PAPER

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Modeling incomplete fusion reactions

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Abstract
We present a new model for describing the dynamics of an incomplete fusion reaction, concentrating on the basic ideas. Calculated α-particle spectra for the $^{12}C+^{118}Sn$ reaction are compared to the experimental data.

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1. Introduction

When a projectile approaches a target with a given kinetic energy, a compound nucleus may be created via complete (CF) or incomplete fusion (ICF) reactions. The so-called ICF is a collision in which part of the projectile fuses with the target while the rest escapes. The ICF mechanism, initially described in the late 1970s [1], was first interpreted in terms of the generalized critical angular momentum model. Soon afterwards, the sum rule model [2] was proposed. It was slightly modified [3] by adding some dissipation effects in the pre-equilibrium stage. In recent years, a number of cross-sections have been measured [4, 5] by off-line γ-spectrometry. Cross-sections for nuclei created through αxn channels were much bigger than those predicted assuming the CF mechanism. The influence of ICF on the population of high-spin states has been shown in [6]. The models proposed so far, however, do not handle the dynamics of the process—the creation of the compound nucleus and fragment emission.

Our model describes ICF for the case when an α-particle escapes. It is based on the assumption that ICF is a two-stage process. In the first stage, the projectile breaks up into an α-particle and the projectile residue during the approach towards the target. In the second stage, the projectile residue fuses with the target and the α-particle escapes. The model allows the spin and excitation energy of the compound nucleus to be evaluated, as well as the energy and the direction of the escaping α-particle. The part describing the determination of spin and excitation energy was recently compared with experimental results for γ-ray fold distributions [7]. In this work, we focus on the α-particle emission.

2. Description of the model and parameterization

In order to determine the probability distribution of the entrance angular momentum leading to ICF, we applied the generalized concept of critical angular momentum [1]. Generalizing, ICF with α-particle escape occurs for an entrance angular momentum above the critical angular momentum L_{CR}, proposed by Wilczyński [8]. The value of L_{CR} is calculated from the effective nuclear radius R_O, a model parameter that can be interpreted as the half-density radius of the nucleus.

Once the entrance angular momentum of the projectile is chosen, it is possible to describe the dynamics of the collision. A model based on a semi-empirical description is proposed. While the projectile approaches the target nucleus, its kinetic energy in the center of mass system decreases from its initial energy, E_{CM}, to a minimum value reduced by the Coulomb barrier, V_{CM}. We assume that the projectile can breakup during the approach. To calculate the breakup distance, we introduce the probability distribution controlled by the F parameter. The kinetic energy of the projectile when the breakup occurs is $E_P = f \cdot E_{CM}$, where

$$f = 1 - \frac{V_{CM}}{E_{CM}} \cdot \left(1 - (\mathrm{RND})^F\right) \qquad (1)$$

and RND is a random number between 0 and 1. For an E_P distribution, the distribution of distances between nuclei can be easily obtained. Such a distribution is shown in figure 1. The F value affects the mean distance between nuclei when the breakup occurs. For a value of $F = 5$, the majority of the breakup events occur when the surfaces of both nuclei nearly touch each other. The distribution peaks for

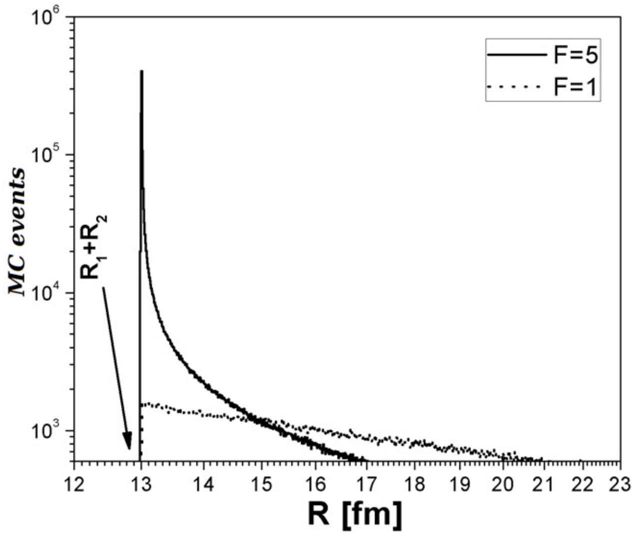

Figure 1. Distributions of the distance between the projectile and the target at the moment of breakup. Calculations were performed for the ^{20}Ne$+^{122}$Sn system at $E_{\mathrm{LAB}} = 150\,\mathrm{MeV}(E_{\mathrm{CM}} = 111\,\mathrm{MeV})$ ^{20}Ne projectile energy for two F values: 1 (dotted) and 5 (solid). The most probable distance between nuclei at the moment of breakup decreases with increasing F. R_1 and R_2 are the radii of the beam and target nuclei, respectively (see the text).

