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дубна

E4-91-213

N.V.Antonenko*, R.V.Jolos

MECHANISM OF ENHANCED YIELD OF LIGHT PARTICLES IN COMPOUND NUCLEUS FORMATION: DIFFUSION DESCRIPTION

Submitted to "Zeitschrift für Physik A: Hadrons and Nuclei"

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*Nuclear Physics Institute, Tomsk, USSR

1991

Антонеко Н.В., Джолос Р.В. E4-91-213

Механизм усиленного выхода легких частиц
при образовании составного ядра: диффузионное рассмотрение

Рассматривается эволюция двойной ядерной системы при слиянии ядер. Усиленный выход легких частиц в некоторых реакциях объясняется динамическими причинами. Обсуждается роль квантовых и тепловых флуктуаций. Подтверждаются результаты предыдущей работы.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1991

Antonenko N.V., Jolos R.V. E4-91-213

Mechanism of Enhanced Yield of Light Particles
in Compound Nucleus Formation: Diffusion Description

In the formation of a compound nucleus the evolution of a dinuclear system is considered. The enhanced yield of light particles for some reactions is explained by the dynamic reasons. The role of quantum and thermal fluctuations is discussed. The results of the previous paper are confirmed.

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

Preprint of the Joint Institute for Nuclear Research. Dubna 1991

1. Introduction

The experiments with Ar and Cr ions [1,2] have demonstrated an enhanced α-particle yield which cannot be explained by the evaporation from a compound nucleus [2,3]. The decay of the dinuclear system, which is formed in this reaction, was expected to happen with high probability due to dynamic reasons [4], before the system equilibrium is established.

In Ref. [5] one of possible realizations of that assumption has been discussed. It was established that when increasing the mass-asymmetry $\eta=(A_1-A_2)/(A_1+A_2)$, where A_1 and A_2 are the fragment mass numbers, the forces arise which make the system approaching the decay barrier. The source of these forces is the coupling of the radial and mass-asymmetry modes of motion. In [5] the parameters of inertia of the dinuclear system have been obtained. The coupling of the R and η-modes has been found to be weak for near symmetric configurations and it enhances strongly if η increases.

For simplicity the coupling of the R and η-modes has been treated classically in [5], e.g. the Newton equations for the averages have been solved. In that approach the consideration of quantum fluctuations has been reduced to the renormalization of the radial potential by the zero-point vibration energy. The temperature influence was not considered. More correctly the fluctuations in radial motion can be taken into account if the evolution of the system is described by the Fokker-Planck equation (FPE). In the diffusion approach the dinuclear system evolution is described by a small number of the collective variables which interact with a "thermostat" formed by the remaining degrees of freedom. The adequate dynamic equation of this model is FPE for the distribution function $f(\vec{q},\vec{p},t)$ of collective coordinates $\vec{q}$ and conjugate momenta $\vec{p}$.

The diffusion model has been found successful in the description of the distribution of deep inelastic collision products [6] and the fission fragments of an exited compound nucleus [7]. In this connection, the methods of solution of FPE have been elaborated.

As noted in [5], due to the nucleon transfer from a light to a heavy nucleus the dinuclear system removes to the potential barrier. In this work we shall consider the dependence of the distance R between the fragment centers on the mass-asymmetry in the framework of the diffusion model which allows us to take into account the barrier penetration, quantum and temperature fluctuations.

2. Model

In the notation of the Ref.[5], we take the collective Hamiltonian of the dinuclear system in the following form

$$H_{coll}=\frac{1}{2}\mu\dot{R}^2+\frac{1}{2}B_{\eta\eta}\dot{\eta}^2-B_{R\eta}\dot{R}\dot{\eta}+V(R,\eta), \tag{1}$$

where $\mu=mA_1A_2/(A_1+A_2)$ is the reduced mass, $V(R,\eta)$ is the potential energy,

$$B_{\eta\eta}=\mu\xi^2+\tilde{B}_\eta , \quad B_{R\eta}=\xi\mu . \tag{2}$$

Expressions for $\tilde{B}_\eta$ and ξ and their values for the considered reactions are given in [5]. The method of calculation of $V(R,\eta)$ is described there as well.

