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THEORETICAL INVESTIGATION OF NEUTRON EMISSION IN THE INTERACTION OF ^{12}C (105 MeV) AND ^{20}Ne (180 MeV) IONS WITH NUCLEI

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I. INTRODUCTION

The existing more than 30 years heavy ion accelerators allow one to investigate interactions of these particles with nuclei and to accumulate rich experimental information on the nature of interactions, especially in the energy region of incident particles of ~10 MeV/nucleon.

The analysis of experimental spectra of light particles (both charged and neutrons) emitted in these processes has reliably established the existence of two sources of these particles[1,2] : The first is connected with emission of particles from a system in the state of thermal equilibrium and is specified by a low nuclear temperature of ~1-1.3 MeV, and the second (high-energy) requires the use of a quite another concept of the properties of a dinuclear system. Thus, heavy ion reactions are an invaluable source of information on interactions of complex nuclei. They are used to get information on processes connected with evolution of an interacting system, which is a more complicated problem in studying both direct processes, where an interaction is of a surface nature, and processes through a compound nucleus, where the system "forgets" its prehistory.

Therefore, in studying spectra of emitted particles, of particular interest is a high-energy component directly connected with the initial stage of collision when a statistical equilibrium is not yet established. We shall consider spectra of emitted neutrons which are not distorted due to the Coulomb field. Experimental study of these preequilibrium particles sets the task of constructing an adequate theoretical model.

A great number of phenomenological models, in spite of good agreement with experimental data, did not clear up the nature of preequilibrium particles.

Therefore, attempts to construct microscopic approaches providing a dynamic description of a dinuclear system evolution are very important.

A microscopic treatment of the process has been proposed in refs.[3,4] in which the contribution to the high-energy part of the neutron spectrum was assumed to come from excitations of an incident ion of the particle-hole type in the continuous spectrum. We shall use this model to calculate interactions of ^{12}C (105 MeV) and ^{20}Ne (180 MeV) ions with the nuclei ^{181}Ta, $^{157,158}Gd$, $^{114,124}Sn$ and ^{56}Fe.

2. THE ASSUMPTIONS OF THE MODEL

The model under discussion describes the initial stage of nuclear interactions. It is based on the assumption that the single-particle mechanism of the kinetic energy dissipation is dominating. It is thought to be reasonable at energies of an incident ions of ~10 MeV/nucleon. Particle-hole excitations produced at the initial stage of the reaction take a considerable portion of the kinetic energy of an incident ion. In the process of reaction, the decay of these particle-hole states into more complex configurations with large density makes the energy transfer onto inner excitations to a great extent irreversible.

The considered excitations include also those in which a particle is in the continuous spectrum. Their decay leads to emission of a nucleon from a nucleus. The Hamiltonian of a multifermion system with a two-particle interaction

$$\hat{H} = \frac{\hbar}{2m}\int d^3x\, \nabla\Psi^+(x)\nabla\Psi(x) + \int d^3x\, d^3y\, \Psi^+(x)\Psi(x)\, v(x-y)\Psi^+(y)\Psi(y), \tag{1}$$

where $\Psi^+(x)$ and $\Psi(x)$ are the Fermi field operators, can be expressed through the density $\rho(x)$ and current $\bar{j}(x)$ operators

$$\rho(x) = \Psi^+(x)\Psi(x),$$
$$\bar{j}(x) = \frac{\hbar}{2mi}(\Psi^+(x)\nabla\Psi(x) - \nabla\Psi^+(x)\cdot\Psi(x)), \tag{2}$$

satisfying the commutation relation

$$[\rho(x), \bar{j}(y)] = \frac{\hbar}{2mi}\frac{\partial}{\partial x}[\delta(x-y), \rho(x)].$$

In this representation it becomes

$$H = \frac{m}{2}\int d^3x\, \bar{j}(x)\rho^{-1}(x)\bar{j}(x) + \frac{\hbar}{\xi m}\int d^3x\,(\nabla\rho(x))^2\rho^{-1} + \int d^3x\, d^3y\, \rho(x)\, v(x-y)\rho(y). \tag{3}$$

