объединенный
институт
ядерных
исследований
дубна

E2-92-320

S.G.Mashnik*

NEUTRON-INDUCED PARTICLE PRODUCTION IN THE CUMULATIVE AND NONCUMULATIVE REGIONS AT INTERMEDIATE ENERGIES

Submitted to "Nuclear Physics A"

---

*E-mail address: MASHNIK@THEOR.JINRC.DUBNA.SU

1992

1. Introduction

One of the frequently used ways to investigate the quark degrees of freedom of nuclei or to search for signals of the phase transition from hadron matter to quark-gluon plasma is studying the emission of fast particles at backward angles into the kinematically forbidden for quasi-free projectile-nucleon interaction region, the so-called cumulative particles. Various efforts, both experimental and theoretical have been made for this purpose not only at high energies of projectiles but also at intermediate ones (see reviews [1-3]).

More than fifty rather different models have been proposed to interpret the cumulative particle production (see the last reviews [1-3]). So among them one can mention models based on:

a) enhanced two-nucleon correlations or short-range order [4-6],

b) reinteraction, multiple scattering, intranuclear cascade [7-9],

c) clustering of nucleons as six-quark or larger clusters, nuclei as a quark-gluon systems [10-13].

Note should be made that the majority of these models have been proposed namely to interpret the cumulative particle production by means of special mechanisms, consider only single-particle scattering process and neglect the effects of rescattering and final state interaction, nevertheless, they succeeded in fitting the shape of experimental particle spectra.

It is of interest to estimate the contribution of "background" usual nuclear mechanisms in the framework of models that are not specially proposed for the description of the cumulative particle production. Such a model is for example our Cascade-Exciton Model (CEM) of nuclear reaction [14]) proposed from the outset to describe nucleon-nucleus reactions at bombarding energies below or ~ 100 MeV and developed after that [15]) for the description of the stopped negative pion absorption by nuclei. The CEM has been afterwards applied [16]) without any modifications to analyze the cumulative particle production in interactions of protons and pions with nuclei from C to Bi at energies of several tens of MeV up to several GeV. It has been found out that the energy spectra of inclusive cumulative particles as well as their A and angular dependences within this model are qualitatively reproduced. The main aspects of the analysis [16]) were found to be the following:

a) The cumulative nucleons at the cascade stage arise mainly from a two-step process, i.e., pion production in projectile-nucleon collisions

$$h + N \to \pi + N_1 + N_2, \qquad (1)$$

followed by absorption on nucleon pairs within this target-nucleus

$$\pi + [NN] \to N' + N'', \qquad (2)$$

while multiple elastic scattering of the projectile is found to be inessential for the cumulative nucleon emission. (Process (2) has been approximated by using experimental data of photo-nuclear reaction on deuterium.)

b) Only a small number (3-5) of collisions proceeds during the cascade development and this number is practically independent of the target mass number A (according to the processes (1) and (2) at least 3 nucleons must be involved in the cascade process).

c) The pre-equilibrium component for medium and heavy target-nuclei follows the course of cumulative nucleon spectra, and its intensity is comparable with the cascade component (at least for not too high particle energies).

Our CEM calculations have shown statistical mechanisms to play an essential role in the inclusive cumulative particle production at bombarding energies up to several GeV and for ejectile energies up to ~ 300 MeV. While at bombarding energies sufficiently below the pion production threshold the cumulative particle emission is dominated by pre-equilibrium processes, with increasing energy the cascade mechanism becomes essential. However, even at energies beyond one GeV the contribution of the pre-equilibrium process must be taken into account. For instance, in pPb interactions at 1.5 GeV both the cascade and pre-equilibrium components contribute with the same intensity to the proton yield at $\Theta_p = 160°$ and $T_p \approx 50$ MeV [16]).

Almost all measurements of the cumulative particle production at intermediate incident energies ≤ 1 GeV have been performed with protons as projectiles. To understand the underlying mechanism of particle production at these energies neutron-induced processes are as important as those of protons. Recently, the first systematic data of neutron-induced inclusive production of p, d, t [17]) and charged pions [18]) on C, Cu, and Bi in the bombarding energy range of 300-580 MeV and for angles between 51° and 165° have been published. These data are very interesting for several reasons. So even these measurements have been performed with special emphasis [17,18]) on the cumulative region; ejectile spectra in the noncumulative region have been also measured with a good energy resolution and statistics. To our knowledge, these measurements [17,18]) are in general the first in which neutron-induced charged particle spectra at intermediate energies have been obtained (besides the early neutron-induced pion production at 600 MeV measured by Oganesyan [19]). Another motivation for the study [17,18] of inclusive particle production by neutrons arises from the increasing interest for particle production in nucleus-nucleus interactions. The results on the nucleon-nucleus reactions can be considered as an intermediate step and can serve as a valuable input for testing models. For this purpose results on neutron-induced particle production are again as important as those obtained by protons. At last, the measurements [17,18]) are of particular interest also for an important applied purpose. Recently, studies on transmutation of long-lived radionuclides produced in reactors are receiving increased attention [20]). One option investigated is transmutation with a spallation source. A large amount of neutron- and proton-induced nuclear reactions data is required for the optimized design of such a device covering the energy range up to 1.5 GeV. The measured [17,18]) cross sections are of interest both as the first experimental data at these intermediate energies and for testing the models which may be used to provide the necessary data.

The aim of this paper is to analyze these new data in the framework of the CEM; to reveal the role of single-particle scattering, the effects of rescattering, the pre-equilibrium emission and "coalescence" mechanism in particle production; to elucidate to what extent one needs certain specific mechanisms for describing the observed cumulative particle and to study the sensitivity of the characteristics to the interaction mechanism considered; finally, to test the CEM for neutron-induced reactions at intermediate energies.

