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Evaluation of Bulk Shield for the JHP Facilities

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ABSTRACT

In the Japanese Hadron Project(JHP), a 1-GeV 200-μA proton beam will be handled, and the radiation shield of the facility will be very massive concrete and iron lump. Since the constructing cost is strongly affected by the shielding design, the design must be severely performed.

The neutron yield in thin targets and a copper beam dump was calculated by the HETC-KFA-2 Monte Carlo code. For the evaluation of the calculational accuracy, the calculational results were compared with the experimental data by Cierjacks and Raupp. The calculated result of heavy element agreed well with the experiment at a low energy region, E_n<10 MeV. The calculated angular distribution of high energy neutrons, however, have stronger forwardness than the measurement. The measured neutron yield (E_n>100 MeV) of 90 deg close to the calculated one of about 60 deg in the absolute value.

The high energy neutron transport in a 5-m-thick iron slab and in an 8-m-thick ordinary concrete slab was calculated with the HETC code and also with the discrete ordinates transport code, ANISN. In the ANISN calculation, the DLC-87/HILO and the DLC-128/LAHIMAC group cross sections were used. The ANISN calculation with the LAHIMAC cross sections gave strong underestimation compared with the HETC calculation. The difference of the shielding lengths calculated by the HETC code and by the ANISN code used with the HILO cross sections was smaller than 6% for the both iron and concrete cases.

I. INTRODUCTION

High energy neutron deep penetration is an old problem, but still a problem today for an accelerator shielding. The Moyer model is very useful for a rough shielding design of a high energy accelerator facility. This model essentially consists of two parameters, that is, the initial dose rate at the inside of an shield (H_0) and the shielding length(λ). These parameters have been measured at several accelerator facilities of GeV energy regions, but have not been constricted. For example, the CERN-LBL-Rutherford collaborative work gave the values of H_0 and λ as 2.3×10^{-13} [Sv m^2 GeV^{-1}] and 120 [g cm^{-2}]

for ordinary concrete from an experiment made at the CERN 13.7 GeV proton synchrotron. On the other hand, the KEK group gave these values as 0.88×10^{-13} and 143 for ordinary concrete. The Japanese Hadron Project (JHP) intends to handle a 1-GeV 200μA proton beam. Using the Moyer model, a necessary thickness of a shielding concrete surrounding a beam dump can be estimated. If the data of CERN-LBL-Rutherford collaboration are used, a 9.27 m thick concrete shield is expected to reduce the dose equivalent rate at the shield surface to 6μSv/h, which is a limit of Japanese law for a radiation uncontrolled area. A value of 10.16 m, however, is obtained when the KEK values are used. A 90 cm thick concrete shield reduces the dose level about one decade. If the dose rate is ten times larger than the expected level, an investment for the additional shield will be remarkable. If the situation is inverse, the lost money is not small. The affair is extremely severe for a spallation neutron source, because to reinforce the shield is very difficult and a redundant shield reduces the usable neutron intensity.

The intra-nuclear-cascade-evaporation Monte Carlo code, HETC-KFA-2, in the HERMES code system,[1] is a very powerful tool for the evaluation of the secondary neutron production by light particles and also of their penetration through a shield. The discrete-ordinates Sn transportation code, ANISN, is also very useful for an accelerator shielding design because of its short calculational time on a deep penetration problem. In this work the calculational accuracy of these codes is evaluated by comparing the calculations with each other and with experiments.

II. NEUTRON YIELD AT THIN TARGETS

Cierjacks et al.[2] measured double differential neutron production cross sections of C, Al, Fe, Nb, In, Ta, Pb, and U elements using 585 MeV protons from the SIN cyclotron. Their data are very good for a benchmark calculation of the HETC-KFA-2 Monte Carlo code. Neutron production cross sections of C, Al, Fe, In, and Pb for 585 MeV protons were calculated by the HETC code under the following condition.

Table 1 Calculational conditions for neutron yield estimation at thin targets.

Element	Density	Thickness	Atomic Densities	Number of Histories
^{6}C	2.20 g/cm^3	5.40 mm	^{12}C : 1.10×10^{23} /cm^3	8.0×10^6
^{13}Al	2.71	5.58	^{27}Al : 6.05×10^{22}	8.0×10^6
^{26}Fe	7.86	3.93	^{54}Fe : 4.92×10^{21}	5.3×10^6
			^{56}Fe : 7.99×10^{22}	
^{49}In	7.31	5.13	^{113}In : 1.65×10^{21}	4.4×10^6
			^{115}In : 3.67×10^{22}	
^{82}Pb	11.34	4.40	^{206}Pb : 8.42×10^{21}	3.5×10^6
			^{207}Pb : 7.29×10^{21}	
			^{208}Pb : 1.73×10^{22}	

The non-isotropic evaporation option was selected for the calculation of C and Al, and the high energy fission option was selected for the other elements. The in-core neutron yield analysis were performed with an angular bin structure of a 20 degree interval between 0 and 180 deg.

The calculational results of the C, Fe and Pb double differential cross sections are shown in Figs. 1, 2 and 3 in small marks connected by straight lines, and the experimental data of Cierjacks are also shown in big marks. The Cierjacks' 90 deg data, for example, are shown in big open triangles, and the corresponding calculational results of neutron emission between 80 and 100 deg are also shown in solid triangles of which size is small. A low energy neutron yield for Pb element, E_n<10 MeV, shows good agreement between calculation and measurement. Since the sum of calculated neutron yield below 1 MeV is marked at 1 MeV, the calculational results are larger than the experiment at 1 MeV. For the carbon target, the difference at the low energy region is especially large for the data of 30 deg. In the 90 and 150 deg experimental data of carbon, there is a rapid decrease at about 4 MeV followed by a small bump at 7 MeV. The spectral tendency is much different for C element between the calculation and the experiment while it is in good agreement for Pb and Fe elements.

The experimental data have larger values at a high energy region, E_n>100 MeV, than the calculation in general, and the experimental spectrum is similar to the calculational one of more forward direction, that is, the experimental spectrum of high energy region at 90 deg is similar to the calculational one of between 60 deg and 80 deg.