The density and current operators satisfy the equation of motion

$$\operatorname{div}\bar{j}(x) = -i\hbar[H, \rho(x)].$$

To use the Hamiltonians (1) or (3) just for studying the emission of particles from a system formed in the collision of two nuclei, one should separate in it the dynamic variables connected with relative motion and inner excitations. The Hamiltonian thus transformed will contain terms connected with inner motion (descibed by the variable R, the distance between the nuclei and its conjugate momentum) and their interaction. If one describes inner excitations only in the harmonic approximation, the expression for the Hamiltonian, with the allowance made for the afore-said, will be

$$\hat{H} = \frac{\hbar^2}{2m}\sum_{k\ell}\frac{\partial}{\partial R_k}\mu^{-1}_{k\ell}\frac{\partial}{\partial R_\ell} + U(R) + \sum_s w_s b^+_s b_{\bar{s}} + \sum_s V_s(R)(b^+_s + \sigma_s b_{\bar{s}}) + \sum_s(\bar{G}_s\nabla_R + \nabla_R\bar{G}_s)(b^+_s - \sigma_s b_{\bar{s}}). \tag{4}$$

Let us consider expression (4). The first two terms are the kinetic and potential energies of the relative motion. The third term is the inner Hamiltonian, and only the last two terms connect the inner and relative motion. One of them describes the influence of a mean field V(R) of each nucleus on the other nucleus, and the second describes the coupling of the relative motion current with the inner current. Using the phonon RPA amplitudes we express the boson operators b^+_s and $b_{\bar{s}}$ through the creation and annihilation operators of particles and holes

$$b^+_s = \sum_{p>F}\sum_{h<F}(\Psi^s_{ph}\alpha^+_p\beta^+_h + \phi^s_{ph}\sigma_{\bar{p}}\sigma_{\bar{h}}\beta_{\bar{h}}\alpha_{\bar{p}}).$$

However, in the Tamm-Dancoff approximation the second term in brackets can be neglected and hence we get the Hamiltonian (1) of ref. [3]

$$H = \bar{H} + H_0 + H_{int}, \quad H_{int} = H_1 + H_2,$$
$$\bar{H} = -\frac{\hbar^2}{2}\sum_{k\ell}\frac{\partial}{\partial R_k}\mu^{-1}_{k\ell}\frac{\partial}{\partial R_\ell} + U(R);\; H_o = \sum_p E_p\alpha^+_p\alpha_p + \sum_h E_h\beta^+_h\beta_h, \tag{5}$$
$$H_1 = \sum_{ph} V_{ph}(\alpha^+_p\beta^+_h + \beta_{\bar{h}}\alpha_{\bar{p}}),$$
$$H_2 = \sum_{ph}(\bar{G}_{ph}(R)\nabla_R + \nabla_R\bar{G}_{ph}(R))(\alpha^+_p\beta^+_h - \beta_h\alpha_p),$$

H_1 and H_2 are responsible for the transition of particles from bound states into a continuum if the densities of colliding nuclei are overlapping. Just they are of interest for the study of emitted particles.

To calculate preequilibrium emission of particles from an excited nucleus, one should have momentum distribution of nucleons in this nucleus.

In the first perturbation order

$$\langle t|a_p^+ a_p|t\rangle = \sum_{s<F} \{|\frac{1}{\hbar}\int_0^t dt' \langle s|H_1|\bar{p}\rangle \exp[\frac{1}{\hbar}(E_p - \tilde{E}_s)t' - \lambda t']|^2 + |\frac{1}{\hbar}\int_0^t dt' \langle s|H_2|\bar{p}\rangle \exp[\frac{1}{\hbar}(E_p - \tilde{E}_s)t' - \lambda t']|^2\}, \qquad (6)$$

where $\tilde{E}_s = E_s + (1/2)mv^2$, the factor $e^{-\lambda t'}$ is connected with the natural decay width of a level. For further consideration, it is convenient to represent H_1 and H_2 in the coordinate representation

$$H_1 = \int d^3x\, U_T(x)\,\rho_p'(x),$$

$$H_2 = m\int d^3x\, \bar{j}_{coll}(x)\frac{1}{\rho_o(x)}\bar{j}_{in}(x). \qquad (7)$$