2. Basic assumptions of the CEM

A detailed description of the CEM may be found in [14]). Therefore, only its basic assumptions are considered below. The CEM assumes that the reactions occur in three stages. The first stage is the intranuclear cascade in which primary particles can be rescattered several times prior to absorption by, or escape from the nucleus. The excited residual nucleus formed after the emission of the cascade particles determines the particle-hole configuration that is the starting point for the second, pre-equilibrium stage of the reaction. The subsequent relaxation of the nuclear excitation is treated in terms of the exciton model of pre-equilibrium decay which includes the description of the equilibrium evaporative stage of the reaction.

So in a general case three components will contribute to each experimentally measured value. In particular, for the inclusive particle spectrum to be discussed later, we have

$$\sigma(\mathrm{p})dp = \sigma_{in}[N^{cas}(\mathrm{p}) + N^{prq}(\mathrm{p}) + N^{eq}(\mathrm{p})]dp$$

The inelastic cross section σ_{in} is not taken from the experimental data or the independent optical model calculations, but it is calculated within the cascade model itself. So the CEM enables us to predict the absolute values for the calculated characteristics and does not require any additional data or special normalization of its results.

An important point of the CEM is the condition for passing from the intranuclear cascade stage to the pre-equilibrium emission. In the conventional cascade-evaporation models fast particles are traced up to some minimal energy, the cut-off energy T_{cut} being about 7-10 MeV below which particles are considered to be absorbed by the nucleus. In the CEM it is suggested to use another criterion according to which a primary particle is considered as a cascade one, namely the proximity of the imaginary part of the optical potential $W_{opt.mod.}(r)$ calculated in the cascade model to the experimental one $W_{opt.exp.}(r)$. This value is characterized by the parameter

$$\mathcal{P} = \mid (W_{opt.mod.} - W_{opt.exp.})/W_{opt.exp.} \mid .$$

In this work, we use the fixed value $\mathcal{P} = 0.3$ extracted from the analysis [14,16]) of experimental proton-nucleus data at low and intermediate energies.

One should note that in the CEM the initial configuration for the pre-equilibrium decay (number of excited particles and holes, i.e., excitons $n_0 = p_0 + h_0$, excitation energy E^* and linear momentum $\mathbf{P}$ of the nucleus) differs strongly from that usually postulated in the exciton models. Our calculations [14−16]) show that the distributions of residual nuclei formed after the cascade stage of the reaction, i.e., before the pre-equilibrium emission with respect to n_0, p_0, h_0, E^* and $\mathbf{P}$ are rather broad.

In nucleon-nucleus reactions complex particles can be produced at different interaction stages and due to many mechanisms. These may be some fast processes like direct knocking-out, pick-up reaction or final state interactions resulting in coalescence of nucleons into a complex particle. In the present version of the CEM we neglect all these processes at the cascade interaction stage. Therefore, fast d and t regarded here can appear, for example, in the CEM only due to pre-equilibrium processes. We assume that in the course of the reaction p_j excited particles (excitons) are able to condense with probability γ_j forming a complex particle which can be emitted during the pre-equilibrium state. The "condensation" probability γ_j is estimated as the integral of overlapping the wave function of independent nucleons with that of the complex particle (cluster). Of course, at the compound stage of the reaction slow complex particles may be evaporated equally with nucleons. We include into consideration emission of d, t, ^3He and ^4He both at the pre-equilibrium and the evaporative stages of reaction.

Pions in our CEM arise from the process (1) and leave the nucleus either directly or after additional elastic rescatterings at the cascade stage of the reaction.

The cascade stage of the interaction is described by the Dubna version of the intranuclear cascade model [21]). All the cascade calculations are carried out in the three-dimensional geometry. The nuclear matter density is described by the Fermi distribution with two parameters taken from the analysis of the electron-nucleus scattering. The energy spectrum of nuclear nucleons is estimated in the perfect Fermi gas approximation with the local Fermi energy. For characteristics of the hadron-nucleon interactions we employ the approximations given in [21]). In this version of the cascade model [21]), the production of boson resonances in the intermediate states are not taken into account explicitly. The pion-nucleus interaction potential was taken to be equal to 25 MeV, being independent of the pion energy. The change of the nucleon density inside the target in developing the cascade is not taken into account. We take account of the diffusivity of the nuclear boundary and nuclear potential as well as the exclusion principle effect on intranuclear collisions of nucleons.

The CEM predicts asymmetrical angular distributions for secondary particles. Firstly, this is due to high asymmetry of the cascade component (for ejected nucleons and pions). A possibility to have asymmetrical distributions for nucleons and composite particles emitted during the pre-equilibrium interaction stage is related to keeping some memory of the direction of a projectile. It means that along with the energy conservation law we need to take into account the conservation law of linear momentum $\mathbf{P}$ at each step when a nuclear state is getting complicated. In a phenomenological approach this can be realized in different ways [14]). The simplest way used here consists in sharing a bringing-in momentum $\mathbf{P}_0$ (similarly to energy E_0) between an ever increasing number of excitons involved in the interaction in the course of equilibration of the nuclear system. In other words, the momentum $\mathbf{P}$ should be attributed only to n excitons rather than to all A nucleons. Then, particle emission will be isotropic in the proper n-exciton system but some anisotropy will arise in both the laboratory and center-of-mass reference frame.

It should be noted that the version of the intranuclear cascade model used here does not take into account the clusterization of nuclear nucleons and exchange effects; besides, the energy spectrum of nuclear constituents is limited by the value of the Fermi energy. Therefore, noticeable deviations might be expected between the CEM predictions and experiment for cumulative characteristics.

In the present paper, all the CEM parameter values are fixed and are the same as in [14]).

3. Results and Discussion

We have analyzed in the CEM the entire set of neutron-induced data measured and published [17,18]) in different representations (double-differential cross sections, invariant cross sections, angular distributions, excitation functions). As measured and calculated characteristics show a fundamental similarity and particle production depends in a monotonic and systematic way on the target mass number, incident neutron energy and particle emission angle, later on we will confine ourselves to the discussion of some exemplary results. In fig. 1 measured [17]) and calculated inclusive spectra of protons are shown. The CEM reproduces well the change in the spectrum shape with increasing emission angle and in passing from light to heavy target-nuclei, providing the right absolute values for the particle yield for all incident energies.

