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Benchmark Experiment for Material Penetration of Several Tens MeV Neutrons

by

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ABSTRACT

This paper describes (i) benchmark experiments of intermediate energy neutron transmission through iron, lead and graphite shields and (ii) estimation of thick target neutron yield by high energy ^{4}He ions.

In the neutron transmission experiments, a collimated beam of neutrons induced by 65-MeV protons in a thick Cu target was utilized in the measurements. Monte Carlo calculations by MORSE were carried out with the DLC-87 Hilo multigroup cross sections. It was found that the DLC-87 data reproduced the measured data well for the graphite shield, but gave partly higher values for the iron shield, and overpredicted the lead transmitted spectra.

Neutron yields for stopping-length target of Cu and Be were estimated for ^{4}He ion bombardment with the intranuclear cascade evaporation Monte Carlo code, HETC/KFA-1. The results were obtained for ion energies from 100 MeV/u to 800 MeV/u. The neutron spectra were fitted to simple evaporation spectra and the systematics on the nuclear temperature was studied. Total neutron yield per incident ^{4}He ion was about 5 times larger than that per proton.

I. Introduction

Treatment of neutron reactions in the energy range above 15 MeV up to 100 MeV is the most difficult part in the neutron transport calculation in high and intermediate energy range. The validity of the intranuclear cascade model, which has been very often used for the neutron transport calculation for high energy accelerators, is limited below several tens MeV energies. Multigroup cross section data DLC-87/1/ are often used in this energy range. The data were evaluated partly depending on the intranuclear cascade evaporation model. However, there are very few neutron benchmark data which enable ones to test accuracy of neutron transport calculations in this energy range./2,3/

The objective of the first half of this paper is to provide benchmark data in this energy range for neutron transmission calculation through several materials.

The remaining part of this paper treats the neutron production from thick targets bombarded by ^4He ions. The work was done mostly for the design calculation of a heavy ion medical accelerator HIMAC. The accelerator is now proceeded to be built by the National Institute of Radiological Science.

Several experimental works on thick-target neutron yield have ever been published in the energy region of 100 to 800 MeV protons/4-7/, but for ^4He ions of energy higher than 100 MeV/u, only one experimental data exist for 710 MeV (177.5 MeV/u) ^4He ions./8/ We estimated the thick-target neutron yields for 100 to 800 MeV/u ^4He ion bombardment, using the HETC/KFA-1 intranuclear cascade evaporation Monte Carlo code./9/

II. Benchmark Experiment for Neutron Penetration through Shields

(1) Experimental Method

The experiment was made at the AVF cyclotron facility of Osaka University. A 1-cm thick (proton stopping range) Cu target was irradiated by 65-MeV protons and generated neutrons in the forward direction were pulled out to an experimental room through a 7.5-cm diameter iron-lined concrete collimator of 50-cm length. The experimental setup is depicted in Fig. 1. Experimental systems were set at locations very close to the collimator exit. Those were iron, lead and graphite shields of the size of about 40 cm by 40 cm in cross section and 10 cm to 100 cm in thickness.

Transmitted neutrons were measured just behind the shield system by a 3-inch (7.6 cm) diameter by 3-inch height NE-213 scintillator. The back-