So far as the tensor of inertia doesn't depend on R, the FPE for the distribution function $f(R,\eta,p_R,p_\eta,t)$ corresponding to Hamiltonian (1) has the form

$$\frac{\partial f}{\partial t}=-(\mu_{RR}p_R+\mu_{R\eta}p_\eta)\frac{\partial f}{\partial R}-(\mu_{\eta\eta}p_\eta+\mu_{R\eta}p_R)\frac{\partial f}{\partial \eta}+\frac{\partial V}{\partial R}\frac{\partial f}{\partial p_R}+$$

$$\left[\frac{\partial V}{\partial \eta}+\frac{1}{2}\frac{\partial \mu_{RR}}{\partial \eta}p_R^2+\frac{\partial \mu_{R\eta}}{\partial \eta}p_Rp_\eta+\frac{1}{2}\frac{\partial \mu_{\eta\eta}}{\partial \eta}p_\eta^2\right]\frac{\partial f}{\partial p_\eta}+ \tag{3}$$

$$\gamma\mu_{RR}\frac{\partial}{\partial p_R}\left(p_R f\right)+\gamma\mu_{R\eta}\frac{\partial}{\partial p_R}\left(p_\eta f\right)+D\frac{\partial^2 f}{\partial p_R^2} .$$

Here γ is the radial friction coefficient, D is diffusion coefficient connected with γ by the Einstein fluctuation-dissipation relation

$$D=\gamma T^* \tag{4}$$

where T^* is an effective temperature,

$$T^*=\frac{\hbar\omega_R}{2}\coth\left(\frac{\hbar\omega_R}{2T}\right) . \tag{5}$$

In (5) $\hbar\omega_R/2$ is the zero vibration energy, T is the thermodynamic temperature. The tensor μ_{ij} is inverse to the tensor of inertia of (1):

$$\mu_{RR}=\xi^2/\tilde{B}_\eta+1/\mu , \quad \mu_{R\eta}=\xi/\tilde{B}_\eta , \quad \mu_{\eta\eta}=1/\tilde{B}_\eta \tag{6}$$

To simplify the solution of (3) we take the average value of $\partial V/\partial\eta$ as it has been done in [5]

$$<\frac{\partial V}{\partial \eta}>=-\frac{A}{2}\frac{V^f-V^i}{A_2^f-A_2^i} , \tag{7}$$

where $V^i(V^f)$ is the value of the driving potential in the initial $A_2=A_2^i$ (final $A_2=A_2^f$) configurations, $A=A_1+A_2$. In this case the motion along R and η-modes takes place in the valley on the energy surface. One of its walls is infinite and the other has a finite height. Therefore one can notice that our task is similar to the consideration of the descent of the fissile nucleus from the saddle-point to the scission line [7]. Since the motion along collective variables is almost classical, one let us search the FPE solution in the form of a multi-dimensional Gaussian with the time-dependent parameters. This method is called the Global Momentum Approach [7]. The Gaussian distribution is completely determined by its first moments,

$$\bar{q}_i(t)=\int q_i f\, d\Gamma , \quad \bar{p}_i(t)=\int p_i f\, d\Gamma \tag{8}$$

and second moments,

$$\chi_{ij}(t)=\int(q_i-\bar{q}_i)(q_j-\bar{q}_j)f\, d\Gamma=\chi_{ji}(t),$$

$$\omega_{ij}(t)=\int(p_i-\bar{p}_i)(p_j-\bar{p}_j)f\, d\Gamma=\omega_{ji}(t), \tag{9}$$

$$\psi_{p_iq_j}(t)=\int(p_i-\bar{p}_i)(q_j-\bar{q}_j)f\, d\Gamma\neq\psi_{p_jq_i}(t),$$

where $i,j=R,\eta$ and $d\Gamma=dR\, dp_R d\eta\, dp_\eta$.