To illustrate the relative role of different proton production mechanisms in the upper part of fig. 2, as an example, for neutron-copper collisions at 425 MeV the cascade, pre-equilibrium and the evaporative components of proton spectra are shown separately. One can see that for slow protons the main contribution to the spectra comes from the evaporation from compound nuclei, while with increasing ejectile energy the emission at the cascade and pre-equilibrium stages becomes decisive. The cascade component describes almost the whole measured spectra at forward angles but with increasing angle of detection the relative role of the pre-equilibrium component rises considerably, and for very backward angles and proton energies less than 80 MeV the contribution of pre-equilibrium emission becomes comparable with the cascade ones. For lighter C nuclei the pre-equilibrium processes are less important but for heavier Bi targets the pre-equilibrium emission contributes more essentially to the hard part of backward emitted particle spectra than for Cu ones. The measured protons correspond to the sum of all three CEM components; therefore there is an agreement for energy spectra in both the shape and absolute value in the entire range of angles and energies of ejectiles, both in the cumulative and noncumulative regions.

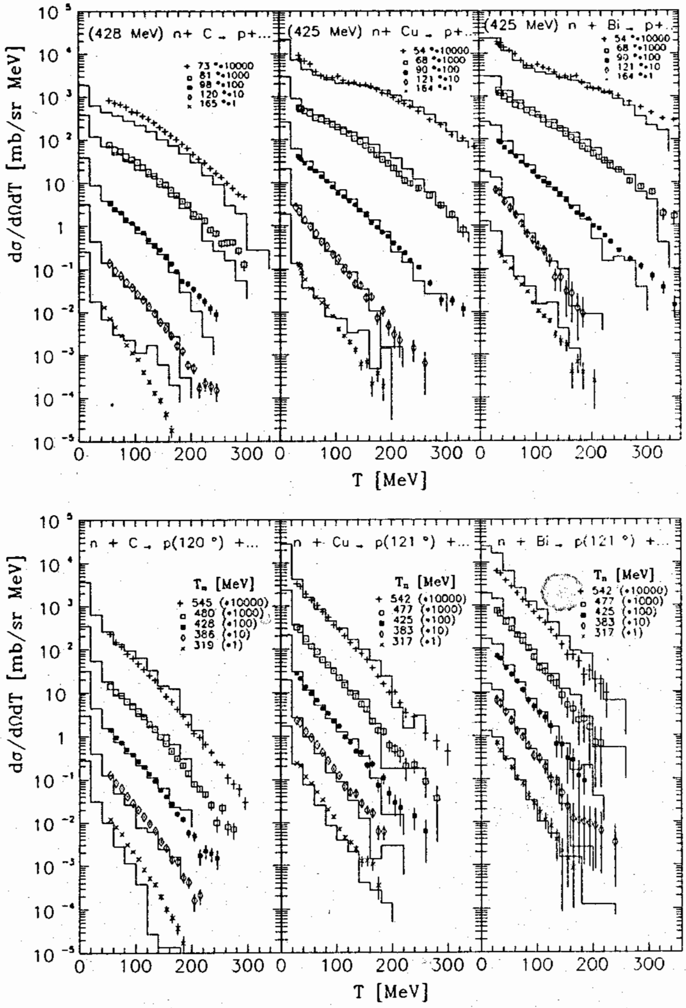

Fig. 1. Measured 17) inclusive proton spectra (symbols) and CEM calculations (histograms). Different emission angles (upper row) and different incident energies (lower row) are drawn with symbols as indicated. The histograms are the sum of all three CEM (cascade, pre-equilibrium and evaporative) components.

To have a more detailed picture of the mechanisms of nucleon production at the cascade stage of the reaction we have estimated the contribution to the cross sections from the events with different value n_c of the number of successive intranuclear interaction acts before proton emission and from events which contain the two-step process (1-2) as intranuclear interaction acts in the course of the reaction. As an example, in the lower part of fig. 2 the contributions to the spectra of protons emitted at the cascade stage of neutron-copper collisions at 425 MeV from events which contain the two-step process (1-2) and from events with $n_c = 1$ and $n_c > 5$ are shown separately.

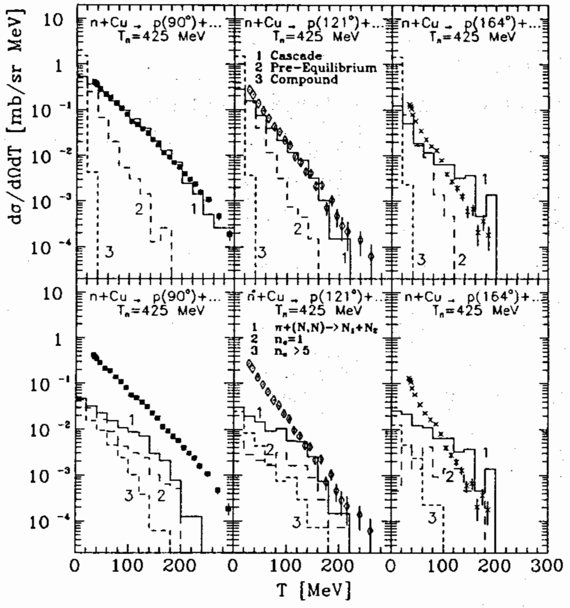

Fig. 2. Inclusive proton spectra from the neutron-copper collisions at 425 MeV. **Upper row:** the histograms 1, 2, and 3 show the contribution of cascade, pre-equilibrium, and evaporative components, respectively; **lower row:** for cascade component the histograms 1, 2, and 3 show the contribution from events which contain the two-step process (1-2) in the course of the reaction (including all possible former and/or subsequent intranuclear collisions), the contribution from the events with $n_c = 1$, and $n_c > 5$, respectively. The value n_c is the number of successive interaction acts before proton emission in the events contributing to the corresponding histograms.

