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THE YIELDS AND SPECTRA OF NEUTRONS FROM CASCADE PROCESS IN THE HIGH ENERGY SPALLATION REACTION

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§ 1 Introduction

As intense neutron sources, in addition to the nuclear reactors, there are accelerator systems using D-T, stripping and spallation reactions. With recent advance of the accelerator technology, prominent characteristics of the neutron sources using the accelerators are getting realized, that is, extreme high neutron intensity of CW or pulse mode. In the case of the spallation neutron source, one-GeV proton accelerator and a uranium-238 thick target will be able to produce about 60 neutrons per proton, and in the case of a sufficiently large target system with moderator and reflector about 100 slow neutrons per proton will be produced. These neutrons are used for the study of material science including the neutron spectroscopy, and may also be used for accelerater breeding of fissile materials and incineration of

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radioactive wastes from the nuclear reactors.

Measurements of the yield and energy spectrum of the spallation neutrons are quite important not only for clarifying the physical process but also efficient application of the sources. The first experiment was performed by a joint group of CRNL and ORNL using the Cosmotron at BNL (1965). It was the measurement of neutrons from various thick targets in the water tank [1]. Recently, the experiments using thick and thin targets are reported by groups of TRIUMF, LANL, KFK, and USSR in the energy range of 300 to 1100 MeV [2,3,4,5]. Especially, the KFK and LANL groups have performed extensive measurements of the spectra at different angles of neutrons emerging from various targets. A remarkable feature seen in their results is the existence of a shoulder around 100 MeV in the neutron spectra, changing with an angle of observation.

Concerning the theoretical works, Metropolis et al. [6] published the first work on the nucleon cascade inside a nucleus extending the Monte Carlo simulation method proposed by Goldberger [7]. Nowadays, computational analyses of the experiments are performed usually by using a nucleon meson transport code system NMTC [8] or its extended version HETC [9], which were developed by Armstrong et [illegible]. to simulate the intra- and inter-nuclear nucleon transport. The improvements of the codes have been done to incorporate the high energy fission into the reaction process [10,11]. At Dubna, also, the Monte Carlo Code was developed (1974) [12].

In contrast to the experimental results, no shoulders are seen in the calculated neutron spectra obtained by the computer code system NMTC or HETC and their improved versions.

In this report, first, we analyse the experimental differential cross sections of the spallation reactions measured by the groups of KFK and others. Then we try to compare the cross sections with ones calculated by the NMTC/JAERI [13], where we change the magnitude of the effective nucleon-nucleon interactions inside the nucleus. This is to enhance the leakage of high energy nucleons from the nucleus.

§ 2 Analyses of the experimental data

The neutron energy spectra from the spallation reactions are roughly considered to consist of two components, that is, the neutron evaporation component, peak of which is at $1 \sim 3$ MeV, and the high energy tail of the cascade neutrons.

The evaporation part is well fitted by a function of $A_i(E/E_{0i}) \exp[-E/E_{0i}]$, where E_{0i} is called nuclear temperature. About the high energy tail, Nakai et al. [14,15] have proposed an exponential function for the cascade nucleon spectra, and they successfully fit their proton spectra in an energy region of 40 to 170 MeV for various nuclei. Therefore, we adopt similar functional form of $A(E/E_0) \exp[-E/E_0]$, to fit the high energy tail.

Nakai et al. suppose that the protons are emitted isotropically with an exponential form of energy spectrum. The invariant cross sections is expressed as

$$\frac{1}{p}\,\frac{d^2\sigma}{dE\,d\Omega} \propto \exp\left[-E^*/E_0\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

in a moving frame with velocity β_s relative to the laboratory frame, where E^* and p are energy and momentum of the emitted nucleon, respectively. The Lorenz transformation to the laboratory frame gives

$$E^* + m = (E + m - \beta_s\, p \cos\theta)/\sqrt{1 - \beta_s^{2}} \quad \ldots \quad (2)$$

where θ is an angle of the detector in the laboratory frame and m is a rest mass of the nucleon. Eq.(1) approximately is reduced to

$$\frac{d^2\sigma}{dE\,d\Omega} \propto E^{1/2} \exp\left[(-E + \beta_s p \cos\theta)/E_0\right] \quad \ldots\ldots \quad (3)$$

if [illegible] $- \beta_s^{2} \sim 1$. The factor $E^{1/2}$ of the right hand side in Eq.(2) tend to E at the extremely high energy of emitted particles. The angular dependence of this function shows that the energy spectra shift to the lower energy with increasing angle θ, the shift being, if M and E_p are mass of the target nucleus and incident proton energy, respectively,

$$\beta_s p \cos\theta \sim \frac{2}{M}\sqrt{E\,E_p}\,\cos\theta \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

As seen in Fig.1, if the observed spectra are peeled off with the functions of $A(E/E_{0i}) \exp[-E/E_{0i}]$ $(i = 1,2)$, the residual component should be considered between the evaporation peak and the high energy tail. The intermediate 3rd component corresponds to the pre-equilibrium component of Nakai et al.

