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MODEL DESCRIPTION OF NEUTRON EMISSION IN HEAVY-ION COLLISIONS

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I. Introduction

Studies of heavy-ion collisions at 10 MeV per nucleon which have been performed during the last years produced the relevant information on the interaction of heavy ions and the properties of a dinuclear system. A part of these data can be interpreted based on the statistical model. For instance, from decay characteristics of the dinuclear system it follows that at least on the later stage of the reaction the system is in thermal equilibrium. This conclusion is confirmed by the phenomenological analysis of nucleon emission spectra, low-energy component of which is due to evaporation from a compound nucleus. Another part of the experimental data requires for the interpretation some new physical ideas. The deviations from the predictions of the statistical model are probably caused by the properties of the initial stage of the reaction.

In /1/ we have developed the model describing the initial stage of heavy-ion collisions. Firstly, this model has been applied to describe the relative motion of colliding nuclei, which is characterised by dissipation of a large part of the initial kinetic energy. The model is based on the assumption that the two-body collisions between nucleons can be neglected and the one-body collisions of nucleus with a time-dependent wall determine the dynamics of the collision. Particle-hole excitations generated at the first stage of the reaction take away a relevant part of the initial kinetic energy. Decay of particle-hole states during the reaction into more complicated configurations with the larger density make the transition of the kinetic energy to the energy of particle-hole excitations irreversible.

Among the particle-hole excitations arising at the first stage of the reaction there are components with the particle in continuum. Decay of these excitations leads with enhanced probability to emission of a nucleon from a nucleus. Since the excitation and decay of these states occur at the initial stage of the reaction when the excitation energy is not yet distributed uniformly between all the degrees of freedom the emitted nucleons may be of a very large energy. As the momentum of relative motion is not distributed uniformly between all the nucleons of the dinuclear system as well, particles will be emitted mainly in the forward direction.

A significant yield of nucleons at small angles with energies exceeding considerably the predictions of the statistical model was observed experimentally in heavy-ion collisions. The present paper is aimed at studying this process within the model suggested in ref. [1].

2. The model Hamiltonian

From the microscopic point of view the time-dependent mean field determines the dynamics of the collision, since the two-body collisions are less important at velocities of relative motion smaller than the Fermi velocity.

The Hamiltonian describing the interaction of two colliding nuclei has been obtained in ref. [1] and contains the coupling of relative and intrinsic motion:

$$H = H_R + H_0 + H_{int}, \qquad H_{int} = H_1 + H_2, \tag{1}$$

$$H_R = -\frac{\hbar^2}{2}\sum_{k\ell}\frac{\partial}{\partial R_k}\mu^{-1}_{k\ell}\frac{\partial}{\partial R_\ell} + U(R),$$

$$H_0 = \sum_p E_p \alpha_p^+ \alpha_p + \sum_h E_h \beta_h^+ \beta_h,$$

$$H_1 = \sum_{ph} V_{ph}(R)(\alpha_p^+\beta_h^+ + \beta_h\alpha_p),$$

$$H_2 = \sum_{ph}(\vec{G}_{ph}(R)\nabla_R + \nabla_R \vec{G}_{ph}(R))(\alpha_p^+\beta_h^+ - \beta_h\alpha_p).$$

The term H_{int} in (1) is the interaction responsible for the transition of a part of nucleons from bound states into a continuum in the course of partial overlapping of the densities of colliding nuclei. In the coordinate representation

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

$$H_2 = m\int d^3x\, \vec{j}_{coll}(x)\frac{1}{\rho_0(x)}\vec{j}_{in}(x).$$

Here U_T is the potential generated by the target-nucleus. The collective current $\vec{j}_{coll}(x)$ has the form

$$\vec{j}_{coll}(x) = f(x)\,\vec{v}(t),$$

where $\vec{v}(t)$ is the relative motion velocity, $f(x) = \rho_p(x)$ in the lab.system of coordinates, ρ_0 is the mean density of the dinuclear system produced, ρ_p' is the fluctuating part of nucleon density in

incident particle. The single-particle current is defined by

$$\vec{j}_{in} = \frac{\hbar}{2mi}\left(\Psi^+(x)\nabla\Psi(x) - \nabla\Psi^+(x)\cdot\Psi(x)\right), \tag{2}$$

where
$$\Psi^+(x) = \sum_{s<F}\tilde{\varphi}_s^*(x)\beta_s + \int d^3p\,(2\pi\hbar)^{-3/2} e^{\frac{i}{\hbar}\bar{p}\bar{x}}\alpha_{\bar{p}}^+$$

$$\tilde{\varphi}_s^*(x) = e^{\frac{i}{\hbar}m\bar{v}\bar{x}}\varphi_s(\bar{x} - \bar{R}(t)).$$

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

Theoretical calculations of the nucleon yield include the calculations of emission of statistical and preequilibrium particles at the initial stage of the reaction.

