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RADIATION PROTECTION AROUND HIGH-ENERGY ACCELERATORS

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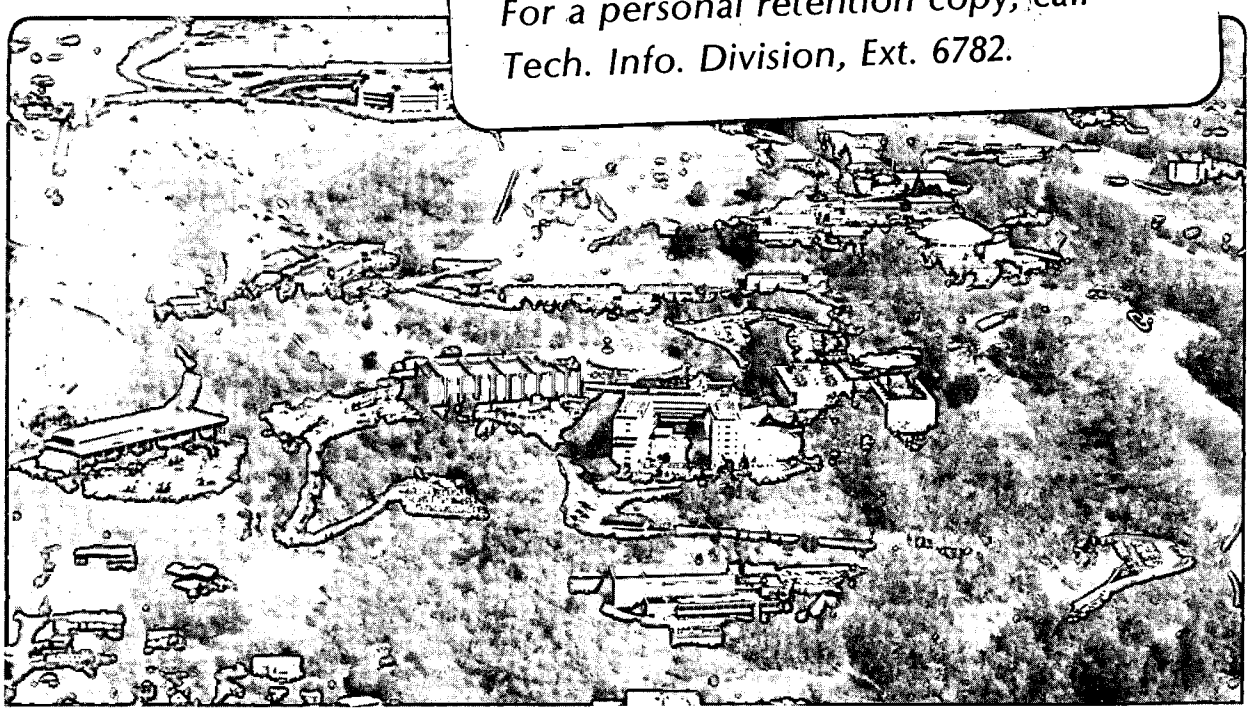

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"It ain't the things we don't know that hurt us. It's the things we do know that ain't so." -- attributed to Artemus Ward. (Charles Farrar Browne, 1834-1867)

# RADIATION PROTECTION AROUND HIGH-ENERGY ACCELERATORS

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## Abstract

The dosimetry of neutrons for radiation protection purposes at high-energy particle accelerators is reviewed.

## 1. Introduction

This paper will limit itself to only one aspect of radiation protection around high-energy particle accelerators: that of the dosimetry techniques used to quantify the neutron component of the radiation environment. Provided the many elements that comprise an adequate accelerator radiation protection program have been addressed (in particular, adequate shielding) it is in fact neutrons that dominate the radiation environment around both high-energy proton accelerators and high-energy, high-intensity electron accelerators.[1,2] Radiation protection at particle accelerators is thus of particular interest because it presents the only instance, save for a few cases at nuclear power reactors,[3] where a significant number of people undergo whole body exposure to neutrons. Radiation dosimetry at particle accelerator laboratories has tended to develop almost independently of work in the mainstream of radiation protection. There are many reasons for this separate development, but it is principally due to the fact that health physicists at accelerator laboratories often have backgrounds in nuclear or particle physics and are thus familiar with techniques used to quantify the physical parameters of radiation fields, in addition to the standard techniques of dosimetry used in health physics.

> "At high-energy accelerators a large variety of particles may be produced, extending over a wide range of energies, and their measurement presents many novel problems. It was, therefore, necessary to investigate in some detail the production and transmission through shielding of accelerator-produced radiation. Radiation detectors initially designed for nuclear physics research are the natural choice for such investigations. With the understanding provided by

> such detectors, all the requirements of a radiation protection program may be undertaken[4]: possible radiation hazards may be anticipated and their magnitude estimated; protective shielding may be designed and operational procedures selected which permit efficient operation under safe conditions; the response of any radiation detector may be correctly interpreted, and, finally, radiation survey instruments with response approximately proportional to dose equivalent may be designed for use in a limited range of environments."[5]

One clear advantage of measurements which define the physical properties of the radiation field is that the parameters so determined are immutable. Quantities which are administratively defined, such as Dose Equivalent, are transient and may vary as changes in their definitions are brought about. While it is always possible to derive dose equivalent quantities from appropriate field quantities, the converse is not true.

This paper will first review the history of our understanding of accelerator radiation fields (Section 2); summarize our present understanding of them and show that neutrons are of principal concern (Section 3). In Section 4 problems associated with the interpretation of physical data in terms of dose equivalent quantities are discussed. The experimental techniques for neutron dosimetry at particle accelerators, both for radiation surveys and neutron spectrometry, are described in Section 5. Finally the paper is summarized, conclusions drawn and suggestions for future studies made.

## 2. Historical Review

Although particle accelerators were invented in the early thirties it was not until the middle and late fifties that the first detailed investigations of the radiation environments of accelerators appear in the scientific literature.[6-9] This apparent lack of interest was probably due to the rather low intensity of particle beams then available and, in addition, because many of the early cyclotrons were constructed underground in order to avoid an unquantified but anticipated radiation problem.[10]

This avoidance of radiation problems did, however, produce a widespread ignorance of accelerator radiation environments. Thus one of the authors (R.H.T.) remembers the general surprise when in the mid-fifties, fast (i.e., a few MeV) neutrons were identified outside the roof shielding of the AERE 110" synchrocyclotron: this despite the fact that any competent nuclear physicist, with a little thought, could have predicted the existence of these neutrons on theoretical grounds. The record suggests that accelerator radiation phenomena were investigated by those groups with accelerators which were constructed above ground--presumably because there was a more pressing need.[4,5,10-12]

During this first twenty-five years there are many amusing, perhaps apocryphal, stories concerning radiation exposures at particle accelerators. Two examples from Berkeley will suffice: The first is the great concern caused when caged rats awaiting irradiation were found dead at the Crocker Cyclotron. One explanation of the rats' demise, in what were

thought to be low radiation levels might have been the extreme biological potency of neutrons. Subsequent study, however, showed that the poor rats had died from asphyxiation.[13] The second anecdote concerns the eminent scientist who, when asked to demonstrate that his neutron beam was "hard" (i.e., of high energy), took an ionization chamber reading in the beam and then interposed his body to demonstrate the ionization buildup.[14] Such an incident, were it to occur today in the United States, would cause a flurry of bureaucuratic activity costing as much as, or more than, these early particle accelerators!

Some urgency to investigate accelerator radiation environments was engendered by the reports in the late forties and early fifties of the observation of cataracts in several French and American cyclotron workers.[15,16] By 1954 Moyer, among others, had identified the principal experimental techniques that would be of value for dosimetry at high-energy accelerators[17] and which are still in use today (see Section 5).

Experience in the mid-to-late fifties at the 184-inch cyclotron at Berkeley, and at the Comotron and Bevatron established our basic understanding of accelerator radiation environments[6-9] and, building upon this foundation, systematic radiation measurements at a variety of accelerators have served to complete our understanding.[18-23]

During the sixties and early seventies several high-energy particle accelerators around the world provided information on the radiation environment at accelerators. New instruments and techniques, including Jaffe ionization chambers to estimate quality factors and the development

of threshold activation detectors capable of determining neutron spectra adequate for radiation protection purposes, provided extremely important information[24-27] and much of this work will be briefly described in the following section.

During this period work proceeded on several fronts:

- clarification of the definition of the concept of dose equivalent[28-32]
- development of activation detector techniques[33,34]
- incorporation of Bonner-spheres and activation detectors[34-36]
- improvement of neutron spectrum unfolding routines[36,37]
- improvement in the interpretation of neutron spectra in terms of dose equivalent.[38-40]

During the thirteen years from 1966-1979 several comparisons of dosimetric methods and results were made by various groups at the CERN 28 GeV proton synchrotron,[41,42] the Stanford 20 GeV electron linac[43] and the 70 GeV protron synchrotron of the Institute of High Energy Physics at Serpukhov.[44] These intercomparisons have been summarized by McCaslin and Thomas[12] who pointed out some important discrepancies. Intercomparisons are continuing at Serpukhov and will hopefully lead to important improvements in dosimetric techniques in the future.[45] Important information is also to be expected from measurements made at the increasing number of high-energy accelerators both in China and Japan.

## 3. Accelerator Radiation Environments

The basic key to our understanding of particle accelerator radiation environments was the realization that in some respects they would be similar to that produced by the interaction of the Galactic cosmic radiation with the Earth's atmosphere. This was of particular value in the case of neutrons[46] and led Patterson et al.[47] to conclude that neutrons between 0.1 MeV and 20 MeV would produce the largest component of dose equivalent around high-energy accelerators. This prediction was borne out by observations around particle accelerators at Berkeley[48-50] and elsewhere[51] and is still valid: As Hoefert has recently commented--"In almost all cases neutrons below 20 MeV predominately contribute to the dose equivalent, hence it is quite justified to speak about neutron dosimetry around high-energy accelerators when actually measurement of total dose equivalent is meant."[45]

In general high-energy particles (i.e., those above 20 MeV in energy) do not make a dominant contribution to the dose equivalent. As early as 1965, however, it became clear that, under certain conditions, as much as 90 percent of the dose equivalent could be contributed by such high-energy particles.[52-53] Such conditions are increasingly important at very high-energy facilities (in the 100 GeV energy range) and it is thus important to improve techniques for the measurement of particles of energy above 20 MeV present in accelerator radiation environments.[54]

Perhaps one of the best summaries of the composition of the radiation field outside the (concrete) shielding of a high-energy proton synchrotron was given by Perry in 1967 (see Table 1).[51]

Finally it is important to again emphasize that accelerator radiation environments are best understood by a determination of particle spectra.[55]

## 4. Interpretation of Accelerator Radiation Measurements

Perhaps the most difficult aspect of radiation protection dosimetry at particle accelerators is the interpretation of measurements in terms of the particular dose equivalent quantities required by regulation and statute.

McCaslin and Thomas[12] have reviewed dosimetry intercomparisons made by various groups at a few different accelerators and in the cosmic radiation and have concluded that, while there is reasonable agreement in the assessment of the physical parameters of a radiation field, there is often disagreement by almost as much as a factor of two in the determination of "dose equivalent" from the physical data. In part such discrepancies are due to some imprecision in the definition of the dose equivalent quantities.