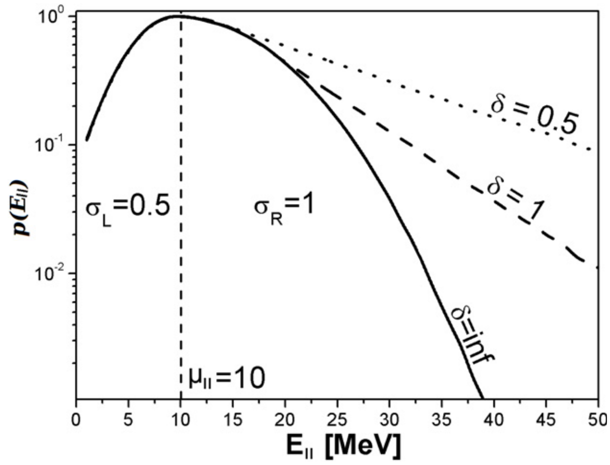

Figure 2. The probability distribution $p(E_\parallel)$, calculated with $\sigma_{\mathrm{L}} = 0.5$, $\sigma_{\mathrm{R}} = 1$ as a function of $E_\parallel$, is shown for three different δ values: $\delta = \infty$ (solid), $\delta = 1$ (dashed) and $\delta = 0.5$ (dotted). The distribution is a combination of an asymmetric Gaussian function (σ_{L}, σ_{R}) and an exponential function (δ) attached to the high-energy slope of the Gaussian.

distances around $R_1 + R_2$, where R_1 and R_2 are the radii of the projectile and the target, respectively. The R_i are calculated as $R_i = R_{\mathrm{O}} \cdot A_i^{1/3}$. It must be noted that in the definition of the f distribution, only breakup induced by the Coulomb interaction is considered. This is motivated by the fact that for beam energies between 4 and 20 A MeV, 'projectile-like' fragments are mainly produced in a quasi-elastic process [9]. The projectile residue subsequently fuses with the target and the α-particle flies away. It has been shown [10–13] that α-particles in an ICF reaction are emitted in the forward direction ($\theta_{\mathrm{LAB}} < 60^\circ$) and their velocity is widely distributed around the beam velocity.

In order to describe the dynamics of the reaction, we suggest the following approach. It is assumed that the α-particle moves in some effective potential:

$$V_{\mathrm{eff}} = e_{\mathrm{f}} \cdot V_{\mathrm{C}}, \tag{2}$$

where V_{C} is given by the equation

$$V_{\mathrm{C}} = \left(V_1(R_1) + V_2(R_2 + x) \cdot \frac{E_{\mathrm{CM}} - E_{\mathrm{P}}}{V_{\mathrm{CM}}} \right), \tag{3}$$

where V_1 is the Coulomb potential between the α-particle and the projectile residue and V_2 is the Coulomb potential between the α-particle and the target nucleus. The collision parameter x is calculated from the entrance angular momentum. R_1 and R_2 are the respective radii of the projectile and the target. Since E_{P} is chosen with the f distribution (see equation (1)), it assumes values from $E_{\mathrm{CM}} - V_{\mathrm{CM}}$ to E_{CM}. Consequently, V_{C} takes values from $V_1(R_1)$ (breakup at maximum distance) to $V_1(R_1) + V_2(R_2 + x)$ (breakup at minimum distance). The e_{f} parameter is a correction factor necessary to describe the fluctuations of the barrier height for the highly deformed precompound nucleus.

