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IMPROVEMENT ON INTRANUCLEAR CASCADE MODEL CALCULATION FOR AN ENERGY RANGE 500-1000MeV

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Abstract: High energy proton beams of about 1GeV may be used for such engineering purposes as incineration of nuclear waste. Computer codes like High Energy Transport Code (HETC) are utilized for designing target systems. These codes treat high energy reactions on the basis of the intranuclear-cascade-evaporation model. They produce a discrepancy in experimetal results in both neutron spectra and mass yields of residual nuclei. Improvement is made on the HETC to eliminate this disagreement. The intranuclear-cascade (INC) calculation is parametrically treated in this study. The preequilibrium calculation is introduced between the processes of INC and evaporation. A better agreement is obtained between the experimental and calculated results for both neutron spectra and residual mass yields.

(proton, intranuclear, cascade, evaporation, spallation, HETC, neutron)

Introduction

High energy protons of about 1 GeV induce spallation reactions in target nuclei, and are potentially capable of producing sufficient neutrons for science and engineering purposes[1]. For example, this spallation reaction is useful for incinerating nuclear waste or breeding fissile materials. Accurate computer codes are necessary in designing such systems.

Since there is no nuclear data file in this energy region, computer codes that have been developed have to treat both nuclear reactions and interatomic particle transport. These codes employ the intranuclear-cascade-evaporation (INCE) model[2,3] for calculating the spallation reaction. They produces an appreciable systematic discrepancy on the neutron energy spectra between the calculation and the experiment. Calculated results for the mass yields of residual nuclei largely differ from the experimental values.

Other models[4] such as a moving source and a fireball have been proposed to express collective or interferent aspects of nucleon motion in the spallation reaction. The INCE model cannot represent these aspects. However, this model describes the reaction in the least ambiguous manner among models proposed, and gives the most detailed information on residual nuclei. In a present stage the INCE model is best suited for the engineering purpose. We will attempt to parametrically improve the code within the frame of the INCE model. Futhermore, the preequilibrium process will be introduced into the code to overcome the limitation of the INCE model.

High energy transport code

High energy transport code (HETC)[5] is used in this study. The program is coded by a Monte Carlo algorithm. The calculation on the nuclear reaction consists of a two-step procedure: intranuclear cascade (INC) and statistical evaporation processes[2,3]. The INC process is composed of a series of quasi-free nucleon collisions in a nucleus. Collision data have been edited from the experimental data on nucleon collisions. For the quasi-free inelastic collision, the experimental data are extended by an isobar model[6]. After the INC process, the particle evaporation is calculated with an assumption of the statistical equilibrium condition.

Along with the nuclear reaction, HETC is capable of treating interatomic nucleon and/or meson transport in a thick target system. In this study, to make the problem simpler, we considers a thin taget. This enables us to avoid the interatomic tansport calculation in a target. The code HETC of Atchison's version[7] is used in this study.

Quasi-free inelastic scattering

Double differential cross sections for neutron production have been measured[8] at Los Alamos National Laboratory at the incident proton energy of 800 MeV. Targets used for the experiment are in a mass range from aluminum to uranium. For emitted neutron energies over 100-300 MeV, the angular distribution is highly peaked forward. This tendency is more remarkable in targets of lighter mass. HETC fails to reproduce these experimental angular distributions.

The inelastic collision cross section is large in the free nucleon-nucleon interaction at an incident energy of around 800 MeV. For instance, the inelastic collision shares about half of the total cross section of proton-proton interaction at 800 MeV. The isobar model[6] considers the inelastic reaction in such a manner that a delta particle is first produced and then it dacays into a nucleon and pion. The delta particle is heavier than the nucleons by

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about 300 MeV. Since this value is relatively small in comparison to the incident energy of 800 MeV, the incident nucleon that produces the delta particle can be recoiled with a kinetic energy of still high value.

