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ON THE VALIDITY OF THE INTRANUCLEAR-CASCADE AND EVAPORATION MODEL FOR HIGH-ENERGY PROTON INDUCED REACTIONS

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Abstract: Validity of the intranuclear-cascade and evaporation model is discussed on the basis of disagreement between experimental and theoretical double differential cross sections of a high-energy Pb(p,xn) reaction. Evaporation model assumptions, the impulse approximation and some scattering processes neglected in the intranuclear cascade are investigated. The effect of these processes is confirmed through analysis with an exciton model, which reduces the disagreement to some extent, but does not thoroughly dissolve it. The introduction of some physical processes is thus required.

(Pb(p,xn), E =590 MeV, DDX, spallation reaction, intranuclear-cascade-evaporation model, exciton model, analysis)

Introduction

Cierjacks et al./1/ and Meier et al./2/ have performed a number of systematic measurement of double differential cross sections(DDX) for the neutron production from various targets bombarded by 318, 590, and 800 MeV protons. They analyzed the measured DDX with the well-known high-energy transport code(HETC)/3/, in which the intranuclear-cascade and evaporation(INCE) model is incorporated.

For the experiment at 800 MeV, the theoretical DDX closely reproduced the measured DDX in the high-energy range(above 15 MeV), but the theoretical value exceeded the measured value by a factor of three or so in the evaporation-energy range(1 to 15 MeV). On the other hand, at 318 and 590 MeV, the HETC code predicted the measured DDX in the evaporation region, but substantially underpredicted it in the high-energy region, especially at large scattering angles.

This disagreement indicates that some basic assumptions of the INCE model may no longer be applicable in high-energy regions. Until now, the root cause of the disagreement has not yet completely identified, and no modified versions of the INCE model nor new alternative models which sufficiently reproduce the experimental results, have been developed.

This paper will discuss to what extent the assumptions of the INCE model are valid and whether or not alternative pre-equilibrium emission model can reproduce the experimental DDX.

We will reexamine the following approximations and assumption:

(1) low temperature approximation for the relation between the excitation energy of a compound nucleus and its temperature,

(2) the impulse approximation of the intranuclear-cascade model, and

(3) the assumption to neglect a certain two body scattering process which is not treated in the intranuclear-cascade model.

Analysis and Discussion

In this work, we will concentrate on analyzing the neutron data at the bombarding energy of 590 MeV/1/ for which several analyses by the HETC code have already been published/1//4//5/.

Problems of Evaporation Process

The disagreement between the measured and theoretical DDX increases when the target varies from C to U/5/, i.e. the HETC code closely reproduces the measured DDX for C, but poorly that for Pb.

Through calculations by the HETC code, we have found that the mean excitation energy of the residual nucleus at the end of the intranuclear-cascade process increases in proportion to the target mass number. For instance, the energy of the carbon target is only 30 MeV, but that of lead reaches 160 MeV. From this, we are led to believ that the level density formula derived under a low temperature approximation is inadequate for using HETC to calculate energy spectra of neutrons evaporating from the highly excited nucleus whose temperature is extremely higher than the Fermi energy. We thus considered this approximation as one of the reasons why the INCE model underestimates high-energy neutrons above 10 MeV, since these neutrons are difficult to evaporate as far as a value of standard level density parameters is used. We therefore decided to investigate if this underestimation can be improved by raising degrees of approximation of the expression between nuclear temperature and nuclear excitation energy(see Eq. (2)).

HETC adopts the usual well-known level density formula:

$$w(E) = \exp(2\sqrt{aE}), \qquad (1)$$

where E is the excitation energy and a the level density parameter. This form is derived from the first term of the relation

$$T = \frac{\pi}{4}A\frac{T^2}{E_f} - \frac{3\pi^3}{80}A\frac{T^4}{E_f^3} - \cdots, \qquad (2)$$

where A is the mass number, E_F the Fermi energy and T the nuclear temperature. One condition for neglecting the higher order terms in T, is

$$E << AE_F . \qquad (3)$$

This condition is sufficiently satisfied even in the calculation for the lead target since the right hand-side is nearly 7000 MeV, but the left hand-side is only 160 MeV. The approximation is thus very accurate, and the disagreement between the measured and calculated DDX can not be explained through problems with the approximation of the level density formula. Furthermore, improvement of the evaporation model will not eliminate the disasgreement because the experimental DDX shows forward peakeng angular distributions, while the theoretical DDX shows isotropic angular distributions.