Angular distributions of neutron yield are shown in Fig. 4 for C, Al, Fe, In and Pb elements. A high energy neutron emission distribution, E_n>100 MeV, is represented with small solid triangles connected with straight lines for the calculation, and with big open triangles for the measurements. In the same manner, squares are for the neutrons of medium energy between 100 MeV and 10 MeV, and circles are for low energy neutrons below 10 MeV. The distribution of low energy neutrons is very flat for all elements. The agreement between calculation and experiment is good for low and medium energies. The calculation gave an under estimation at 90 deg and 150 deg for high energy neutrons. The measured neutron yields at 90 deg and 150 deg are similar to the calculations at about 70 deg and 100 deg, respectively. For the lateral shielding design of a target station, the high energy neutron yield at 90 deg is the most important data. From the above consideration, the calculational neutron yield at 60 deg can be conservatively used as the source data of a shielding calculation at lateral direction.

III. NEUTRON YIELD AT THICK TARGETS

Raupp et al[3], measured neutrons produced by bombardment of 590 MeV protons on a thick uranium target. Their double differential neutron yields are very useful for a benchmark calculation of the HETC-KFA-2 code. They used a 10 cm by 10 cm by 40 cm uranium target, and measured neutron spectra at 30 deg, 90 deg and 150 deg with TOF method. A neutron yield in the whole target was estimated by them and shown in Fig. 5 with large open marks. A HETC-KFA-2 calculation was performed in a similar geometry, and the results are shown in Fig. 5 with small marks connected with lines. At a low energy region, the experiment and the calculation show good agreement for emission angles of 90 deg and 150 deg. Considering the data of Figs. 1, 2 and 3, the absolute value of the experiment at 30 deg seems to have some errors. The calculation also reproduces high energy neutron spectra which agree well with the experimental data of 90 and 150 deg when the angular biasing mentioned in the previous section is introduced.

IV. NEUTRON DEEP PENETRATION

1)HETC Calculation

A neutron deep penetration was estimated by the HETC-KFA-2 code for an 8 m thick ordinary concrete slab and for a 5 m thick iron slab. The neutron sources of these calculation were derived from a HETC-KFA-2 calculation performed with a 10 cm diam by 60 cm long copper beam dump bombarded by 1 GeV protons. The neutron yields between 0 deg and 10 deg and between 50 deg and 70 deg were selected for the source. The latter angular interval is selected as the source for a lateral shield.

Since the neutrons attenuate by several decades with these thick shields, a Monte Carlo calculation in a whole slab is nonrealistic. The calculation was divided into 1 m slabs, that is, a 1-m-thick slab calculation was performed with the source neutrons which normally hit the center of the slab, and the secondary calculation in the next 1-m-thick slab was performed with the source term of neutrons, protons and negative pions which escaped from the back surface of the previous slab. For incorporating the back scattering particles, the slabs were overlapped by 40 cm, that is, a thickness of the 1st slab was actually 140 cm and that of the succeeding slabs was 180 cm. A slab was divided into 4 regions of 25 cm thicknesses, and the neutron flux was evaluated by the track length estimator at each region. Since the lower cutoff energy of neutrons was set at 14.9 MeV, neutron spectra were obtained above 14.9 MeV. The transmission of neutrons, protons and negative pions were considered at the interface between slabs. The contribution of protons was found to be about 2% increase of the neutron flux at the next interface, and that of negative pions was much less. The effect of 40 cm overlapping gives only 0.4% increase. The calculation was performed with 100000 histories for each slab, and the cpu time was about 30 minutes on a FACOM-M780 computer.

2)ANISN Calculation

A deterministic radiation transport code, ANISN, is made on a one dimensional discrete ordinates methods. This code can perform a deep penetration calculation in much shorter time than a Monte Carlo code.

Using the same source of neutron yield in the copper beam dump bombarded by 1 GeV protons, high energy neutron penetrations through an 8 m thick ordinary concrete slab and a 5 m thick iron slab of infinite lateral size were calculated by the ANISN code with the DLC-87/HILO and DLC-128/LAHIMAC group cross sections. These neutron and gamma coupled group cross sections have neutron energy structures of from thermal to 400 MeV for HILO and from thermal to 800 MeV for LAHIMAC. The order of the Legendre expansion is P_5 and P_3 for HILO and LAHIMAC, respectively.

The ANISN shell source was placed at the left surface of the slab geometry. An S_{32} angular quadrature set was used, and the source was entered at the 33rd angle in order to simulate normal injection. Calculations were performed with sources of all the 8 directions. The source spreads up to 1 GeV, and the neutrons with energies above the upper limit of the group cross sections were treated as neutrons having the upper limit energy. For the conservation of the total energy, weights of the neutrons were increased by the ratio of the original energy and the upper limit energy. The cpu time was only several minutes for each calculation, which is less than 1/60 of the HETC calculation.

3)Results and Discussion

The calculated neutron spectra at 9 depths in the 8 m thick concrete slab are shown in Fig. 6. The source neutrons used are the yield in the copper beam dump at the angle between 50 and 70 deg. The calculated results of the HETC code are shown in small marks and the histograms represent the results of the ANISN code used with the HILO cross sections. The spectral shapes of these calculations are in good agreement. The jump at the top energy group in the ANISN spectra at shallow depths came from the energy truncation of the source spectrum mentioned in the previous section. The absolute value of the ANISN calculation, however, decreases as the depth increases.

Attenuation curves of the dose equivalent rate (H_{1cm}) in the concrete slab are shown in Fig. 7. The open and solid circles are of the HETC calculation, and the lines are of the ANISN calculation performed with the HILO cross sections. The dose rates shown in this figure are due to the neutrons of energy above 14.9 MeV. With the increase of the emission angle of the source neutrons, the absolute value of the dose rate becomes small and the slant becomes steep. At the entrance of the slab, the ANISN results are larger than that of HETC because of the weight increase in the energy truncation of the source spectrum. The difference between the HETC and the ANISN calculations is only a factor of 4 at 8 m depth, and it can be concluded that the ANISN calculation with the DLC-87/HILO group cross sections gives good results compared with the HETC code. The DLC-128/LAHIMAC cross sections, however, gave much underestimation, that is, a 1/200 value at the 8 m depth.

The dose equivalent distributions due to whole neutrons and secondary gamma rays calculated with the HILO cross sections are shown in Fig. 8. The increase coming from low energy neutrons and gamma rays is about a factor of 2.