The angular distibution of delta particles is not derived from the isobar model used in HETC. There are not enough experiments to precisely determine the angular distribution of delta particles which are generated in nuclei. HETC offers three options on the angular distribution of delta paticles in c.m. system: (1) isotropic, (2) emission only in the direction of 0 deg. (forward) and 180 deg. (backward) with the same probability, (3) mixture of (1) and (2) in 50% each. These options, however, gives almost the same results for the neutron production, and fail to reproduce the experimental neutron spectra.

In the present study, we make a simple supposition on the angular distribution of delta particles. The range of emission angle is considered as an adjustable parameter. We, then, assume that the delta particles are emitted uniformly in the backward direction of an angle range of 135-180 deg.

Mean free path correction

The INCE code evaluates the mean free path of nucleons by using both the collision cross section between free nucleons and the nucleon number density in a target nucleus. In this evaluation, Pauli's exclusion principle is included. When results of the mass yield experiments are compared with the INCE predictions, the excitation energy after the INC process is considered to be much higher in the calculation than in the actual phenomena. This is attributed to the short mean free path of nucleons evaluated in a nucleus. When the mean free path is estimated from the imaginary part of optical model potential, it is certainly several times longer[9] than the value given by the INC model.

It may be useful to take the longer mean free path into account within the frame of the INCE calculation. The range of nucleon interaction is considered to be the sum of de Broglie wave length and the range of nuclear force. It may be possible for a few nucleons to be present within the interaction range[10].

In order to treat the problem within a frame of the INCE model, we assume that there is a probability of colliding with a nucleon cluster[11] in a nucleus. Discussions follow on this assumption later on in this paper. After the microscopic calculation on the nucleon-cluster collision, all nucleons are checked by Pauli's exclusion principle whether their energy exceeds the Fermi level. When this principle has been satisfied, the collision can be allowed. Otherwise, the collision is inhibited. Collisions are allowed with a less probability in the nucleon-cluster collision than in the nucleon-nucleon collision. Therefore, introduction of clusters in the INC process makes the mean free path longer.

Table 1 Probability for cluster collision as a function of energy

Energy (MeV)	Number of nucleons in a cluster 1	2	4
<130	0.1	0.3	0.6
130~200	0.3	0.3	0.4
200~300	0.5	0.3	0.2
>300	0.7	0.3	0.0

Appropriate values are taken as probability of the nucleon-cluster collision. Unlike the work of Mathews[11], the present method is not based on experimental data on collision between nucleon and light nucleus. This method is a kind of parametric approach. The cluster is considered to consist simply of 2 or 4 nucleons. The collision probalitity assumed is listed in Table 1. Since de Broglie wave length increases with decreasing the kinetic energy, the nucleon with lower kinetic energy tends to collide with 4 nucleon cluster. Formation of a 4 nucleon cluster has a larger probability for a nucleon of lower energy. As for the angular distribution in the nucleon-cluster collision, an isotropic scattering is assumed in c.m. system.

Introduction of preequilibrium process

Experimental neutron energy spectra show that they are composed of three components[12]. While the higher energy part is attributed to the cascade process, the lower comes from evaporation. It is suggested that the median energy part is caused by the preequilibrium process. This process is considered to cool nuclei further before the evaporation process is reached. It is desirable to add the pre-equilibrium process to the original INCE model. This HETC should be composed of three steps.

Gudima[13] advocated a cascade exciton model for nuclear reaction with a incident energy of ~100 MeV. We apply his approach to reactions in

