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DESY D3-77
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Fluence Spectra and Dose Equivalents of Neutrons Behind Shielding of High Energy Proton Accelerators

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Presented at the *8th International Conference on Radiation Shielding*, April 24-28, 1994, Arlington, Texas USA

ABSTRACT

Neutron fluence spectra were determined behind side shieldings of high energy proton accelerators using a set of passive detectors with a response from thermal energies up to several hundred MeV. All spectra show two peaks, one with its maximum at around 600 keV due to evaporation neutrons and another near 80 MeV originating in high energy cascade processes. Dose equivalents derived from these spectra are compared with readings of an Andersson-Braun counter and the carbon-11 activation method. Calculations with Monte Carlo codes confirm the two peaks of the fluence spectra.

I. INTRODUCTION

Neutrons are the main component of the dose equivalent behind the shielding of high energy proton accelerators. At beam energies above 1 GeV the energies of these neutrons extend from thermal energies to more than 100 MeV. Commonly used rem-meters (e. g. of the Andersson-Braun type) or methods (e. g. activation of materials such as carbon or sulphur) usually do not cover the total energy range and the measured readings have to be corrected.

To get the maximum information of a neutron field behind shielding the fluence spectrum of the neutrons has to be determined. For this reason an assembly of detectors with responses covering a wide energy range is used at DESY as a neutron spectrometer.

This spectrometer was studied extensively and used around the DESY accelerators and it was tested in a benchmark experiment at CERN in the frame of an International Collaboration. The CERN group will report on the set-up of this experiment and the collaboration at this conference.

The experimental details of the neutron spectrometer and the evaluation procedure can be found in the literature and only the most important features are repeated here.[1] Spectra are presented which are measured behind bulk shielding during normal accelerator operation at DESY as well as spectra under well defined shielding and beam conditions at CERN. The results are discussed and compared with preliminary results from Monte Carlo calculations.

II. THE NEUTRON SPECTROMETER

To determine the neutron field around a high energy accelerator we are faced with two main problems. One is the large energy range which has to be covered by detectors and the other is the problem arising with pulsed radiation. At DESY the duty cylce of the radiation field can be 10^{-6} in case of beam losses at injection, moreover short and non-repetitive beam losses can occur. Electronic devices suffer from dead time problems and are improper in such fields.

To meet these requirements we decided to use passive, integrating detectors. The assembly of detectors consists of seven polyethylene moderators of the Bonner type (with diameters 18″, 12″, 8″, 6.75″, 5″, 3″and 2″) provided with pairs of thermoluminescence detectors (TLD) ^{6}LiF/^{7}LiF in their centers. Two other detectors without moderators are added, one covered with 2 mm of cadmium. In addition, nuclear track detectors are applied to extend the response to higher neutron energies. Tracks of fission products of (n,f)-reactions on thorium and bismuth are registered in polycarbonate foils.

This spectrometer is suited for dose equivalents between 0.1 and 10 mSv and is completely independent of the dose rate. The arrangement of detectors covers the range from thermal energies up to energies above 100 MeV as may be seen in Figs. 1 and 2.

After exposure the TLDs are evaluated by a commercial reader. The polycarbonate foils are chemically etched and the tracks are registered by a spark counter. The calibration of this set-up was performed by neutrons of an Am-Be-source, the contribution of the Bi(n,f)-reaction was calculated.

The readings of the detectors are mathematically unfolded. For redundancy reasons three independent codes using different calculational methods are applied. For most evaluations the program LOUHI is used, together with a response matrix originating in works going back to 1965 and compiled in more recent publications.[2,3]

From the fluence spectra dose equivalents can be derived using conversion coefficients reported in ICRP21 or ICRP51, the latter with a suggested extension for energies above 20 MeV.[4]

III. RESULTS OF MEASUREMENTS

At **DESY** a series of measurements was performed at beam energies of 7.5 and 40 GeV behind shielding between 1 and 2.5 m of concrete (or equivalents of sand). All fluence spectra look very similar. A typical example is show in Fig. 3. The fluence is divided into 57 energy groups. For each group the number of neutrons per cm^2 and per logarithmic energy interval ("unit lethargy") is plotted in a linear scale as a function of the neutron energy. In this way an area under the curve between two energy bounds is proportional to the fluence between these bounds. The spectrum is normalized to an integral fluence of 1 neutron per cm^2.