One can see that for fast backward emitted protons, as in the case of proton-induced reactions 16), the two-step mechanism (1-2) contributes essentially to the hard part of spectra and its relative role increases with the angles and energies of ejected protons. In the majority of cases, fast protons are emitted in the backward direction after 2-4 acts of intranuclear interactions, while the contributions from events in which protons are emitted during the first quasi-free interaction of bombarding neutron with an intranuclear proton ($n_c = 1$; a mechanism similar to that proposed in [4]) or after many acts of successive intranuclear collisions (large value of n_c; a mechanism similar to that proposed by Kopeliovich [7]) are lower than 10%. The relative role of the processes with different values of n_c can be better seen in fig. 3, where the measured angular distribution of fast protons from $n(542 MeV) + Bi$ collisions is shown together with the CEM prediction for the sum of all three CEM reaction mechanisms (the upper histogram in the lower-right part of figure) and separately for the cascade components with different n_c. The largest contribution to the fast backward proton emission comes from events with $n_c = 2 - 4$.

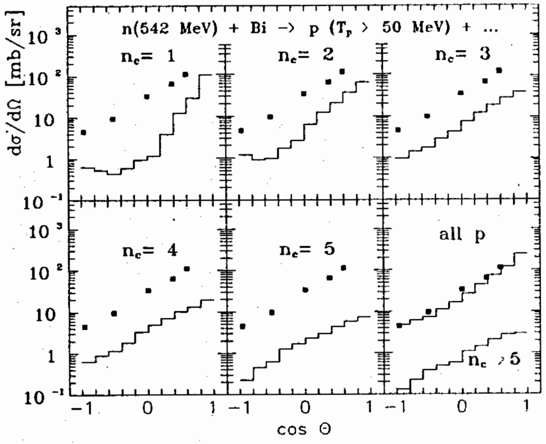

Fig. 3. Angular distributions of fast protons ($T_p > 50$ MeV) from the neutron-bismuth collisions at 542 MeV. The sum of all CEM components (in the lower-right part) and the contribution from cascade particles with different values of n_c are shown as indicated. Experimental points [17]) are related to the sum over all emission mechanisms.

As one can see from fig. 4, the mean number of acts of intranuclear collisions involved in the backward emission of fast protons $< n_c >$ is about 2.5 for C nuclei-targets and increases weakly up to ~ 3 for Bi ones and practically does not depend on bombarding energies regarded here.

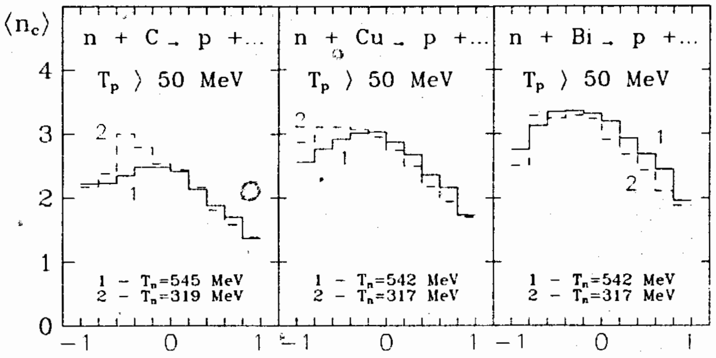

Fig. 4. The averaged value of the number of interacting acts $< n_c >$ in the events contributing to the emission of fast protons ($T_p > 50$ MeV) at the cascade stage of reaction as a function of $cos\Theta$ of the ejectiles as indicated.

As an example, fig. 5 shows inclusive spectra of secondary neutrons from neutron-copper collisions at 425 MeV predicted by the CEM. Our analysis has shown that the mechanisms of neutron production are the same as of proton ones.

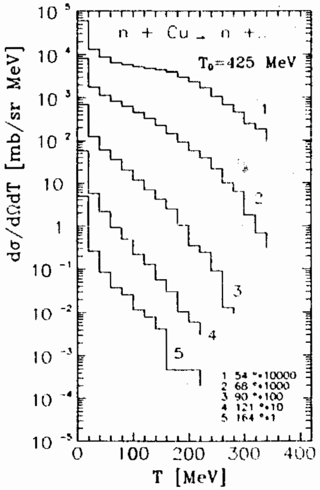

Fig. 5. The CEM predictions of neutron spectra from neuron-copper collisions at 425 MeV.

Figs. 6 and 7 show inclusive spectra of deuterons and tritons measured 17) and calculated in the CEM, and, as an example, fig. 8 shows inclusive spectra of ^3He and ^4He from neutron-copper collisions at 425 MeV predicted by the CEM.

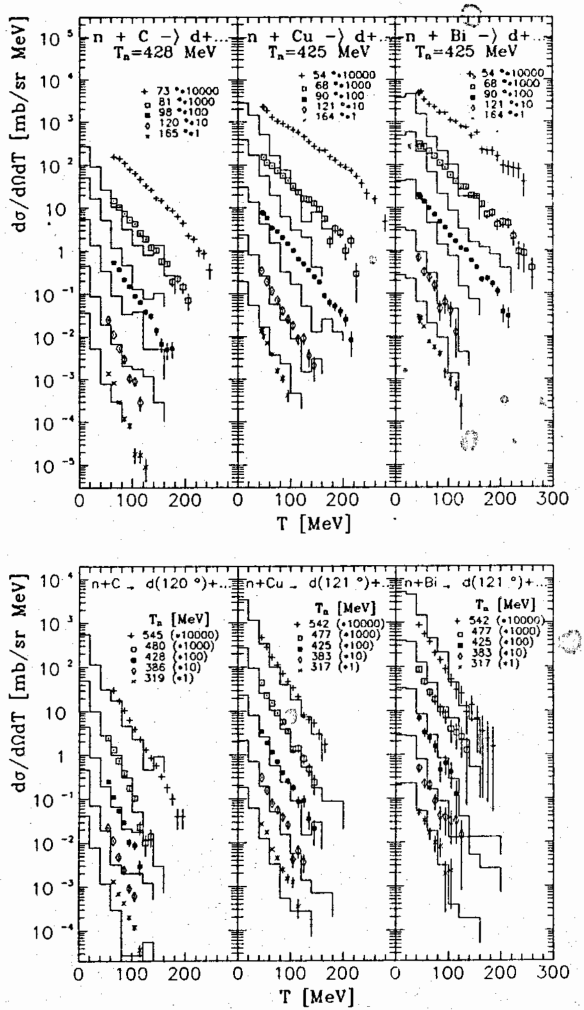

Fig. 6. Inclusive deuteron spectra; histograms are the sum of pre-equilibrium and evaporative components calculated within the CEM, the rest notation is the same as in fig. 1.