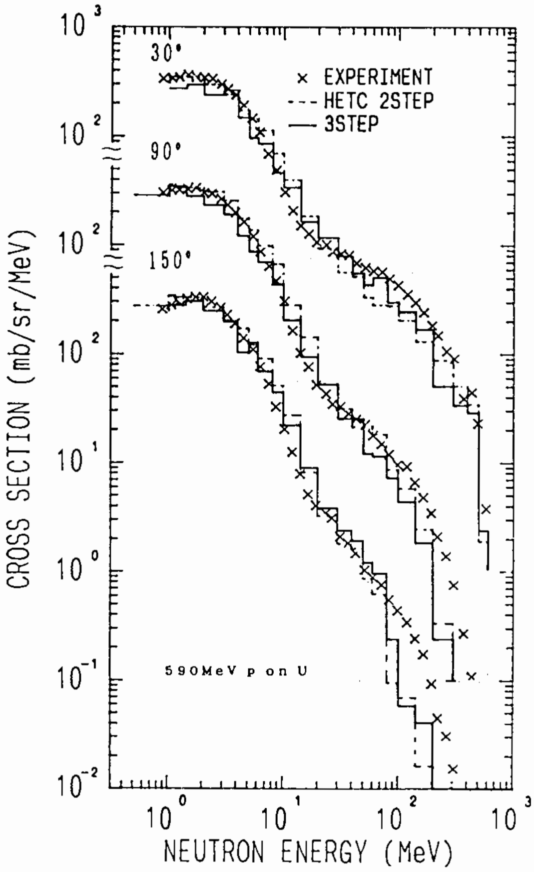

Fig. 1 Neutron production cross sections for incidence of 590 MeV proton on uranium.

the spallation region. A Monte Carlo algorithm was shown for a preequilibrium calculation by Nakahara and Nishida[14]. This algorithm is used for coding the program.

The present approach differs in some parts from the conventional exciton model. The configuration of two particles and one hole is usually adopted as the initial condition of the preequilibrium process. Instead, the initial number of excitons is considered to be equal to that of particles and holes that are generated in the INC process. For computation efficiency, the calculation is terminated when excitation energy per exciton becomes below a criterion which is defined appropriately. In this code, the particles considered range from proton to Li including their excited states.

The evaporation calculation is made following the preequilibrium process. The fission is taken into account as a process competitive to the evaporation.

Calculated results

Calculated results of neutron production cross section are shown in Fig. 1 by solid lines for 590 MeV proton incidence on a uranium target. The mark of the cross indicates the experimental data[15] of KfK. The dashed lines stand for results of the original HETC. Fig. 2 shows results for a lead target at 590 MeV. One can see in Figs. 1 and 2 that the solid lines show an improvement of the HETC. The effects of inelastic scattering are relatively small in this energy region, so that the assumption for angular distribution of delta particles has a very small contribution to this improvement.

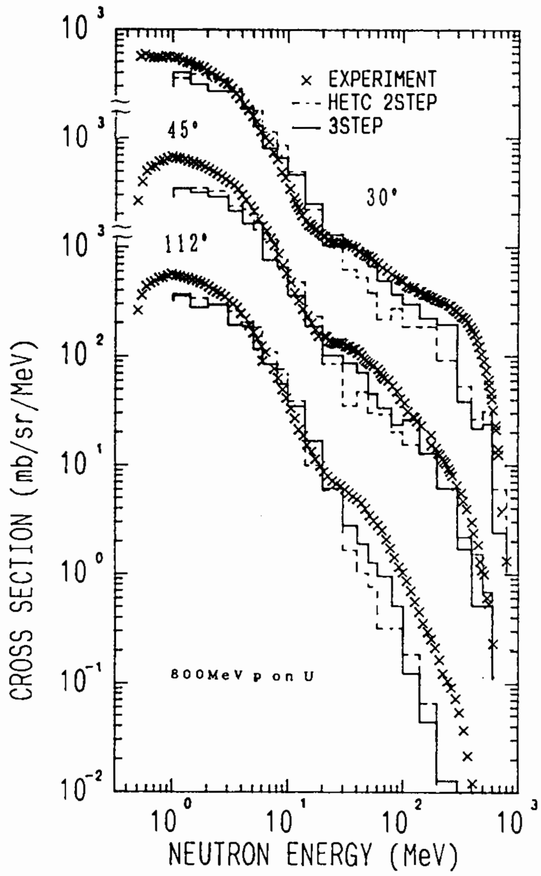

Fig. 3 Neutron production cross sections for incidence of 800 MeV proton on uranium.