Problems of Mean Free Path

Tsukada and Nakahara/6/ did not consider the impulse approximation, which is used in treatment of the nucleon-nucleon scattering process in the intranuclear-cascade model, as a good approximation, and suggested a modified calculating method in which a prolonged nucleon mean free path is used. This method increases the number of high-energy nutrons since the number of collisions decreases and the cascading nucleons can easily exit from nuclei.

They calculated the thick target yield of a Pb(p,xn)X reaction at 590 MeV/6/ making the mean free path(MFP) 1.1 times as large as the original one, and obtained an improvement in the disagreement between the experimental and calculated yield. We cannot, however, agree with their method.

First, we believe that the improvement occurred only in the thick target experiment and not in the thin one, such as Ref. 1. This is because in the former experiment transport process in target matter(the internuclear-cascade) is very important and thus not negligible, and because the process prevents the high-energy neutrons from exiting outside the target. On the other hand, this prevention effect does not exist at all in the thin target experiment.

Second, it is inacceptable to prolong MFP in all of the energy range from the incident energy to the cut-off energy, since the required condition for impulse approximation is well satisfied for the nucleon that is moving at the kinetic energy range above 130 MeV. At this energy, the de Broglie wave length of the nucleon reaches to the mean distance between two nucleons inside the nuclei.

Thus, we propose an alternative method to reduce the nucleon-nucleon scattering cross sections($\sigma_{N\text{-}N}$) for the nucleon below the energy at which the impulse approximation is no longer adequate. Contrary to previous results/6/, the disagreement between the experimental and calculated DDX could not be improved even though we used values of $\sigma_{N\text{-}N}$ 10 % smaller than the originals as was done in Ref. 6.

A recent experiment/7/ has shown that MFP calculated by the method of Kikuchi and Kawai/8/, which is theoretically similar to the method of HETC, is about half of the experimental values obtained by the optical model analyses from elastic scattering of 80-180 MeV protons. We thus tried to calculate DDX using values of $\sigma_{N\text{-}N}$ 75 % smaller than the original cross sections, but were still unable to eliminate the disasgreement. In particular, the neutron yield in the evaporation region was substantially underestimated since high-energy neutrons can easyly escape and the excitation energies of the residual nucleus decrease accordingly.

Analysis by HMB Model

Harp, Miller and Berne/9//10/ have developed a model which can be applied to nucleon-induced reactions at high incident energies(hereafter, we will refer to this as the HMB model). This model, in contrast to the intranuclear-cascade model of HETC, takes into account the scattering process among nucleons excited above the Fermi level. Though such a process may possibly increase high-energy neutrons and reduce the disagreement, unfortunately we cannot directly compare the exprimental DDX with the theoretical DDX because the HMB model does not formulate a calculating method of angular distributions. Thus, we calculated angle-integrated cross sections by both the HMB model and those by the HETC code, and high-energy neutron yield calculated by the HMB model exceeds that calculated by the HETC code by a factor of 2 to 3. This implies that the collision process is quite important and cannot be considered as negligible.

In the next section, we calculate angular distributions by utilizing an exciton model/11/, which is understood to be physically equivalent to the HMB model in treating the intranuclear-cascade process.

Analysis by Exciton Model

In order to resolve the disagreement between the experimental DDX and DDX calculated with the INCE model, Nakahara and Nishida/12/ have attempted to integrate a pre-equilibrium particle-emission process between the intranuclear-cascade process and the evaporation process. We cannot, however, support this attempt since Harp et al./10/ confirmed that upon finishing the intranuclear-cascade process, the nucleus has already reached a thermal-equilibrium state. We have thus adopted an alternative two step model consisting of the pre-equilibrium and equilibrium process.