One of the first attempts to relate dose equivalent to the fluence of neutrons (or protons) at energies greater than several tens of MeV was made by Neary and Mulvey.[56] These calculations gave the ratio of the dose equivalent at the position of maximum development of the cascade initiated by these particles to the fluence of the incident particles remaining in the cascade at that point. In fact what is required is rather the relationship between the dose equivalent in an anthropomorphic phantom, or other defined phantom, and the fluence of particles which would have existed without the phantom present. Later calculations by groups at Oak Ridge (see for example refs. 57,58) determined, among other parameters, the maximum dose equivalent that could be found in a 30 cm

thick, parallel-sided, tissue-equivalent slab phantom irradiated uniformly from one side only, in a direction perpendicular to the face of the slab. The dose equivalent to fluence ratios so obtained define a function $g_m(E)$ which can be multiplied by an incident spectrum $\phi(E)$ to give a quantity, $H_m$, originally called the Maximum Dose Equivalent, (MADE).*

$$H_m = \int_{E_{min}}^{E_{max}} g_m(E)\ \phi(E)\ dE \qquad (1)$$

This procedure is not entirely logically consistent since the argument of the integral contains two elements--the first a hypothetical neutron fluence, which would exist if the phantom or body were not present; the second a fluence to dose equivalent conversion coefficient for a particular neutron energy. These conversion coefficients are, however, determined by locating the maximum dose equivalent which occurs in the phantom. The location of this maximum varies with neutron energy. The procedure of integration (summation) of maximum dose equivalents which occur at different positions in the phantom will thus overestimate the actual dose equivalent produced by accelerator type spectra. This procedure was, however, used at several British and U.S. high-energy accelerators in the

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*In what follows the suffices m,p and s indicate parameters (e.g., dose equivalent, H, or conversion coefficients, g,) corresponding to the maximum dose equivalent in the human body (or phantom), $H_m$; to the dose equivalent at or near the surface of the human body, Hs; or to the practical dose equivalent, $H_p$ (see text). The dose equivalent at or near the surface of the body, $H_s$, is more rigorously defined by $H_{10\ mm}$, usually abbreviated to $H_{10}$ as: "The dose equivalent in the ICRU sphere at a point on the principal radius at a radial depth 10 mm from the surface in an aligned and expanded radiation field."

1960's and was endorsed in the recommendations of ICRP Publication 21. This concept was further formalized by Harvey to define the Dose Equivalent Ceiling.(59)

A somewhat different method of determining dose equivalent in practical situations at accelerators was adopted at CERN.(31,60) Here it was argued that in many cases the radiation penetrating a thick concrete shield essentially had achieved an equilibrium particle spectrum which would not be significantly altered by the presence of the human body. In such circumstances the human body merely acts as additional attenuating material and the maximum of the depth-dose equivalent distribution will lie close to the body surface. Furthermore it is a feature of the radiation survey instruments that are commonly used in operational health physics, (e.g., tissue-equivalent ionization chambers), that the wall thickness is selected so that the measurement determines the dose near the body surface. With this philosophy one can take the values of the dose equivalent at or near the surface of the phantom in the calculations mentioned above to define a new conversion function, $g_s(E)$, which when integrated with the spectrum as before,

$$H_s = \int_{E_{min}}^{E_{max}} g_s(E)\phi(E)dE \qquad (2)$$

defines a surface dose equivalent, $H_s$, in a way which is rigorously correct for spectra of particles because a definite position in the phantom is now being considered.

Yet another approach was suggested by Shaw et al.[38,39,61] who calculated the distribution of dose equivalent versus depth in a 30 cm parallel sided phantom irradiated bilaterally with broad neutron spectra typical of those to be found outside the shielding of high-energy proton accelerators. The maximum of the depth-dose equivalent curves was taken to define another dose equivalent quantity, the practical dose equivalent, $H_p$. The relationship between the three quantities, normalized to $H_p$, for the spectra used by Shaw et al. is given in Table 2.

The neutron spectra referred to in Table 2 and elsewhere may be briefly described thus:

1/E the familiar 1/E differential energy spectrum.

RT a neutron spectrum determined at the CERN 28 GeV proton synchrotron (CPS) above the earth shielding with a target intercepting the beam as a primary radiation source.

PSB measured at the CPS above a concrete shield, again with a target acting as the primary source.

BEV measured at the University of California Radiation Laboratory (now Lawrence Berkeley Laboratory) 6.3 GeV proton synchrotron.

X2 measured at the 7 GeV proton synchrotron of the Rutherford Laboratory, outside concrete shielding.

P1 measured as for X2 but outside steel shielding.

PLA the ambient neutron spectrum around the 50 MeV proton linac of the Rutherford Laboratory.

CR the Hess Comic Ray neutron spectrum.

Inspection of Table 2 shows that $H_m$ is systematically greater than and sometimes nearly twice as large as $H_p$ whereas, for these spectra $H_s$ never underestimate $H_p$ by more than 15 percent, but may overestimate it by as much as 70 percent.

In the past decade the ICRU and ICRP have introduced concepts with the intention of clarifying the quantities to be determined for radiation protection purposes. These important contributions, however, have perhaps had the effect of adding only to the existing confusion, rather than mitigating it.

In 1973 the ICRU first introduced the concept of the "dose equivalent index"[62] and three years later extended the concept to include shallow and deep indexes.[63] These concepts have not been taken up with great enthusisam by working health physicists for a variety of reasons. There is no practical means of locating the maximum dose equivalent in a 30 cm tissue equivalent sphere and there is a growing list of undesirable properties of the index quantities including non-additivity (spatial and secular) and non-point-specificity. In recognition of these problems the ICRU has established a group to examine the practical determination of the dose equivalent index quantities, or suitable alternative quantities.[64]

At high energies there is very little difference to be expected between fluence to dose equivalent conversion coefficient derived either from a 30 cm sphere or a 30 cm parallel-sided slab. This fact, and those mentioned in the preceding paragraph, led Stevenson et al.[31] to suggest that the concept Dose Equivalent Index was in fact redundant for dosimetry at accelerator laboratories and that $H_s$, determined for the appropriate condition of unilateral or bilateral irradiation was an

adequate quantity to "attempt to relate the absorbed dose to the risk of the resulting biological effect."[65]

Despite these problems with the Index Quantities the ICRP, in 1977, compounded the difficulty by introducing a new concept, the Effective Dose Equivalent, $H_E$, as the quantity of interest in radiation protection and by further stating that, for external radiation exposure, $H_E$ could be approximated by a determination of the deep dose equivalent index.

> "With external exposures to penetrating radiation, on those occasions when information is lacking concerning the actual distribution of dose equivalent in the body, it is possible to assess the maximum value of dose equivalent in the body, that would occur in a 30 cm sphere (the deep dose-equivalent index, $H_I$). The limitation of the dose-equivalent index to an annual value of 50 mSv would afford a level of protection that would be at least as good as that provided by the method recommended in paragraph 104."[66]

At this point the authors cannot resist the temptation to offer an editorial opinion and suggest that in retrospect the invention of the index quantities has not well served radiation protection dosimetry. In retrospect it would seem to have been better to have drawn from established concepts and techniques of measurements, rather than attempt to impose new and untried concepts upon dosimetry. In a similar manner the ICRP was perhaps unwise to publish paragraph 108 in Report 26 before sufficient data had been obtained to support its assertion. Calculations are now under way to fully understand the relationship between the dose equivalent indexes and Effective Dose Equivalent.[67-75] In particular the relationship between Effective Dose Equivalent and fluence is under study by a Task Group of the ICRP,[64] but it is clear that this relationship is not a simple function such as $g_m$ or $g_s$ but depends upon many variables, one of the most important being the irradiation geometry.

Such considerations lead one to conclude that non-specific comparisons of "dose equivalent" derived from fluence measurements may be expected to show large differences. Proper comparisons will only follow when the dose equivalent quantities to be examined are rigorously specified. Many of the apparent discrepancies reported in the literature arise from this ambiguity in the definitions of dose equivalent. It is unfortunate that it is possible for authors to behave like Humpty Dumpty: "When I use a word," Humpty Dumpty said in a rather scornful tone, "it means just what I choose it to mean--neither more nor less."(76)

## 5. Experimental Techniques for Neutron Dosimetry at Particle Accelerators

Neutron dosimetry for radiation protection purposes at particle accelerators may be divided into two categories:

- Radiation Surveys
- Determination of Neutron Spectra

While radiation surveys in the field provide useful after-the-fact data, the goals of radiation protection may only be met when the origin, attenuation through shielding, and transport through the air of accelerator-produced radiation are fully understood. As we have seen in the previous sections, the dominant radiation protection problem around high-energy accelerators is expected to be due to neutrons. Thus knowledge of the neutron spectra found around particle accelerators provides an essential starting point for a thorough basis for an understanding of accelerator radiation protection.

Neutron spectra are also a fundamental starting point in the measurement of the dose equivalent, since they permit an optimum choice of radiation detector combinations; they enable LET-distributions to be calculated in phantoms; and, finally, they facilitate the calculation of dose equivalent from appropriate fluence to dose equivalent conversion coefficients. In this section the spectra to be expected around high-energy proton accelerators will be described, the optimization of the

choice of detectors used to measure them will be mentioned, and some other methods of determining dose equivalent described. Finally, some comments will be made on dosimetry-intercomparison experiments published in the literature.

## 5.1 Techniques of Measurement of Neutron Spectra

Despite much discussion in the literature supporting the need to measure neutron spectra, such measurements have in fact been made at only a few laboratories. This is no doubt partly because the techniques are protracted and long periods of stable operation are required (not a usual feature of particle accelerators used in research), partly because spectrum unfolding requires some mathematical ability or familiarity with some of the many computer programs (and, as a corollary, access to a computer facility), but principally because sufficient resources have not been made available at any National Laboratory or University for a systematic study of accelerator radiation environments.

The techniques used for spectrum measurement at particle accelerators are well established and have been extensively described in the literature.[77] Many of the techniques used are, in fact, reviewed in this issue of Radiation Protection Dosimetry.[78] The basic techniques used or attempted at high-energy accelerators are:

- Threshold detectors. These may be either of the active[79] (e.g., bismuth fission chambers)[80-82] or the passive type[83-85] (e.g., the production of $^{11}C$ from $^{12}C$ in a plastic scintillator).[86-89]

Suitable nuclear reactions, their thresholds and sample materials are indicated in Table 3. Care must be taken in the particular reactions selected because in the high-energy environments of accelerators multiple reactions may be possible, with the resultant productions of many radionuclides. This restriction to reactions which are both simple and readily detectable often eliminates some reactions for use in high-energy environments which are perfectly acceptable around lower-energy facilities.

Activation detectors have the advantage of not being susceptible to a dose equivalent rate dependence as are pulse-counters which often suffer counting rate losses at the high instantaneous fluence rates found at accelerators resulting from low duty cycles and because of the radio-frequency structure superimposed on the beam current within a pulse. However, significant experimental ingenuity is often required to achieve the sensitivities needed to measure radiation fields at the occupational exposure level with activation detectors. This has inhibited the development of some otherwise very interesting reactions such as, for example, $^{149}$Tb production in gold or mercury.[90,91] As may be seen in Table 3, most feasible reactions have thresholds in the energy region from 3-50 MeV and so activation detectors must be used in conjunction with other techniques if the entire energy spectrum of the accelerator environment is to be spanned. Because of the limited number of reactions available the use of activation detectors is necessarily of low resolution, limited to the determination of neutron spectra without detailed structure. The

techniques most frequently used to supplement activation detectors below 1 MeV is that of Bonner Spheres or "multi-spheres."