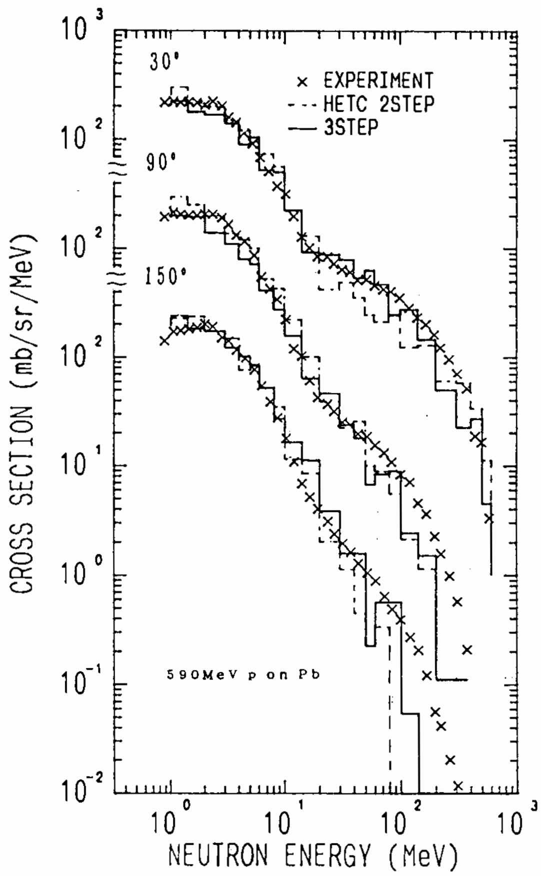

Fig. 2 Neutron production cross sections for incidence of 590 MeV proton on lead.

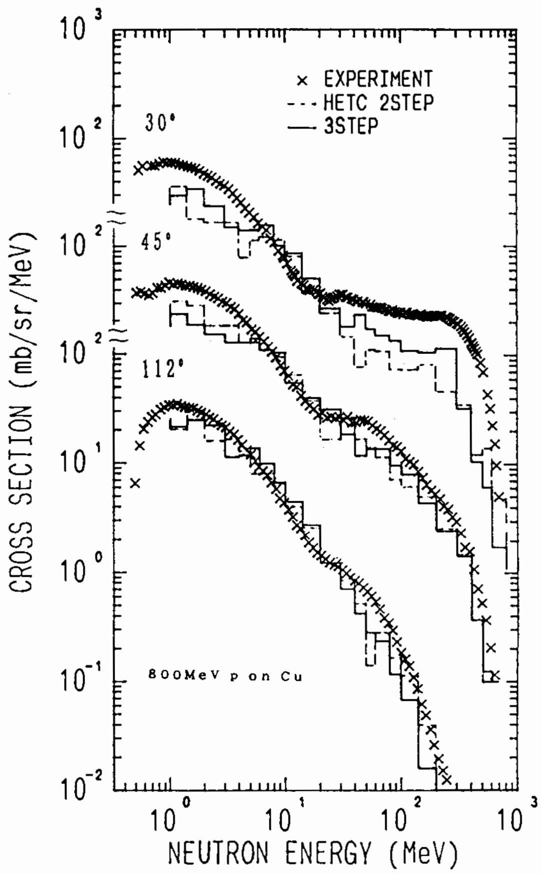

Fig. 4 Neutron production cross sections for incidence of 800 MeV proton on copper.

Results for the 800 MeV proton incidence are shown in Figs. 3 and 4 for targets of uranium and copper, respectively. The mark of the cross stands for the data[8] taken at Los Alamos National Laboratory. Solid curves reproduce the experimental data better than dashed curves. Agreements between solid lines and experimetal data are not sufficient for copper. A more elaborated study is required for such nuclei of relatively light mass.

