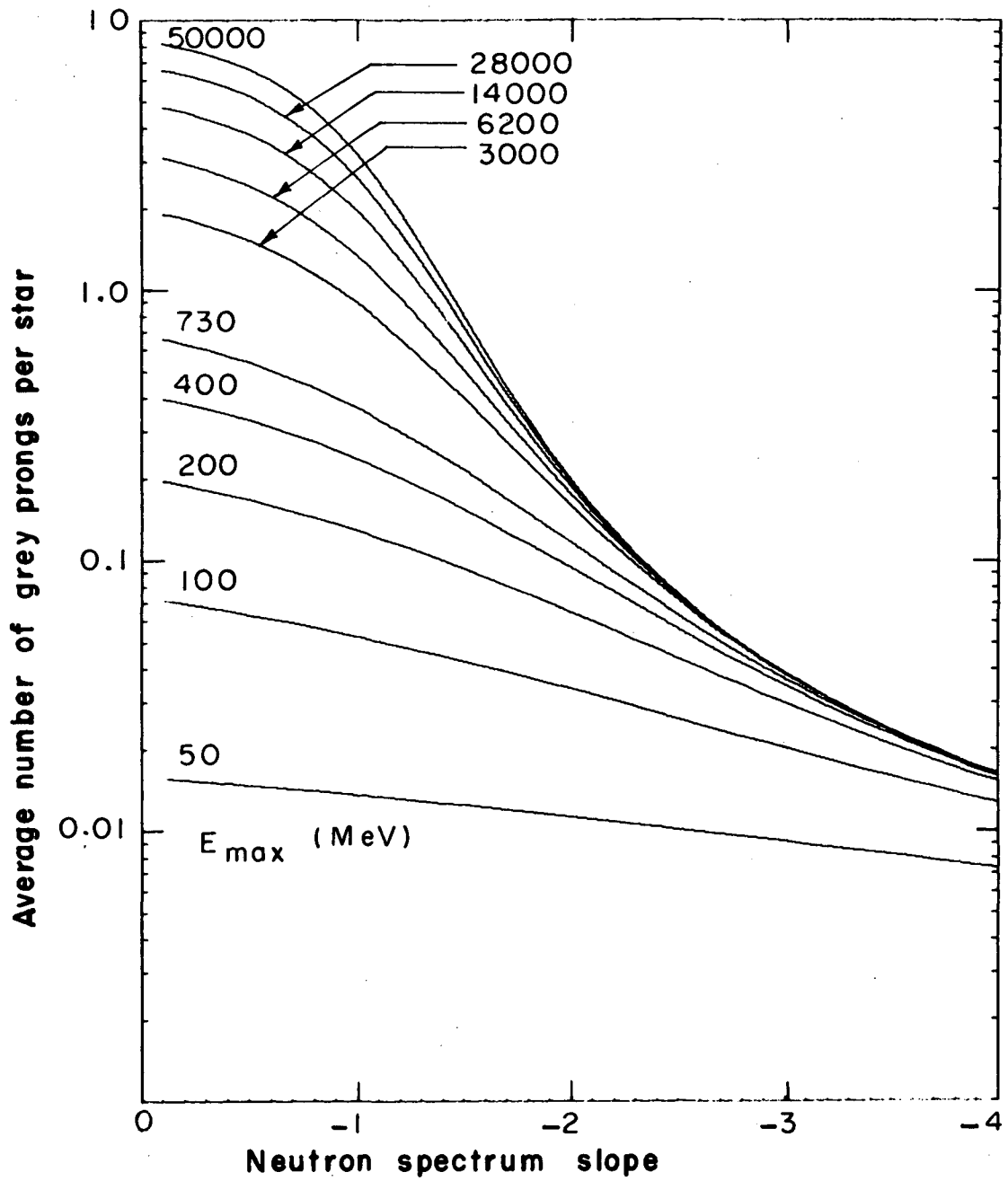