Since the dependence of f on R has a particular interest for us, we suppose for simplicity

$$f(R,\eta,p_R,p_\eta,t)=f_g(R,p_R,p_\eta)\ \delta(\eta-\bar{\eta}). \qquad (10)$$

In this case the fluctuations of η are not taken into account. The parameterization (10) allows one to reduce the number of equations for covariances. The function $f_g(R,p_R,p_\eta)$ is a three-dimensional Gaussian. The dependence on p_η is included in f_g to take into account thermal fluctuations. According to (10) the change of the value of η is purely classical.

Using (1) and (7-10) and neglecting the moments higher than second order ones, we arrive at a system of equations for the moments. Coefficients μ_{ij}, γ, D and potential energy are supposed to depend on the corresponding averages.

$$\frac{d\bar{R}}{dt}=\mu_{RR}\bar{p}_R+\mu_{R\eta}\bar{p}_\eta ,$$

$$\frac{d\bar{\eta}}{dt}=\mu_{\eta\eta}\bar{p}_\eta+\mu_{R\eta}\bar{p}_R ,$$

$$\frac{d\bar{p}_R}{dt}=-\frac{\partial V}{\partial\bar{R}}-\gamma\mu_{RR}\bar{p}_R-\gamma\mu_{R\eta}\bar{p}_\eta-\frac{1}{2}\frac{\partial^3V}{\partial\bar{R}^3}\chi_{RR} ,$$

$$\frac{d\bar{p}_\eta}{dt}=-\frac{\partial V}{\partial\bar{\eta}}-\frac{1}{2}\frac{\partial\mu_{RR}}{\partial\bar{\eta}}(\bar{p}_R^2+\omega_{RR})-\frac{\partial\mu_{R\eta}}{\partial\bar{\eta}}(\bar{p}_R\bar{p}_\eta+\omega_{R\eta})-$$
$$-\frac{1}{2}\frac{\partial\mu_{\eta\eta}}{\partial\bar{\eta}}(\bar{p}_\eta^2+\omega_{\eta\eta}),$$

$$\frac{d\chi_{RR}}{dt}=2\left\{\mu_{RR}\psi_{p_RR}+\mu_{R\eta}\psi_{p_\eta R}\right\} ,$$

$$\frac{d\omega_{RR}}{dt}=2\left\{-\frac{\partial^2V}{\partial\bar{R}^2}\psi_{p_RR}-\gamma\mu_{RR}\omega_{RR}-\gamma\mu_{R\eta}\omega_{R\eta}+D\right\} ,$$

$$\frac{d\omega_{R\eta}}{dt}=-\left\{\frac{\partial\mu_{RR}}{\partial\bar{\eta}}\bar{p}_R\omega_{RR}+\frac{\partial\mu_{R\eta}}{\partial\bar{\eta}}(\bar{p}_R\omega_{R\eta}+\bar{p}_\eta\omega_{RR})+\frac{\partial\mu_{\eta\eta}}{\partial\bar{\eta}}\bar{p}_\eta\omega_{R\eta}\right. \qquad (11)$$
$$\left.+\gamma\mu_{RR}\omega_{R\eta}+\gamma\mu_{R\eta}\omega_{\eta\eta}+\frac{\partial^2V}{\partial\bar{R}^2}\psi_{p_\eta R}\right\} ,$$

$$\frac{d\omega_{\eta\eta}}{dt}=-2\left\{\frac{\partial\mu_{RR}}{\partial\bar{\eta}}\bar{p}_R\omega_{R\eta}+\frac{\partial\mu_{R\eta}}{\partial\bar{\eta}}(\bar{p}_R\omega_{\eta\eta}+\bar{p}_\eta\omega_{R\eta})+\frac{\partial\mu_{\eta\eta}}{\partial\bar{\eta}}\bar{p}_\eta\omega_{\eta\eta}\right\} ,$$

$$\frac{d\psi_{p_RR}}{dt}=-\frac{\partial^2V}{\partial\bar{R}^2}\chi_{RR}+\mu_{RR}\omega_{RR}+\mu_{R\eta}\omega_{R\eta}-\gamma\mu_{RR}\psi_{p_RR}-\gamma\mu_{R\eta}\psi_{p_\eta R} ,$$

$$\frac{d\psi_{p_\eta R}}{dt}=\mu_{RR}\omega_{R\eta}+\mu_{R\eta}\omega_{\eta\eta}-\frac{\partial\mu_{RR}}{\partial\bar{\eta}}\bar{p}_R\psi_{p_RR}-\frac{\partial\mu_{R\eta}}{\partial\bar{\eta}}(\bar{p}_R\psi_{p_\eta R}+\bar{p}_\eta\psi_{p_RR})$$
$$-\frac{\partial\mu_{\eta\eta}}{\partial\bar{\eta}}\bar{p}_\eta\psi_{p_\eta R} .$$