Here $U_T(x)$ is the potential generated by the target-nucleus. The collective current $\bar{j}_{coll}$ has the form $\bar{j}_{coll} = f(x)\bar{v}(t)$, where $\bar{v}(t)$ is the relative motion velocity, $f(x) = \rho_p(x)$, in the lab.system, ρ_o is the mean density of a produced dinuclear system, and ρ_p' is the fluctiating part of the nucleon density in an incident particle. The single-particle current is given by expression (2), where

$$\Psi^+(x) = \sum_{s<F} \tilde{\Psi}_s^*(x)\,\beta_s + \int d^3p\,(2\pi h)^{-3/2}\exp(\frac{1}{\hbar}\bar{p}\bar{x})\,a_p^+,$$

$$\tilde{\Psi}_s^* = \exp(\frac{i}{\hbar}m\bar{v}\bar{x})\,\Psi_s(\bar{x} - \bar{R}(t)).$$

Here Ψ_s is the single-particle wave function of a bound state in an incident nucleus.

Substituting (7) into (6) we get

$$\langle t|a_p^+ a_p|t\rangle = \sum_{s<F} |\int_0^t dt' \frac{1}{2(2\pi\hbar)^{3/2}} \exp[\frac{i}{\hbar}(E_p - E_s - \frac{mv^2}{2})t' - \lambda t'] \times$$

$$\times \int d^3x \exp[-\frac{1}{\hbar}(\bar{p} - m\bar{v})\bar{x}](\frac{f(x)}{\rho_o(x)} - 1)(\bar{v}\nabla + \frac{1}{\hbar}mv^2 + \frac{1}{\hbar}\bar{p}\bar{v}) \times$$

$$\times \Psi_s^*(\bar{x} - \bar{R}(t))|^2 + \sum_{s<F} |\frac{1}{\hbar}\int_0^t dt' \exp[\frac{1}{\hbar}(E_p - E_s - \frac{mv^2}{2})t' - \lambda t'] \times$$

$$\times \frac{1}{(2\pi\hbar)^{3/2}}\int d^3x \exp[-\frac{i}{\hbar}(\bar{p} - m\bar{v})x]\,U_T(x)\,\Psi_s(\bar{x} - \bar{R}(t'))|^2.$$

We have chosen rather a simple form of the wave functions of the continuous spectrum states, the plane waves, and did not take into account possible excitations of an incident ion.

As in refs. [3,4], we assume that the radial parts of the wave function in the surface region behave in a similar manner and can be approximated by a square root of density. The arising product of densities under the integral is changed by the approximate expression

$$\frac{\rho_T(x)\,\rho_p^{1/2}(x - R)}{\rho_o(x)} \approx \rho_{ef}^{1/2}\exp[-\frac{(\bar{x} - \bar{R})^2}{d^2}],$$

where the quantities ρ_{ef}, d and R are determined from the requirement of the best approximation of the left-hand side. The parameters d and ρ_{ef} are related with the depth of mutual penetration of nuclei.

After simple transformations expression (8) becomes

$$\langle t|a_p^+ a_p|t\rangle = \frac{1}{\hbar^3}(\frac{t^2(\bar{p}\bar{v})^2}{\hbar^2} + \frac{(\bar{v}\bar{R})^2 t^2}{a_T^2 R^2} + 4\rho_{ef.}U_o^2) \times$$

$$\times \sum_{s<F} \frac{1}{A_p}\rho_{ef}\, d^6 \exp[-\frac{d^2}{\hbar^2}(\bar{p} - m\bar{v})^2][1 - e^{-2\lambda t} - \qquad (9)$$

$$- e^{-\lambda t}\cos[(E - E_s) - \frac{mv^2}{2} - \frac{R_T}{R}(\bar{p} - m\bar{v})\bar{v})\frac{t}{\hbar}] \times$$

$$\times [\frac{t^2}{\hbar^2}(E - E_s - \frac{mv^2}{2} - \frac{R_T}{R}(\bar{p} - m\bar{v})\bar{v})^2 + \lambda^2 t^2].$$