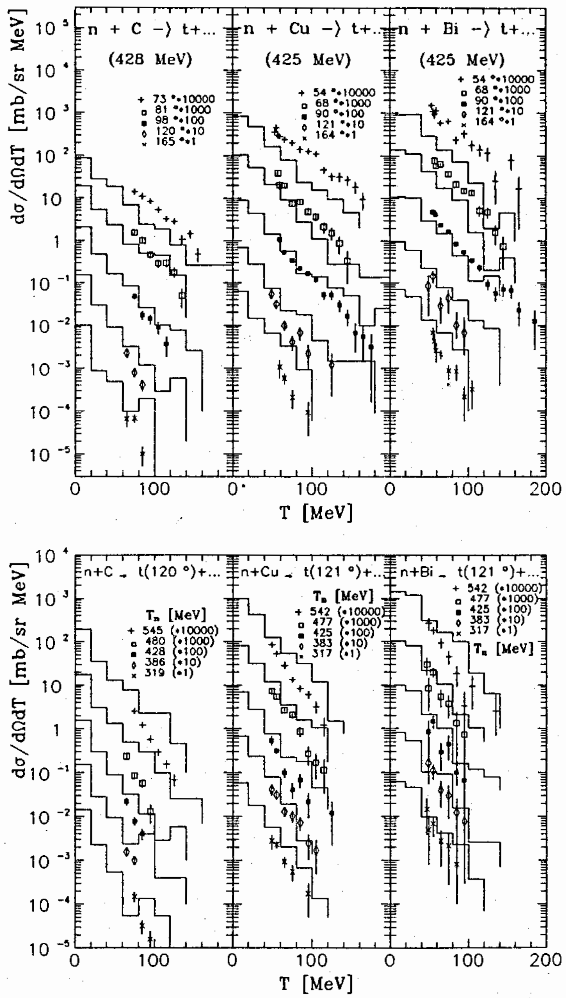

Fig. 7. Inclusive spectra of tritons. Notation is the same as in fig. 6.

The low energy parts of the complex particle spectra calculated in the CEM are formed by the complex particles evaporated at the compound stage of the reaction, while the high energy ones are determined by the pre-equilibrium emission. It can be seen that the CEM reproduces correctly the shape and the absolute value of the backward complex particle spectra. Some overestimations in the case of very backward fast tritons are probable, caused by the using here the fixed set of the CEM parameter values fitted at bombarding energies ≤ 100 MeV. To describe better the complex particle spectra at these intermediate energies we have also to take into account the dependence of the level-density parameter a on the excitation energy E^* of nuclei and to calculate more carefully the "condensation" probabilities γ_j.

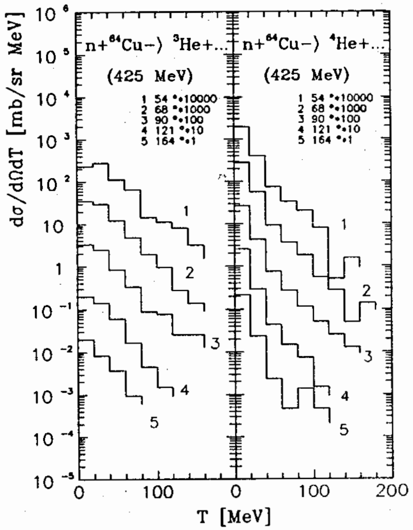

Fig. 8. CEM predictions for ${}^3He$ and ${}^4He$ spectra from neutron-copper collisions at 425 MeV.

So the CEM predicts a great contribution to the measured complex particle spectra from the pre-equilibrium processes and for fast backward emitted deuterons and tritons this contribution is comparable with the experimental data. But for forward angles the CEM gives a strong underestimation of the experimental data. This happens because we neglect in our approach such fast processes of complex particle production as pick-up, knocking-out and coalescence of complex particles from fast nucleons emitted at the cascade stage of the reaction. All these processes contribute especially to the forward complex particle emission and their disregard in the CEM results in such an essential underestimation of the forward emitted complex particle spectra.

To estimate the contribution of the "coalescence" mechanism in complex particle production we use here the coalescence model frequently applied $^{22-25}$) for the description of heavy-ion-induced reactions.

Let us use as an input for the coalescence model the calculated above spectra of the neutrons $d^2\sigma_n/(dTd\Omega)$ and protons $d^2\sigma_p/(dTd\Omega)$ emitted at the cascade stage of the reactions. For the coalescence component of the complex particle spectra in our neutron-induced reaction case we have

$$\frac{d^2\sigma_f^{coal}}{dTd\Omega} = \left(\frac{4\pi p_0^3\gamma}{3\sigma_{in}Ep}\right)^{x+y-1} \frac{1}{x!y!}\left(\frac{1+N_t}{Z_t}\right)^y \left(\frac{d^2\sigma_n}{dTd\Omega}\right)^y \left(\frac{d^2\sigma_p}{dTd\Omega}\right)^x,$$

where T is the complex particle laboratory kinetic energy per nucleon, x is the number of protons and y is the number of neutrons in the complex particle, N_t and Z_t are, respectively, the neutron and proton number of the target; σ_{in} is the neutron-nucleus reaction cross section calculated above in the CEM. The values of radius of the momentum sphere for coalescence p_0 (or $\tilde{p}_0$)

$$\tilde{p}_0 = p_0\left(\frac{2^A}{A^3(2s+1)}\right)^{\frac{1}{3(A-1)}}$$

(s is the spin of the complex particle and $A = x + y$) are free parameters of the coalescence model and usually are fitted for every target, projectile, incident energy and ejectile. Here, for p_0 we use values (see table 1) close to ones used $^{22-25}$) for the description of heavy-ion-induced reactions at the similar bombarding energies per nucleon.