The equations for the first moments differ from the generalized Hamilton equation by the presence of the second moments. These terms don't appear when the fissile nucleus motion from the saddle-point is considered [7]. It is supposed there that V doesn't contain the terms with R^3 and momentum covariances are neglected as small values of the second order. It is possible to show in our case that terms $0.5\cdot\partial^3V/\partial R^3\cdot\chi_{RR}$ in the equation for $\bar{p}_R$ correspond to renormalization of the radial potential by the zero vibration energy. It is shown in [5] that this effect strongly influences the dinuclear system evolution.

Approximation (7) and smallness of ξ at the initial interaction stage allow one to consider the R and η-modes as normal in the definition of the initial distribution function. Both the coordinate and momentum initial distributions along R-mode are supposed to be equilibrium

$$\bar{R}(0)=R_m^i ,\quad \bar{p}_R(0)=0,\quad \chi_{RR}(0)=T^*(0)/\left(\frac{\partial^2V}{\partial R^2}\right)_{R_m^i,\eta^i} , \qquad (12)$$

$$\omega_{RR}(0)=T^*(0)\mu(0), \qquad \psi_{p_RR}(0)=0.$$

Also along η-mode the initial coordinate distribution is supposed to be a δ-function and the momentum initial distribution is equilibrium [7]

$$\bar{\eta}(0)=\eta^i,\ \bar{p}_\eta(0)=(2T(0)\tilde{B}_\eta(0)/\pi)^{1/2},$$

$$\omega_{\eta\eta}(0)=T(0)\tilde{B}_\eta(0)(1-2/\pi). \quad (13)$$

$$\psi_{p_\eta R}(0)=0, \quad \omega_{R\eta}(0)=0. \quad (14)$$

In (12) and (13) R_m^i is the initial position of the radial potential minimum, η^i is η in the entrance channel.

It is necessary to supply equations (11) with the equation for the change of the excitation energy E^* during the evolution and to use the following coupling between T and E^*

$$T(t)=(10E^*(t)/A)^{1/2}. \quad (15)$$

As in [5], for the radial dependence of the potential we use the following simple parameterization

$$V(R,\eta)=E_m+(E_b-E_m)\left[3\left(\frac{R-R_m}{R_b-R_m}\right)^2-2\left(\frac{R-R_m}{R_b-R_m}\right)^3\right], \quad (16)$$

where R_m is the position of the potential minimum, R_b is the barrier radius and E_m (E_b) is V at $R=R_m(R_b)$. Expression (16) well approximates the realistic potential at $R<R_b$. At $R>R_b$ the function (16) decreases more rapidly than the realistic potential. Therefore it is better to use the following dependence at $R>R_b$

$$V(R,\eta)=E_m+(E_b-E_m)\left[3\left(\frac{R-R_m}{R_b-R_m}\right)^2-2\left(\frac{R-R_m}{R_b-R_m}\right)^3\right]\frac{1}{1+(R-R_b)^4}, \quad (16')$$

which is sewed (up to the third derivation) with (16) at $R=R_b$. The quantities R_m, R_b, E_m and E_b depend on η. These dependences are supposed to be linear

$$(E_b-E_m)=V_b^i+(V_b^f-V_b^i)\frac{A_2^i-A_2}{A_2^i-A_2^f},$$

$$R_b-R_m=(R_b-R_m)^i+\frac{(R_b-R_m)^f-(R_b-R_m)^i}{A_2^i-A_2^f}(A_2^i-A_2), \quad (17)$$

where $V_b^i(V_b^f)$ is the depth of the potential pocket in the initial (final) configuration. Also we suppose that

$$\xi=\xi_i+\frac{\xi_f-\xi_i}{A_2^i-A_2^f}(A_2^i-A_2),$$

$$\tilde{B}_\eta=\tilde{B}_\eta^i+\frac{\tilde{B}_\eta^f-\tilde{B}_\eta^i}{A_2^i-A_2^f}(A_2^i-A_2). \quad (18)$$