Ramdom Walk Exciton Model The ramdom walk exciton model developed by Gudima et al./11/ assumes that the decay rate of the excited state (n,E) labeled by the exciton number n and the excitation energy E is given by

$$\Lambda(n, E) = \lambda_{+}(n, E) + \lambda_{0}(n, E) + \lambda_{-}(n, E) + \Sigma_{j}\, W_{j}(n, E), \tag{4}$$

where the first three terms are the internal transition rate and $W_j(n,E)$ is the total rate of emitting the particle of type j. Emission of protons and neutrons only was considered in accordance with HETC. For example, the first transition rate of (4) is calculated from

$$\lambda_{+}(n, E) = \langle \lambda_{+}^{NN}(u) \rangle, \tag{5}$$

$$\lambda_{+}^{NN}(u) = u\sigma(u)\rho, \tag{6}$$

where u is the relative velocity of the colliding nucleons, $\sigma(u)$ their quasifree-scattering cross-sections, ρ the number density of nucleus and the bracket(< >) denotes the average over all of the excited nucleons. The intranucler-transition rate $\lambda_{+}^{NN}(u)$ is averaged according to Ref. 13. The total emission rate of type-j particle is evaluated from the equations

$$W_{j}(n, E) = \int_{V_j}^{E-B_j} \lambda_{c}^{j}(n, \varepsilon)\, d\varepsilon, \tag{7}$$

$$\lambda_{c}^{j}(n, \varepsilon)\, d\varepsilon = \frac{(2S_j+1)\,\mu_j\,\sigma_{inv}(\varepsilon)}{\pi^2 \hbar^3} \cdot \frac{\omega(p-1, h, E-B_j)}{\omega(p, h, E)}\, d\varepsilon, \tag{8}$$

$$\omega(p, h, E) = \frac{g^{n} E^{n-1}}{p!\, h!\, (n-1)!}, \tag{9}$$

where the meaning of symbols follows Ref. 11.

The kinetic energy of the emitted nucleon is determined from (8). Note that the well-known level-density formula (9) by Ericson/14/, which is commonly used in a number of exciton models, is derived under the assumption that a nucleus is characterized by the model with single-particle levels equidistantly spaced, rather than the Fermi-gas model used in the INCE model of HETC. On this point, the two models are inconsistent, but we expect that the energy spectra are not so dependent on the forms of the level-density formula because only the level density ratio appears in (8). Further, for the sake of simplicity, we neglect the correction on (9) resulting from the

Pauli principle.

Angular Distributions We calculate directions of escaping nucleons by the method developed by Niita/15/, since Gudima et al./11/ do not provide a method of calculating angular distributions.

The direction is determined from the unnormalized distribution function

$$\lambda_c^j(n, \varepsilon, \Omega) \propto \left[E - B_j - \varepsilon - \frac{(\mathbf{P}-\mathbf{p})^2}{2\mu_j n}\right]^{\frac{3n-8}{2}}. \qquad (10)$$

where **p** is the momentum of the nucleon emitted and **P** the total linear momentum of the nucleus.

Evaporation Process from an Equilibrium State

Treatment of the equilibrium emission follows Ref. 11. The equilibrium state is defined as a state in which all internal transition rates become equally probable. Unlike the intranuclear-cascade process, we take into account the evaporation of six kind of particles, i.e., p, n, d, t, ^{3}He and ^{4}He.

Comparison with Experiment

We have developed a computational code which calculates DDX on the basis of the exciton model. The code is programmed in the Monte Carlo algolithm and is named MCEXCITON. Strictly speaking, we neglect the kinematical recoil effect of the target nucleus, pion production process and the effect of refraction and reflection at the nuclear surface, and transport process in a target material.

Throughout actual calculation, we used A/13 MeV^{-1} as the value of g, 37.5 MeV as the Fermi energy and 7.5 degrees as angular acceptance, and calculated DDX in such a way that its relative error was less than 10.0 %.

Figure 1 shows the calculated results by HETC together with the experimental data. We can clearly see that the calculations substantially underestimate the neutron yield above 30 MeV, especially at 90° and 150°.