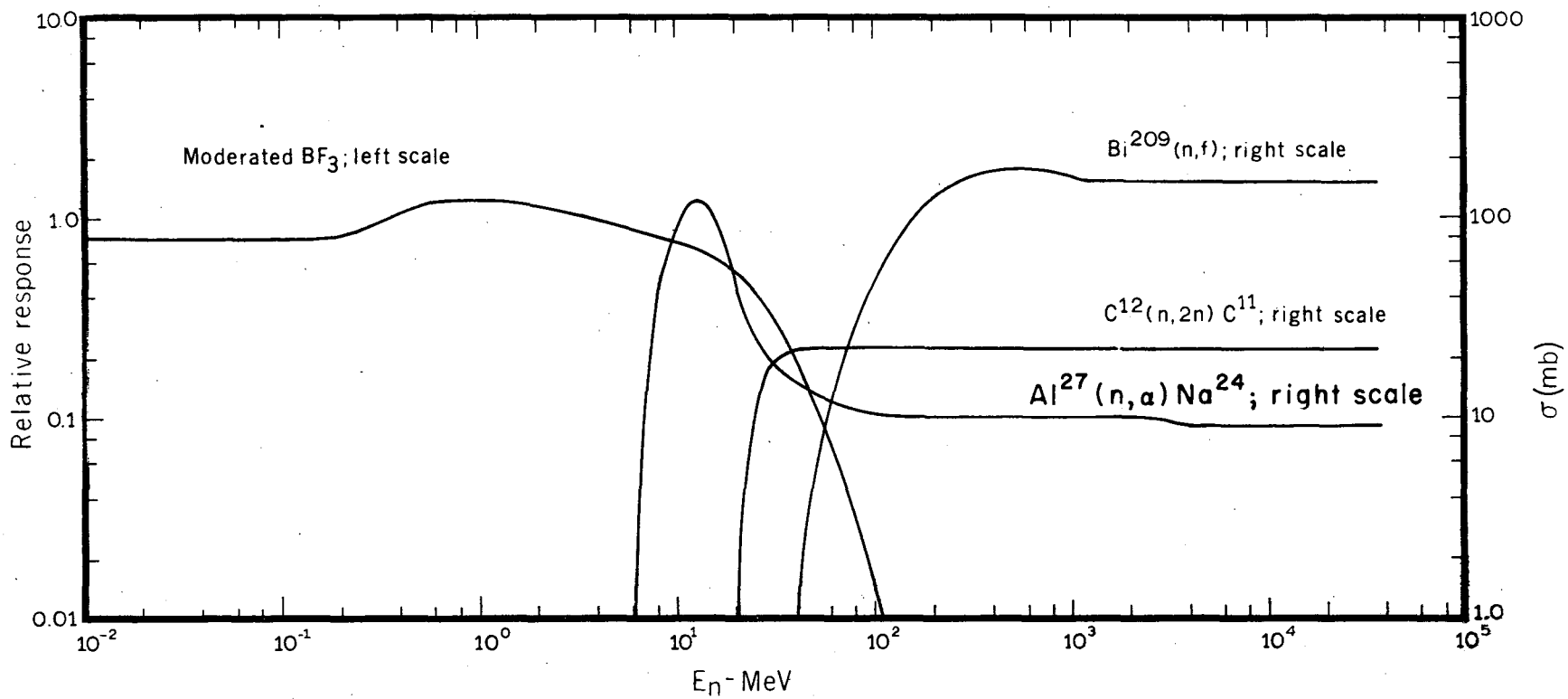