The emission of statistical nucleons is calculated in the framework of the standard cascade-evaporative model, whereas the emission of preequilibrium particles requires the wave function of the dinuclear system at small interaction time [2].

As we have already mentioned, our model is based on the one-particle mechanism of dissipation of kinetic energy. A time-dependent mean field of each nucleus excited in the partner particle-hole states including those in the continuous spectrum. Just the latter are important for nucleon emission. Though, on the whole, distortion of the wave functions of colliding nuclei may be rather large [2], the weight of each concrete particle-hole component will be small and they can be calculated by perturbation theory. In such an approximation the momentum distribution of nucleons provides

$$\langle t|a_{\bar{p}}^+ a_{\bar{p}}|t\rangle = \sum_{s<F}\Big\{\Big|\frac{1}{\hbar}\int_0^t dt'\langle s|H_1|\bar{p}\rangle e^{\frac{i}{\hbar}(E_p - \tilde{E}_s)t' - \lambda t'}\Big|^2 + \Big|\frac{1}{\hbar}\int_0^t dt'\langle s|H_2|\bar{p}\rangle e^{\frac{i}{\hbar}(E_p - \tilde{E}_s)t' - \lambda t'}\Big|^2\Big\}, \tag{3}$$

where $\tilde{E}_s = E_s + \frac{1}{2}mv^2$, the factor $e^{-\lambda t'}$ is related with a natural width of a level.

Substituting (2) into (3) we get

$$\langle t|a_{\bar{p}}^+ a_{\bar{p}}|t\rangle = \sum_{s<F}\Big|\int_0^t dt'\frac{1}{2(2\pi\hbar)^{3/2}} e^{\frac{i}{\hbar}(E_p - E_s - \frac{mv^2}{2})t' - \lambda t'} \cdot \int d^3x\, e^{-\frac{i}{\hbar}(\bar{p} - m\bar{v})\bar{x}}\Big(\frac{f(x)}{\rho_0(x)} - 1\Big)\Big(v\bar{\nabla} + \frac{i}{\hbar}mv^2 + \frac{i}{\hbar}\bar{p}\bar{v}\Big)\varphi_s^*(\bar{x} - \bar{R}(t'))\Big|^2 + \sum_{s<F}\Big|\frac{1}{\hbar}\int_0^t dt' e^{\frac{i}{\hbar}(E_p - E_s - \frac{mv^2}{2})t' - \lambda t'}\frac{1}{(2\pi\hbar)^{3/2}}\int d^3x\, e^{-\frac{i}{\hbar}(\bar{p} - m\bar{v})\bar{x}} U_T(x)\varphi_s(\bar{x} - \bar{R}(t))\Big|^2 \tag{4}$$

We have chosen rather a simple form of the wave functions of the states in the continuous spectrum-plane waves.

As in ref. [1] we assume that the radial parts of the single-particle wave functions in the surface region are similar and can be approximated by square root of density. To simplify calculations we substitute in the integrand for densities product the expression:

$$\frac{\rho_T(x)\,\rho_0^{1/2}(x-R)}{\rho_0(x)} \approx \rho_{eff}^{3/2}\,\frac{1}{\rho_0(R_c)}\,exp\left(-\frac{\bar{x}-\bar{R}_c(t)}{2d^2}\right), \tag{5}$$

where the ρ_{eff}, d and R_c values are determined by the requirement of the best approximation of the left-hand side of (5). The parameters d and ρ_{eff} are related with the depth of interpenetration of nuclei. The integral could be calculated exactly; however, we thought it to be useful by physical considerations to simplify somewhat the problem for a better qualitative analysis.