The ANISN code can perform an adjoint calculation, in which particles are traced inversely. An adjoint transmission of the dose equivalent response function was evaluated by using this option. The results for an 8 m thick ordinary concrete are shown in Fig. 9. The adjoint flux is the same as the dose equivalent importance function, and it can be seen that the only high energy neutrons contribute to the dose rate after a thick shield.

V. CONCLUSION

Neutron emissions from thin and thick targets were calculated by the HETC-KFA-2 Monte Carlo code, and compared with experimental data. The calculation was found to give reasonable results if some angular biasing is introduced for high energy neutron emissions. Deep penetrations of the secondary neutrons produced in a copper beam dump bombarded by 1 GeV protons were calculated with the HETC code and also with the ANISN discrete ordinates transport code. The difference between these two calculations was not large.

References

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3) F.Raupp, S.Cierjacks, Y.Hino, S.D.Howe, M.T.Rainbow, M.T.Swinhoe, and L.Buth, ICANS-V, Jül-Conf-45, Jülich p333 (1981)

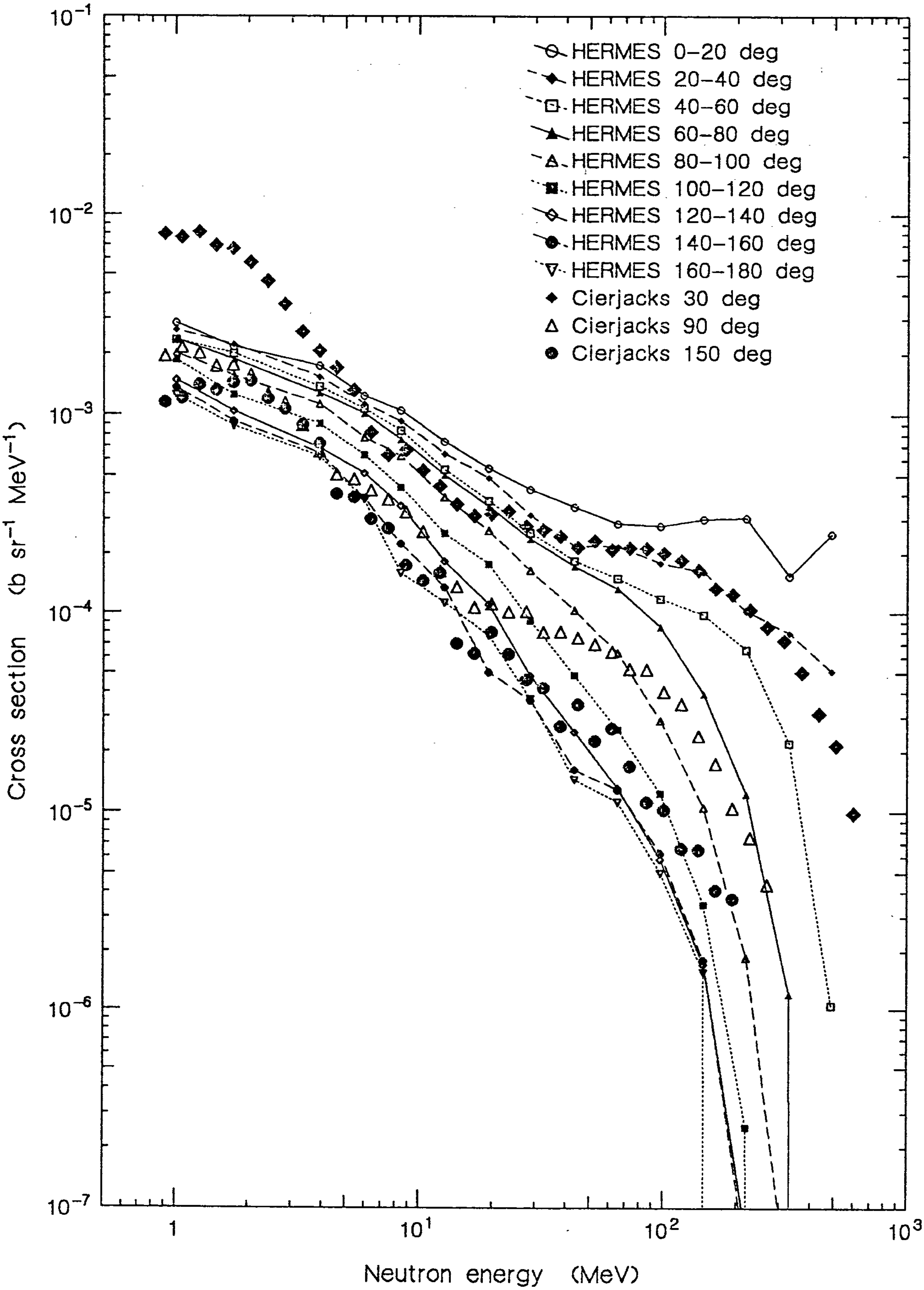

Fig. 1 Calculated and Measured double differential neutron production cross sections of carbon bombarded by 585 MeV protons.