In deriving (9) we have used the substitution

$$U_T = U_o\frac{\rho_T(x)}{\rho_o}.$$

3. CALCULATION OF THE YIELD OF PREEQUILIBRIUM NUCLEONS AND AN EVAPORATIVE CROSS SECTION COMPONENT

A nucleon emitted from an incident particle under the interaction $H_{int} = H_1 + H_2$ with momentum p may immediately appear outside the target-nucleus or pass a part of the path through the target-nucleus. Correspondingly, one should either disregard absorption of the particle in the system or take it into account.

In this paper we disregarded absorption of particles in the system.

Based on the above consideration for the double differential cross section of the emission of preequilibrium nucleons we have

$$\frac{d^2\sigma}{dE\,d\Omega} = (2m)^{3/2} E^{1/2} (\pi R_T^2)^2 \; \langle t | a_p^+ a_p | t \rangle .$$

Let us discuss the values of the parameters used. It is to be noted that the parameters of the single-particle potential have been taken from ref./5/ ; and the values of the decay width of the particle-hole level in the continuous spectrum, from the calculations within the exciton model/6/ . Thus, d is the main parameter of our model characterising the region of overlapping of colliding nuclei. This value also determines the slope of the obtained spectrum of nonequilibrium nucleons.

To analyse the experimental data one should calculate the yield of evaporative neutrons. For this purpose we have used the GROGIG program/7/ which is a modification of the GROGI2 program/8/ . It allows for the competition between the fission channel and the channel of particle (n, p, α) yield and γ-emission and the dependence of the value of the fission barrier on momentum. A system resulting from the interaction of an incident ion with the target-nucleus has a large excitation energy and large angular momenta. Therefore, the contribution from the fission channel can be essential/9/ even for the nuclei that are not fissionable in the ground state. The criterion of validity of the performed statistical calculation was the comparison of the calculated and the experimental values of σ_n/σ_f for heavy fissionable nuclei, whereas for light compound system the values of fusion cross sections were compared. This allowed us to choose the parameters/10/ of the optical potential for the entrance channel. However, it is to be emphasized that calculations are not very sensitive to them. The maximal angular momentum of the compound system has been estimated by the Bass model/11/ . As in ref./12/ we have calculated the values of double differential cross sections.

4. DISCUSSION OF THE RESULTS

As is seen from formulae of Sec.2, the momentum distribution with allowance made for all approximations depends mainly on the parameters ρ_{ef} , R , and d which are all connected with each other as the effective distance between nuclei, R , is assumed to be $R = R_{int} - d$. The value of the effective density ρ_{ef} is also connected with the value of d. Therefore, we had only one free parameter varying within 1.5-2 fermi. Now we shall discuss the chosen values of other parameters. Since the chosen value of R corresponds to the density twice smaller than at the centre of nucli, U_0 is taken half the real part of the single-particle potential, i.e. 20 MeV. The value of t is 10^{-22} s according to the calculations/3,4/ and the relative velocity is $v_{in}/2$.

We have chosen two groups of experimental data/13/ and/14/ and tried to reproduce them.

For the interaction of ^{12}C and ^{20}Ne with ^{181}Ta (Figs.1,2) we have calculated neutron spectra in the interval 1 MeV $\le$ $\le$ En $\le$ 40 MeV for the angles of emission of 0°,30°, 80°,120° (^{12}C ion) and 0°, 20° 40°, 120° (^{20}Ne ion). In both the reactions the best agreement is achieved at d = 1.8 fermi. However, in both the cases, as in other papers/1,2/, at $E_n > 12$ MeV for large scattering angles there is no agreement with experimental data. Apparently, this is due to the neglect of neutron rescattering from intermediate excited states of the nucleus projectile and of the yield of particles from the target-nucleus. Moreover, the cross section at large angles will be contributed by other reaction mechanisms, first of all, by a direct knockout and stripping, i.e. quasielastic processes. For a correct description of experimental data in the interaction of ^{12}C ions with the nuclei ^{56}Fe and $^{141,124}Sn$ (Figs.3,4,5) the parameter d is chosen to be equal to 1.3 fm and 1.6 ÷ 1.8 fm, respectively. With increasing mass of the nucleus projectile and target nucleus the yield of neutrons increases.