If the whole spectrum is peeled off with the functions of $A_i(E/E_{0i}) \exp[-E/E_{0i}]$,

$$\frac{d^2\sigma}{dE\,d\Omega} = \sum_{i=1}^{3} A_i (E/E_{0i}) \exp\left[-E/E_{0i}\right] \quad \ldots\ldots\ldots \quad (5)$$

Then,

$$\frac{d\sigma}{d\Omega} = \sum_{i=1}^{3} A_i E_{0i} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

The results of the analysis of the KFK data are shown in Table 1. The angular dependences of E_{0i} $(i = 2,3)$ are much larger than expected from Eq.(4). The target mass M in Eq.(4), however, should be considerd as an effective local mass [illegible] the target nucleus. If we estimate M to be about ten, then the variation of the components ($i = 2,3$) with angle θ will be explained by Eq.(4). This is consistent with the results of ref.[15]. The value of A_3E_{03} at $\theta = 23°$ is anomlonsly large, but between 30° and 150° the change of $d\sigma/d\Omega$ is similar with one in Fig.4 in ref.[16].

§ 3 Comparison between the experimental spectra and the calculations of the cascade process

A comparison between the measured and calculated spectra shows rather large discrepancies in the high energy part as seen in Fig.6 of ref.[4]. The calculations give smaller than the measurements. In the computer codes mentioned in § 1 the cross sections of the nucleon-nucleon scattering in the free space are used, though Pauli-blocking effect is taken into consideration during the intranuclear cascade.

Recently, several papers concerning the mean free path of a nucleon inside the nucleus have been published [17, 18]. Anomalous behaviours of the mean free path are reported and it is generally very large, though in an energy region higher than 500 MeV the mean free path becomes to that expected with the free-space cross sections between the nucleons.

Therefore, we multiply some constant factor (>1) to the mean free path in the NMTC/JAERI calculations. As seen in Fig.2, the high energy parts of the spectra are increased, and the shoulders appear with a multiplication factor of 1·1 ∿ 1·5.

However, with increasing the factor, the total neutron yield decreases rapidly as seen in Fig.3. Therefore, the increase of the mean free path should be at most a few tens per cent.

In our calculations, a rod target of 60 cm long and 10 cmφ is used and the total neutron yield is the total number of the neutrons created in the cylinder per one proton. Neutron fluxes are obtained by making integration over angle and taking average on the surface. Mean free paths for the spallation neutrons in the target material are larger than the target radius, so that the high energy component of the neutron yield will correspond to the differential cross sections around 90°, though the average proton energy is much lower than the incident value (590 MeV for KFK).

§ 4 Concluding remarks

(1) In the present report we adopt the functional form of $A_i(E/E_{oi})\exp[-E/E_{oi}]$ for the high energy part. This is from an assumption of the fire-ball

model. Though the assumption is still questiona the fitting to the experimental data is fairly well.

(2) Most of the intermediate component of the spectra, that is, pre-equilibrium one, can be considered actually to be included in the cascade calculations.

(3) A shoulder of the neutron spectrum can be reproduced by the calculation using the stretched mean free path. With increasing the mean free path, the neutron yield decreases in the present target system, but, with larger target system, the yield may not decrease so rapidly.

(4) We are planning to make the calculations with the increased mean free path which is a function of the neutron energy as pointed out in ref. [18], and, also, the neutron yield in large target systems.

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Table 1 Spectral Analysis of the Spallation Neutrons (KFK data [4])

θ	23°	30°	90°	150°
A_1	0.82	0.68	0.68	0.68
E_{01}	3 MeV	2 MeV	2 MeV	2 MeV
A_1E_{01}	2.46	1.36	1.36	1.36
A_2	0.035	0.015	0.011	0.018
E_{02}	25 MeV	25 MeV	20 MeV	10 MeV
A_2E_{02}	0.88	0.38	0.22	0.18
A_3	0.033	0.010	0.0039	0.0034
E_{03}	100 MeV	70 MeV	50 MeV	30 MeV
A_3E_{03}	3.3	0.70	0.20	0.102
$\sum_{i=1}^{3} A_iE_{0i}$	6.6	2.4	1.8	1.6