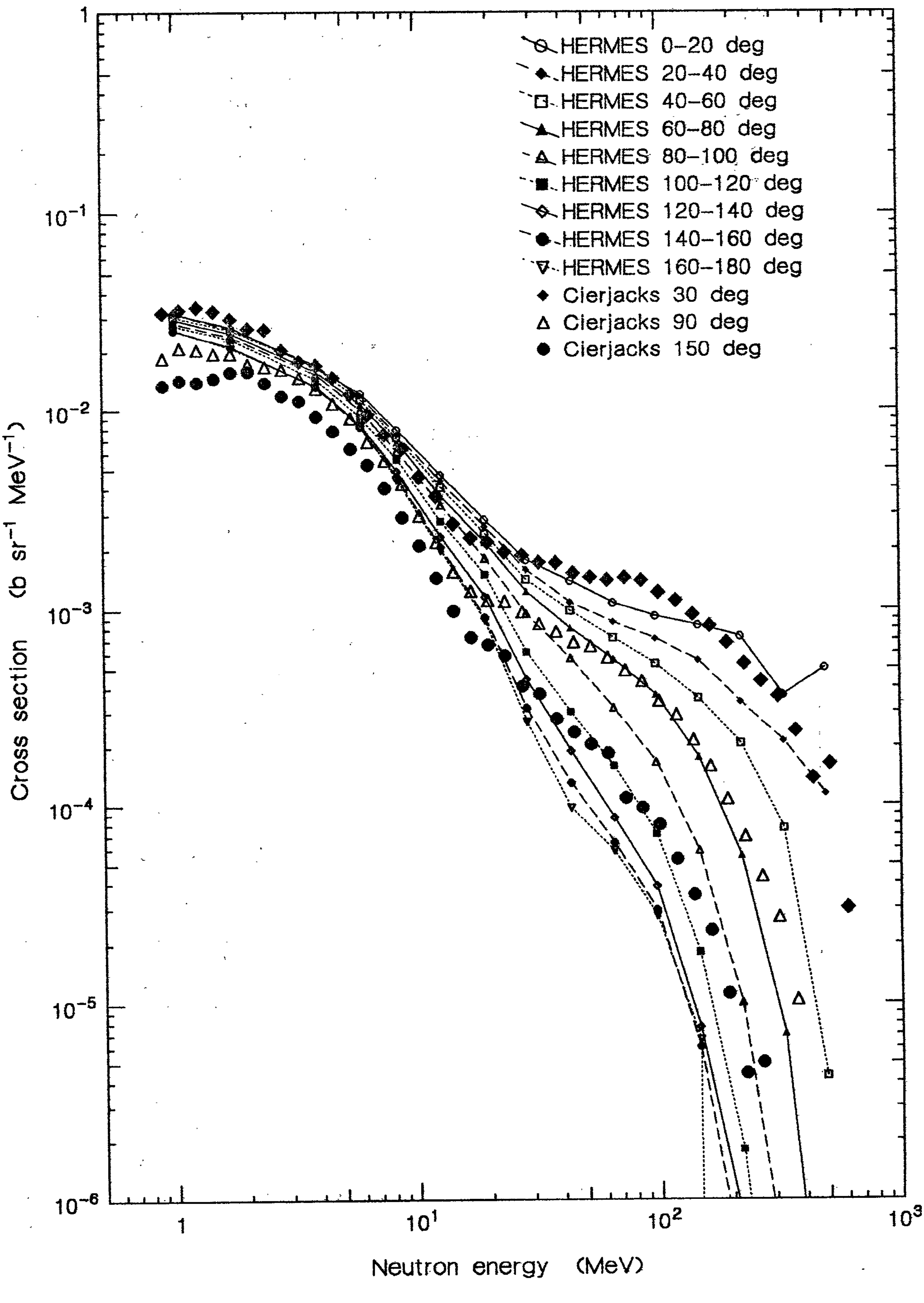

Fig. 2 Calculated and Measured double differential neutron production cross sections of iron bombarded by 585 MeV protons.

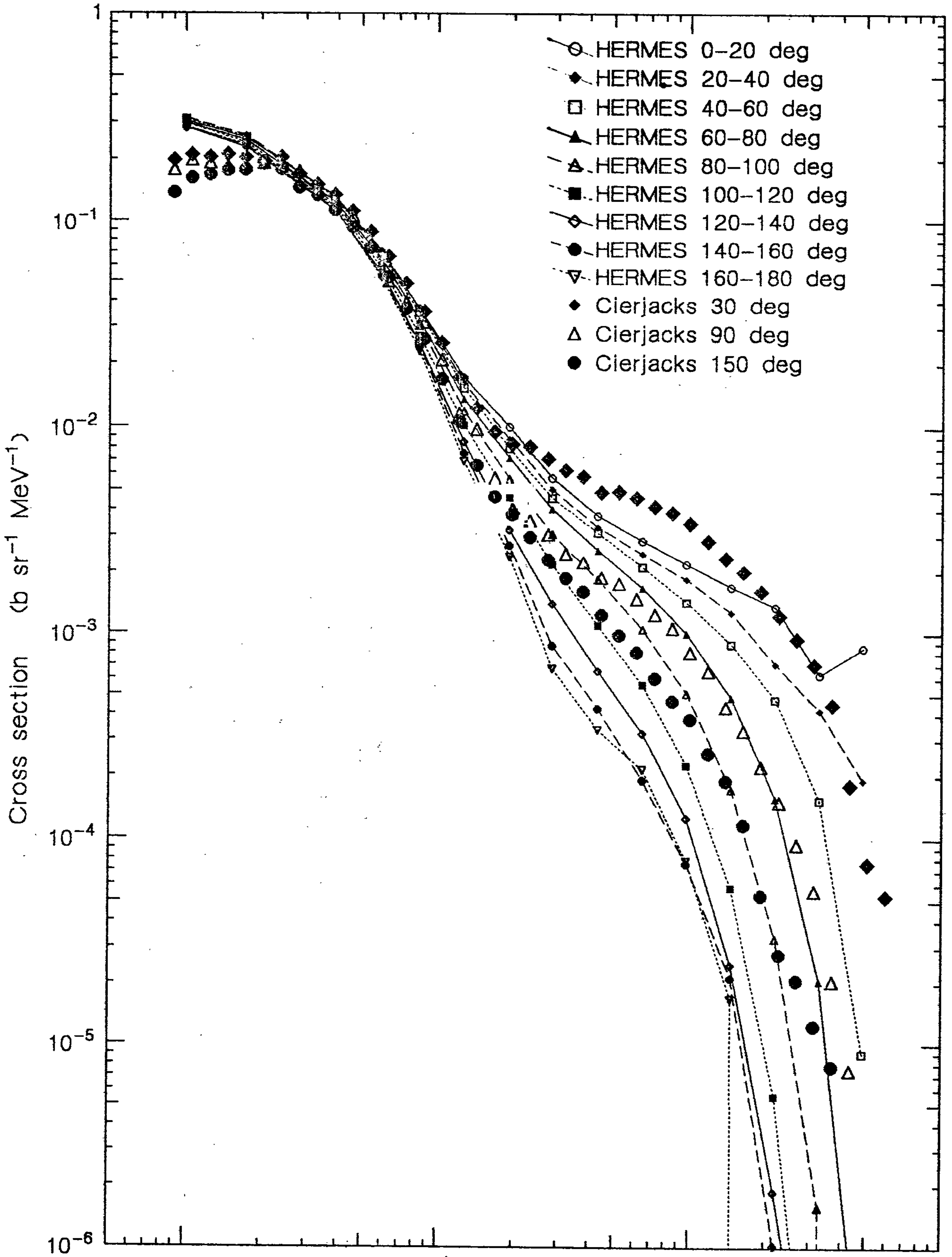

Fig. 3 Calculated and Measured double differential neutron production cross sections of lead bombarded by 585 MeV protons.