For the definition of $T^*(t)$ from (5) we also use the linear parameterization

$$\hbar\omega_R=(\hbar\omega_R)^i+\frac{(\hbar\omega_R)^f-(\hbar\omega_R)^i}{A_2^i-A_2^f}(A_2^i-A_2). \quad (19)$$

To simplify the solution of (11) and presentation of the results, the following substitutions

$$\frac{d}{dt}=\left(\frac{A^2}{8\tilde{B}_\eta}\frac{\partial V}{\partial\bar{A}_2}\right)^{1/2}\frac{d}{d\tau}, \qquad \bar{A}_2=\frac{1-\bar{\eta}}{2}A, \qquad \bar{r}=\bar{R}-R_m$$

can be done.

The distribution function of the distance between the fragment centers in the exit channel is of a particular interest for us.

$$P(R,t)=\int f_g(R,p_R,p_\eta)\,dp_R dp_\eta=(2\pi\chi_{RR}(t))^{-1/2}\exp\left(-\frac{(R-\bar{R}(t))^2}{2\chi_{RR}(t)}\right).$$

Solving the system of equations (11) with the initial condition (12-14) we can find the dependence of the moments of P(R,t) on the mass number of a light fragment A_2. Note that the main advantage of the use of FPE for the dynamic description of the dinuclear system is the possibility to include the diffusion through the potential barrier, thermal and quantum fluctuations.

3. Calculational results

Let us consider the α-particle configuration of the dinuclear system as the exit channel. All the necessary quantities entering into expressions (6,7,12-19) are taken from [5]. The radial friction coefficient can be defined by the "window" formula [8], $\gamma=3.5\cdot10^{-22}$ $\mathrm{MeV\cdot fm^{-2}s}$. However, it is indicated in [9] that γ can be increased more than by factor 1.5 for a strongly asymmetric system. The value of γ which has been used in [10] is by one order larger. Therefore we fix γ so that the complete fusion of nuclei was reached at the zero momentum of collision (J=0ħ) for such combinations of nuclei when the total mass is A>200 and the projectile is either C or Ne. For simplicity we shall not consider the deformation of parts of the dinuclear system.

There is the term $0.5\partial^3V/\partial\bar{R}^3\cdot\chi_{RR}$ in the equation for $\bar{p}_R$ (11) which is absent in the ordinary classical equation. This leads to the following. When the value of $\bar{R}$ reaches the bend-point of the radial dependence of the potential, the value of χ_{RR} begins to increase exponentially. In this case the value of $\bar{R}$ begins to increase quickly as well and reaches the barrier (R_b) rapidly. This behaviour of $\bar{R}$ is illustrated (Fig.1, solid lines) for the reaction ^{40}Ar+^{197}Au at J=0ħ. Since our tensor of inertia does not depend on R, then at $\bar{R}$>>R_b such calculation loses sense. The dinuclear system can decay during the evolution to the compound nucleus. Due to the small depth of the potential pocket we overestimate the decay probability for the region near the entrance channel in our calculation. That is why we are going to start the consideration with a more asymmetric configuration. For instance, in the reaction ^{40}Ar+^{197}Au we start the calculation with the configuration ^{22}Ne+^{215}Fr characterized by a more deep radial potential pocket. The part of collisions coming to the configuration with ^{22}Ne will appear as the norm factor.

In Fig.1 the calculated dependences of $\bar{R}$ and χ_{RR} on A_2 for the initial configuration ^{22}Ne+^{215}Fr are presented by dashed lines. The friction plays the stabilizing role and decreases the probability of decay of the dinuclear system.