Figure 2 shows the comparison of the measured DDX and the DDX calculated by MCEXCITON. The exciton model closely reproduces the data at 90° and 150°, although the model still underestimates the data at 30°.

We found that the angle-integrated energy-spectrum calculated by MCEXCITON coincides with those calculated by HETC, and thus believe that the discrepancy between the two DDX results from the different methods of calculation for angular distributions. We therefore conclude that the impulse approximation is not suitable even at this high-incident energy of 590 MeV.

Influence of Initial Exciton Number The energy spectra calculated by the exciton model are sensitive to the initial exciton number(n_0), and become soft in proportion to n_0. Hence, the disagreement between the experimental and calculated DDX, especially at 30° ,may possibly be improved if we change n_0. We thereupon attempted to obtain the optimized n_0 so as to reproduce the measured DDX as closely as possible, and found that $n_0=13$ gives the best fit for the data at 30° (see Fig. 3). On the other hand, agreement is worse in the high-energy part of the neutron spectra at 90° and 150°: where the calculated DDX considerably overestimates the measured one. In addition, the calculated spectra do not reveal the forward-angle peaking characteristic of the pre-equilibrium spectra, and are rather isotropic. Consequently, the agreement at 30° is probably due to mere coincidence and has no physical meaning.

Influence of Transition Rate If we increase the intranuclear-transition rate $\lambda_{+}^{NN}(n)$, the ratio of total internal-transition rate to the total emission rate will increase. The emission rate for large exciton numbers will increase as well. As a result, we expected that the calculated energy-spectra between 30 and 100 MeV may rise and closely reproduce the experimental results. Although we tried to perform such a calculation, agreement with the measured DDX at 30° was not obtained.

Influence of Level-Density Parameters The level-density parameter of the exciton model has the ability to change the shape of the energy spectra. We therefore calculated its influence, but we have been unable to obtain good results even though we varied the level-density parameter throughout the physicaly acceptable range.

Conclusions

We investigated the validity of some aproximations that are used within the intranuclear-cascade and evaporation model. We have found that the disagreement between the measured and calculated DDX cannot be improved even if the order of approximation in the evaporation model was raised. In order to take into account the effect of collisions among the excited nucleons above the Fermi energy, which effect is disregarded in the HETC code, we carried out a number of calculations with the exciton model, and found that the exciton model reproduces the measured DDX at both 90° and 150°, but fails to do so at 30°. From this result, we concluded that the use of the impulse approximation is inadequate at least for the calculation of angular distributions.

In conclusion, we now believe that the introduction of some physical processes, which were disregarded in this research, seems to be inevitable in order to resolve the disagreement between the experimental and theoretical DDX.

REFERENCES

1. S. Cieljacs et al.: Proc. Conf. on Nuclear Data for Science and Technology, Antwerp, Sept. 383(1982).
2. M. M. Meier et al.: Proc. int. Conf. on Nuclear Data for Basic and Applied Science, Sante Fe, New Mexico, 1415(1985).
3. K. C. Chandler and T. W. Armstrong: ORNL-4744 (1972).
4. T. W. Armdtrong and D. Filges: Proc. Conf. on Nuclear Data for Science and Technology, Antwerp, 387(1982).
5. D. Filges et al.: Jül-1960(1984).
6. K. Tsukada and Y. Nakahara: The 3rd Int. Conf. Emerging Nucl. Energy Systems, Helsinki, 186(1983).
7. A. Nadsen et al.: Phys. Rev. C23, 1023(1981).
8. K. Kikuchi and M. Kawai: 'Nuclear Matter and Nuclear Reactions'(North-Holland, Amsterdam, 1968), p. 33.
9. G. D. Harp et al.: Phys. Rev. 165, 1166(1968).
10. G. D. Harp et al.: Phys. Rev. C3, 1847(1971).
11. K. K. Gudima et al.: Yad. Fiz. 21, 260(1975); Engl. transl. in: Sov. J. Nucl. Phys. 21, 138(1975).
12. Y. Nakahara and T. Nishida: JAERI-M-86-074 (1986).
13. E. Gadioli et al.: Nucl. Phys. A217, 589(1973).
14. T. Ericson: Adv. in Phys. 9, 425(1960).
15. K. Niita: Z. Phys. A316, 309(1984).