It was interesting to consider emission of particles when a compound nucleus produced in the interaction is the same , while target projectiles differ greatly in the neutron binding energy. This situation has been studied in ref./14/ for

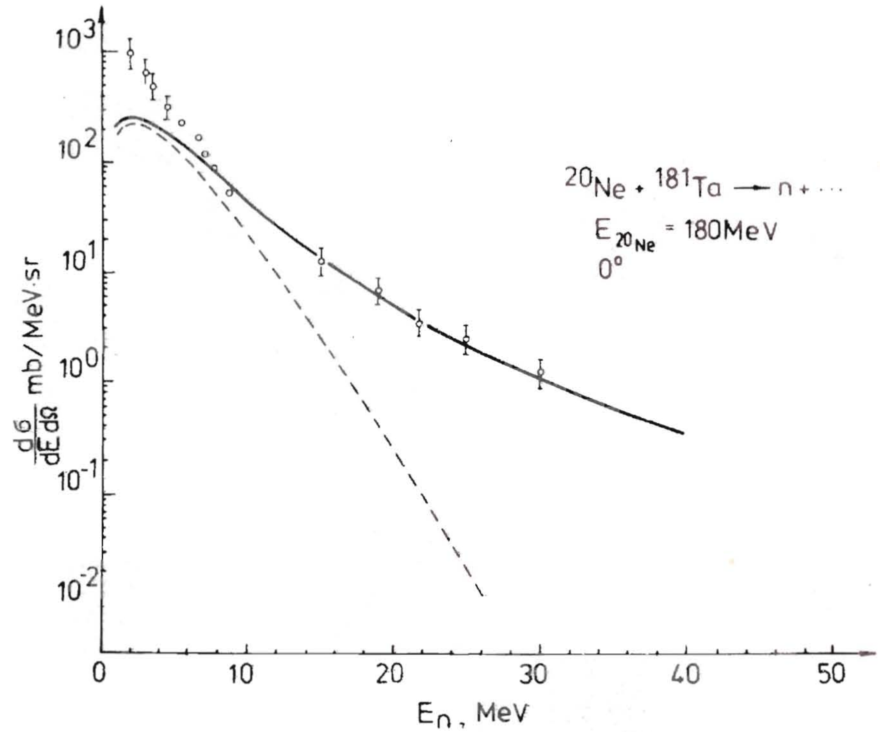

Fig.1. Double differential cross section of inclusive neutron emission; dashed curves - calculation by cascade-evapolative model; continuous curve - total theoretical cross section relevant experimental data from ref. /13/ .

the reactions ^{158}Gd (^{12}C(150 MeV)) and ^{157}Gd (^{13}C(140 MeV)), (Fig.6). Both the reactions proceed through the same compound nucleus ^{170}Yb and have similar values of excitation energies in the produced system. The difference in the neutron binding energy in ^{12}C and ^{13}C is essential (18.7 MeV and 4.9 MeV, respectively).

Here coincidence with the experimental curves can be obtained by varying the parameter d in the interval 1.7 ÷ 1.9 fm.