Results of mass yields of residual nuclei are shown in Figs. 5 and 6 for gold targets[16]. The incident proton energy is 490 and 1000 MeV for Figs. 5 and 6, respectively. Improvements are obatined at the degree of the agreement between the calculation and the experiment. Both the lengthening of the mean free path and the introduction of the preequilibrium process successfully lower the excitation energy of the nuclei before the evaporation process takes place. The lower excitation energy is useful for decreasing the number of particles to be emitted from nuclei in the evaporation process. For this reason, results of the three step calculation come closer to the experimental mass yields.

Discussion

Collective, interferent or frictional phenomena may be induced in a nucleus in the energy region of the spallation reaction. Nevertheless, these phenomena cannot be described by a conventional INC model. The present study assumed that there is the probability of nucleon-cluster collision. Although its physical evidence is not quite clear, it served to improve the calculated results. The present supposition for the nucleon-cluster collision may equivalently represent these phenomena to some extent.

As an alternative approach, it can be considered to modify the momentum distribution of nucleons from the Fermi distribution[17]. When the high momentum component is intentionally increased, it may also result in the longer mean free path. By any means, such corrections of the mean free path may be required to describe the spallation reaction within a frame of the INCE model.

Conclusion

Both the angular distribution in the quasi-free inelastic scattering and the length of the mean free path of a nucleon were corrected in the high energy transport code. The exciton model calculation was inserted between the intranuclear-cascade and evaporation processes. The resultant three step code was found to improve the degree of the agreement of the calculated results with the experimental data.

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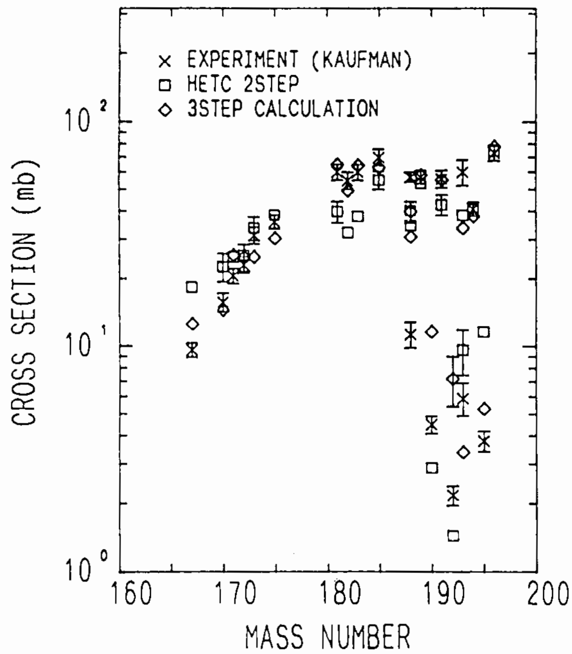

Fig. 5 Mass yields for incidence of 490 MeV proton on gold.

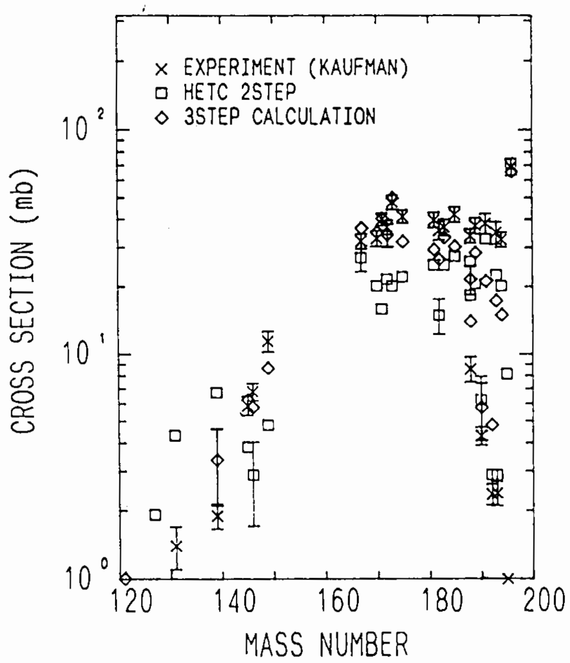

Fig. 6 Mass yields for incidence of 1 GeV proton on gold.