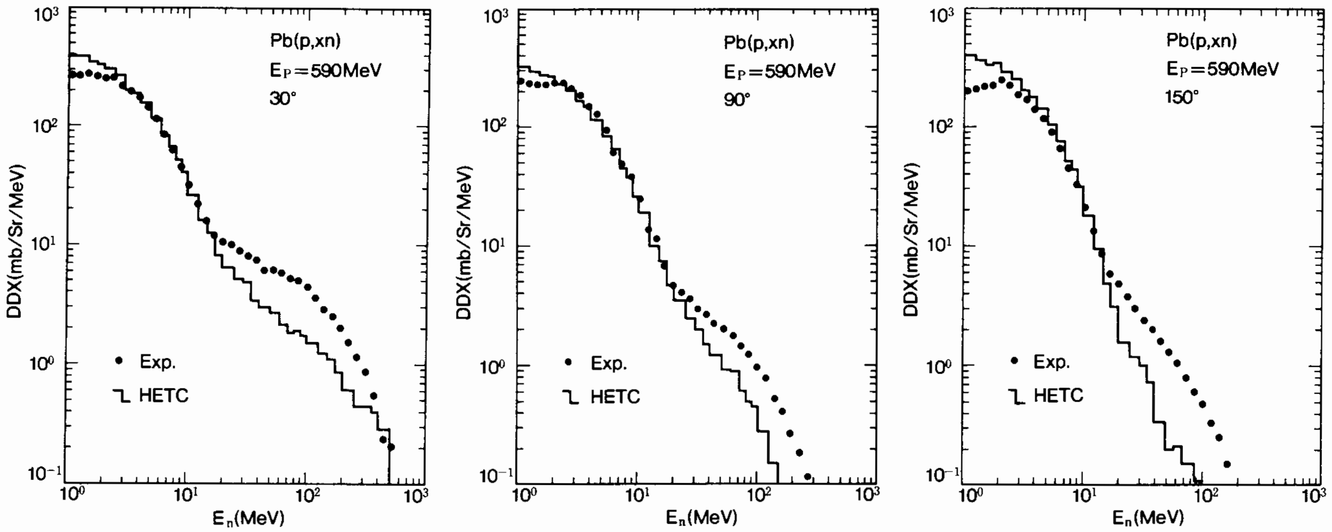

Fig. 1 Experimental and calculated DDX for neutrons emitted at 30, 90 and 150 deg. from a thin lead target for an incident proton energy of 590 MeV. The solid circles are the experimental data taken from Ref. 5. The solid curves are calculated with HETC.