- Multisphere Techniques. Bonner spheres of various sizes may be used with a variety of thermal neutron detectors. Suitable detectors in practice have been found to be: $BF_3$ or $^3He$ proportional counters; $^6LiI$ scintillation counters; indium or gold activation foils and $^6LiF$-$^7LiF$ thermoluminescent dosemeter pairs. The specific choice of the detector is determined by constraints of the temporal nature of the radiation field. As with the use of activation detectors, the multisphere method is of low-energy resolution. It has the added disadvantage that the constraints built into unfolding techniques to prevent the generation of physically unreasonable spectra also inhibit the detection of real structure in the spectra. Furthermore the detector response functions have not been determined experimentally over the entire energy range for which the technique is used, and one is therefore dependent upon the theoretically generated response functions.[92]
- Proton Recoil Spectrum Measurements. Nuclear emulsions can be used to record recoil proton spectra, but their evaluation is tedious and time-consuming.[93,94] They also require techniques and equipment which are no longer in readiness at many laboratories. Proton spectra have also been measured using bulk plastic scintillation detectors.[95] Both these techniques are only able to give neutron spectral information in the energy range 2-20 MeV. At higher

energies star prong counting has been utilized to give crude information on spectrum slope.[96,97]

At higher energies special counter-telescope arrangements[98-100] or spark-chamber arrays[101-104] are required. These techniques both derive directly from high-energy physics detectors and require a complex infrastructure typically beyond the capabilities of small accelerator laboratories.

## 5.2 Typical Neutron Spectra

As examples of neutron spectrum measurements we have selected a few from the available literature.

Figure 1 snows spectra measured by the Lawrence Berkeley Laboratory Group during the middle 1960's.[36,46,47] A four-detector combination was used: a boron trifluoride counter in a cylindrical moderator, the $^{27}Al$-$^{24}Na$ and $^{12}C$-$^{11}C$ passive activation detectors, and a bismuth ionization chamber. These spectra can be reasonably well constrained in the 100 keV to 100 MeV region. Outside this energy range the spectra are not well determined by the measurements but general physical principles are invoked to give reasonable spectral shapes. From these early measurements several features emerge. The "ring-top" spectrum (RT) was measured above the earth shielding of the CERN 28 GeV proton synchrotron. This earth contained more moisture than the concrete shield of PS bridge at the same accelerator where the PSB spectrum was measured. The Bevatron spectrum (BEV) shows a broad peak in the 1-100 MeV region; the

negative slope of the Cosmic Ray spectrum (CR) in this energy region coupled with the response of the moderated $BF_3$ counter implies a peak in the spectrum below 1 MeV.

Spectra were obtained at the 7 GeV proton synchrotron accelerator of the Rutherford Laboratory, "Nimrod," using the multisphere technique with a $^6LiI$ scintillator as the thermal neutron detector.[36] Some of these are given in Fig. 2. All the spectra shown are relatively flat: the X2 spectrum, taken directly outside the shield around an extracted beam target, is significantly harder than the P1 spectrum which was measured in an environment where the outer surface of the direct shield was of iron and there was a significant contribution to the field from neutrons scattered by local concrete blocks.

Spectra obtained by the Princeton-Pennsylvania Health Physics Group also using Bonner spheres (see Fig. 3) show a much more oscillatory character,[35] probably reflecting the different spectrum unfolding routine used from that used at the Rutherford Laboratory.

Figure 4 shows the results of a theoretical calculation by O'Brien[105,106] where the observed features of 1/E type spectrum coupled with a peak in the 1-10 MeV energy range are confirmed. In addition the calculation by O'Brien reveals a second peak in the 100 MeV energy region, where none of the measurements described above would be expected to give good resolution. This high-energy peak is, however, confirmed experimentally by Madey et al.[107] and also in calculations reported by Stevenson of the high-energy cascade in iron (see Fig. 5).[54]

## 5.3 The Determination of Dose Equivalent by the Use of Multiple Detectors

As shown in the previous section there are significant differences between the neutron spectra found outside high-energy accelerator shielding. Because of the variety of spectra and because of the ambiguities in the definition of dose equivalent quantities, no single detector which is simple to use can be expected to give a response proportional to "dose equivalent" under all circumstances.

Resort must therefore be made to combinations of detectors and the "art" of accelerator radiation protection dosimetry has been in optimizing the selection of detectors to be used.

Having conceded that more than one detector will be needed to determine the dose equivalent from neutrons, the most general expression for the approximate value of dose equivalent, $H_a$, determined from the measured response $R_i$ of n detectors is:

$$H_a = \sum_{i=1}^{n} a_i(\text{radiation type; energy range})\, R_i \qquad (3)$$

where the $a_i$'s are suitably chosen response to dose equivalent conversion coefficients and will depend upon many parameters and the $R_i$'s are the detector responses.

In general the larger the value of n the more accurately will $H_a$ approach the desired dose equivalent quality (e.g., $H_{10}$, $H_m$, $H_s$, $H_p$).

Experience has shown that two techniques are in general use at accelerator laboratories for the determination of dose equivalent--one utilizing moderated thermal neutron detectors and the other the production of $^{11}C$ in plastic scintillator.

In this section these two techniques are briefly described, followed by a description of some systems used at various laboratories using multiple detectors.

### 5.3.1 Moderated Thermal Neutron Detector Techniques

Many accelerator laboratories use the Andersson-Braun counter[108,109] as the standard instrument for the assessment of dose equivalent produced by neutrons below 20 MeV. This is true, for example, at CERN, where the REM/N proportional counter instrument produced by 20th Century Electronics Ltd., based on the original design of the group at A.E.R.E. Harwell (Harwell type 1940A), is regarded as the reference dose equivalent meter. For area monitoring the ionization chamber version of this instrument is routinely used at CERN.

The response as a function of energy of the REM/N instrument is shown in Fig. 6. There are two sets of calibrations at energies less than 20 MeV, the original work of Leake and Smith at AERE Harwell[110] and the more recent work of the PTB group at Braunschweig.[111,112] It will be seen that the more recent calibrations give a slightly higher response than the earlier work. The point a 280 MeV is derived from a calibration by Hoefert of the ionization chamber version.[113] The

standard calibration reference normally used is 1.01 nSv per count from the detector, when exposed to a Am-Be neutron source. (The solid line shown in Fig. 6 is the curve used later to calculate and determine the response of the instrument in typical accelerator spectra.)

Another commonly used detector of this type is an indium foil in a spherical (or cylindrical) hydrogenous neutron moderator.[114] The specific detector chosen as an example for discussion here is the 7-in.-diam. paraffin wax moderator in a cadmium can used at the Rutherford Laboratory. The indium foil placed at the centre of the sphere was beta-assayed by a thin end-window Geiger counter. This device was calibrated by Simpson[115] and these calibrations can be related to the response of a 7-in.-diam. polyethylene sphere with a $^{6}LiI$ crystal as detector (derived from the calculations of McGuire)[116] to give the response of the wax sphere over the whole energy range (Fig. 7). The detector is calibrated in terms of the apparent flux density of 2 MeV neutrons, but a dose equivalent per unit fluence of 15 $fSv.m^2$ was found to be most appropriate for the determination of dose equivalent in typical accelerator spectra.[117]

Given the response functions for these two detectors (Figs. 6 and 7), their reading in any particular neutron environment may be calculated. Figure 8 shows the response of each in a 1/E spectrum. The readings are normalized to the dose equivalent at 10 mm depth in soft tissue proposed by Stevenson et al.[31] and shown as a function of the maximum (cut-off) energy of the spectrum. Inspection of Fig. 8 reveals that at a cut-off energy of 1 GeV the Andersson-Braun detector underestimates the dose equivalent by 30 percent.

These two detectors are often use to specify the dose equivalent due to neutrons below 20 MeV. Since there is contribution to the total response from higher energy neutrons it is of interest to compare the reading of these instruments to the actual dose equivalent below 20 MeV. This is done in Table 4 in a variety of neutron spectra.

### 5.3.2 $^{11}C$ Activation Measurements

Perhaps the most important technique unique to accelerator radiation protection dosimetry is the determination of $^{11}C$ production in carbon or plastic scintillator to measure neutron fluences. The technique was used to monitor cyclotron beam intensity using the $^{12}C(p,pn)^{11}C$ reaction, but it was Sharpe and Stafford[86] who first suggested using the (n,2n) reaction to measure low neutron fluences. They reported that a 4.5 gm anthracene crystal could detect flux densities as low as 15 $cm^{-2}s^{-1}$. Baranov and Goldanskii[87] first suggested the use of liquid scintillator both as convenient target and detector. McCaslin[88] and Shaw[89] have described the experimental technique using solid plastic scintillator in detail. The use of large scintillators (2.7 kg) has made possible the determination of neutron fluences as low as 1 $cm^{-2}s^{-1}$ (Ref. 34).

A distinction between between energy regions in accelerator radiation protection dosimetry is often made at 20 MeV both because this energy roughly corresponds to the upper limit of useful response of many of the moderator-devices (as has been seen in Section 5.1) and, more importantly, because the threshold of the $^{12}C(n,2n)^{11}C$ reaction is 20 MeV. In the

past the assumption has largely been made that, in the absence of a significant contribution from any other component of the radiation field activity of $^{11}C$, $A_{sat}$, is entirely produced by neutrons and is given by:

$$A_{sat} = K \int_{E_{thresh}}^{E_{max}} \sigma_n(E)\ \phi_n(E)\ dE \qquad (4)$$

where K is an instrumental constant, $\sigma_n(E)$ is the $^{11}C$ production cross section at energy E and $\phi_n(E)$ is the neutron flux density between energies E and E + dE.

Early interpretations of the measurements of the cross section $\sigma(E)$ suggested a step-like excitation function with threshold at 20 MeV, rising rapidly to a constant value of 22 mb.[34]

It is usual to compute a nominal neutron fluence, $\phi_{nom}$, given by:

$$\bar{\sigma}_n \phi_{nom} = \int_{E_{thresh}}^{E_{max}} \sigma_n(E)\ \phi_n(E)\ dE \qquad (5)$$

where $\sigma_n$ is the constant cross section of the excitation function.

Combining equations (4) and (5) we thus obtain:

$$\phi_{nom} = \frac{A_{sat}}{K\bar{\sigma}_n} \qquad (6)$$

The interpretation of this measured fluence in terms of dose equivalent has led to some considerable discussion in the literature. Baarli and his colleagues[118,119] determined a fluence to dose equivalent conversion factor by the simple expedient of a "direct" measurement. Plastic scintillator was exposed in the (roughly) monoenergetic neutron beam of the CERN synchrocyclotron and $\phi_{nom}$ calculated. The dose equivalent was determined by measuring the absorbed dose with a tissue equivalent ionization chamber and multiplying the results by the "measured" quality factor obtained using a recombination chamber.[25,26] A conversion coefficient of 28 $fSv.m^2$ (corresponding to a neutron fluence of 10 $cm^{-2}$ $s^{-1}$ being equivalent to 1 mrem/hour) was chosen as a result of these measurements to give a conservative estimate of dose equivalent.

Shaw et al.[39] at the Rutherford Laboratory adopted a more empirical approach by determining an appropriate conversion factor that gave fair to good estimates for a variety of accelerator spectra. For values of $H_{10}$ a conversion coefficient of 60 $fSv.m^2$ was obtained--in good agreement with the value of 50 $fSv.m^2$ suggested somewhat later by Stevenson and based upon similar considerations.[117]

Clearly there is a wide discrepancy between these two values and that due to Baarli et al. It is only recently, however, that this matter has been rexamined.

Since the pioneering of McCaslin and his colleagues new cross section data have become available. In particular the excitation function for neutrons no longer appears to be a step function but has the typical resonance pattern exhibited by the proton excitation function.

Stevenson[54] has analyzed both the influence of these new cross sections and the influence of the $^{11}C$ production by charged particles (protons, pions) on the conversion coefficients. By using a Monte Carlo method he calculated the neutron, pion, and proton spectra which exist outside steel shielding surrounding a 30 GeV proton beam (Fig. 9). Values of conversion coefficients in the range 40-50 $fSv.m^2$ were obtained. However, conversion coefficients in the range 27-36 $fSv.m^2$ were obtained for neutron spectra (charged particles ignored) taken from the work of O'Brien.[105,106] These spectra were calculated for a lateral concrete shield 1000 $g.cm^{-2}$ thick using spherical harmonics solution of the Boltzmann Transport Equation. O'Brien used an upper energy cut off of 500 MeV in his calculations.