It has to be mentioned that the widths of the peaks can be influenced by the choice of the parameters used in the unfolding procedure. The present parameters were optimized in a way that best reproductions of test spectra were obtained. The integral of a peak is not affected by variation of the parameters. In addition, the unfolding programs tend to shift a peak maximum by one or even two groups to lower energies.

Each spectrum behind concrete shielding shows two prominent peaks, a higher one at around 80 MeV and a smaller one somewhat below 1 MeV. The high energy peak is caused by cascade processes like spallation while the low energy peak is due to evaporation neutrons. The shape of the spectra is independent of beam energies and shielding thicknesses in the ranges under consideration. The relative intensities of both peaks depend on thickness and location of the source of the stray radiation. In case the position of the beam loss is far from the point of observation the evaporation peak is enhanced while measurements very close to a target give just the opposite phenomenon.

To get the spectral distribution of the dose equivalent the fluence of each energy bin has to be multiplied by the corresponding conversion coefficient. We used the set of coefficients listed in ICPR 21 giving maximum dose values in a slab of 30 cm thick tissue equivalent material (ICRP51 together with the extension of ref. 4 gives dose equivalents which differ less than 20%). The dose distribution of the sample spectrum is shown in Fig. 4. The high energy peak now is even more pronounced. A rem-meter with an upper response limit of 20 MeV would detect roughly 30% of the total dose equivalent (energy independent response assumed), whereas a carbon activation detector using the reaction $^{12}C(n,2n)^{11}C$ with a threshold at 20 MeV detects around 70%.

In 1993 we had the chance to test the method at **CERN** under well defined conditions in a special test area. A beam of high energy hadrons was directed to a copper target and the neutron field could be studied behind a side shielding of 80 cm concrete and 40 cm iron very close to the target. The monitoring of the beam allowed a normalization of fluences and dose equivalents to the number of primary particles. Fluence spectra were determined behind both shielding materials and the dose equivalents obtained from the neutron spectrometer could be compared with doses measured by an Andersson-Braun counter as well as with the ^{11}C-activation method. The results of these investigations during three experimental periods are summarized in a preliminary report.[5]

Spectra measured behind concrete and iron shielding are presented in Figs. 5 and 6, both are normalized to $2 \cdot 10^6$ primary particles of 120 GeV. The difference is evident. Behind the concrete shielding the spectrum found at DESY could be reproduced with its both peaks approximately at the same energies (Fig. 5). The spectrum behind iron looks completely different (Fig. 6). A large evaporation peak is dominating with its maximum around 400 keV. The shape appears to be slightly asymmetric and with a long tail down to 1 keV. Its intensity comprises around 80% of the total fluence (in case of concrete: 30%). The high energy peak behind 40 cm of iron equals approximately that behind 80 cm of concrete but the evaporation neutrons which are fed by these high energy neutrons cannot be absorbed in iron as well as in concrete. The well known fact that iron (without other additional material) is an improper shielding material for neutrons is confirmed.

The total dose equivalents were calculated using these spectra and were compared with the readings of the Andersson-Braun counter and of the ^{11}C-method. We found that in case of concrete shielding the AB-counter registered 42% of the total dose equivalent and the ^{11}C-method 62%. Using the fluence spectrum and the response function of an AB-counter one calculates an efficiency of 51%. Behind iron shielding the AB-counter overestimated the dose equivalent and saw 130%, the ^{11}C-method only 15%. Especially the poor efficiency behind concrete shielding documents the interest in a rem-counter with an extended energy response and people working in this field should be encouraged to continue their efforts in realization of such an instrument. Progresses in this field are subject of another report in this conference.

IV. CALCULATION OF FLUENCE SPECTRA

Since a few years there exist Monte Carlo progam systems like FLUNEV or FLUKA which simulate the hadronic cascade in arbitrary materials and geometrical configurations.[6,7] They are able to generate and transport neutrons in thick shieldings down to very low energies. These program systems were used to calculate fluence spectra for comparison with the previous measurements.

Generally it is very time consuming to follow the particles through thick material and all geometrical details of a real arrangement down to thermal energies. For a qualitative but quick valuation it appeared to be sufficient to use a generalized and simple cylindrical geometry.