After simple transformations expression (4) takes the following form:

$$\langle t|a_{\bar p}^{+}a_{\bar p}|t\rangle = \frac{1}{(2\pi\hbar)^3}\left(\frac{(\bar p\bar v)^2}{\hbar^2} + \frac{(\bar v\bar R)^2}{a_T^2R^2} + \frac{\rho_0(R_c)}{\rho_{00}^2}\frac{1}{\hbar^2}U_0^2\right)$$
$$\cdot\sum_{s<F}\left|\int_0^t dt'\,e^{\frac{i}{\hbar}(E_p-E_s-\frac{mv^2}{2})t'-\lambda t'}\int d^3x\, e^{-\frac{i}{\hbar}(\bar p-m\bar v)\bar x}\frac{\rho_T}{\rho_{00}}\psi_s^*(\bar x-\bar R(t'))\right|^2. \tag{6}$$

Substituting (5) into (6) we find

$$\langle t|a_{\bar p}^{+}a_{\bar p}|t\rangle = \frac{1}{\hbar^3}\left(\frac{(\bar p\bar v)^2}{\hbar^2} + \frac{(\bar v\bar R)^2}{a_T^2R^2} + \frac{\rho_0(R_c)}{\rho_{00}}\frac{1}{\hbar^2}U_0^2\right)$$
$$\times\sum_{s<F}\frac{\rho_{eff}^3 d^6}{A_p\,\rho_0^2(R_c)}\,e^{-\frac{d^2}{\hbar^2}(\bar p-m\bar v)^2}\,\frac{\left(1+e^{-2\lambda t}-e^{-\lambda t}\cos\left[\left(E-E_s-\frac{mv^2}{2}-\frac{R_T}{R}(\bar p-m\bar v)\bar v\right)^2+\lambda^2\right)\frac{1}{\hbar^2}\right]}{\frac{1}{\hbar^2}\left[E-E_s-\frac{mv^2}{2}-\frac{R_T}{R}(\bar p-m\bar v)\bar v\right)^2+\lambda^2\right]}.$$

In deriving (6) we used:

$$U_T = U_0\,\frac{\rho_T(x)}{\rho_{00}}.$$

3. The yield of preequilibrium nucleons

A nucleon emitted from an incident particle with momentum $\bar p$ may immediately appear outside the target-nucleus or pass the path through the target-nucleus.

Consequently, one should either neglect the absorption of a particle in the system or take it into account.

We solved this problem in a pure geometrical way considering a possible position of an incident particle with respect to a target-nucleus. A portion of particles emitted from the projectile and absorbed in the target is determined by the impact parameter, nuclear radii R_T, R_p and the dimensions of the overlapping region of nuclei. The part of particles absorbed in the nucleus depends on the mean free path at given energy [3].

Based on such a consideration we have for the double differential cross section of preequilibrium nucleons

$$\frac{d^2\sigma}{dE\,d\Omega} = (2m)^{3/2}E^{1/2}\langle t|a_{\bar p}^{+}a_{\bar p}|t\rangle\left[1-\frac{1}{6}\left(1-\int_0^{\pi/2}\sin\alpha\cos\alpha\,d\alpha\right.\right.$$
$$\left.\left.\times\exp\left[-\frac{2R_T}{\Lambda}\frac{\left|\frac{p_0}{p}-\cos(\theta+\alpha)\right|}{\sqrt{1+\frac{p_0^2}{p^2}-2\frac{p_0}{p}\cos(\theta+\alpha)}}\right]\right)\left(1+\frac{R_T-\frac{1}{2}d}{R_T+\frac{1}{2}d}\right)(1-\sin\theta)^2\right], \tag{7}$$

where θ is the angle of particle emission. Here the parameters of the single-particle potential are taken from ref. [4]; the decay width of the particle-hole states in the continuum, from the calculations by the exciton model [5]; and the nucleon mean free path, from ref. [3]. The main parameter of our model is d defining the region of mutual overlapping of colliding nuclei. This parameter characterizes the slope of the spectrum of nonequilibrium nucleons.

4. The evaporation cross section

To analyse experimental data one should calculate the yield of evaporative neutrons. For this purpose we have used the GROGIG program [6] which is a modified version of GROGI2 [7]. It includes the competition of the fission channel with the channel of particle (n,p,α) and γ-emission and the dependence of the value of the fission barrier on momentum. A system formed as a result of interaction of an incident ion with a target-nucleus has a large excitation energy and high angular momentum. Therefore, the contribution of the fission channel can be very large [8] even for the nuclei which are not fissionable in the ground state.

We have investigated the dependence of the cross section of evaporated neutrons on the statistical model parameters. It was found that it is most sensitive to the value of ℓ_{cr}. The choice of ℓ_{cr} depends on the experimental value of the fusion cross section for the given reaction.