The final kinetic energy of the escaping α-particle is assumed to be the sum of the two components, namely the perpendicular $E_\perp$ and the parallel $E_\parallel$ energies:

$$E^{\alpha}_{\mathrm{CM}} = E_\perp + E_\parallel. \tag{4}$$

The emission angle is then

$$\theta^{\alpha}_{\mathrm{CM}} = \arccos \frac{\sqrt{E_\parallel}}{\sqrt{E_\perp + E_\parallel}}. \tag{5}$$

The energies $E_\parallel$ and $E_\perp$ are calculated using a probability distribution that is a combination of an exponential function, controlled by the parameter δ, attached to the high-energy slope of an asymmetric Gaussian, controlled by the parameters σ_{L} and σ_{R}. In the case of the parallel component, σ_{L} and σ_{R} are the standard deviations. Since the velocity of the α-particles is distributed around the beam velocity, the mean value of the Gaussian function is calculated as $\mu_\parallel = E_{\mathrm{IC}} + V_{\mathrm{eff}}$. The α-particle created has kinetic energy E_{IC}, which is calculated as $E_{\mathrm{IC}} = E_{\mathrm{P}} \cdot \frac{4}{A_1}$, where A_1 is the mass number of the projectile. Therefore, the expression for $\mu_\parallel$ approximates the initial α-particle kinetic energy. Figure 2 illustrates the $p(E_\parallel)$ distribution, calculated with fixed values of $\sigma_{\mathrm{L}} = 0.5$ and $\sigma_{\mathrm{R}} = 1$ and three different values of δ. Such an approach allows both the acceleration and the deceleration of α-particles emitted in an ICF process to be described. The change of velocity can be attributed to the Fermi motion of light particles inside the nucleus. The exponential tail, described by the parameter δ, allows the description of the high-energy α-particles originating in deep inelastic interactions. Such high-energy α-particles were measured by Borcea *et al* [11, 12]. In the case of the perpendicular component $E_\perp$, the mean value $\mu_\perp = 0$ is used and the probability distribution is only the right half of the Gaussian function (with standard deviation σ_{R}).

The present model consists of the Wilczyński radius R_{O} and five new parameters: F, e_{f}, σ_{L}, σ_{R} and δ. It must be noted, however, that for the cases studied the parameters do not vary significantly. Moreover, the asymmetric Gaussian can be replaced by a symmetric Gaussian ($\sigma_L = \sigma_R$), limiting the number of new parameters to four. Good agreement with experiment is usually obtained with $R_O \approx 1.03$, $F \geqslant 5$, e_f varying from 0.3 to 0.4, $\sigma_L = \sigma_R \approx 0.6$ and $\delta \approx 0.5$. The model also allows the excitation energy and spin of the compound nucleus to be determined. A detailed description of this part will be published elsewhere. It has already been shown that fold distributions obtained for $^{51}V + ^{97}Mo$ ICF reaction channels can be well described by the present model [7].

3. Comparison with experimental results

The model described herein has been included in the Monte Carlo code COMPA[4] , allowing us to compare its predictions with some experimental data. The code is based on a statistical description. It provides complete information on the reaction products: the entry state spin and energy distributions, the reaction point coordinates, the directions and velocities of the recoils and the emitted light particles. The present ICF model, as well as a description of the stopping of the reaction products in the passive elements of the setup—e.g. the target and backing—are incorporated into COMPA. Thanks to this, COMPA allows an easy comparison of predictions and experimental results to be made.

The most complete set of experimental data representative of the ICF phenomenon was obtained by Borcea *et al* [11, 12]. They were analyzed in terms of our model by Lieder *et al* [7]. Another theoretical approach was proposed by Zagrebayev *et al* [14, 15]. The high-energy part of the spectra was reproduced in terms of a dissipative massive transfer model.

It is also necessary to make a comparison with the spectra gated on specific γ-transitions from a given residual nucleus. Interesting data were collected by Arnell *et al* [16] for the $^{12}C + ^{118}Sn$ reaction, at an energy of 118 MeV for the ^{12}C projectiles. The results of the present calculations are compared to α-particle spectra obtained by gating on ^{121}Xe and ^{122}Xe transitions as shown in figure 3. The spectra were measured at $\theta = 20°$. The calculations were performed using the parameter set $R_O = 1.03$, $F = 10$, $e_f = 0.35$, $\sigma_L = \sigma_R = 0.65$ and $\delta = 0.5$, with the assumption that the particle detector covered angles between 15° and 25°. Both the $^{118}Sn(^{12}C, \alpha 5n)^{121}Xe$ and $^{118}Sn(^{12}C, \alpha 4n)^{122}Xe$ reactions can be produced via CF and ICF. The ^{122}Xe spectrum is fitted well, whereas the ^{121}Xe spectrum has a high-energy tail that is not reproduced in the present calculations. Such high energies are difficult to explain in terms of a statistical model. According to COMPA calculations, the compound nucleus created after the escape of an α-particle of 50 MeV kinetic energy does not have enough excitation energy to evaporate five more neutrons. Except for this, the data are rather well reproduced. The general conclusion, however, is that we lack satisfactory experimental data. A complete set of measurements should consist of cross-section measurements, γ-ray fold distributions and particle spectra