Table 1

Values for the coalescence parameters p_0 and $\tilde{p}_0$ (MeV/c)

Ref.	System	Bombarding energy (MeV/A)	Complex particle	p_0	$\tilde{p}_0$
$^{22-24}$)	${}^{20}Ne+U$	400	d	129	71
			t	129	94
	${}^4He+U$	400	d	126	69
			t	127	92
^{25})	$Ne+U$	400	d	205	113
			t	207	150
Present work	$n+C$	319÷545	d	174	96
			t	179	130
	$n+Cu$	317÷545	d	162	89
			t	129	94
	$n+Bi$	317÷542	d	129	71
			t	129	94

Figs. 9 and 10 show measured inclusive spectra of *d* and *t* and the sum of the CEM and of coalescence model predictions for them.

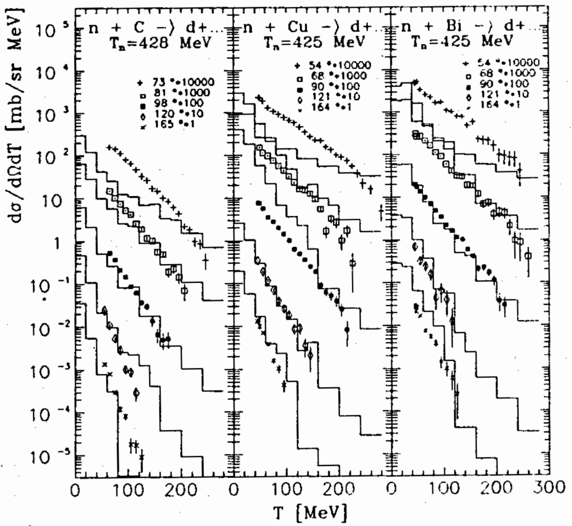

Fig. 9. Measured [17]) inclusive deuteron spectra and the sum of the CEM and the coalescence model calculations. The histograms are the sum of pre-equilibrium, evaporative, and coalescence components.

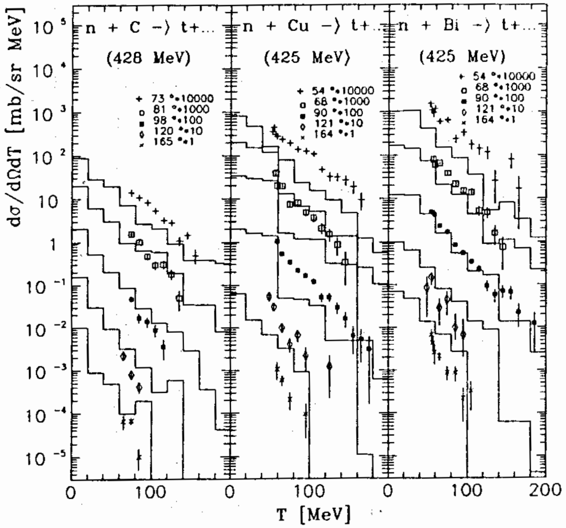

Fig. 10. Inclusive spectra of tritons. Notation is the same as in fig. 9.

One can see that the disagreement (see figs. 6 and 7) between the calculated and measured spectra at forward angles decreases. But some underestimation still remains, which indicates pick-up and knocking-out processes neglected in our calculations.

No charge separation of the pions has been possible in the experiment [18]), so the sum of pions of both charge states was measured. As an example, in fig. 11 a part of measured [18]) charged pion spectra is compared with our CEM calculation.

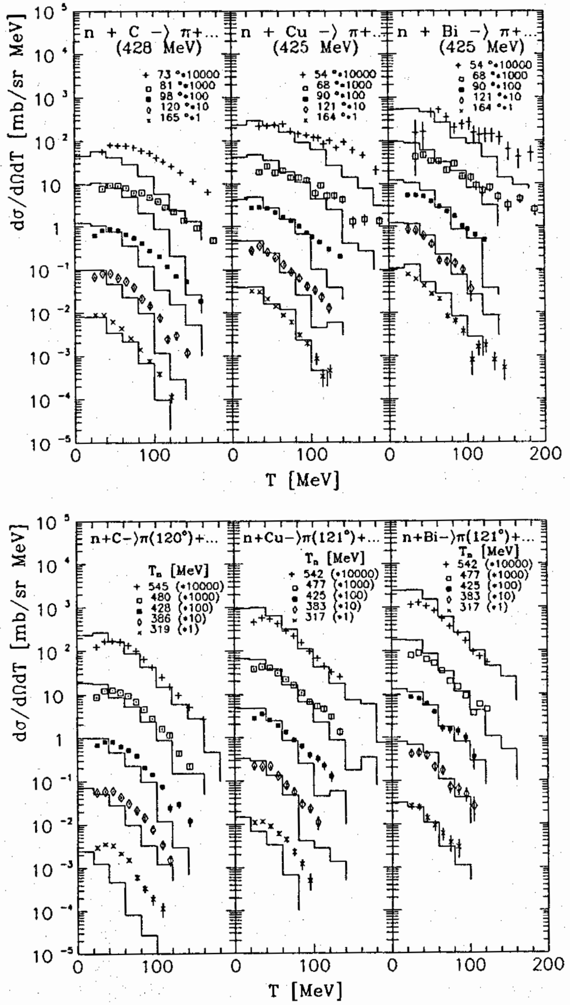

Fig. 11. Inclusive spectra of charged pions. The histograms are the CEM calculations, the symbols are experimental data [18]) as indicated.