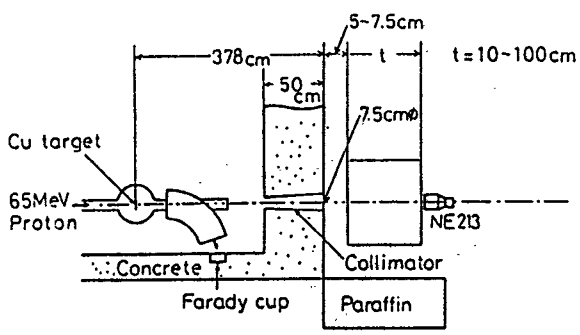

Fig.1 Experimental arrangement

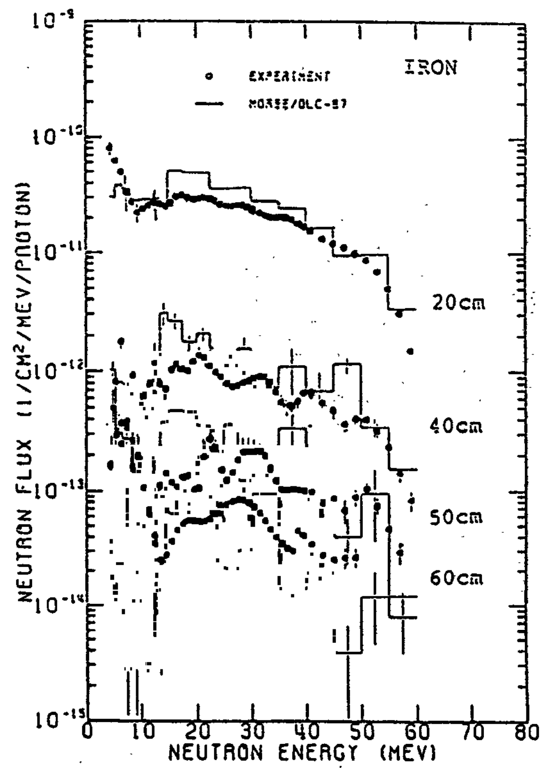

Fig.2 Transmitted neutron spectra through iron shields

background data were obtained in the same geometrical condition except that the collimator was closed by an iron plug. The source spectrum was measured without the shield.

The obtained neutron pulse-height spectra were unfolded to energy spectra by FERDO-U code./10/ Required response fucntions for the unfolding were constructed from measured response data./11/

(2) Calculation

The calculation of the transmitted neutron spectra through the shields was made by the MORSE code/12/ with multigroup cross sections DLC-87./1/ The experimental geometry after the collimator exit was simulated in the calculation. The collimator was not included in the model. Instead, source neutrons generated based on the measured spectrum were emitted from the target within a sharp cone of 3.14×10^{-4} sr.

(3) Results of the Benchmark Experiment

Neutron transmission spectra behind the iron shields are showed in Fig. 2. The measured spectra exhibit some sort of fluctuation as the shield thickness becomes larger due to poorer statistics. The overall agreement between the calculation and the experiment is well except that the systematic disagreement is seen at energies 15-30 MeV.

There are several reported measurements of the total cross sections and a few experiments for nonelastic cross sections of iron for neutrons above 15 MeV. The data in the DLC-87 are compared with those measured data.