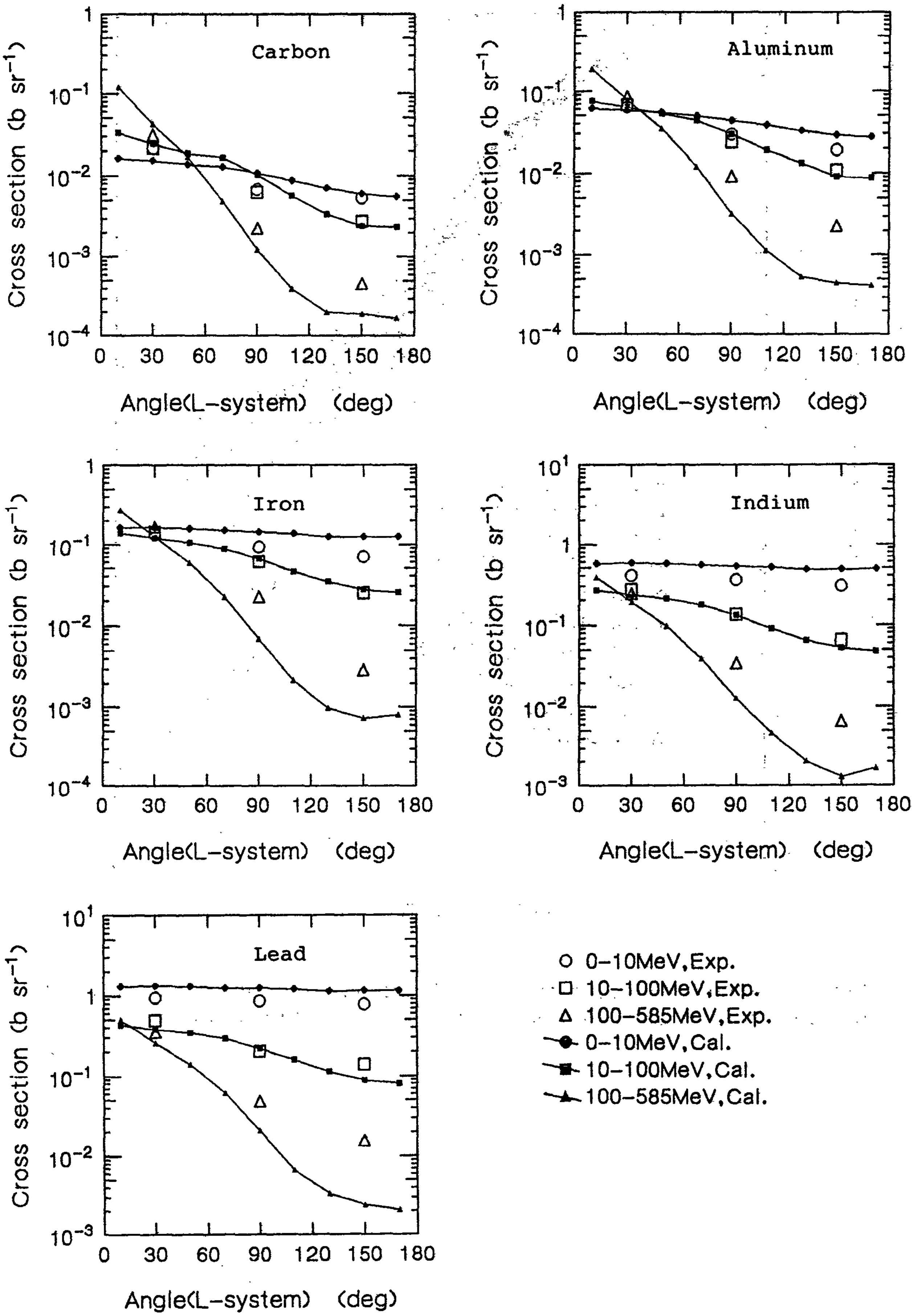

Fig. 4 Calculated and measured angular distribution of neutron yield from C, Al, Fe, In, and Pb elements bombarded by 585 MeV protons.