Thus it may well be that the difference between conversion coefficients obtained by the Rutherford Laboratory Group and by Baarli and his colleagues can be explained by the contribution to the $^{11}C$ activity by charged particle reactions. Further studies of the problem are clearly needed.

### 5.3.3 A Comparison Between the Determinations of Dose Equivalent Due to Neutrons Made by Two Laboratories Using Two Neutron Detectors

Experience shows that three detectors are the minimum that may be used to determine dose equivalent in the environment of particle accelerators, with sufficient accuracy for radiation protection purposes (in the terms of equation 3: $n \geq 3$).

Typically the 3 detectors used are:

- An air ionization chamber to determine the dose equivalent contribution from charged particles and photons.
- A "low-energy" ($E < 20$ MeV) neutron detector--usually one of the many types of moderated thermal neutron detectors (see Refs. 35, 36, 108, 109, 114, 115, 120-124).
- A "high-energy" ($E \geq 20$ MeV) neutron detector--most frequently based on the $^{12}C\ (n,2n)^{11}C$ reaction (see Refs. 86-89).

Such a scheme has been the basis for measurements at Berkeley (LBL), CERN, and the Rutherford Laboratory for many years.

At CERN the total dosimetry system consists of four instruments--the three specified above plus a tissue equivalent ionization chamber to determine absorbed dose--and gives an indication of the average quality factor of the radiation field. This dosimetry system has somewhat whimsically been named "Cerberus" after the many headed monster of Greek mythology.*

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*Cerberus is referred to by many poets including Hesiod, Homer, and Virgil. There is not general agreement as to the number of heads carried by this monster. While most reports state two or three, at least one suggests as many as 50. (Most accelerator dosimetrists would agree that this is too many!) Perhaps the physicist who named the CERN detection system after Cerberus had in mind the task of this dog which was to prevent the escape of the inmates of Hades. We in accelerator radiation protection still await our erstwhile Hercules, to perform his labour of bringing Cerberus up from the underworld.(125-127)

In what follows we will only compare the determination of dose equivalent made by two elements of the detector system, made by CERN and the Rutherford Laboratory.

At CERN the low-energy ($E < 20$ MeV) neutron dose equivalent is determined using an Andersson-Braun instrument. The ionization chamber version of the detector is used and a correction is made to the recorded ionization current for the contribution due to photons and charged particles. Calibration is achieved using an Am-Be neutron source. The high-energy ($E \geq 20$ MeV) neutron dose equivalent is determined from the nominal $^{11}C$ fluence (see Section 5.3.2) using a conversion coefficient of 28 $fSv.m^2$.

At the Rutherford Laboratory the dose equivalent, $H_A$, is given by:

$$H_A = 15\ \phi_{IN} + 50\ \phi_C \qquad (7)$$

where the dose equivalent is in units of fSv and the neutron fluence in $m^{-2}$. $\phi_{IN}$ is the fluence determined by paraffin wax moderated detector and $\phi_C$ is the nominal $^{11}C$ fluence (Section 5.3.2). The conversion coefficients used in eqn. 7 are appropriate to $H_{10}$.

Comparison of the dose equivalents which could be obtained in a variety of accelerator spectra is shown in Table 5. The estimates of $H_{10}$ by both laboratories are seen to be good and (with exception of the theoretical O'Brien spectra) never worse than 25 percent.

This good agreement between the two laboratories for dose equivalent values does not, however, persist when the dose equivalents which would be determined for neutrons below and above 20 MeV are compared.

Table 6 shows the ratio of dose equivalent contributed by neutrons below 20 MeV to that contributed by neutrons above 20 MeV, as would be determined by the CERN and Rutherford Laboratory prescriptions, for the several accelerator spectra used here. In addition the correct value of this ratio is given for comparison. The CERN recipe is seen to systematically overestimate this ratio whereas the RL recipe usually underestimates it. This state of affairs may be corrected by readjustment of the calibration coefficients: a matter of administrative rather than physical difficulty. Nevertheless, these differences must be borne in mind when interpreting dosimetry intercomparisons published in the literature.

## 5.4 Other Methods of Dose Equivalent Determination

The dose equivalent produced by a neutron field can also be derived from the measurement of absorbed dose, using a tissue-equivalent ionization chamber, and a multiplication of this by an assumed or measured quality factor.

Several techniques of measuring quality factor have been suggested. For example, the characteristics of columnar recombination in ionization chambers are dependent on the LET of the charged particles causing the ionization. One approach due to Zielczynski is to use a double ionization chamber in which one part is operated at saturation voltage and another at a lower voltage in which a certain amount of columnar recombination can occur.[24] It was shown to be possible to adjust the lower

voltage so that the ratio of the currents from the two parts of the chamber is a linear function of quality factor, which means that the difference in ionization current from the two parts of the chamber will be directly proportional to the dose equivalent.

Another method based on columnar recombination relies on the observation that over a large voltage range, the current is empirically related to the polarizing voltage by a relation of the form:

$$i = kV^n \tag{8}$$

The index n is approximately proportional to Q and so a determination of n in a neutron field can give an estimate of the average quality factor to be applied to a measurement of absorbed dose.[25-27]

Another effect that can be used to obtain an estimate of radiation quality is the light output from a plastic scintillator. The method devised by Pszona[128-130] relies on the simultaneous measurement of currents from an ionization chamber and a photomultiplier tube attached to a plastic scintillator. The ratio of the currents is a complex function of LET, but it can be used to give a measure of an average Q in an unknown field.

Since LET and event-size (Y) spectrometry are discussed in detail in another part of this journal issue they will not be further mentioned here.[131] However, Baum and others of Brookhaven National Laboratory have developed a more robust and improved ion chamber which also reduces the need for frequent gas-filling.[132-134] Two signals are extracted; one is proportional to the dose rate, independent of LET; the other is

processed by nonlinear amplifiers to produce an amplitude dependence which varies with LET in the same manner as does Quality Factor.

Yet another technique, described by Tesch,[135] is to use pulse-shape discrimination on the pulses coming from an organic scintillator to discriminate against photons, and to choose a suitable discriminator threshold so that the pulse rate is proportional to dose equivalent.

All these techniques have given satisfactory estimates of quality factor and dose equivalent in near-laboratory conditions of exposure. However, as yet, there is no universal dose equivalent meter which is both sufficently sensitive and robust enough to withstand the rigours of measurement in the field, and give reliable results at occupational radiation levels. This is to be contrasted with the multiple detector systems described earlier in this section, which have been shown reliably consistent for more than twenty years.

## 5.5 Intercomparison of Dose Equivalent Determinations

An important way to establish confidence in the determination of dose equivalent is to compare measurements by various groups, using different experimental techniques.

Ideally such intercomparisons should be made under carefully controlled condition. Thus, for example, the instruments used should make measurements at the identical locations in a radiation field which is spatially uniform. In addition it is essential the same dose equivalent quantity be compared.

Rarely, if ever, have these criteria been exactly met. Thus a large contribution to the discrepancies revealed in the CERN--Lawrence Berkeley Laboratory--Rutherford Laboratory intercomparison of Gilbert et al.[34] was due to the fact that the CERN group determined $H_{10}$ whereas the other two groups determined $H_m$. None of the participating groups fully understood this subtlety, which has become apparent in the past decade, at the time the measurements were made. As Table 2 shows, estimates of the ratio of $H_m$ to $H_s$ (or $H_{10}$) in accelerator environments lies in the range 1.15 to 1.41. In the two spectra in which measurements were made at CERN the ratio has the value 1.41 (RT) and 1.34 (PSB). Interestingly enough the ratio of the doses equivalent reported by LBL to those reported by CERN was 1.31.[36]

Similar reasons may possibly be invoked to explain the discrepancies between measurements made by the BNL Universal Dose Equivalent Meter and by the LBL Health Physics Group.[43] Here, McCaslin et al. reported that the ratio of the Dose Equivalent determined by the LBL group was a factor 1.8 greater than that measured by the BNL instrument (which measures $H_{10}$). Table 2 gives a value for the ratio of 1.24. The hypothesis here is less satisfactory but it is not discounted for two reasons--firstly, the calculation summarized in Table 2 used a different "Bevatron" spectrum than that used for the measurements reported by McCaslin et al.; and secondly, the BNL Universal Dose Equivalent Meter suffered from instrumental difficulties during the measurements.

These two examples do, however, point out the great importance in any intercomparison of selecting the dose equivalent quantities to be determined.

Extensive efforts have been made at CERN and Serpukhov to make intercomparisons where the same neutron dose equivalent quantities are compared. In this case $H_{10}$ was chosen. Hoefert[41,42] has described the first comparison made at CERN in 1975, where measurements were made with the CERN Cerberus system, the BNL Universal Dose Equivalent meter and a commercially available version of the chamber developed by Zielczynski, the REM2. The results of the measurements are given in Table 7 and are divided into groups according to whether muons, low- or high-energy neutrons dominate the radiation environment.

The overall agreement between the three measurement systems is fair. When intermediate and fast neutrons dominate the radiation field the Cerberus system gives a higher estimate of dose equivalent than the other two, almost certainly due to the known over-reading of the Rem-Ion chamber to intermediate energy neutrons. The situation is not easily explainable since the dose equivalent and absorbed dose measurements by this instrument were both higher than for the other two systems. As would be expected the agreement is much better in those situations where the dose equivalent is dominated by radiation of low LET.

Antipov et al.[44] have reported on measurements made in three locations around the 70 GeV proton synchrotron at Serpukhov. The detectors used included an LET spectrometer, a recombination chamber device (SUKHONA-2) and various thermal neutron detectors in moderating spheres (called SNMO-5, SNMO-3, SNM-3 and $^{103}Rh$) which are used in conjunction with $^{11}C$ measurements and measurements with an aluminium walled air ionization chamber. Different matrices were used to correct

the response of one detector due to components of the radiation field other than the one expected to be measured (KM-1 and KM-2). A simplified summary of the results of the measurements are given in Table 8. The two matrix methods used to derive the Serpukhov Group values will provide estimates of the MADE and can thus be expected to be higher than the $H_{10}$ estimate of the Cerberus system. Again, if intermediate and fast neutrons dominate then the Cerberus system gives a high result.

## 6. Summary and Conclusions

This brief review of neutron dosimetry at high-energy accelerators leaves the authors of two minds.

On the one hand we draw satisfaction that several techniques are available for the determination of physical parameters of radiation fields. These techniques are reliable and of reasonable accuracy. In fact recent intercomparisons indicate less divergence than in some other fields of radiation-protection dosimetry (e.g., low-energy x rays).

On the other hand, this situation was essentially achieved 10-15 years ago. Since that time there has been little progress in our understanding of accelerator radiation environments. The derivation of dose equivalent from physical data is still fraught with uncertainty and can lead to variations of almost a factor of two.

One basic reason for the lack of progress in recent years has been the lack of any systematic program to develop the identified refinements in techniques of measurement that are necessary and to use them in a systematic program of measurement. The large accelerator laboratories have, in a sense been lulled into a complacency, by the success of their radiation-protection programs in the sixties and early seventies.

At the early cyclotrons it was predicted that neutrons below 20 MeV in energy would be the most important component of the radiation field--and so experience showed. With declining budgets available for high-energy physics research, there has been a corresponding reduction in the strengths of accelerator health physics groups. Typically, most groups

have been reduced to the minimum necessary to ensure safe operation under normal operating conditions. Few resources are now allocated to the experimental investigation of accelerator radiation environments and the development of new dosimetric techniques.