$$\frac{d^2\sigma}{dE\,d\Omega} = \sum_{i=1}^{3} A_i\,(E/E_{0i})\,\exp[-E/E_{0i}]$$

$$\frac{d\sigma}{d\Omega} = \sum_{i=1}^{3} A_i\,E_{0i}$$

E_p = 590 MeV, lead target

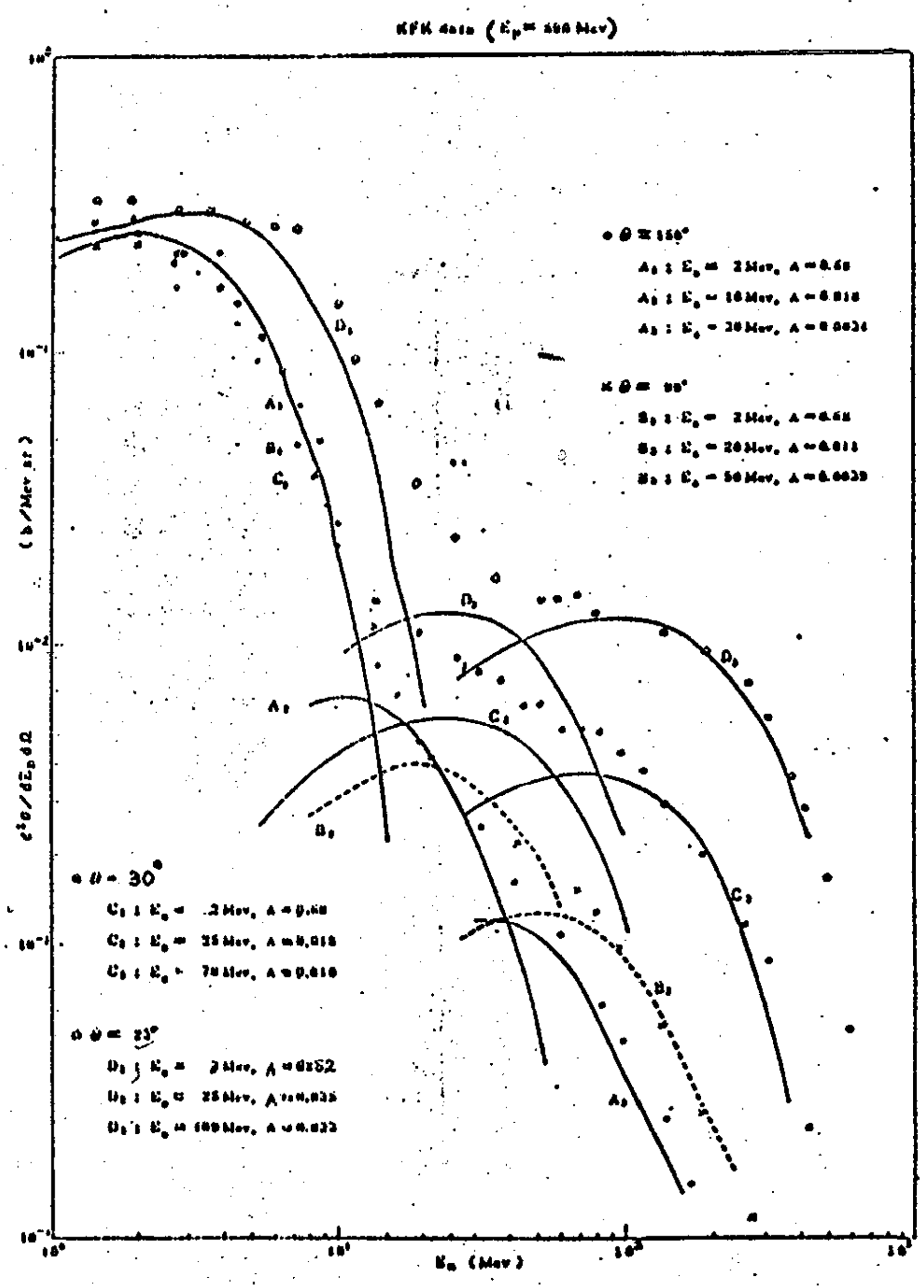

Fig.1

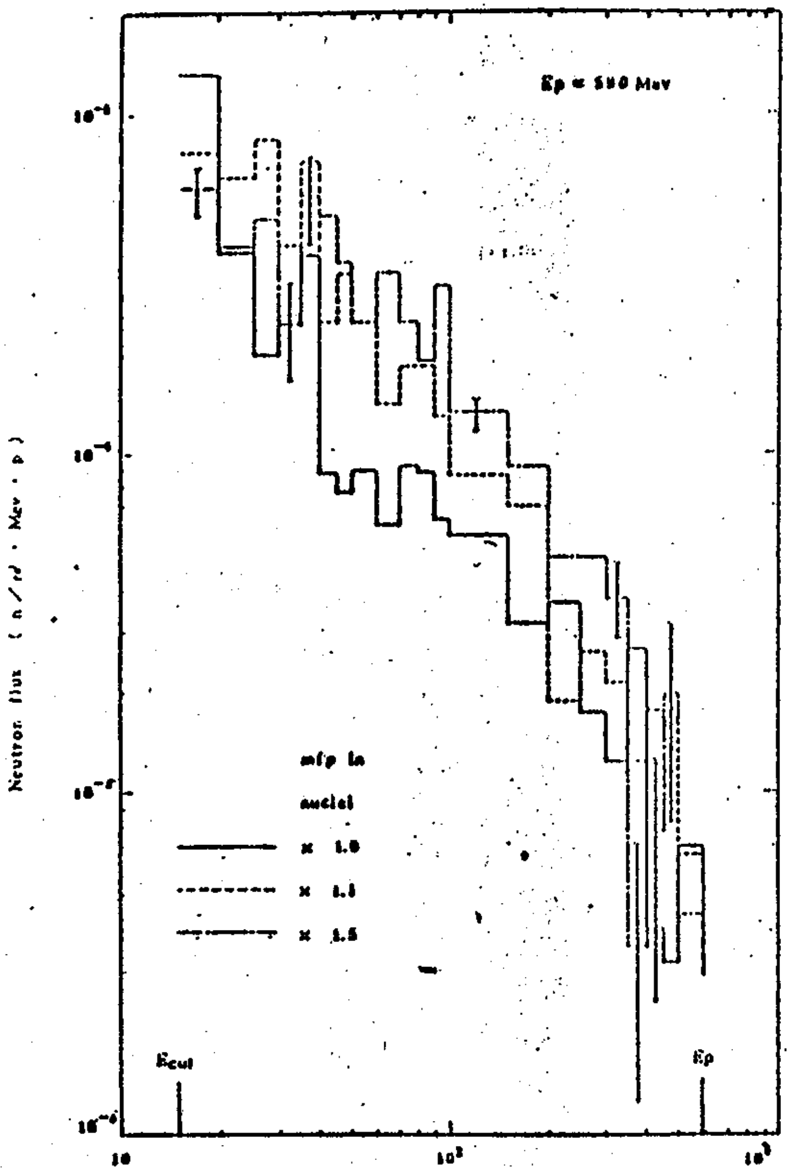