The general agreement between the calculations and the data is good, both in the cumulative and non cumulative regions, taking into account that no normalization was applied to adjust the calculations. The pions in the CEM arise only from intranuclear inelastic collisions of nucleons (1) followed (or not) by additional elastic intranuclear scatterings. As one can see from fig. 11, this simple mechanism of pion production is able to reproduce satisfactorily the shape and the absolute value of pion spectra simultaneously for all regarded here nuclei-targets and bombarding energies even at 317 MeV which is about 30 MeV above the threshold for elementary production. This reflects the influence of the nuclear medium by means of Fermi motion and in the CEM one doesn't need production on effective targets or clusters with masses larger than the nucleon mass or other specific mechanisms for the description of pion production in these reactions.

The Monte Carlo CEM method permits easily the calculation of the characteristics of ejected pions separately for π^-, π^0 and π^+ and, as an example, in fig. 12 the CEM prediction for π^-, π^0 and π^+ meson spectra from $n + Cu$ collisions at T_n =425 MeV is shown.

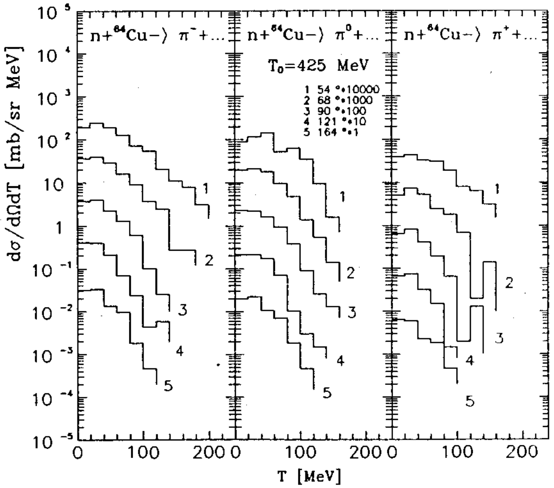

Fig. 12. The CEM predictions for π^-, π^0, and π^+ meson spectra from neutron-copper collisions at 425 MeV.

4. Summary and conclusion

Thus, in the framework of the CEM the neutron-induced inclusive production of p; d, t, and charged pions has been analyzed at intermediate energies. Without any free parameters the CEM is able to reproduce correctly the shape and the absolute value of the inclusive spectra of ejectiles emitted both in the cumulative and noncumulative regions. Several mechanisms participate in particle production and their relative role changes with incident energy T_0, mass-number of nucleus-target, angle and energy of ejectile. Apparently, as in the case of proton-induced reactions [16]), the "background" nuclear mechanisms (rescattering, two-step process (1-2), pre-equilibrium emission) determine the main part of the fast backward particle production at intermediate energies also in reactions induced by neutrons.

The results obtained do not imply, of course, that nucleon-nucleus interaction physics is completely covered by the reaction mechanisms regarded here. We point out that the agreement between experimental and present CEM calculations does not claim to be better than about 50%. The accuracy of the calculated cross section is about 40%, originating from the limited accuracy (about 30%) of the introduced pion absorption probability and uncertainties of the CEM parameters and from the statistical accuracy of Monte-Carlo calculations. In other words, the CEM calculations explain an essential part of the particle yield but do not exclude some contributions from other reaction mechanisms. Moreover, by analyzing Komarov's *et al.* measurements of proton-nucleus reactions at T_0 = 640 MeV, we have succeeded in describing both forward and backward inclusive spectra of secondary protons, while we couldn't describe in our approach the two-proton coincidence cross sections in the kinematical region chosen to select events connected with the scattering of the projectile on two-nucleon groups inside the nuclei [16]). We have considered this fact as a direct indication of a proton – two-nucleon "cluster" interaction inside the nucleus (being absent in our CEM), as a small contribution (~ 25%) to the mechanisms of the cumulative proton production [16]).

It should be noted that some preliminary data of reactions analyzed here have also been well described in the framework of the Cluster Exciton Model [26]). The authors of the experiments have successfully analyzed their p, d, t, and π spectra in the framework of the Quasi-Two-Body Scaling and Moving-Source Models, and the spectra of charged pions also in the framework of a version of the Intranuclear Cascade Model of Cugnon *et al.* [27]) quite different from ours. This indicates once again that the inclusive spectra of ejectiles are characteristics not enough sensitive to find out the mechanisms of particle production.

In some sense, the mechanisms under consideration are "background" ones. But at intermediate bombarding energies, for the medium and heavy nuclei-targets and not too high energies of ejectiles these mechanisms are apparently determinative. From our point of view, for medium and heavy nuclei-targets and for ejectile energies less than several hundreds MeV, such mechanisms will contribute to the cumulative particle production also at higher bombarding energies (and also for other projectiles), as a second stage of the reaction, after specific fast mechanisms involving quark degrees of freedom of nuclei, or even a nucleus being a quark-gluon system. The contribution of specific mechanisms can be estimated as a difference between experimental data and the calculated "background". This circumstance should be taken into account in attempts to get information about quark degrees of freedom of nuclei or about signals of quark-gluon plasma from data on cumulative particle production.

More strict kinematic constraints and analyses of more "delicate" characteristics of nuclear reactions are required to establish unambiguously the interaction mechanisms and especially their absolute contributions. In this aspect, inclusive particle distributions feel weakly the specific features of reaction mechanisms. To have a more convincing evidence of the existence of the specific interaction mechanism, the correlation and polarization measurements are needed.

The overall satisfactory agreement of the calculated spectra with the experimental data for all considered here target-nuclei, bombarding energies, angles and energies of ejectiles (taking into account, that no normalization was applied to adjust the calculation) may be looked as a byproduct of this work. This fact, together with the good description of proton-induced particle production at intermediate energies published in [16]), point out the predictive power of the CEM and are an indication of the possibility of using the CEM to provide the nuclear data at intermediate energies needed for different important applications [20]).