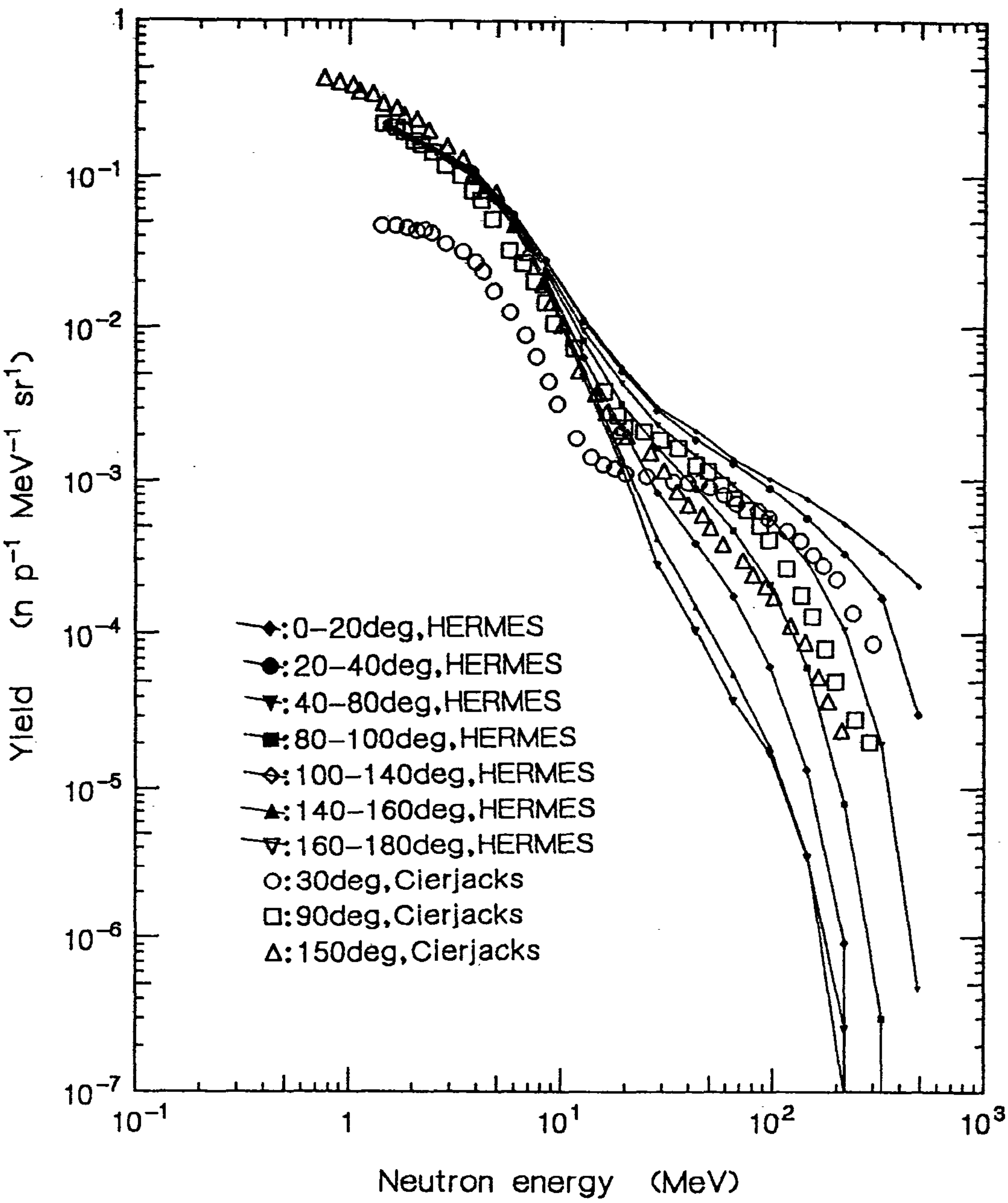

Fig. 5 Calculated and Measured double differential neutron production distribution at a thick uranium target bombarded by 585 MeV protons.

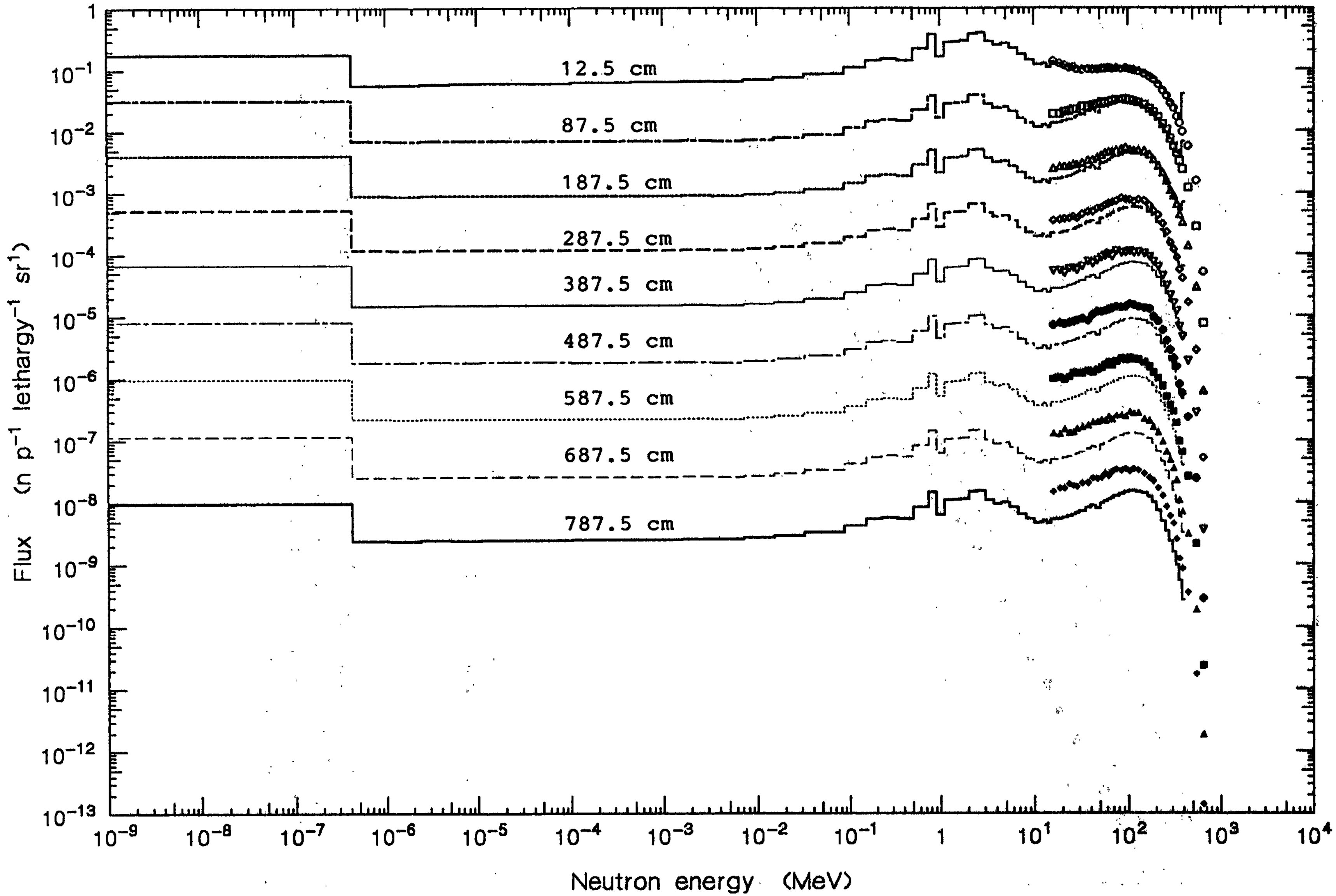

Fig. 6 Calculated neutron lethargy spectra in a 8 m thick ordinary concrete slab. The source was the neutrons produced between 50 deg and 70 deg in a copper beam dump bombarded by 1 GeV protons.