Thus, the calculations reproduce the experimental data on the yield and energy dependence of the cross section for a wide range of target nuclei and incident particles. The mecha-

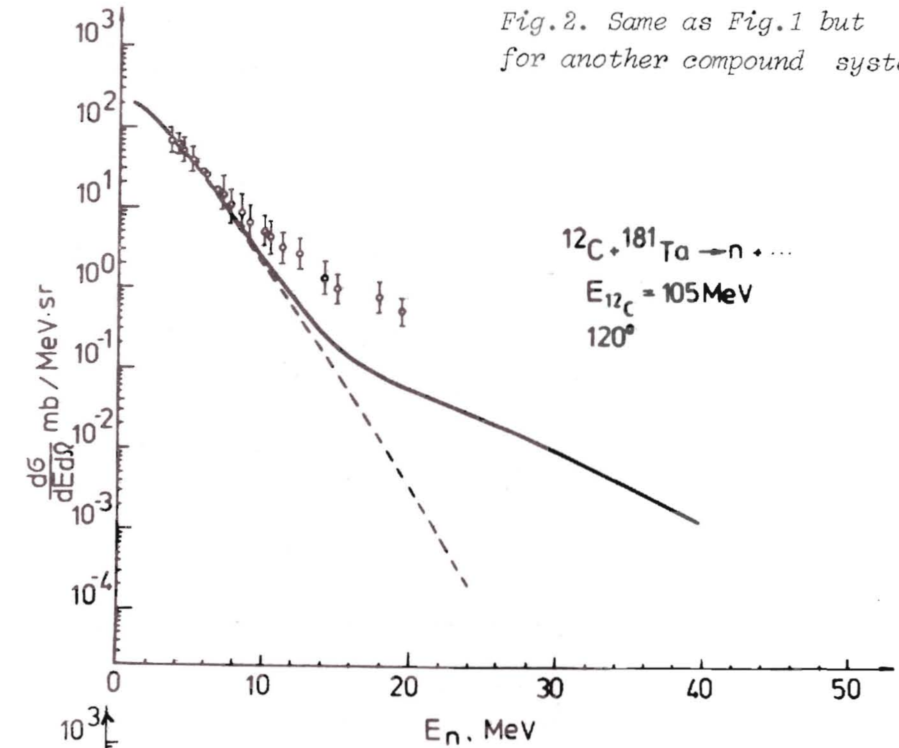

Fig.2. Same as Fig.1 but for another compound system.

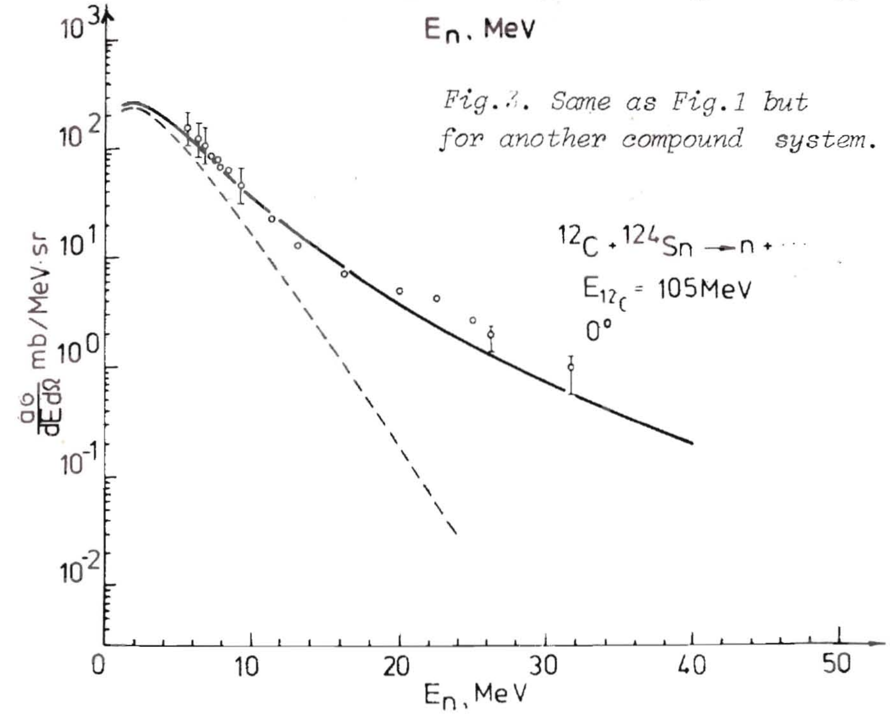

Fig.3. Same as Fig.1 but for another compound system.