Such otiosity carries with it possible dangers. During the past ten years the radiation environments around high-energy accelerator facilities have undergone a subtle change. The external radiation fields from the earliest proton synchrotrons (Cosmotron, Bevatron) mainly came from the bulk shielding of the accelerators themselves. As the shielding of the accelerator-proper was improved the dominant radiation sources came from the extracted primary beam lines (AGS, CPS, Nimrod). Secondary beams from these second-generation proton synchrotrons were of little importance as radiation sources. However, at the highest energy facilities (Fermilab and the CERN SPS) it is possible for secondary beams to have intensities equal to or greater than the intensity of the early synchrotrons. These secondary beams are typically transported through lightly shielded areas, often without roof shielding, because beam losses are small. It is expected that quality of the radiation fields around these unshielded, or lightly shielded high-energy (>100 GeV) beams will be very different from those found around the well shielded second-generation proton synchrotrons.

Theoretical cascade calculations predict the presence of significant intensities of protrons and charged pions. The existence of this charged component to the field is of great importance: the techniques currently used to measure dose equivalent may not be entirely adequate. The conventional interpretation of the readings of personal dosimeters (e.g.,

film) may be incorrect. Charged particle fluence to dose equivalent conversion coefficient (particularly for negatively charged pions) need to be determined.

Finally, there is a continuing need for intercomparisons of dosimetry of the type described in this review. This will require a major effort to be mounted on two fronts--the first is the establishment of dedicated facilities that can provide a variety of radiation environments (primary proton and electron beams, under different shielding configurations). The second is the organization of a series of intercomparisons on a comprehensive and systematic rather than the ad hoc and limited basis characteristic of some of the earlier intercomparisons.

It is indeed unfortunate that no University Department, National or International Laboratory has found the problem of accelerator radiation dosimetry for radiation protection to offer a sufficient intellectual challenge to mount the sustained program of research and development necessary to tackle the problems summarized here.[136] We look forward to the time when this omission may be rectified and we may say, as Henry did at Harfleur:

> "I see you stand like greyhounds in the slips,
> Straining upon the start. The games afoot!
> Follow your spirit."[137]

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Table 1

Radiation Spectrum Above Nimrod Extracted Proton Beam Shielding

| Type of Radiation | Energy Range | Estimated percentage of neutron flux density | Estimated percentage 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 2

Comparison of Calculated Values of Various Dose Equivalent Quantities in Several Typical Accelerator Neutron Spectra

| Spectrum | $H_m$ | $H_s$ | $H_p$ |
|---|---|---|---|
| RT | 1.21 | 0.86 | 1.00 |
| PSB | 1.33 | 0.99 | 1.00 |
| BEV | 1.58 | 1.26 | 1.00 |
| X2 | 1.23 | 0.96 | 1.00 |
| P1 | 1.73 | 1.49 | 1.00 |
| PLA | 1.94 | 1.68 | 1.00 |
| CR | 1.73 | 1.53 | 1.00 |

Table 3

Threshold Detector Techniques[77,79,84]

| Reaction | Sample Material | Threshold (MeV) |
|---|---|---|
| $^{32}S-^{32}P$ | Sulphur powder or pellets | 3 |
| $^{27}Al-^{27}Mg$ | Aluminium discs or pellets | 3 |
| $^{27}Al-^{24}Na$ | Aluminium discs or pellets | 6 |
| $^{27}Al-^{22}Na$ | Aluminium discs or pellets | 35 |
| $^{27}Al-^{18}F$ | Aluminium discs or pellets | 35 |
| $^{19}F-^{18}F$ | Teflon cylinders | 12 |
| $^{12}C-^{11}C$ | Polyethylene cylinders or Plastic scintillators | 20 |
| $^{12}C-^{7}Be$ | Polyethylene cylinders or Plastic scintillators | 35 |
| Bi-fission | Fission chamber | 50 |

Table 4

Ratio of the Apparent Dose Equivalent to
the Dose Equivalent of Neutrons
Below 20 MeV for Different Accelerator Spectra

| Spectrum | Andersson-Braun Counter | 7-in. Moderated Indium |
|---|---|---|
| 1/E | 1.40 | 1.03 |
| RT | 1.54 | 0.32 |
| PSB | 1.37 | 0.74 |
| BEV | 1.38 | 0.76 |
| X2 | 1.67 | 0.92 |
| P1 | 1.14 | 1.25 |
| PLA | 1.10 | 1.18 |
| CR | 1.29 | 0.84 |
| O'B | 2.09 | 0.50 |

Table 5

CERN and RL Detector Responses and Dose Equivalent Rates Calculated for Different Spectra

| Spectrum | Detector Responses | | | Dose Equivalent Rates ($\mu Sv.h^{-1}$) | | |
|---|---|---|---|---|---|---|
| | Andersson-Braun Counter (counts $s^{-1}$) | $\phi_{In}$ ($m^{-2}s^{-1}$)* | $\phi_{C}$ ($m^{-2}s^{-1}$)* | CERN | RL | $H_{10}$ |
| 1/E | 88.9 | 0.43 | 0.21 | 53 | 61 | 68 |
| RT | 20.1 | 0.28 | 0.70 | 142 | 138 | 143 |
| PSB | 11.9 | 0.43 | 0.26 | 69 | 69 | 67 |
| BEV | 15.5 | 0.57 | 0.27 | 82 | 78 | 81 |
| X2 | 9.4 | 0.34 | 0.33 | 67 | 77 | 77 |
| CR | 18.4 | 0.80 | 0.08 | 74 | 54 | 66 |
| P1 | 5.2 | 0.39 | 0.03 | 22 | 26 | 21 |
| PLA | 6.3 | 0.46 | 0.02 | 25 | 29 | 25 |
| O'B | 18.8 | 0.30 | 0.81 | 148 | 159 | 103 |

Total flux density is normalized to $10^{6}m^{-2}s^{-1}$.

*Values must be multiplied by $10^{6}$.

Table 6

Ratio of Apparent Dose Equivalent From Neutrons
E < 20 MeV to That From Neutrons E ≥ 20 MeV

| Spectrum | Ratio Determined | | True Ratio |
|---|---|---|---|
| | CERN | RL | |
| 1/E | 1.5 | 0.6 | 0.5 |
| RT | 1.0 | 0.1 | 0.4 |
| PSB | 1.6 | 0.5 | 0.8 |
| BEV | 2.1 | 0.7 | 0.9 |
| X2 | 1.0 | 0.3 | 0.3 |
| CR | 8.8 | 3.0 | 4.1 |
| P1 | 6.5 | 3.9 | 3.8 |
| PLA | 10.4 | 6.6 | 5.2 |
| O'B | 0.8 | 0.1 | 0.3 |

Table 7

CERN 1975 Dose Equivalent Intercomparison Data

| Radiation Field | Detector System: Cerberus H rate* | Cerberus Q | REM2 H rate* | REM2 Q | BNL H rate* | BNL Q |
|---|---|---|---|---|---|---|
| A. Muons important | | | | | | |
| (a) Experimental area | 17 | 1.7 | 14 | 2.1 | 17 | 1.7 |
| (b) End stop | 30 | 1.5 | 22 | 1.5 | 31 | 1.4 |
| B. Intermediate and fast neutrons important | | | | | | |
| (a) Labyrinth | 230 | 3.4 | 150 | 3.4 | 220 | 4.6 |
| (b) Normal shielding | 320 | 6.1 | 220 | 7.5 | 240 | 4.2 |
| (c) Linac area | 450 | 8.6 | 330 | 9.7 | 350 | 7.6 |
| C. High-Energy Cascade Important | | | | | | |
| (a) Lateral shield | 380 | 4.0 | 300 | 5.6 | 470 | 4.5 |
| (b) Lateral shield | 180 | 4.6 | 120 | 5.1 | 220 | 4.6 |

*Dose equivalent rates in $\mu Sv.h^{-1}$

Table 8

Simplified Summary of Serpukhov
Dose Equivalent Intercomparison Data

| Method | Dose Equivalent (nSv) | QF |
|---|---|---|
| A. Muons dominate dose equivalent | | |
| KM-1 ($^{103}$Rh) | 67 ± 6 | 1.1 ± 0.2 |
| KM-2 ($^{103}$Rh) | 66 ± 9 | 1.2 ± 0.2 |
| Cerberus | 53 ± 3 | 1.0 ± 0.1 |
| LET spectrometer | 65 ± 6 | 1.2 ± 0.1 |
| B. Intermediate and fast neutrons dominate dose equivalent | | |
| KM-1 (SNMO-5) | 390 ± 30 | 3.9 ± 0.3 |
| KM-1 (SNM-3) | 210 ± 10 | 2.8 ± 0.3 |
| KM-2 (SNM-3) | 190 ± 10 | 3.5 ± 0.4 |
| Cerberus | 290 ± 20 | 6.1 ± 0.5 |
| Sukhona-2 | 180 ± 20 | 3.6 ± 0.2 |
| LET spectrometer | 110 ± 10 | 2.0 ± 0.2 |
| C. Cascade particles dominate dose equivalent | | |
| KM-1 (SNMO-5) | 340 ± 20 | 3.2 ± 0.6 |
| KM-1 (SNMO-3) | 300 ± 20 | 3.0 ± 0.3 |
| KM-2 (SNM-3) | 240 ± 20 | 3.4 ± 0.4 |
| Cerberus | 270 ± 20 | 4.2 ± 0.3 |
| Sukhona-2 | 290 ± 30 | 4.2 ± 0.4 |
| LET spectrometer | 200 ± 20 | 2.8 ± 0.3 |

List of Figures

Fig. 1. Neutron spectra measured by the Health Physics Group of the Lawrence Berkeley Laboratory in the mid-1960's (see text for the explanation of the designations PSB, RT, BEV and CR).

Fig. 2. Neutron spectra measured at the 7 GeV proton synchrotron--Nimrod--of the Rutherford Laboratory using Bonner spheres (see text for the explanation of the designations PLA, P1, X2).

Fig. 3. Neutron spectra measured at the Princeton-Pennsylvania 3 GeV proton synchrotron using Bonner spheres.

Fig. 4. O'Brien neutron spectrum.

Fig. 5. Comparison of three neutron spectra: the open circles indicate the lateral iron spectrum of Fig. 9, the solid line is the concrete spectrum of Fig. 4, and the crosses are the experimental data from Madey et al.[107]

Fig. 6. Response of the REM/N neutron dose equivalent meter as a function of neutron energy measured by groups at AERE (o), PTB (x), and CERN (□) (see text for details).

Fig. 7. Response function of 7-in.-diam. paraffin wax moderated indium foil detector.

Fig. 8. Readings of the Andersson-Braun and 7-in.-diam. moderated indium detectors in a 1/E spectrum, as a function of spectrum cut-off energy.