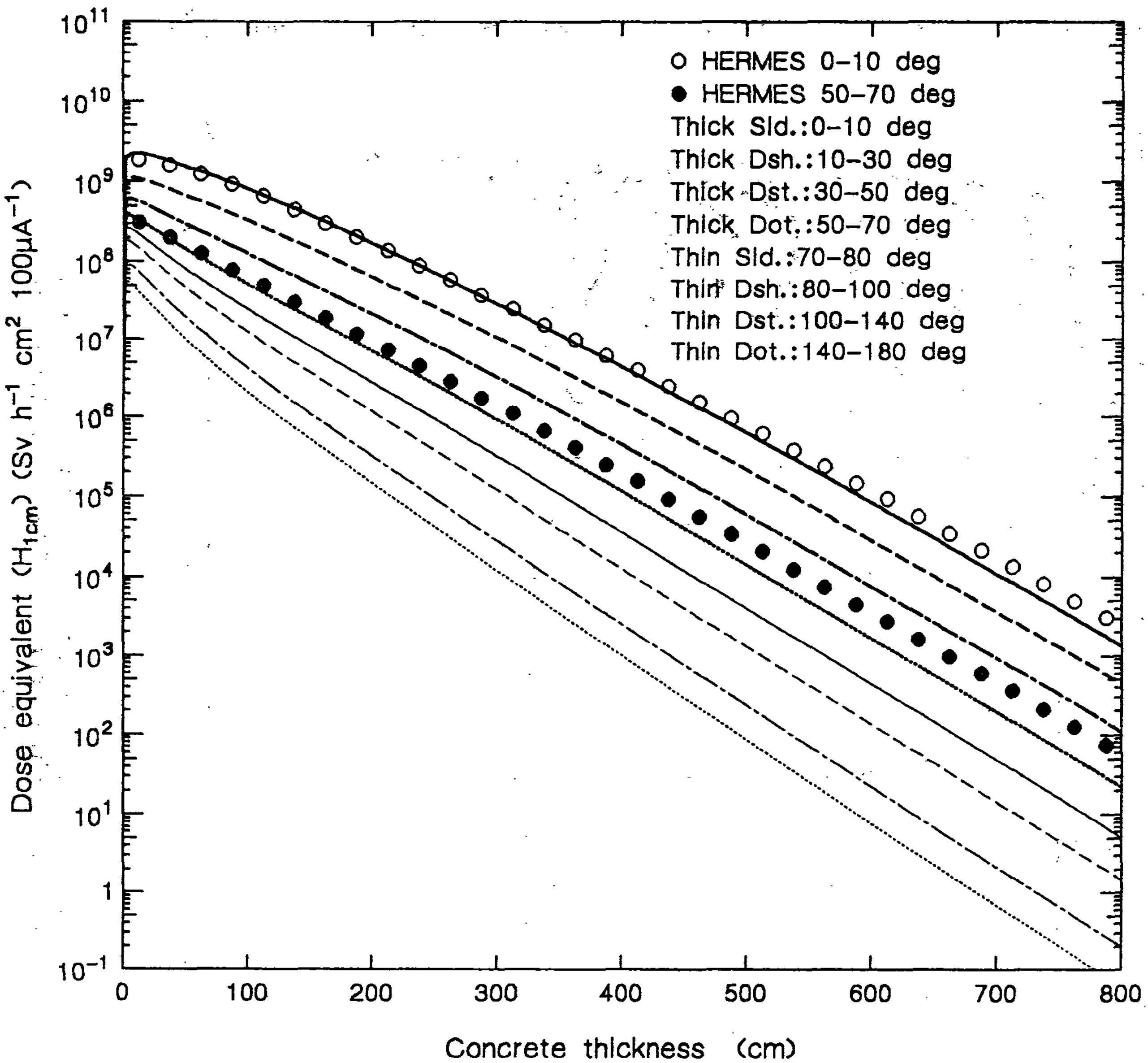

Fig. 7 Calculated dose equivalent attenuation of high energy neutrons (En>14.9 MeV) in a 8 m thick ordinary concrete slab. The source was the neutrons produced between 50 deg and 70 deg in a copper beam dump bombarded by 1 GeV protons.