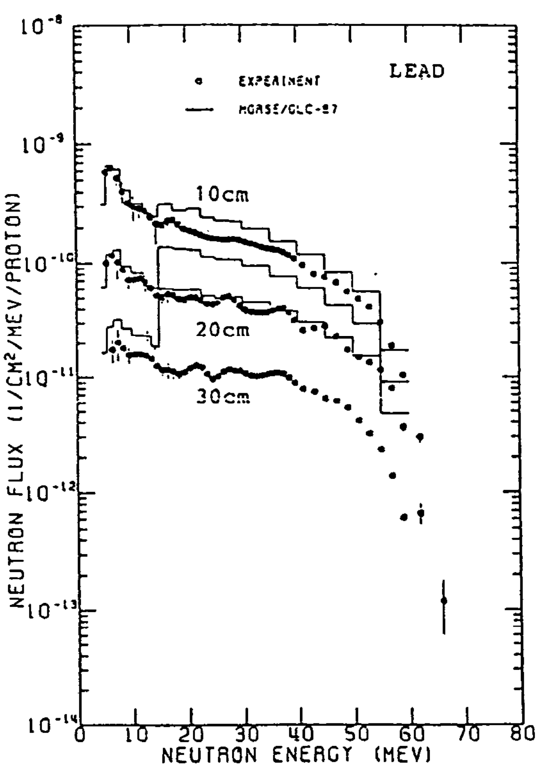

Fig.3 Transmitted neutron spectra through lead shields

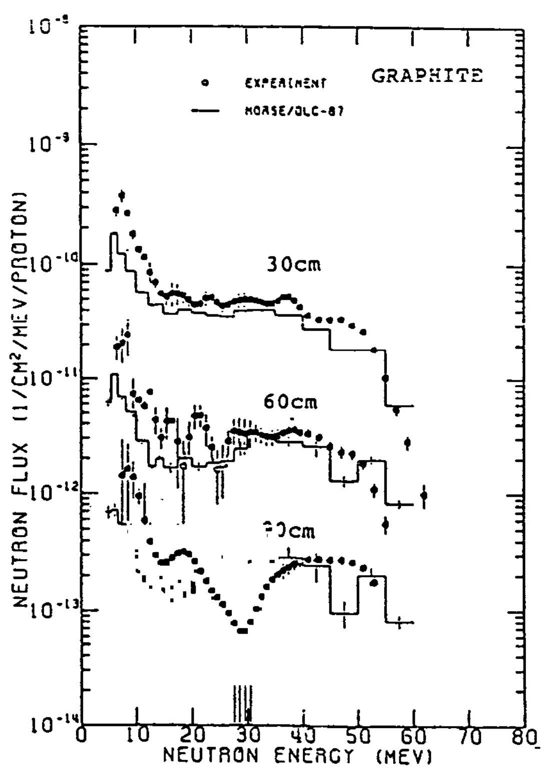

Fig.4 Transmitted neutron spectra through graphite shields

It was found that the underestimation of the iron total cross section is made at energies 15-30 MeV in the DLC-87. This is the reason for the overprediction of the transmitted neutron fluxes by the MORSE/DLC87 calculation observed in the corresponding energy range.

Figure 3 shows comparison of the lead transmitted neutron spectra between the MORSE/DLC-87 calculation and the experiment. The MORSE calculation overestimates the spectra very much in the energy range above 15 MeV, the tendency being pronounced as the lead shield becomes thicker. Because of this overestimation, the fluxes in the lower energy range below 15 MeV are also slighly overpredicted for the 30-cm thick shield, probably through the down scattering of neutrons from higher energies.

The DLC-87 lead cross section data were examined by comparing the data with some of existing measured data. The elastic scattering was ignored in evaluating the lead data above 15 MeV, and nonelastic cross sections were treated as total cross sections in the DLC-87. This is the main reason for the overprediction of transmitted fluxes. Moreover the nonelastic cross sections seemed to be somewhat underestimated above 20 MeV. This may be another reason for the overprediction of the transmitted neutron fluxes.

Neutron spectra transmitted through graphite shields are shown in Fig. 4. The overall spectra of each set of data agrees well with each other. A weak underestimation by the MORSE/DLC-87 calculation is observed at the lowest energy part below 10 MeV. The reason for this is still not clear. The big depression in the measured energy flux of the 90-cm thickness around 30 MeV is due to the subtraction of the oscillating background spectrum. A small fluctuation is also seen in the measured 60-cm spectrum.

III Estimation of Thick Target Neutron Production for ^{4}He Ions

(1) HETC Calculation and Comparison with Experiment

Neutron production by ^{4}He ions was simulated using the HETC/KFA-1 Monte Carlo code to generate systematic neutron source data for the design of the HIMAC heavy ion medical accelerator.

Before doing systematic calculations of the neutron yield, the calculational accuracy of the HETC/KFA-1 code was checked by comparing the results with the measured data by Cecil et al. They measured energy spectra and total yield of neutrons produced from a stopping length iron target (10.2cm by 15.4 cm size and 4.445 cm thickness) bombarded by 710 MeV ^{4}He ions.

Figure 5 shows the comparison between the measurement and the HETC calculation. Results of the HETC calculation were integrated over angular intervals of 0° to 30°, 30° to 70°, 70° to 110° and 110° to 180° by the SIMPEL code to decrease the statistical errors. For direct comparison, the differential neutron yield data of Cecil et al. (given at angles 0°, 6°, 15°, 30°, 45°, 60°, 90°, 120°, and 150°) were also integrated over the same angular intervals.