Fig. 9. Calculated particle spectra in lateral and forward geometry in steel. 30 GeV incident protons (see Stevenson).[54]

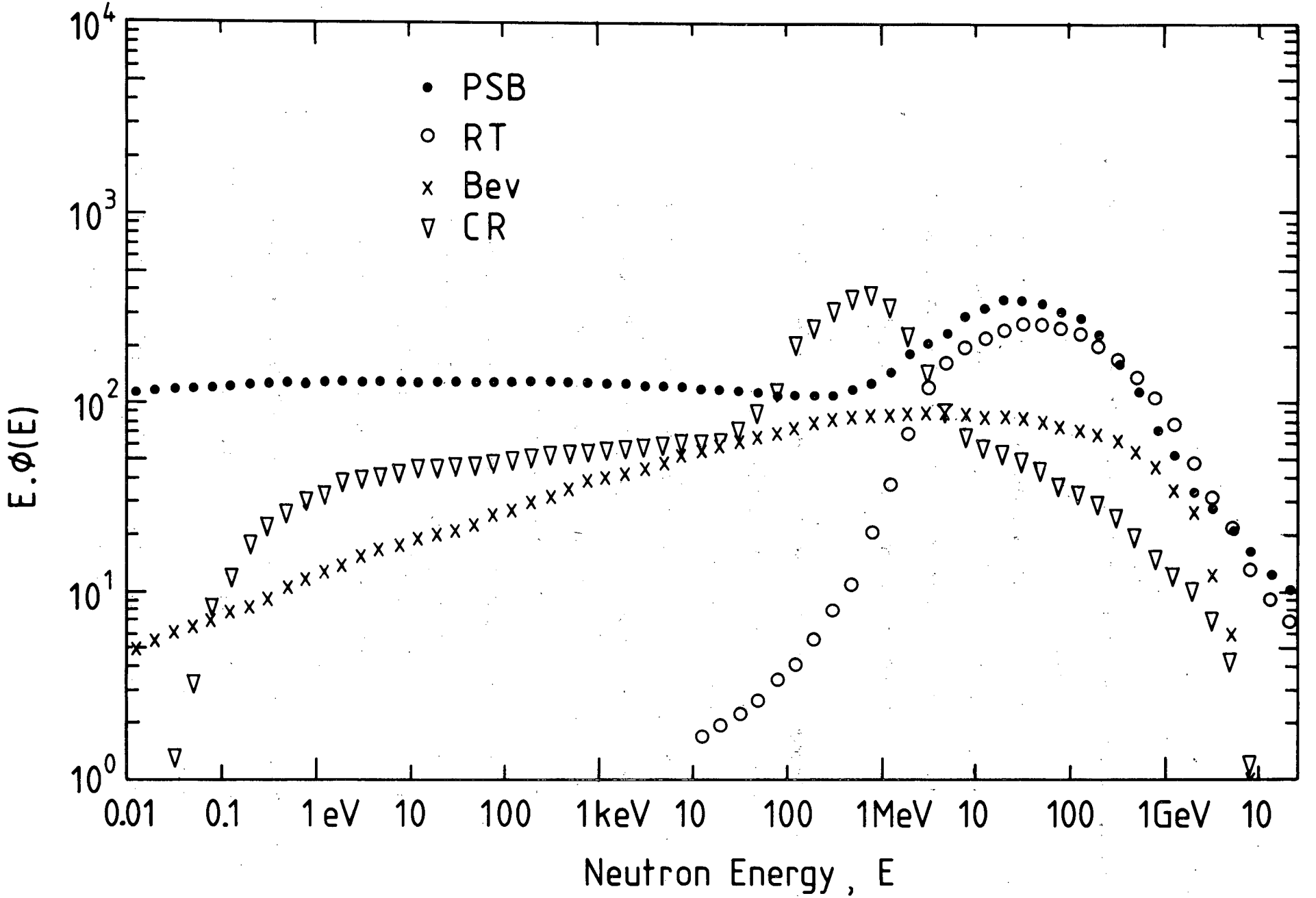

PSB
RT
Bev
CR
E.Φ(E)
Neutron Energy , E
0.01
0.1
1 eV
10
100
1keV
10
100
1MeV
10
100
1GeV
10
10^0
10^1
10^2
10^3
10^4

Fig. 1

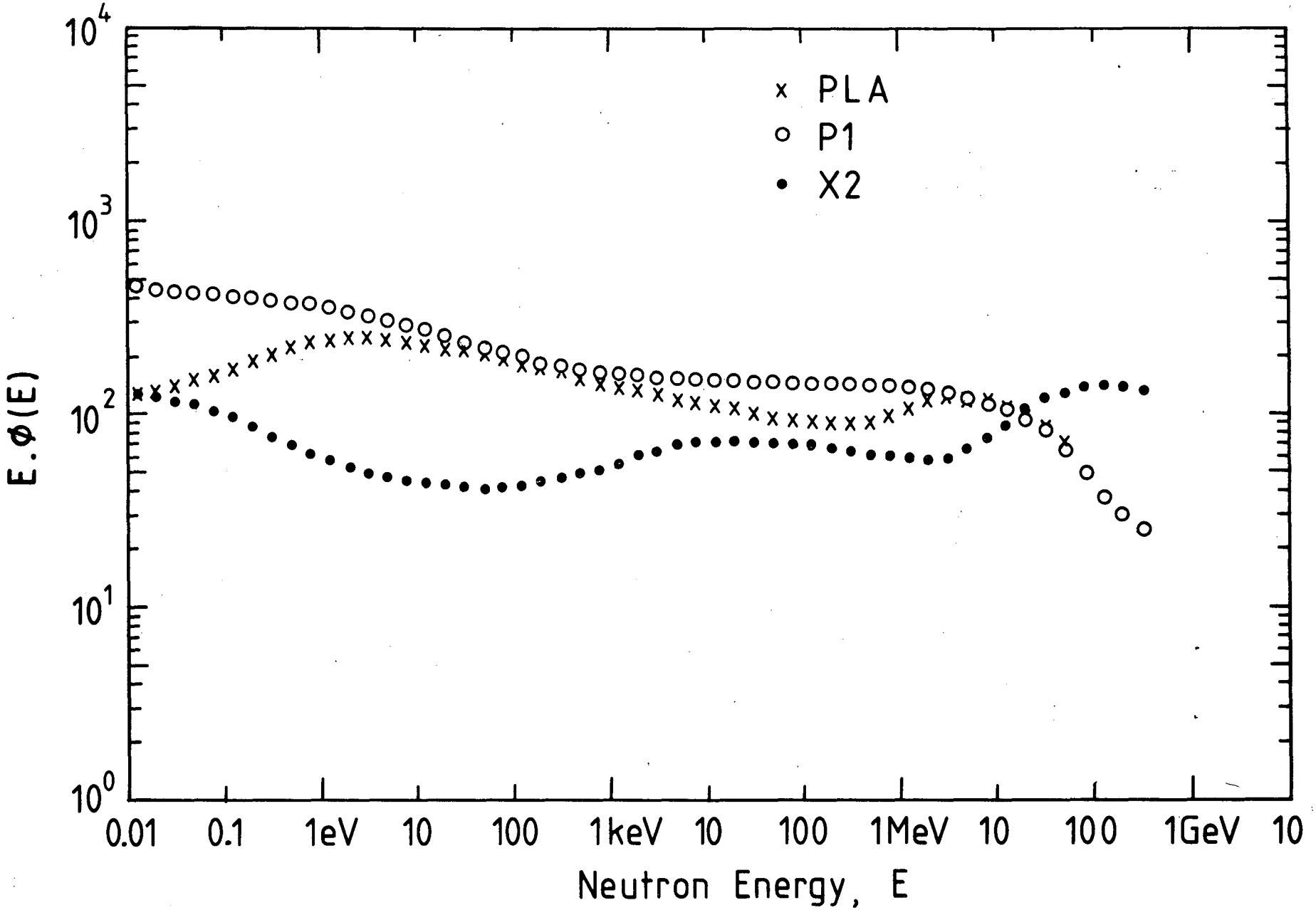
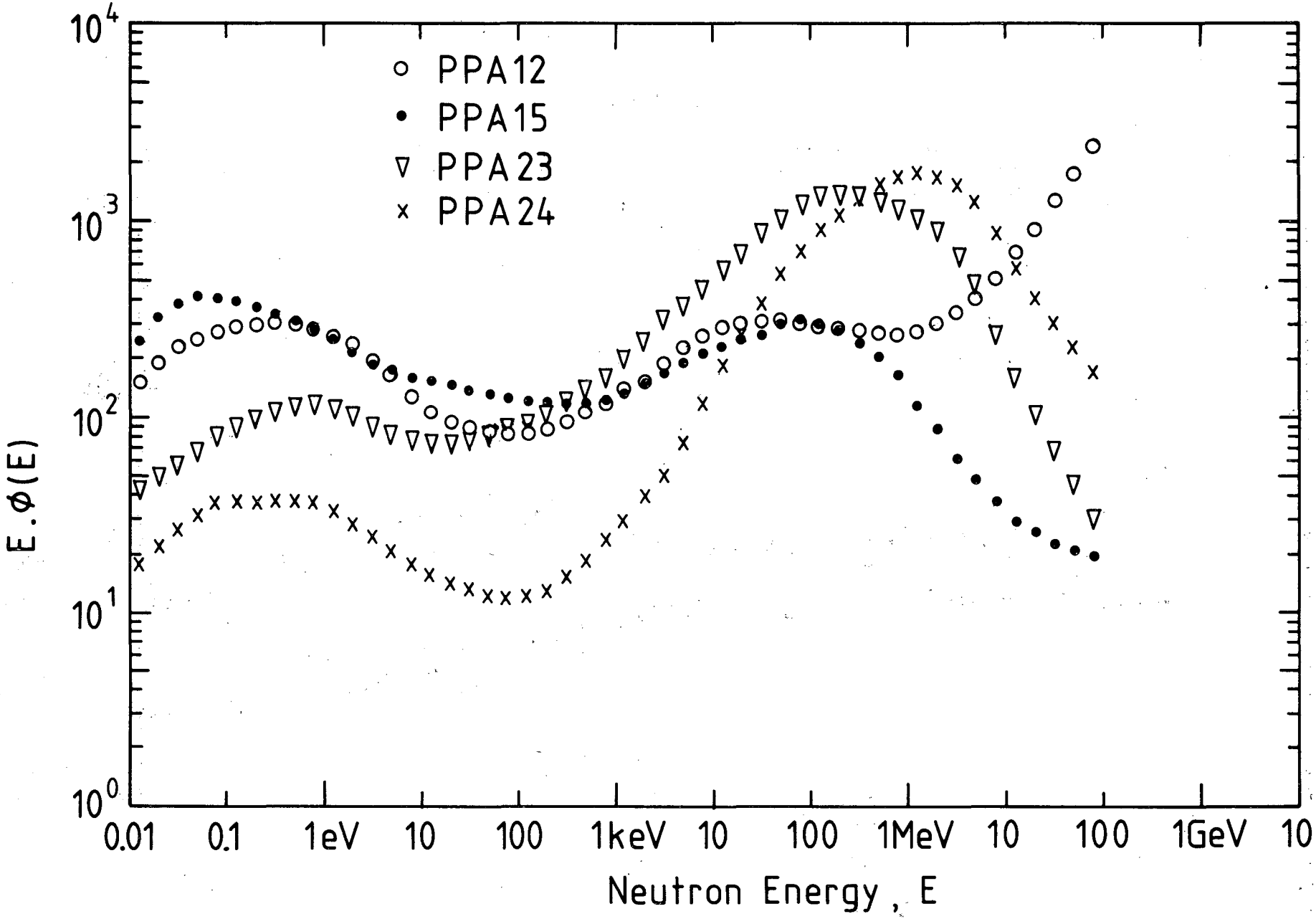

PLA
P1
X2
E.φ(E)
Neutron Energy, E
0.01
0.1
1eV
10
100
1keV
10
100
1MeV
10
100
1GeV
10
$10^0$
$10^1$
$10^2$
$10^3$
$10^4$