Using this geometry fluence spectra behind concrete and iron were calculated and are shown in Figs. 7 and 8. The primary protons had energies of 100 GeV and hit a cylindrical iron target of 2 cm diameter and 200 cm length. Neutrons crossing the outer surface of the shielding within ± 1 m relative to the center of the target are scored. Both spectra are normalized to $1 \cdot 10^6$ primary particles. The spectra are clearly different for concrete and iron shielding and the similarity to the two corresponding spectra of Figs. 5 and 6 is evident, even if the parameters do not match completely.

Calculations modeling the geometry of the CERN experiment are still in progress. A preliminary spectrum behind concrete shielding shows two peaks at positions being nearly the same as in the measurements. The intensities of evaporation neutrons and high energy neutrons as well as dose equivalents agree with the experimentally determined values within a factor of two.

REFERENCES

1. H. Dinter, K. Tesch, "Determination of Neutron Spectra Behind Lateral Shielding of High Energy Proton Accelerators", *Rad. Prot. Dosim.* **42**, 5 (1992)

2. J. T. Routti, J. V. Sandberg, "General Purpose Unfolding Program LOUHI78 with Linear and Nonlinear Regularizations", *Comp. Physics Communication*, **21**, 119 (1980)

3. A. V. Alevra, B. R. L. Siebert, "Influence of Neutron Spectra and Fluence Response Data on the Determination of Dose Equivalent with Bonner Spheres", Physikalisch Technische Bundesanstalt, Braunschweig, Germany, *PTB-Bericht*, PTB-ND-28 (1986)

4. G. R. Stevenson, "Dose Equivalent per Star in Hadron Cascade Calculations", CERN, Divisional report TIS-RP/173 (1986)

5. H. Dinter, B. Racky, K. Tesch, "Measurements of Spectra and Dose Equivalents of High Energy Neutrons Behind Shielding", Laborbericht DESY D3-83 (1993)

6. J. M. Zazula, "User's Guide for FLUNEV code: An Extension of the FLUKA Hadronic Shower Code to Calculate Production and Transport of Secondary Neutrons Below 50 MeV", Internal Report DESY D3-66 (1990)

7. A. Fassò, A. Ferrari, J. Ranft, P. R. Sala, G. R. Stevenson, J. M. Zazula, "A Comparison of FLUKA Simulations with Measurements of Fluence and Dose in Calorimeter Structures", CERN/TIS-RP/93-2/PP (1993)