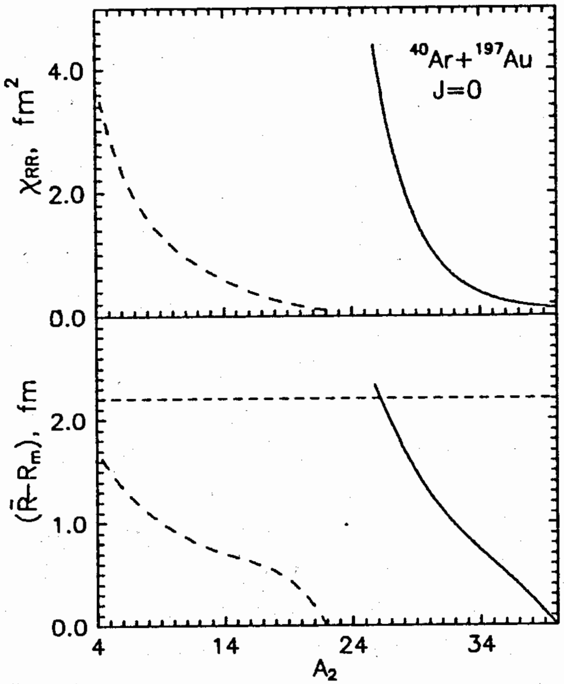

Fig.1 Dependences of χ_{RR} (upper part) and $(\bar{R}-R_m)$ (bottom part) on A_2 at J=0ħ, $\gamma=7\times10^{-22}\mathrm{MeV\cdot fm^{-2}s}$, T_0=1.5MeV and $r_w=1.17\times2^{1/3}$fm for the system ^{40}Ar+^{197}Au are presented by solid lines. Calculational results for the initial configuration ^{22}Ne+^{215}Fr are presented by dashed lines. The horizontal dashed line in the bottom part shows the value of (R_b-R_m) for the α-particle configuration.

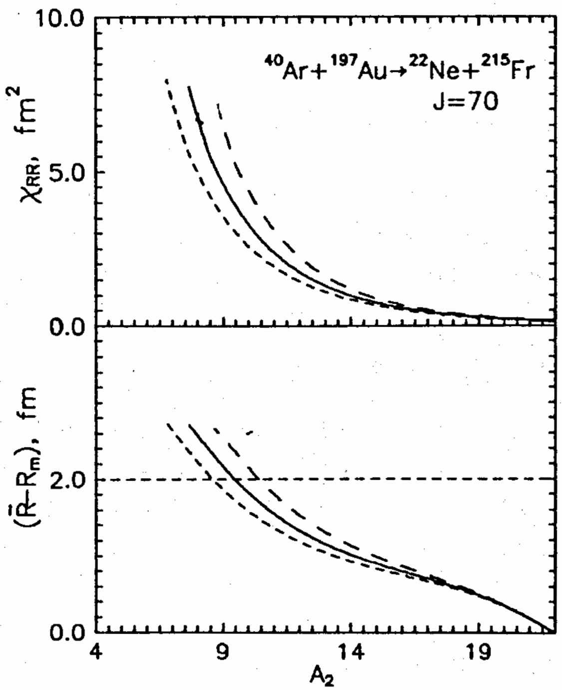

Fig.2 Dependence of χ_{RR} (upper part) and $(\bar{R}-R_m)$ (bottom part) on A_2 at J=70ħ, $\gamma=7\times10^{-22}\mathrm{MeV\cdot fm^{-2}s}$ and $r_w=1.17\cdot2^{1/3}$fm for the system ^{22}Ne+^{215}Fr in the entrance channel. Calculational results for T_0=1.5, 1.0 and 2.0MeV are presented by solid, short-dashed and long-dashed lines, respectively. The horizontal dashed line in the bottom part shows the value of (R_b-R_m) for the α-particle configuration.

We suppose $\gamma=7\cdot10^{-22}$MeV$\cdot$fm^{-2}s and fix the window radius $r_w=1.17\cdot2^{1/3}$fm. Note that the displacement of the calculation-starting point from ^{40}Ar to ^{22}Ne makes more realistic the linear approximation (7). In this case the motion along η will start practically from the Businaro-Gallone point [11]. It is seen (Fig.1) that in the considered interval of the change of $\bar{R}$ the value of χ_{RR} is not so large and the Gaussian approximation is valid in (10).