Fig. 2


PPA12
PPA15
PPA23
PPA24
E.Φ(E)
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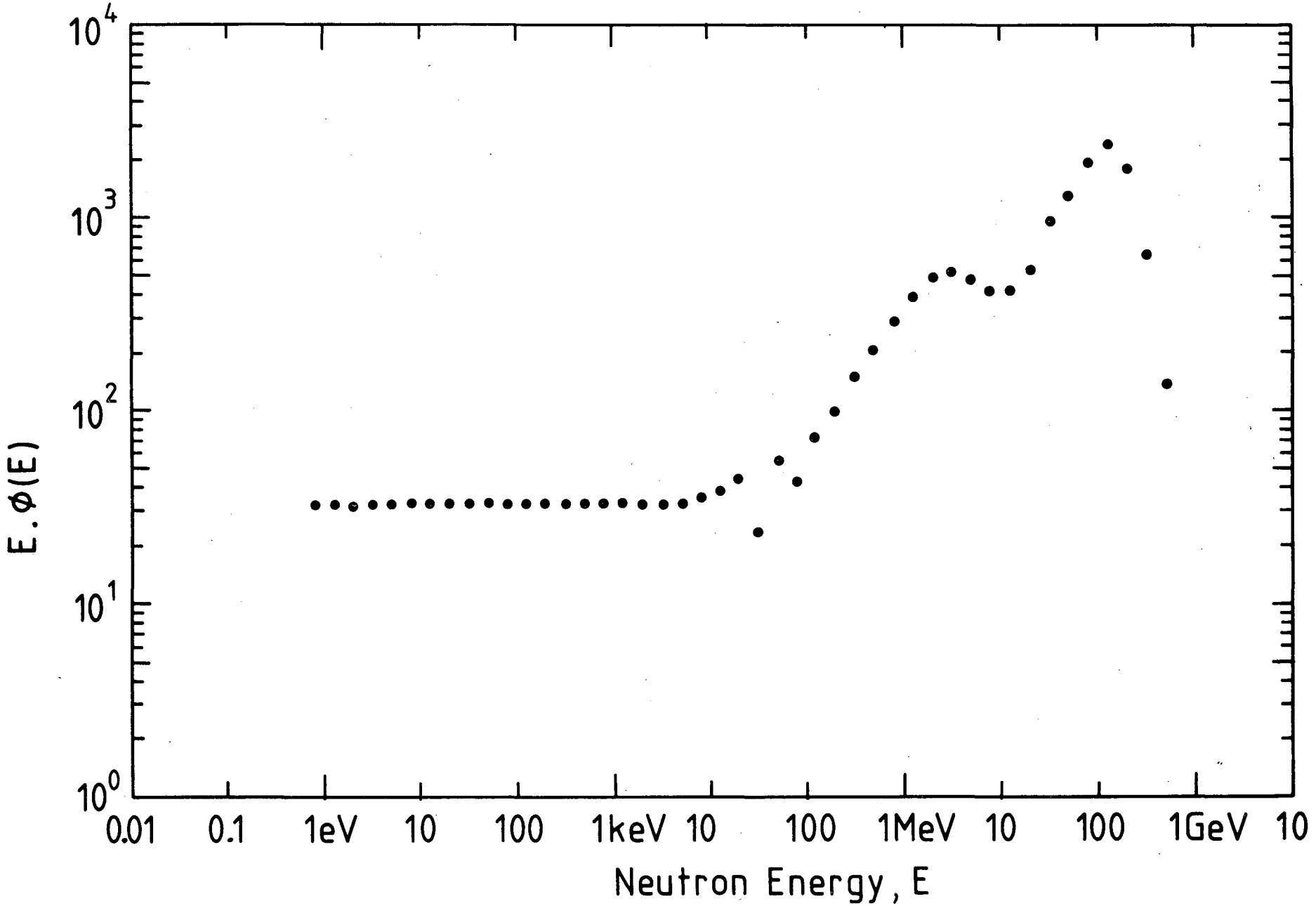
100
1keV
10
100
1MeV
10
100
1GeV
10

Fig. 3


$10^4$
$10^3$
$10^2$
$10^1$
$10^0$
E. Φ(E)
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0.1
1eV
10
100
1keV
10
100
1MeV
10
100
1GeV
10
Neutron Energy, E

Fig. 4

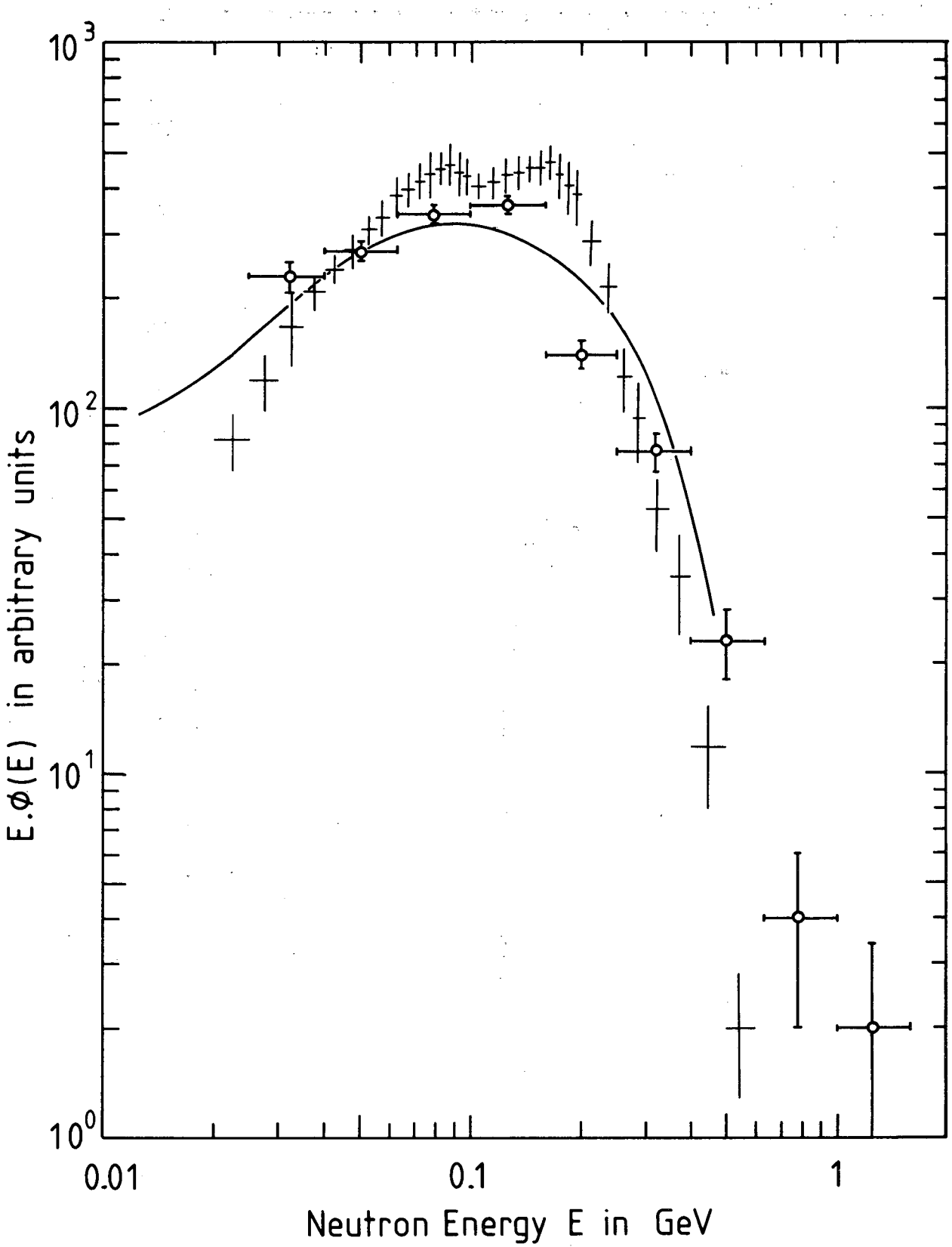

$10^3$
$10^2$
$10^1$
$10^0$
E.ϕ(E) in arbitrary units
0.01
0.1
1
Neutron Energy E in GeV

Fig. 5

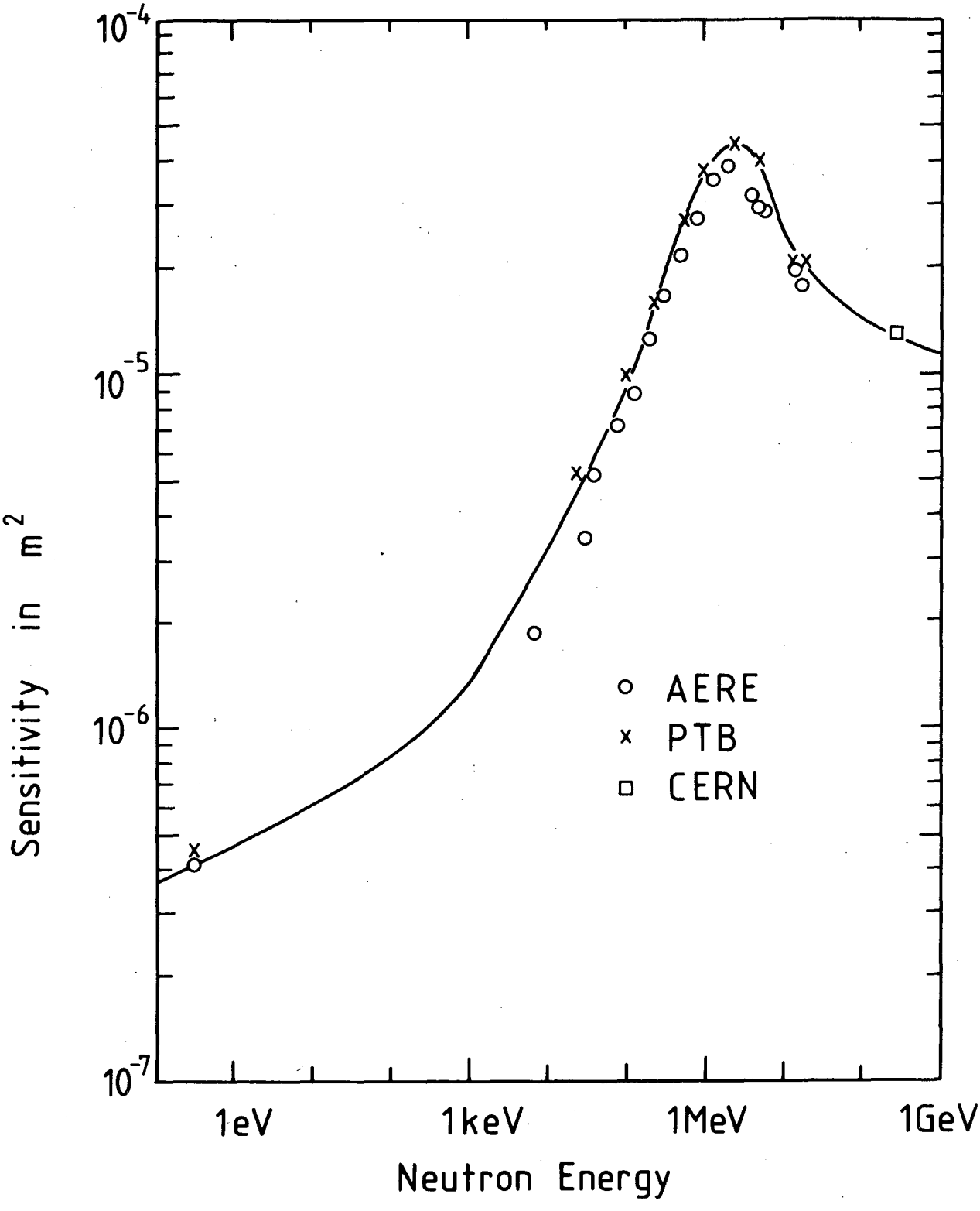

$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
Sensitivity in $m^2$
AERE
PTB
CERN
1eV
1keV
1MeV
1GeV
Neutron Energy