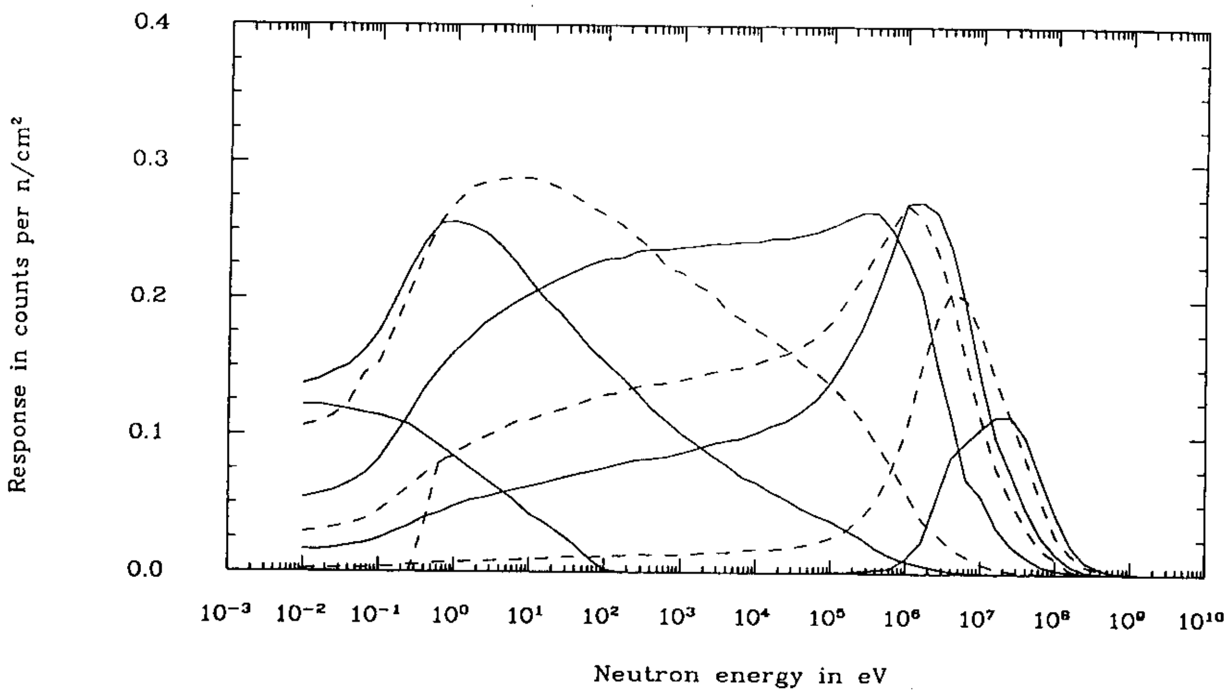

Fig.1 Response functions for the Bonner spheres used for the measurements.

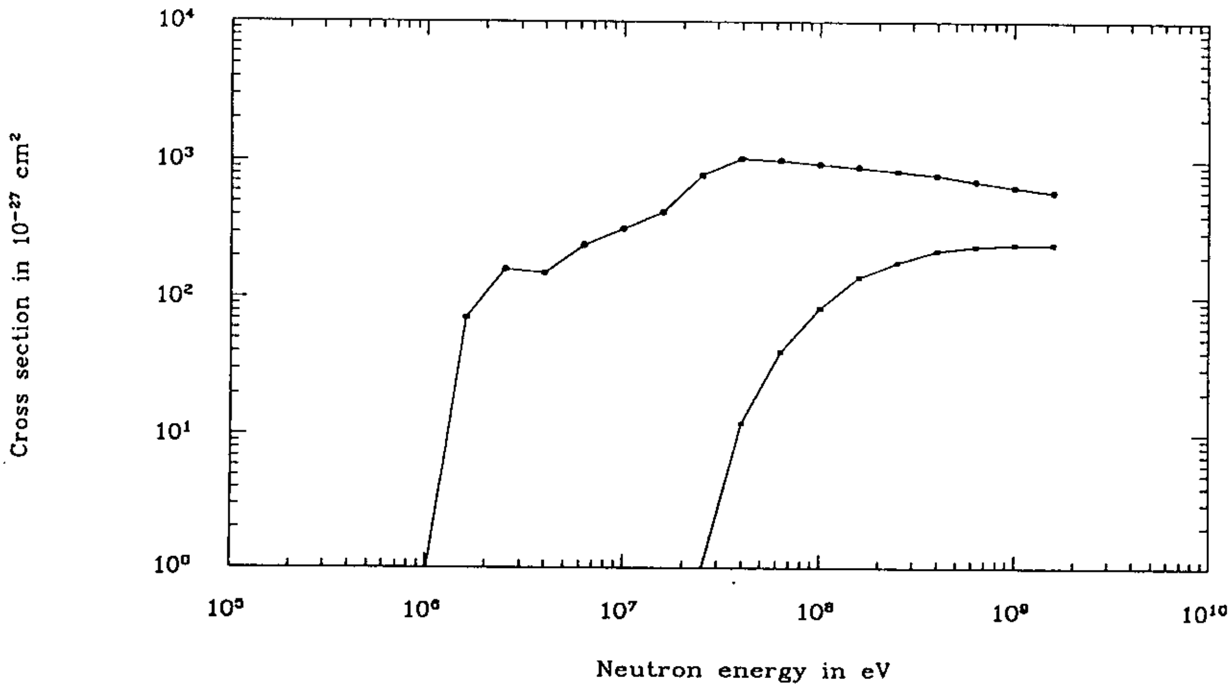

Fig.2 Cross sections of the reactions ^{232}Th(n,f) (upper curve) and ^{209}Bi(n,f) (lower curve)