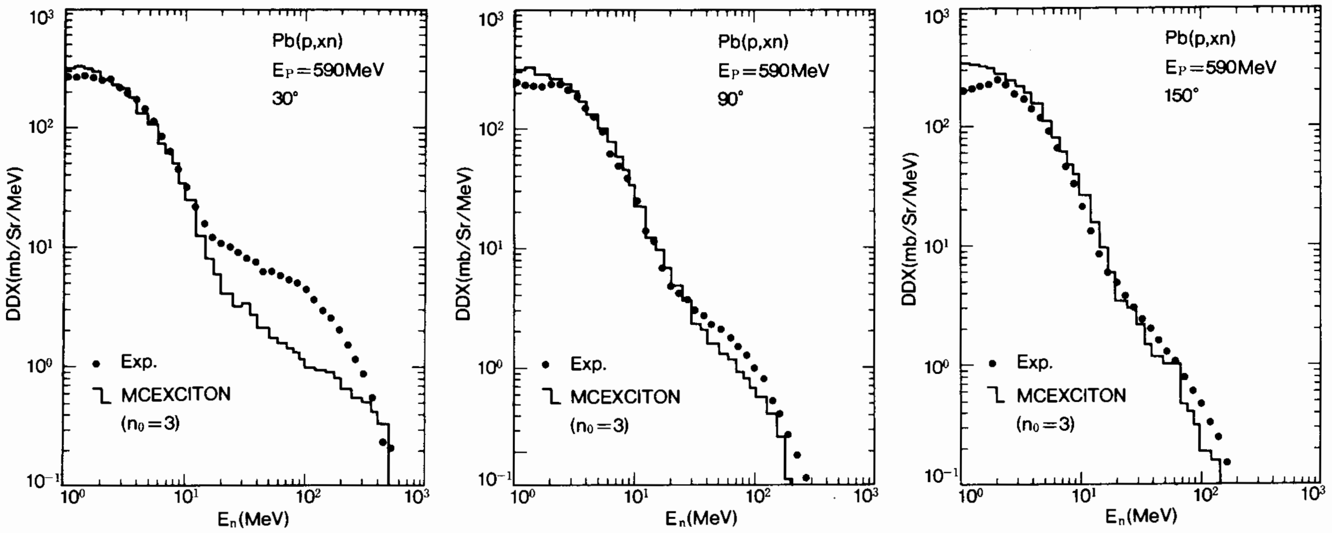

Fig. 2 Experimental and calculated DDX for neutrons emitted at 30, 90 and 150 deg. from a thin lead target for an incident proton energy of 590 MeV. The solid circles are the experimental data taken from Ref. 5. The solid curves are calculated with MCEXCITON. The initial exciton number is 3.

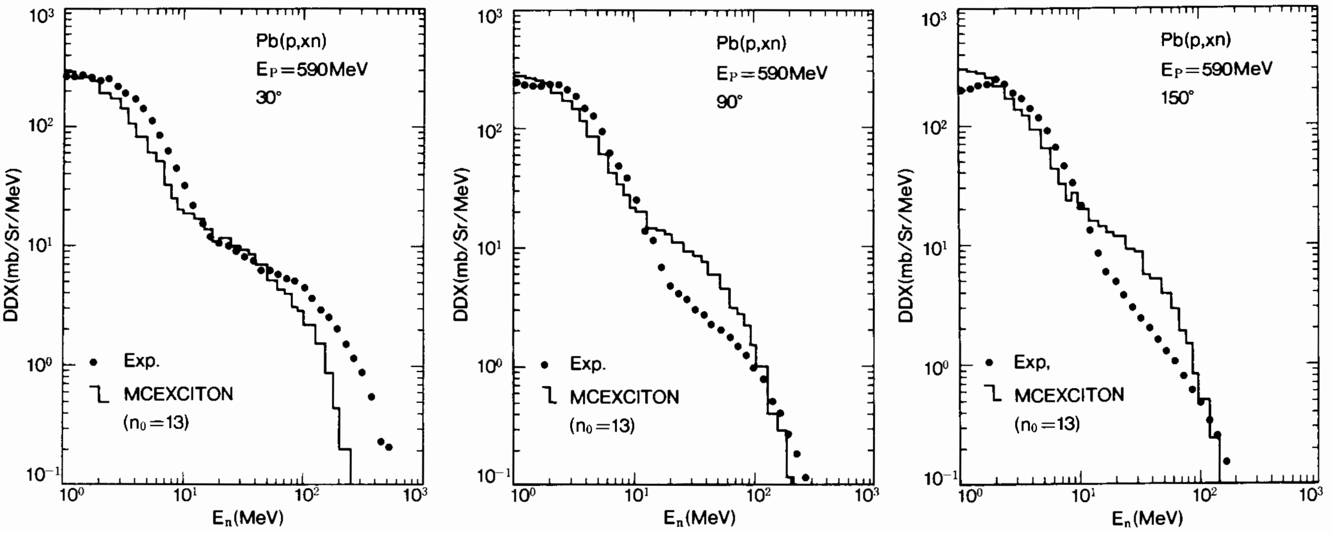

Fig. 3 Experimental and calculated DDX for neutrons emitted at 30, 90 and 150 deg. from a thin lead target for an incident proton energy of 590 MeV. The solid circles are the experimental data taken from Ref. 5. The solid curves are calculated with MCEXCITON. The initial exciton number is 13.