Fig. 6

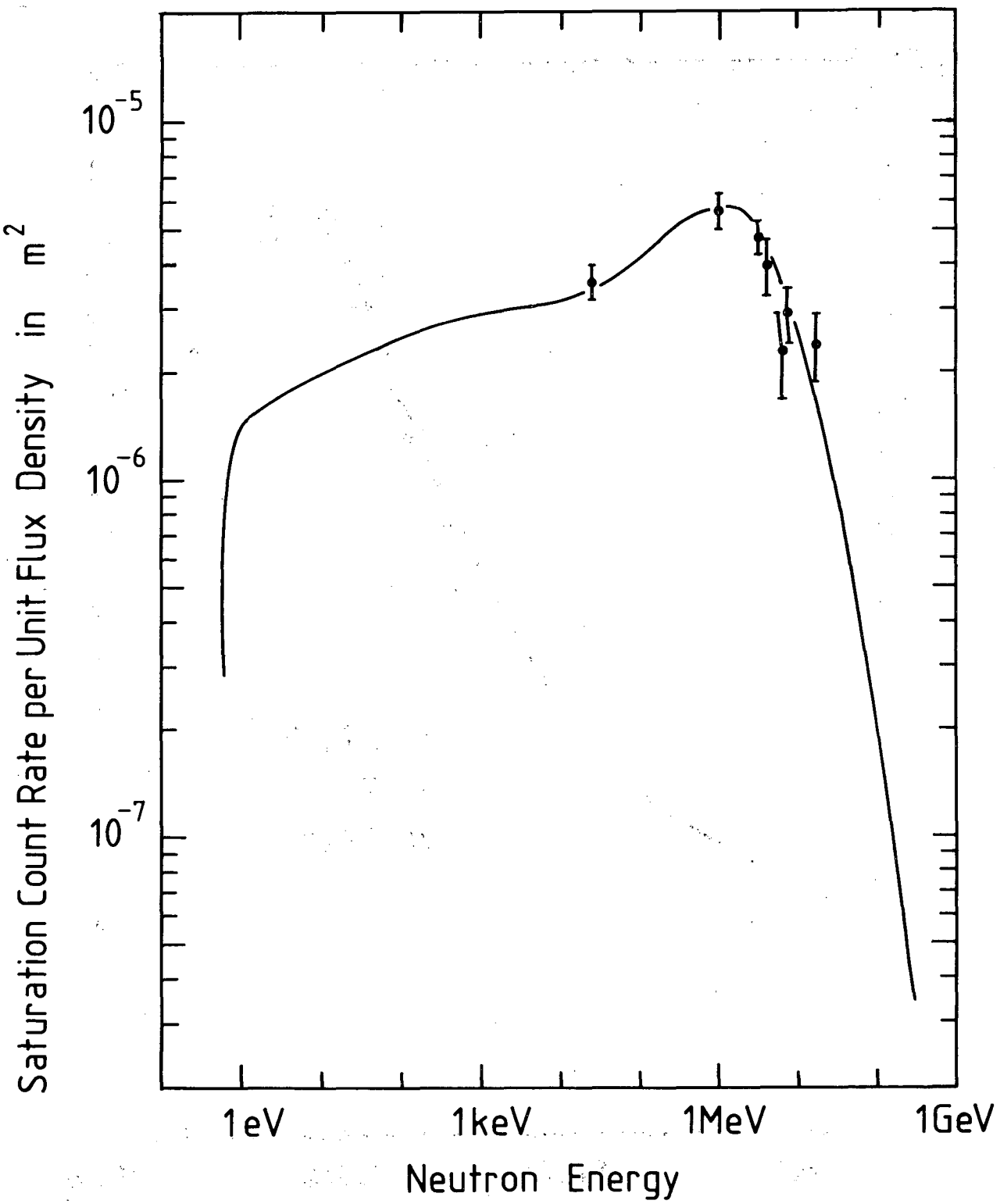
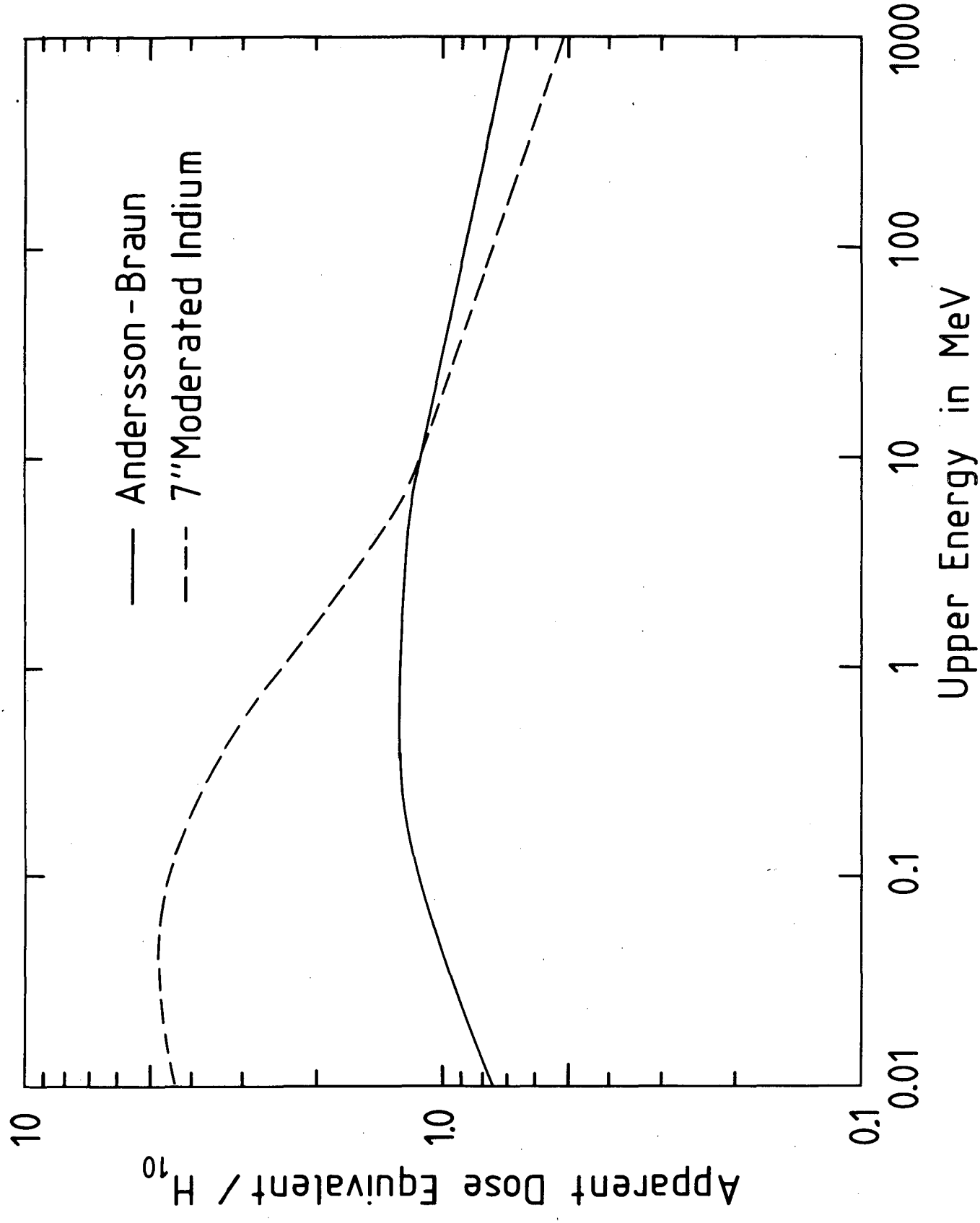

Saturation Count Rate per Unit Flux Density in m$^2$
$10^{-5}$
$10^{-6}$
$10^{-7}$
1eV
1keV
1MeV
1GeV
Neutron Energy

Fig. 7


Apparent Dose Equivalent / $H_{10}$
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0.1
0.01
0.1
1
10
100
1000
Upper Energy in MeV
Andersson-Braun
7"Moderated Indium

Fig. 8

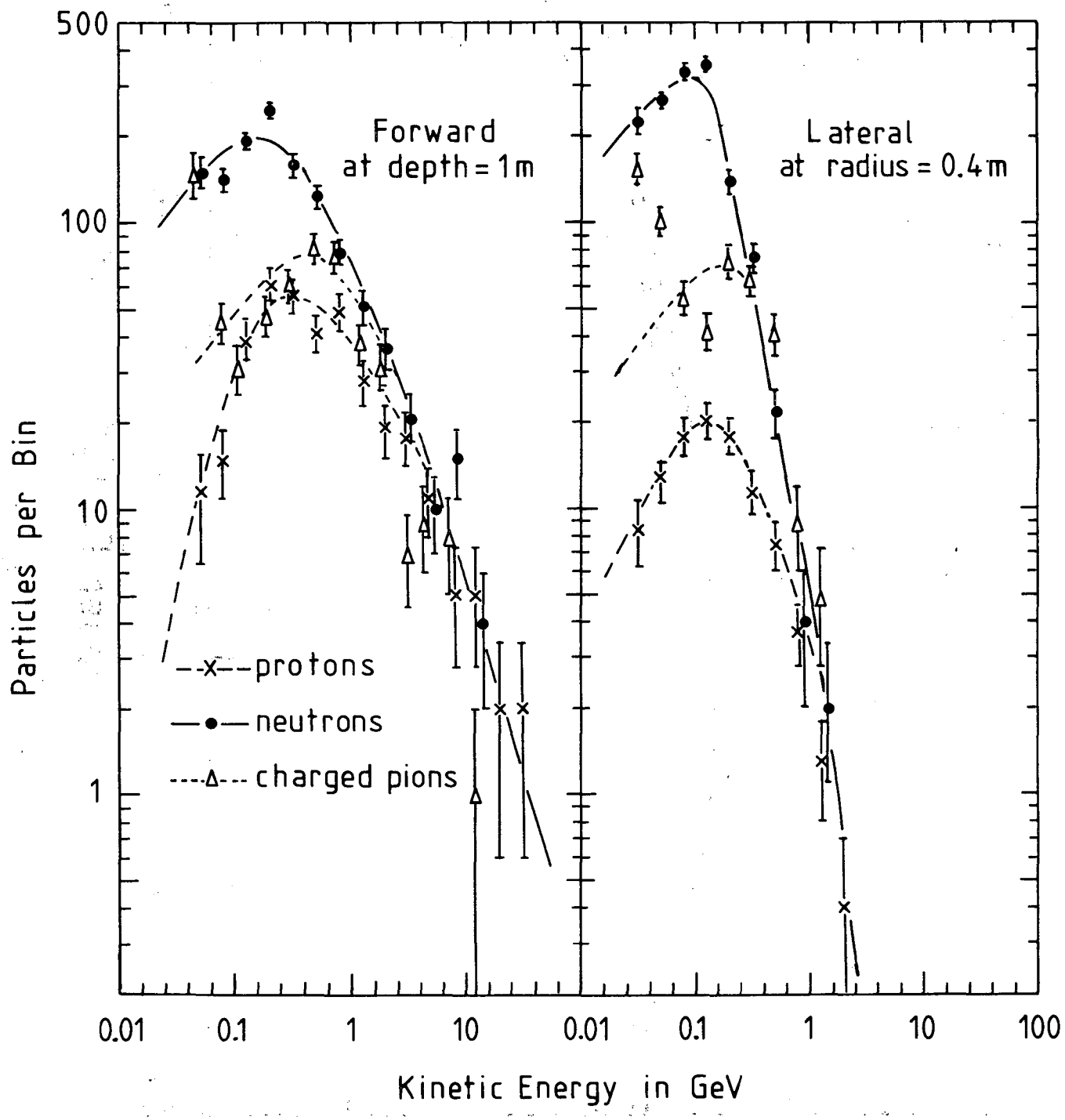
500
100
10
1
Particles per Bin
Forward
at depth = 1m
Lateral
at radius = 0.4m
protons
neutrons
charged pions
0.01
0.1
1
10
0.01
0.1
1
10
100
Kinetic Energy in GeV

Fig. 9

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