Fig.2 Comparison of spallation neutron fluxes on the side boundary of Pb cylinder (60 cm length , 10 cm dia.)

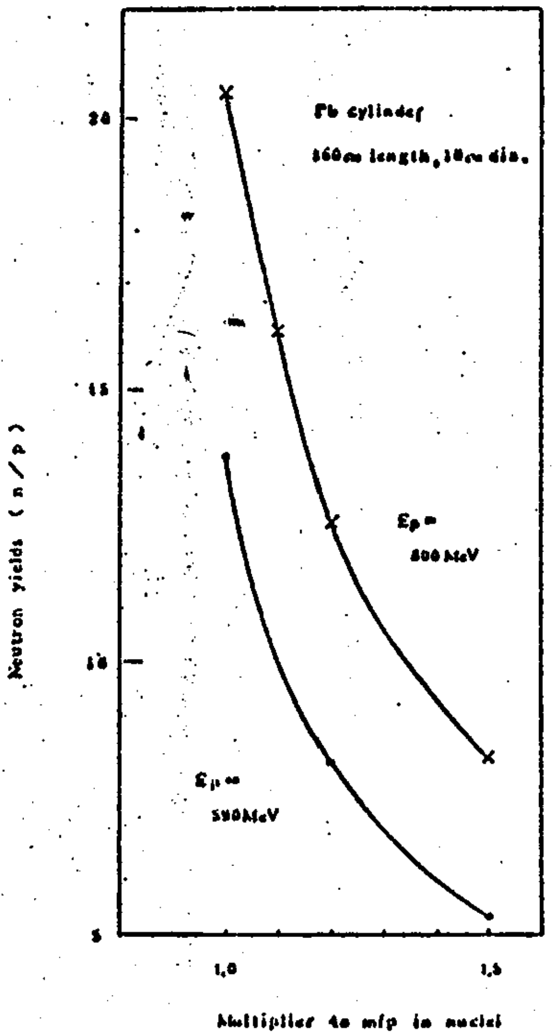

Fig.3 Influence of effective mfp in nuclei on total neutron yields

$(0 \leq E_n \leq E_p)$