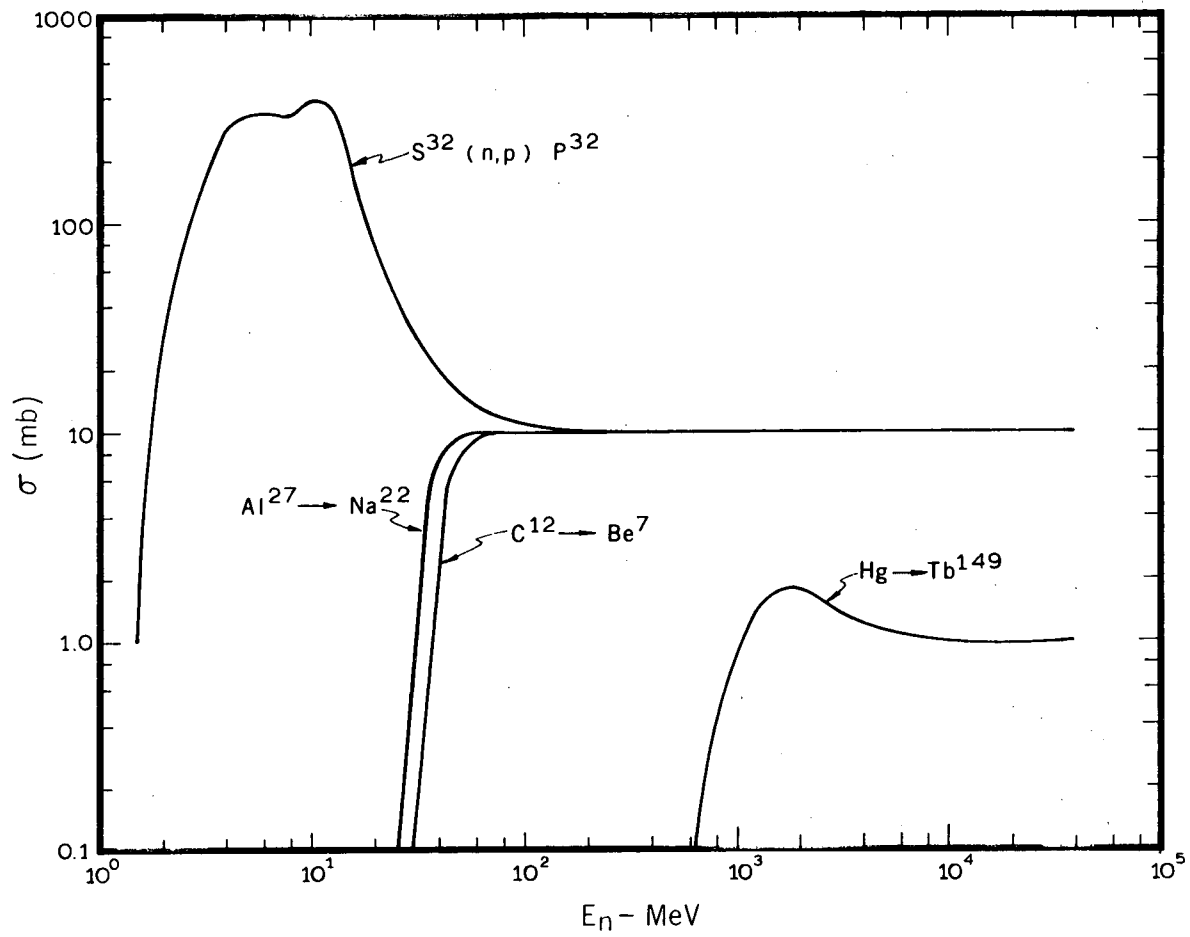
Fig. 7



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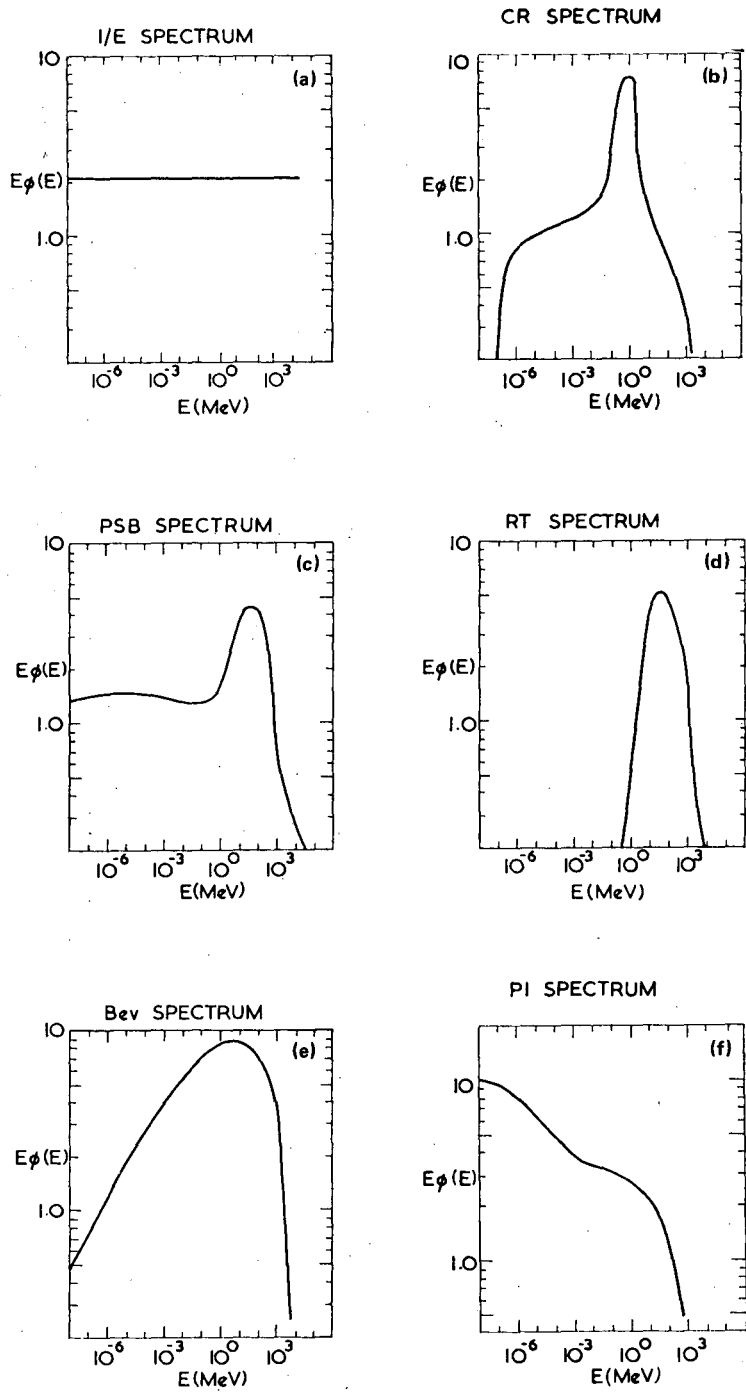
Fig. 8