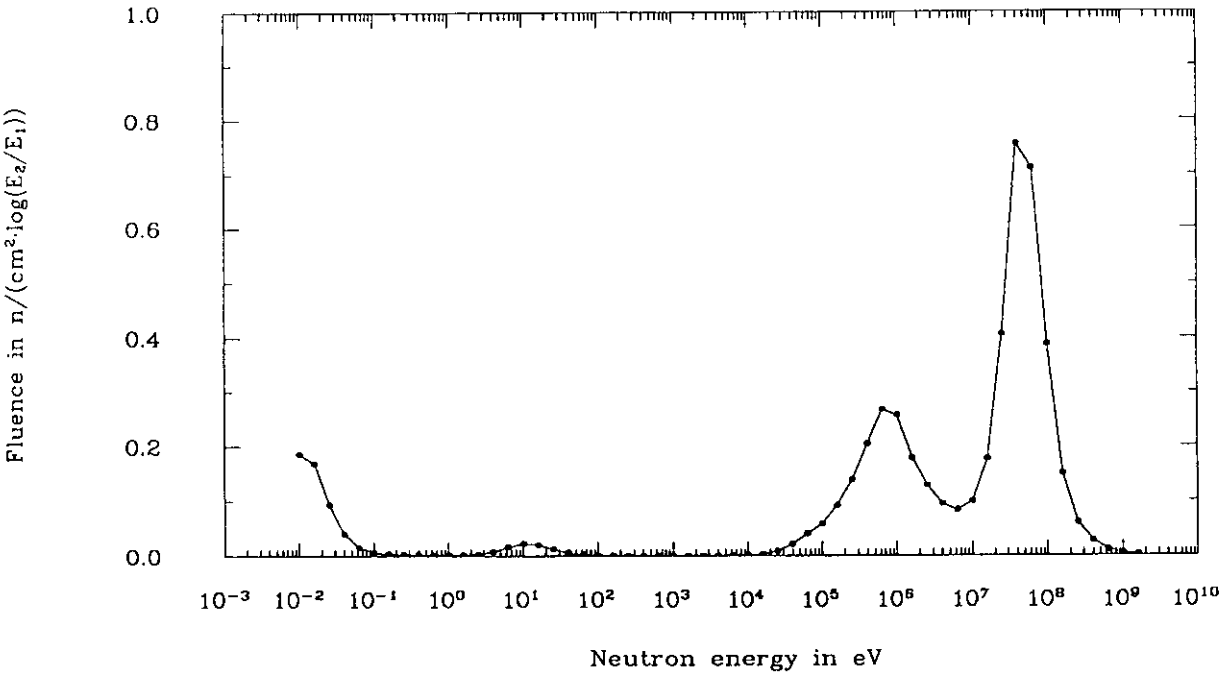

Fig.3 Fluence spectrum obtained at DESY behind 2.5 m of Sand.
Normalized to a total fluence of 1 n/cm^2.