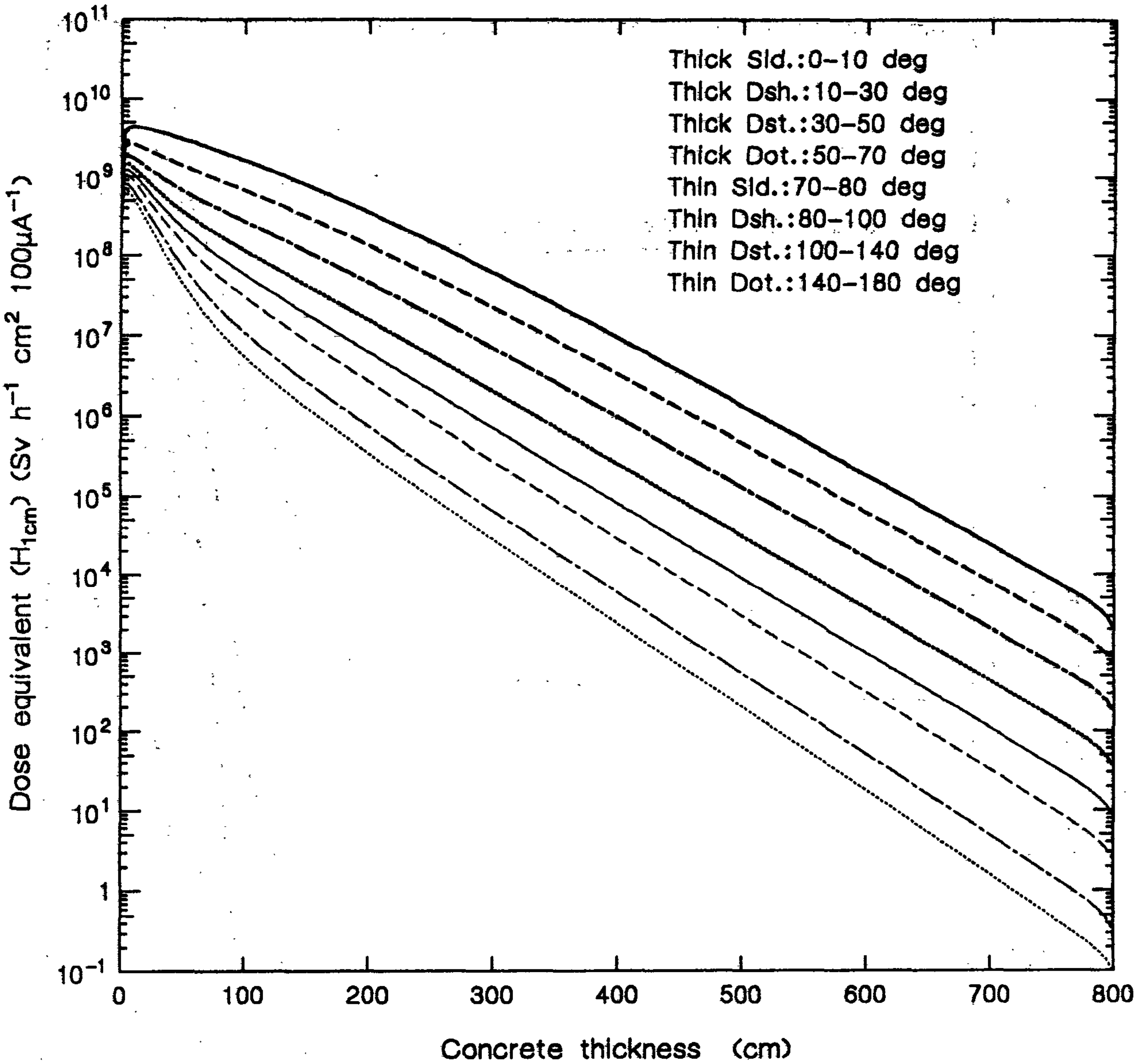

Fig. 8 Calculated dose equivalent attenuation of whole neutrons and secondary gamma rays in a 8 m thick ordinary concrete slab. The source was the neutrons produced between 50 deg and 70 deg in a copper beam dump bombarded by 1 GeV protons.

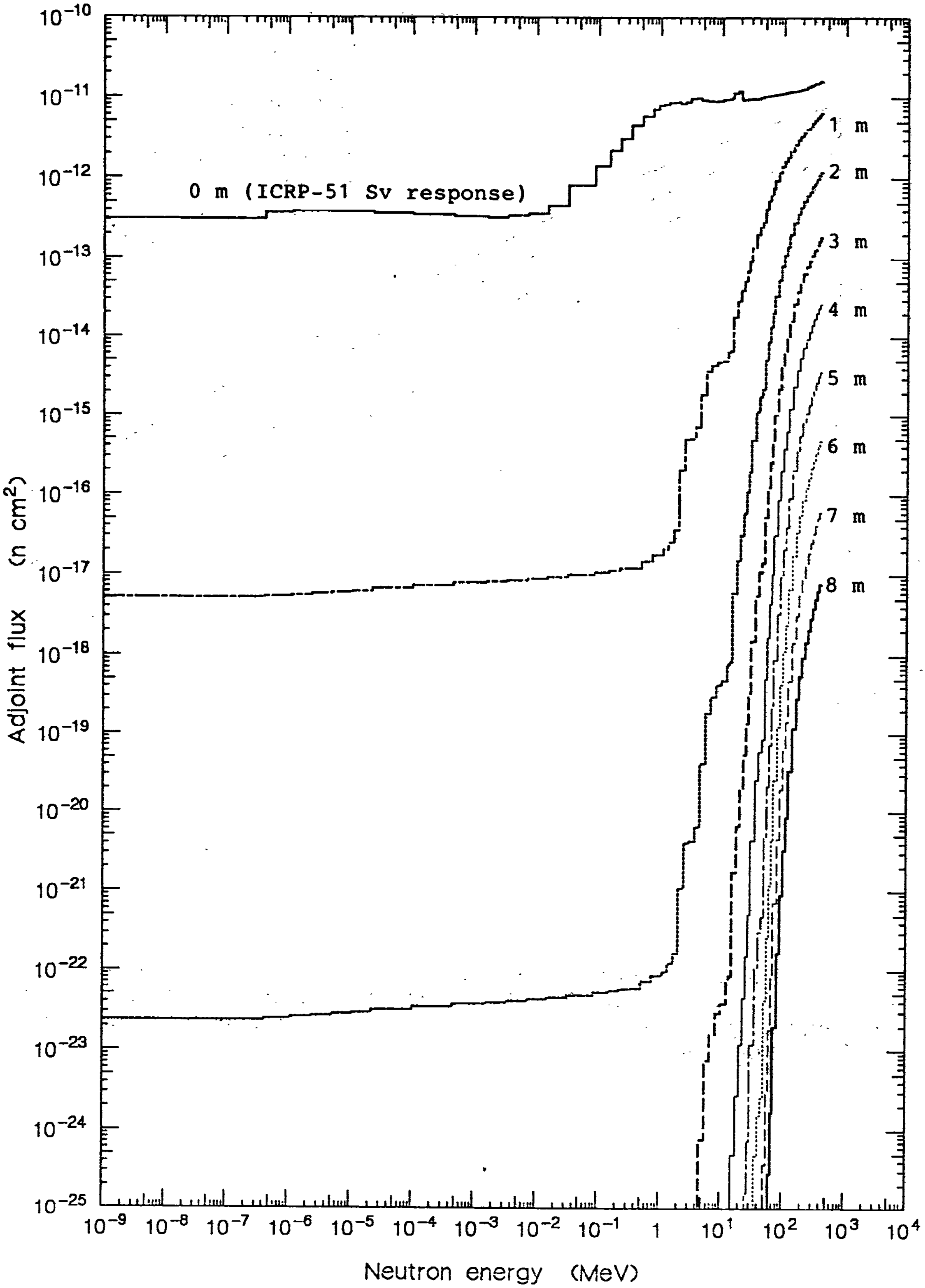

Fig. 9 Adjoint neutron flux distribution in a 8 m thick ordinary concrete slab for a source of the dose equivalent response function given in the ICRP-51.