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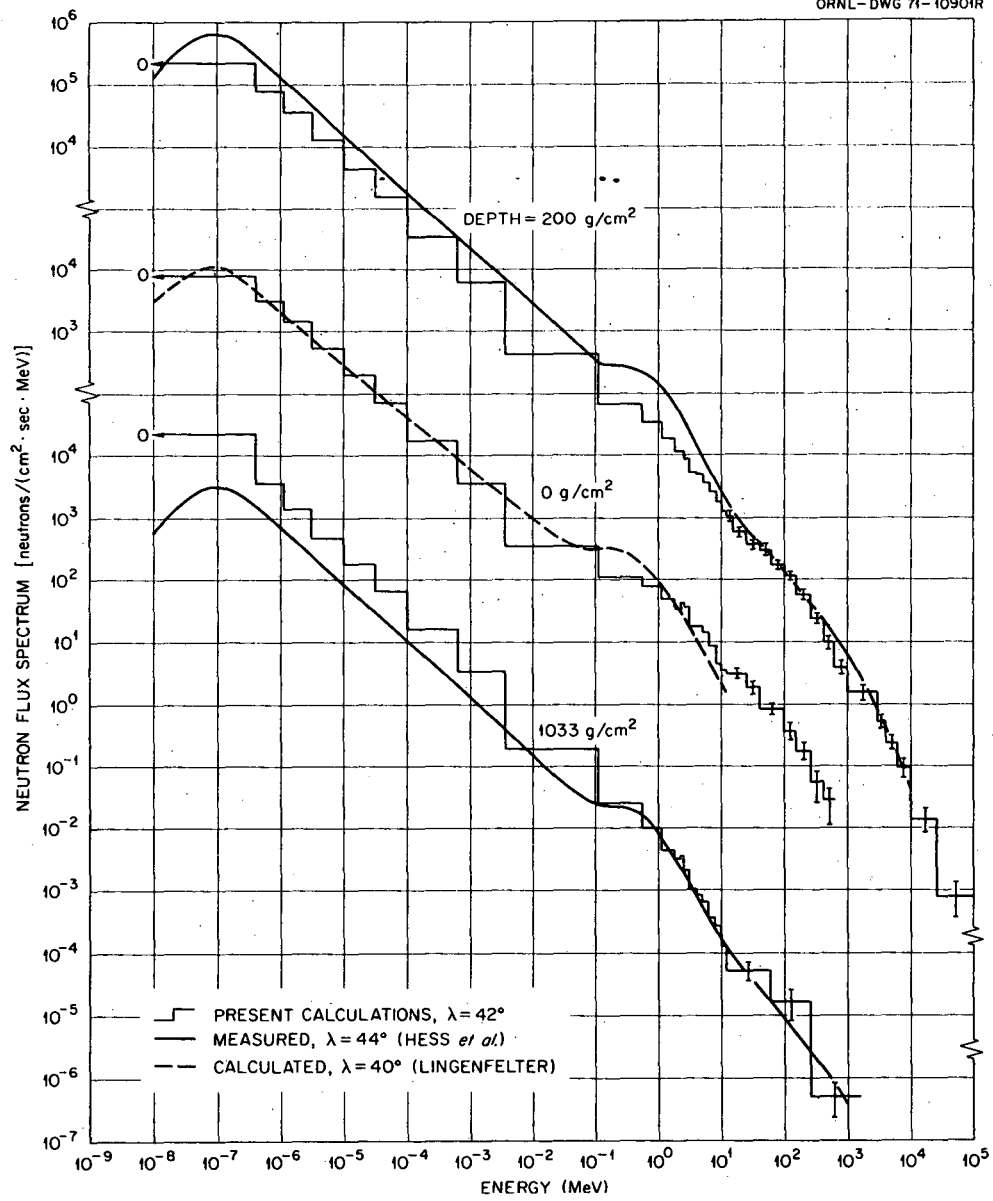
XBL 682 4492

Fig. 9



XBL 729-1912

Fig. 10



XBL 729-1939

Fig. 11

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LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720