It is seen in the figure that the HETC calculation gives the overestimation of absolute neutron yield in the forward direction,

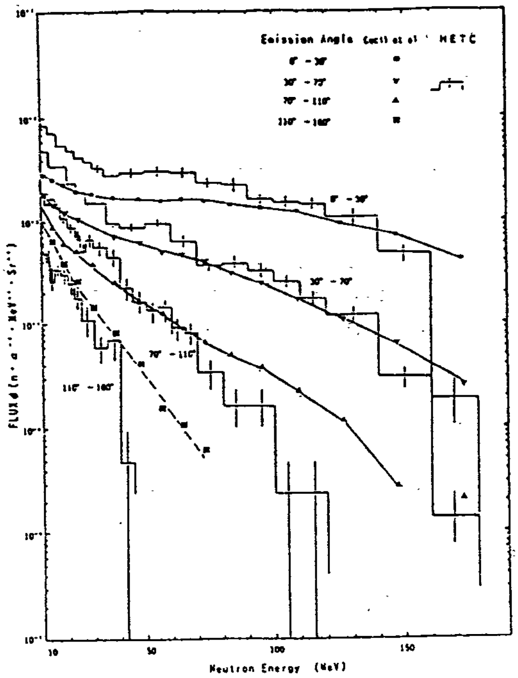

Fig.5 Neutron spectra produced from thick iron target by 710 MeV ^{4}He

Table I Targets assumed in the neutron yield calculations

Energy of α-beam E_0 (MeV)	Target Material	Target HxWxL (cm)	Number of History
800	Cu	20x20x40	15600
600	Cu	x30	20000
500	Cu	x20	20000
225	Cu	x10	20000
100	Cu	x 2	20000
500	Be	x80	18800
α-beam		W H L	Statistical Error < 1 %

particularly in the lower energy range. This overestimation becomes less with the emission angle. The calculated spectra are softer than the measured spectra at all angles. This tendency is also shown in thick-target neutron data for protons in Refs./4-7/, but more remarkable for ^{4}He ions.

The total integrated neutron yield above 10 MeV was calculated. It was 0.65 neutron/ion. It is in a good agreement with the experimental value of 0.51 neutron/ion, being 1.27 times the measured value.

From this comparison it was revealed that the HETC code gives reasonable estimation of total neutron yield.

(2) Estimation of Neutron Yields
(i) Calculational method

The HETC calculations were performed for several ^{4}He energies and the target materials indicated in Table I. The target thickness was set to the stopping length of the incident beam. Copper was selected since it was main material in magnet, and beryllium was considered in the HIMAC design as a target for secondary radioactive beam production. The history numbers of the calculations were 20000 at maximum and the statistical errors in total yield were less than 1%.

To test the difference of neutron yields between ^{4}He and p beams, the HETC calculations were also made for copper target with the incidence of 225 and 500 MeV protons, and for the beryllium target with 500 MeV protons.