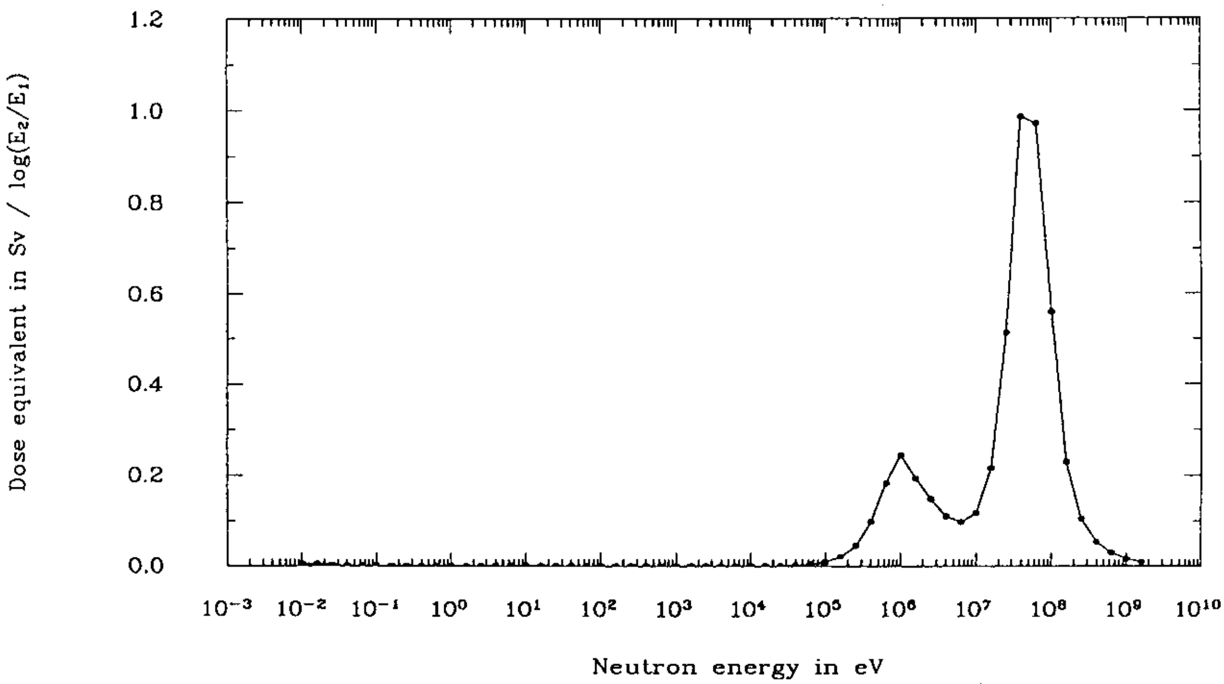

Fig.4 Spectrum of dose equivalent of the fluence spectrum Fig.3.
Normalized to a dose equivalent of 1 Sv.

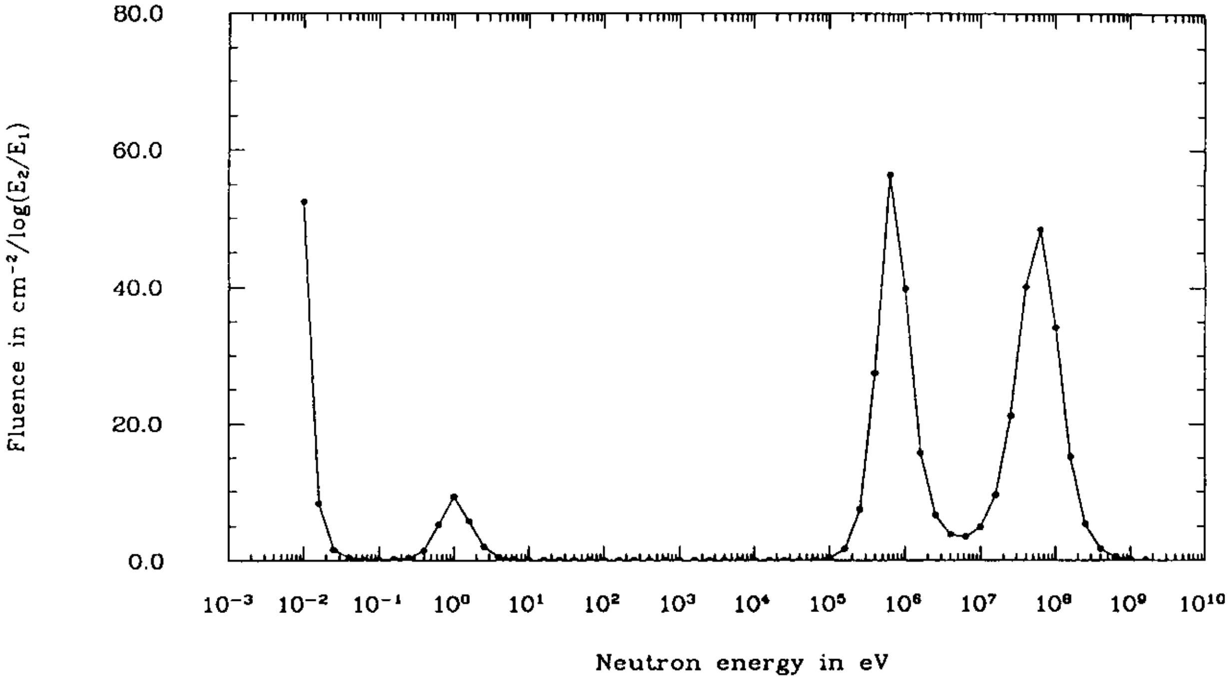

Fig.5 Fluence spectrum measured at CERN behind 80 cm of concrete at 120 GeV. Normalized to $2 \cdot 10^{6}$ primary particles.