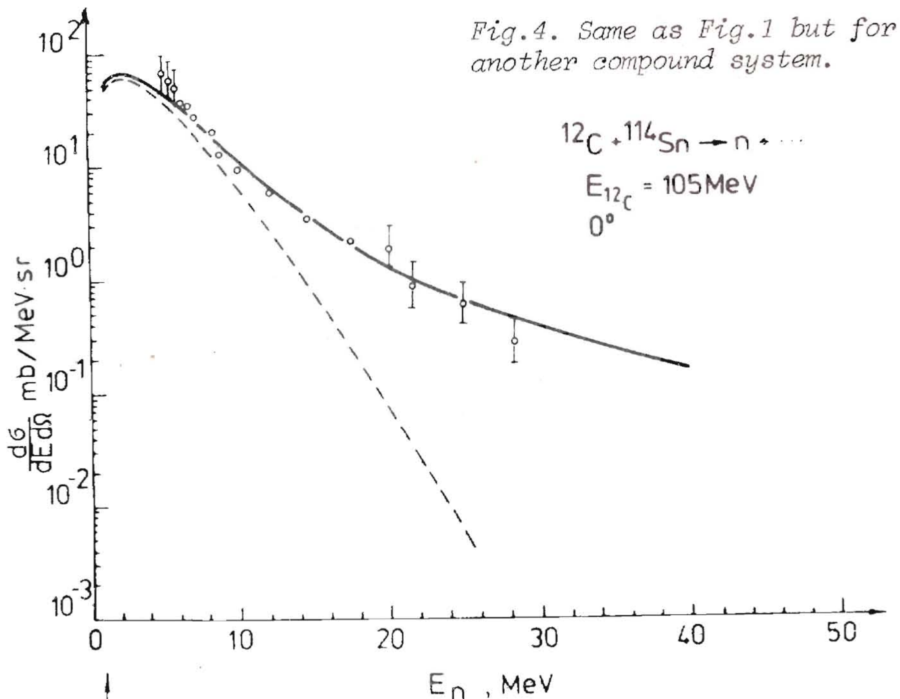

Fig.4. Same as Fig.1 but for another compound system.

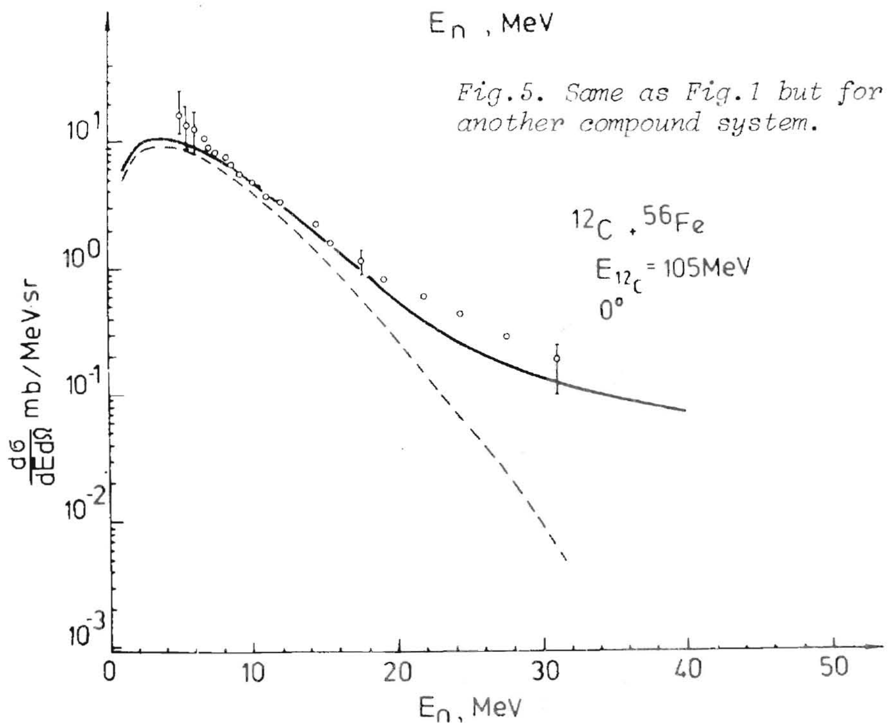

Fig.5. Same as Fig.1 but for another compound system.