[4] The COMPA code and documentation are available at http://www.slcj.uw.edu.pl/compa

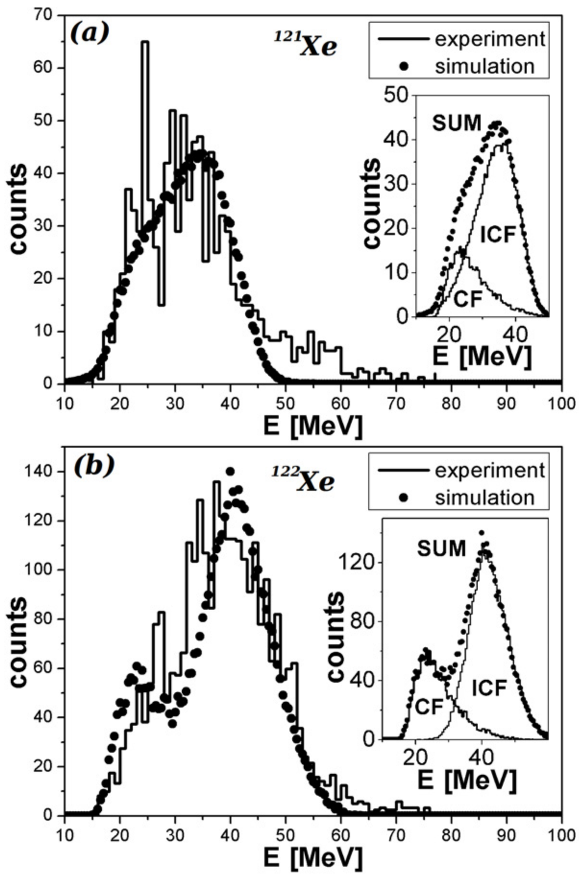

Figure 3. Experimental α-particle spectra (solid histogram) gated on γ-transitions from ^{121}Xe (a) and ^{122}Xe (b), measured at $\theta_{LAB} = 20°$ for the reaction $^{118}Sn + ^{12}C$ ($E_{LAB} = 118$ MeV) [16]. They are compared with the results of COMPA simulations (dots) taking into account both CF and ICF mechanisms. The decomposition of the simulated spectra into the CF and ICF components is shown in the insets of each figure.

with angular distributions, all attributed to a given residual nucleus. A summary of the available experimental results[4] indicates that the study of more cases is necessary to further verify the model. To the best of our knowledge such data have not been published before. Measurements for the $^{122}Sn(^{20}Ne, \alpha xn)^{138-x}Ce$ reaction, at energies of 141 and 150 MeV for ^{20}Ne, have been carried out [17]. The spectra corresponding to the production of ^{132}Ce and ^{133}Ce were measured for both energies at angles varying from 20° to 160°. Analysis of the data is in progress.

4. Summary

A new model of ICF has been presented briefly. Calculations performed with the Monte Carlo code COMPA were carried out for the $^{12}C + ^{118}Sn$ reaction, at an energy of 118 MeV for the ^{12}C beam. The results of the simulations were compared to the experimental α-particle spectra accompanying the production of ^{121}Xe and ^{122}Xe isotopes. The competition between CF and ICF calculated in terms of our model allows the shape of the α-particle spectra to be explained.

The present model consists of five semi-empirical parameters. It satisfyingly describes the available experimental data for different projectile–target combinations with the number of parameters reduced to four. It helps us to identify missing experimental data and the direction that future experiments should follow. Since a similar approach to the present one was not available previously, this model may help in the development of new theoretical models based on microscopic calculations.

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