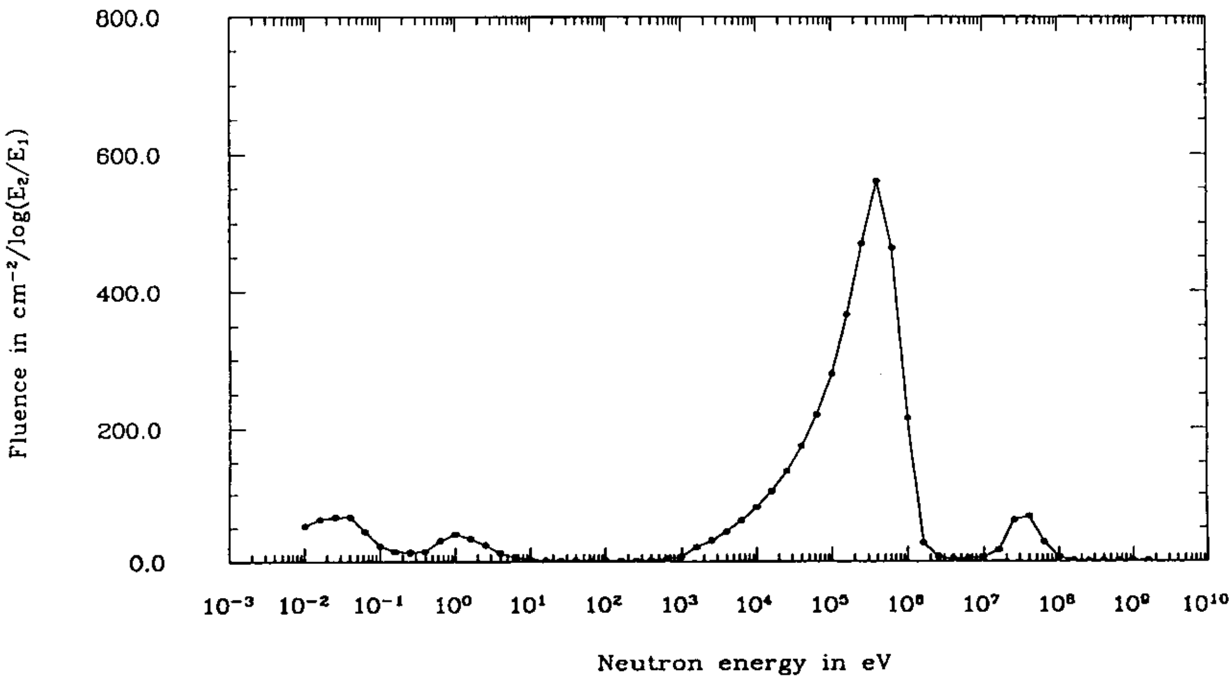

Fig.6 Fluence spectrum measured at CERN behind 40 cm of iron at 120 GeV. Normalized to $2 \cdot 10^{6}$ primary particles.