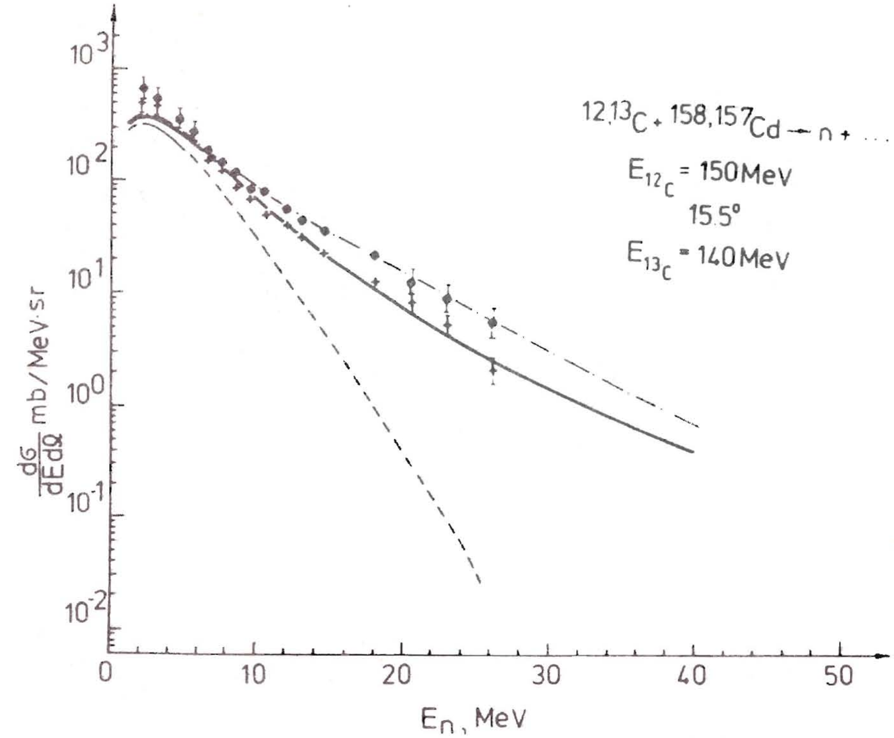

Fig.6. Double differential cross section of inclusive neutron emission; dashed curve - calculation by cascade-evaporative model; continuous curve - total theoretical cross section for system $^{12}C + ^{158}Gd \to xn + \dots$; dashed-points curve - total theoretical cross section for system $^{13}C + ^{157}Gd \to xn + \dots$; +. ● - experimental data from ref. [14] .

nism of emitting nonequilibrium particles proposed in ref.[3,4] is one of the sources of emission of these particles. However, it is essential that the value of the parameter d should be obtained from general considerations of the nature of interactions.

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Теоретическое исследование эмиссии нейтронов при взаимодействии ионов ^{12}C (105 МэВ), ^{20}Ne (180 МэВ) с ядрами

В рамках предложенной ранее модели описания вылета быстрых частиц на начальной стадии реакции проводятся вычисления выходов инклюзивных нейтронов в реакциях ионов ^{12}C(105 МэВ), ^{20}Ne(180 МэВ) с ядрами. Выход низкоэнергетических нейтронов рассчитывается на основе каскадно-испарительной модели.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

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Theoretical Investigation of Neutron Emission in the Interaction of ^{12}C (105 MeV) and ^{20}Ne (180 MeV) Ions with Nuclei

The description of the high-energy particle emission is calculated in the framework of the early suggested model for the reactions of ^{12}C (105 MeV), ^{20}Ne (180 MeV) iones with nuclei. The low-energy neutron yield is calculated by cascade-evaporative model.

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

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