The results of calculation of the functions $\bar{R}(A_2)$ and $\chi_{RR}(A_2)$ for the reactions ^{40}Ar+^{197}Au and ^{12}C+^{232}Th at J=70ħ and various initial temperatures (T_0) are presented in Figs.2,3. It is well seen that the results for these reactions are qualitatively different. One has $\bar{R}<R_b$ for the reaction ^{12}C+^{232}Th in the α-particle configuration and $\bar{R}>R_b$ for the reaction ^{40}Ar+^{197}Au. Thus, due to the dynamic coupling of motions along R and η-modes the relative yield of the light particles is larger in the latter case. Probably this mechanism can explain a discrepancy of about one order between the results of the statistical calculation and experimental data. Let us estimate the relative yield of the α-particles by the approximative expression

$$\sigma_\alpha/\sigma_f \simeq \int_{R_b}^{\infty} P_\alpha(R)\,dR \Big/ \int_0^{R_b} P_\alpha(R)\,dR \ ,$$

where $P_\alpha(R)$ is the distribution function of R for α-particle configuration, σ_α and σ_f are the cross sections of the α-particle production and the fusion, respectively. Our estimations show that

$$(\sigma_\alpha/\sigma_f)_{Ar}\ /(\sigma_\alpha/\sigma_f)_C \simeq 4.5\,.$$

This ratio is much larger than unity but it is less than the experimental result. Additional increase of the α-particle yeild can be connected with the decrease of the window radius for a strongly asymmetric configuration and appearance of the weak rolling in the exit channel [5].

As it is seen from Figs.2,3, the increase of the initial temperature leads to a more strong increase of χ_{RR} and $\bar{R}$. Thus

the thermal fluctuations decrease the stability of the dinuclear system. The thermal fluctuations are more important for the entrance channel where the quantity $\hbar\omega_R/2$ is relatively small.

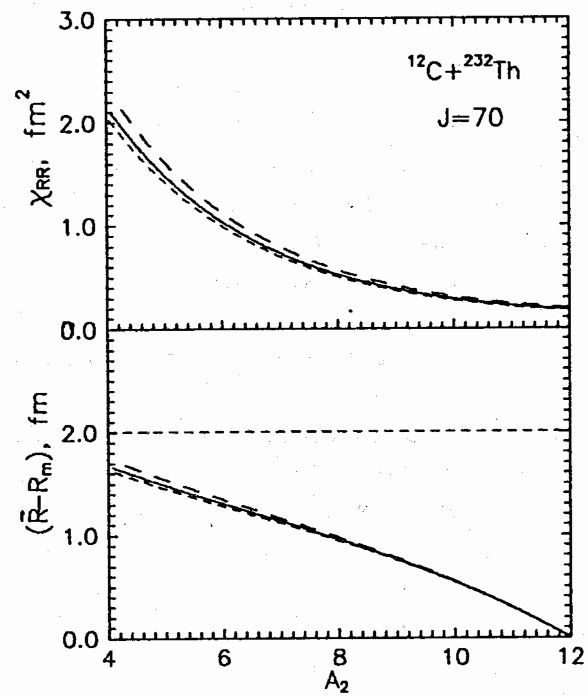

Fig.3 The same as in Fig.2, but for the system ^{12}C+^{232}Th.

4.Summary

Within the diffusion model, the evolution of the dinuclear system to the compound nucleus was considered. It was shown that behaviour of the system depends on the entrance channel. Because of the dynamic coupling of R and η-modes of the motion, the relative yield of the light particles in the reaction ^{40}Ar+^{197}Au is larger than in the reaction ^{12}C+^{232}Th. This fact is confirmed by the experimental data. The inclusion of fluctuations influences strongly the results of calculation.

Acknowlegement
Authors wish to thank Prof. V.V.Volkov for his active attention and comments.

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Received by Publishing Department
on May 14, 1991.