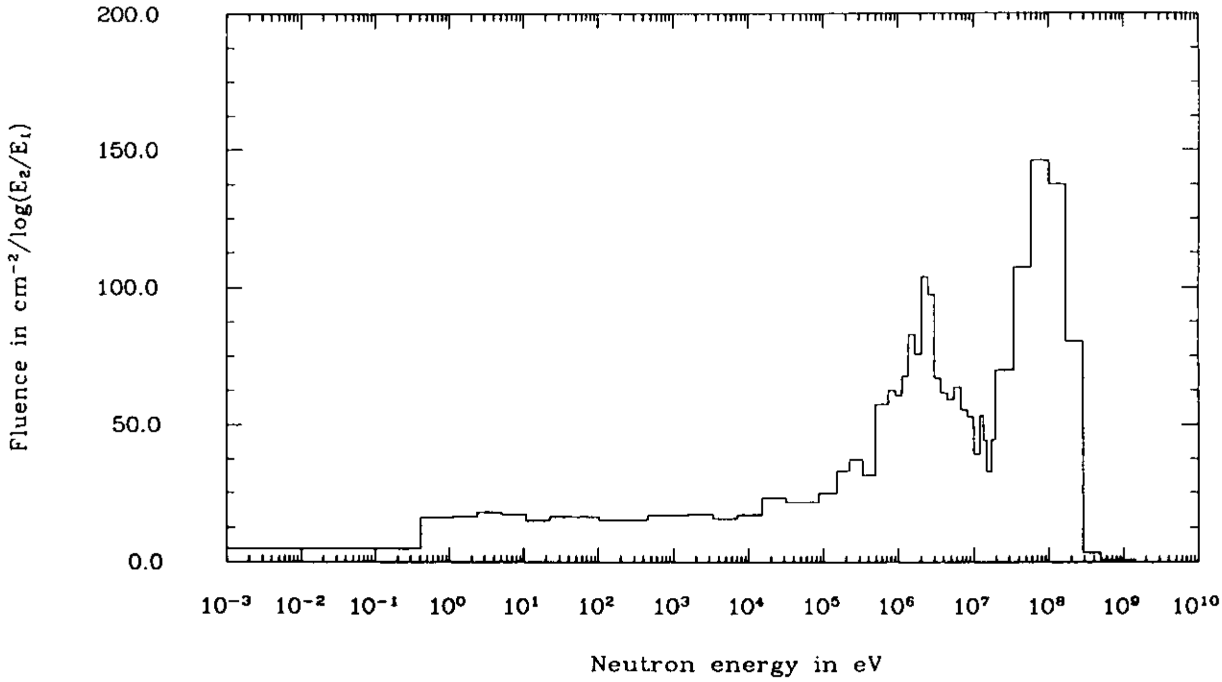

Fig.7 Fluence spectrum calculated for 60 cm of concrete at 100 GeV. Normalized to $1 \cdot 10^6$ primary protons.

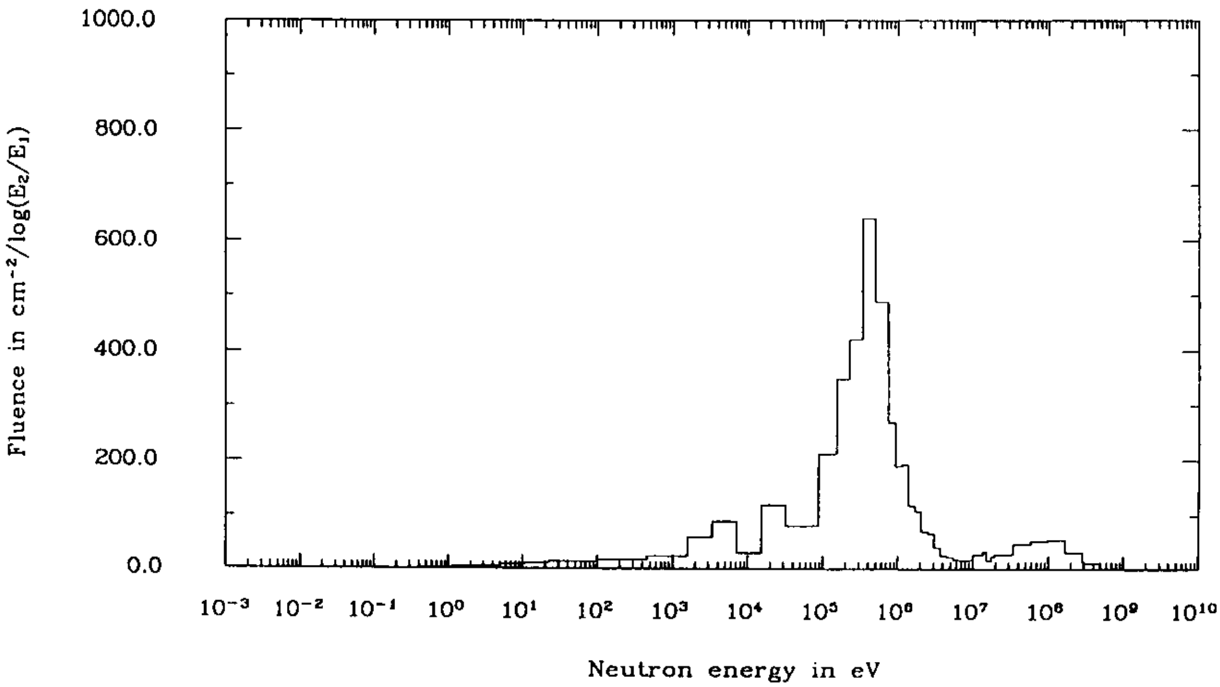

Fig.8 Fluence spectrum calculated for 30 cm of iron at 100 GeV. Normalized to $1 \cdot 10^6$ primary protons.