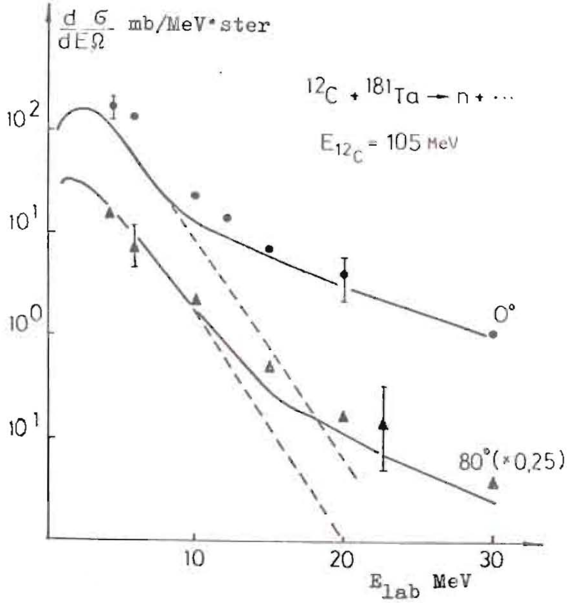
Theoretical calculations of the neutron yield at small energies naturally provide values somewhat less than the experimental ones since an additional neutron yield at these energies is related with their emission from fission fragments.

The optical potential parameters used for the calculation of the fusion cross section have been taken from ref. /9/. The level-density parameters a and Δ have been chosen according to systematics /10/. The program used for statistical calculations provides the values of $\frac{d\sigma}{dE}$ integrated over all angles. The transition to $\frac{d^2\sigma}{dE\,d\Omega}$ proceeds following ref. /11/.

5. Discussion

Based on the results of the preceding sections we have analysed the experimental data /12/ on the neutron yield in the reactions $^{12}C + ^{181}Ta$, $E_{^{12}C} = 105$ MeV in the lab.system. The figure shows the results of calculations of the double differential cross section of inclusive neutron emission. The dashed curve is the calculation by the cascade-evaporative model; the continuous curve is the total theoretical cross section. The points and triangles are the relevant experimental data.

It is seen from the figure, that up to the neutron energy of 10 MeV the experimental cross sections are described within the cascade-evaporative model. With increasing energy of an emitted particle the statistical mechanism contribution to the cross section sharply decreases whereas the yield of nonequilibrium particles increases.



The fast neutrons component in the cross section is defined by expression (7). It is obvious that the absolute value of the yield of preequilibrium neutrons depends on both the geometric dimensions of colliding nuclei and the dimensions of the region of mutual overlapping of nuclear densities. The d defines also the energy dependence of the preequilibrium component since the effective temperature is represented by $\hbar^2/2md^2$. The angular anisotropy of the cross section is determined by the velocity of the relative nuclear motion that changes at the initial stage of the reaction from $v_0 = \sqrt{\frac{2E_{c.m.}}{\mu}}$ to zero. In concrete calculations we have used the value $\bar{v} = \frac{1}{2} v_0$.

It is seen from the figure, that the experimental data on the yield and energy dependence of the cross section are reproduced in the calculations.

The angular anisotropy observed experimentally is described qualitatively in our calculations. The figure exemplifies for two angles, for which the agreement of theoretical calculations with experimental data is good. However, with increasing angle of emission the theoretical values of the cross section decrease more sharply than experimental data. An analogous result has been obtained in ref. /13/ for the model with two sources.

It should be noted that we discussed the yield of nonequilibrium nucleons from an incident particle; however, the emission of high-energy neutrons is also possible from the target-nucleus. Therefore, inclusion of these two sources of fast particles may improve a quantitative agreement. However, the fact that our numerical results are close to experimental data allows us to state that the mechanism of the yield of nonequilibrium nucleons suggested in this paper describes one of the sources of emission of high-energy particles.

Analogously one can investigate emission of protons in heavy-ion reactions.

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Модельное описание эмиссии нейтронов
в реакциях с тяжелыми ионами

Изучается эмиссия нейтронов в реакциях с тяжелыми ионами. Предложена модель описания вылета быстрых частиц в начальной стадии реакции. Она основана на предположении о том, что вылет быстрых частиц в существенной степени связан с распадом частично-дырочных возбуждений ядра. Высокоэнергетическая часть спектра удовлетворительно описывается данной моделью. Выход низкоэнергетических нейтронов рассчитывается в рамках статистического подхода.

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Model Description of Neutron Emission
in Heavy-Ion Reactions

The neutron emission in heavy-ion induced reactions is studied. The model describing the high-energy-particle emission is suggested. The model is based on the assumption that one-body collisions of nucleons with a time-dependent wall determine the dynamics of the collision. The high energy part of the spectrum is described correctly in the frame of this model. The low-energy part of the spectrum is calculated by the statistical approach.

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

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