Acknowledgments

The author would like to thank Professor E. Rössle who kindly sent him a disk with the complete set of experimental data. Helpful discussions with many colleagues, in particular with Doctor K.K. Gudima, Professors M. Blann, V.B. Kopeliovich, V.D. Toneev and G.M. Zinovjiev, are gratefully acknowledged.

References

1) V.B. Kopeliovich, Phys. Rev. **139** (1986) 571

2) V.B. Gavrilov *et al.*, Preprint ITEP 128-89, Moscow (1989)

3) L.L. Francfurt *et al.*, Phys. Rep. **160** (1988) 237

4) R.D. Amado and R.M. Woloshin, Phys. Rev. Lett. **36** (1976) 1435

5) L.L. Frankfurt and M.I. Strikman, Phys. Lett. **B69** (1977) 93

6) T. Fujita and J. Hufner, Nucl. Phys. **314** (1979) 317

7) V.B. Kopeliovich, Sov. J. Nucl. Phys. **26** (1977) 87

8) K.K. Gudima, S.G. Mashnik and V.D. Toneev, JINR Communication E2-11307, Dubna (1978)

9) N.S. Amelin and G.I. Likasov, Yad. Fiz. **33** (1981) 194

10) A.M. Baldin, Prog. Part. Nucl. Phys. **4** (1980) 95

11) I.G. Bogatskaya *et al.*, Phys. Rev. **C22** (1980) 209

12) A.V. Efimov, Prog. Part. Nucl. Phys. **8** (1981) 345

13) C.E. Carlson *et al.*, Phys.Lett. **B263** (1991) 277

14) K.K. Gudima, S.G. Mashnik and V.D. Toneev, Nucl. Phys. **A401** (1983) 329; JINR Communications P2-80-774, P2-80-777, Dubna (1980)

15) S.G. Mashnik, Proc. 20th Winter School Leningrad Inst. Nucl. Phys., vol. 3 (Leningrad, 1985) p. 236

16) V.I. Komarov *et al.*, Nucl. Phys. **A326** (1979) 297;
S.G. Mashnik and S. Tesch, Z. Phys. **A312** (1983) 259;
S.G. Mashnik, in: Proc. 18th Winter School Leningrad Inst. Nucl. Phys., vol. 3 (Leningrad, 1983) p. 172;
S.G. Mashnik, S. Tesch and S.V. Dzemuhadze, Preprint Inst. Appl. Phys. 84-3, Kishinev (1984);
V.N. Baturin *et al.*, Preprint LINP-1302, Leningrad (1987)

17) J. Franz *et al.*, Nucl. Phys. **A510** (1990) 774

18) R. Büchle *et al.*, Nucl. Phys. **A515** (1990) 541

19) K.O. Oganesyan, Sov. Phys. JETP **27** (1968) 679

20) E. Sartori, Review of Nuclear Model Codes Comparison Exercises, Talk presented at the Workshop on Computation and Analysis of Nuclear Data Relevant to Nuclear Energy and Safety (ICTP, Trieste, Italy, 10 February - 13 March 1992); M. Blann and P. Nagel, Specifications for an International Code and Model Intercomparison for Intermediate Energy Reactions, NEA/NSC/DOC(92)3, Gif-sur-Yvette, France (1 July 1992)

21) V.S. Barashenkov and V.D. Toneev, Interaction of high energy particles and nuclei with atomic nuclei (Atomizdat, Moscow, 1972) (in Russian)

22) H.H. Gutbrod *et al.*, Phys. Rev. Lett. **37** (1976) 667

23) A.Z. Mekjan, Phys. Rev. **C17** (1978) 1051

24) M.C. Lemaire *et al.*, Phys. Lett. **B85** (1979) 38;
J.P. Kapusta, Phys. Lett. **C21** (1980) 1301

25) J. Gosset *et al.*, Phys. Rev. **C16** (1977) 629

26) Zs. Kovács and H. Müller, Preprint KFKI-1985-111, Budapest (1985)

27) J. Cugnon, Phys. Rev. **C22** (1980) 1885;
J. Cugnon and M.C. Lemaire, Nucl. Phys. **A489** (1988) 781

Received by Publishing Department
on July 23, 1992.

Машник С.Г.
E2-92-320

Рождение частиц в кумулятивной
и некумулятивной областях в нейтрон-ядерных взаимодействиях
при промежуточных энергиях

В рамках каскадно-экситонной модели анализируются первые систематические измерения рождения p, d, t и заряженных пионов в области углов 51°-165° при взаимодействии нейтронов с энергией 300 ÷ 580 МэВ с ядрами C, Cu и Bi. Исследована роль квазисвободного рассеяния, внутриядерных перерассеяний, предравновесной эмиссии и механизма "слипания" в образовании частиц в кумулятивной (т.е. кинематически запрещенной для рождения на квазисвободном внутриядерном нуклоне) и некумулятивной областях. Отмечается слабая чувствительность инклюзивных распределений к специфике механизма реакции, необходимость проведения корреляционных экспериментов и измерения поляризации рождающихся частиц.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1992

Mashnik S.G.
E2-92-320

Neutron-Induced Particle Production
in the Cumulative and Noncumulative Regions
at Intermediate Energies

The first systematic measurements of neutron-induced inclusive production of protons, deuterons, tritons and charged pions on carbon, copper, and bismuth in the bombarding energy range of 300-580 MeV and in the angular interval from 51° to 165° have been analyzed in the framework of the Cascade-Exciton Model. The role of single-particle scattering, the effects of rescattering, the preequilibrium emission and "coalescence" mechanism in particle production in the cumulative (i.e., kinematicelly forbidden for quasi-free intranuclear projectile-nucleon collisions) and noncumulative regions are discussed. A week sensitivity of the inclusive distributions to the specific reaction mechanisms and a need of correlation and polarization measurements are noted.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna 1992