(ii) Results of Calculation

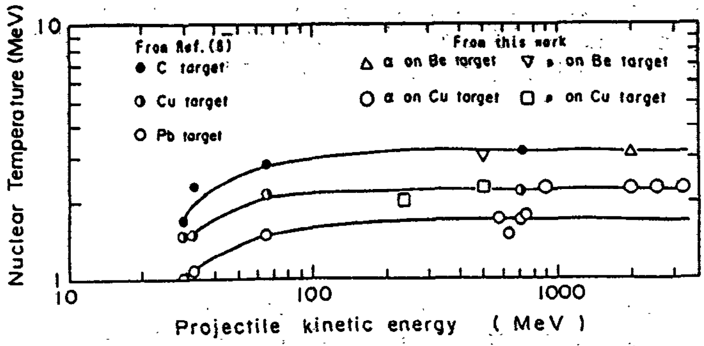

Fig.6 Nuclear temperature of the equilibrium component

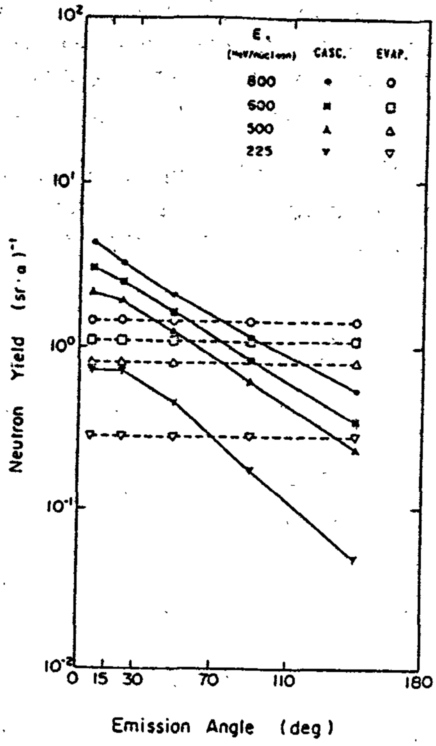

Fig.7 Angular distributions of calculated neutrons

Calculated differential neutron yield data were fitted by the phenomenological hybrid expression proposed by Nakamura/13/ with the evaporation spectrum plus two maxwellian-type spectra. The first term expresses the equilibrium component and the other two are for nonequilibrium neutrons.

Figure 6 shows the nuclear temperature of the equilibrium component as a function of projectile kinetic energy. The figure indicates that the nuclear temperature increases with increasing the projectile kinetic energy and with decreasing the target mass. It approaches a saturated value at energies higher than 100 MeV.

The angular distribution of the neutron flux was obtained by integrating the spectra over the neutron energy. The obtained fluxes for the copper target are shown in Fig. 7 for each of the cascade and evaporation components as a function of the angle. The angular distributions of the cascade and total neutron yield can be roughly approximated by the exponential shape of $\phi = \exp(-\beta\theta)$. The beta values are showed in Table II.

Figure 8 shows the total neutron yield as a function of incident particle energy per nucleon. The results obtained in this work are added to those given in Ref.14. For ^{4}He projectiles, two dashed curves for C and Cu targets were given by connecting experimental data./14/ The present results are higher than the extrapolation of the curves to higher energies.

It is noteworthy that the total neutron yields of Ref.14 were estimated values by assuming the pure Maxwellian distribution to extrapolate measured low energy neutron spectrum to further lower energies where data were not given because of the discrimination of the measurement. In the HETC calculation, there were excess number of neutrons at lower energies whose spectrum was not represented by the maxwellian distribution. Those may be due to the neutron multiplication and energy degradation in a bulky target.

For the 500 MeV/u energy, the ratio of neutron yield by ^{4}He to that by proton was 4.37 for the Cu target and 4.15 for the Be target. This was almost equal to the ratio of number of nucleons in the projectiles.

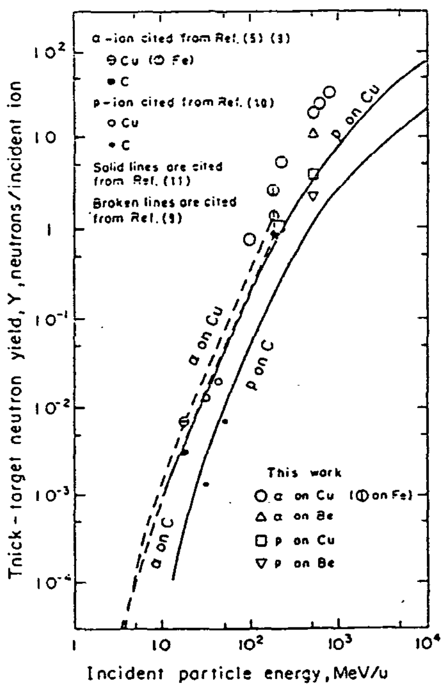

Fig.8 Neutron total yield as a function of ion energy per nucleon

Table II Beta values for exponential formula of neutron angular distributions

Projectile	Energy E_0 (MeV/nucleon)	Target	β ϕ casc.(θ)	β ϕ total(θ)
α	800	Cu	0.87	0.43
	600		0.92	0.45
	500		0.95	0.46
	225		1.12	0.55

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Q(I.M.Thorson): Did you do one "bad" geometry experiments when you did your "good" geometry experiment?

A(K.Shin): Since the background level in the counting room is rather high, it is not possible to measure scattered neutrons. However, it is very important thing to obtain informations in a bad geometry.