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R.Schmidt, V.D.Toneev

EVOLUTIONS WITHIN THE ANGULAR DISTRIBUTIONS OF DIC

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1. INTRODUCTION

In recent years in heavy ion physics much attention has been paid to reactions with a large amount of energy, mass and charge transfer. It has been observed that the reaction characteristics seem to be strongly affected by the delicate balance between the Coulomb force and friction force, resulting in a great variety of properties of the reaction products. This variety has generated some semantic difficulties in naming rather close phenomena.

For the theoretical description of the so-called deep inelastic collisions between heavy ions, the classical mechanics (Newton equations) is commonly used for a few collective degrees of freedom. The energy loss is accounted for by introducing friction forces. Statistical fluctuations have been treated by means of Fokker-Planck or master equations. A dynamical coupling of the collective and inner (statistical) degrees of freedom has been investigated by Hofmann and Siemens [1].

Following ref. [1], we propose a dynamical model of deep inelastic collisions based on the Fokker-Planck

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cussing effect). A great part of the final products has a kinetic energy well below the Coulomb barrier (calculated for spherical nuclei) (hence the term "QF"). QF products exhibit a narrow mass distribution peaked at the projectile and target masses. QF like reactions are observed only for heavy systems.

The theoretical decomposition of the total reaction cross section according to certain impact parameters or orbital angular momentum can be very useful for a detailed discussion of possible reaction mechanisms which take place in a HI reaction. From the measured kinetic energy distributions two rather well separated components can be extracted: fully damped and partially damped collisions. Only in the former case the reaction leads to the transistory existence of a DNS which results in a full damping of the kinetic energy. The measured cross sections allow one to determine the corresponding windows in the orbital angular momentum space.

3. THE MODEL

On the one hand, the quasi-classical and two-body character [6] of the process allows for the theoretical description the employment of classical Newton type equations including dissipative friction terms. Such calculations have been performed by many authors [11-16] in order to estimate such quantities as fusion and deep inelastic cross sections or the energy and orbital angular momentum losses of the relative motion. On the other hand, the experiments have emphasized the statistical

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are Newton-type equations for the polar coordinates $\{i, k\} = \{R, \theta\}$ which describe the relative motion of the two ions. The R-dependent quantities V, m^{ik}, γ_{ik} represent the interaction potential, the inertial and frictional tensor, respectively. These equations (2) together with those of the second moments are solved simultaneously with the following choice of basic assumptions:

(i) For the nucleus-nucleus interaction potential appearing in the equations of motion for the first moments we have inserted the proximity potential V^{I} [21] for the entrance channel.

(ii) For the form factor $f(R)$ of the elements of the frictional tensor diagonal in polar coordinates ($\gamma_{RR} = a_R f(R)$; $\gamma_{\theta\theta} = a_{\theta} f(R) R^2$) the expression given by Gross and Kalinowski [11] has been taken, $f(R) = (\partial V^{I}/\partial R)^2$. In order to fix the radial and tangential frictional constants a_R, a_{θ} we proceeded as in ref. [11]: the experimental fusion cross section was fitted over a broad range of target-projectile combinations and energies leading to $a_R = 5$ *fm/c·MeV*; $a_{\theta} = 0.01$ *fm/c·MeV*. Although, such a model fits the fusion data it is impossible to describe the experimental energy loss. Thus, for the description of DIC the deformation degree of freedom has to be taken into account.

(iii) In order to simulate the large deformation mainly produced in the exit channel, we correct the ion-ion interaction, and write the exit nucleus-nucleus interaction potential V^{E}

$$V^{E} = V^{I} + E_{d}(1 - g(R)). \qquad (3)$$

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$^{40}Ar + ^{232}Th$ (**388 *MeV***)
0.25).
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ime. In order to obtain
$d\sigma/d\Omega$ we integrate
over the variables P_θ,
performed) and the impact
definition of $d\sigma/d\Omega$),

$$[\theta - \bar{\theta}(\ell)]^2$$

4. *ANGULAR DISTRIBUTIONS IN DIC*

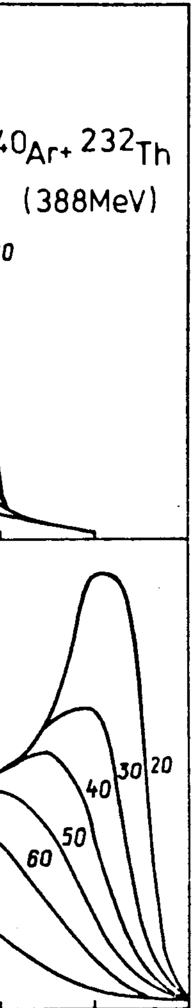
The model formulated above allows one to compute the mass integrated angular distributions. The thermal fluctuations smooth out the classical rainbow-infinity [22]. Consequently, in contrast to a pure classical calculation [11] it is possible to compare the calculated and experimental angular distributions in widths and shapes.

Recently, the effect of the mass exchange on the relative motion has been investigated by introducing the mass asymmetry parameter [23]. But still the widths of the calculated mass-integrated angular distributions come out to be too small compared with experiment.

As is shown in ref. [24] the influence of the deformation degree of freedom improves the agreement with the experimental data and should be taken into account within such considerations of the DIC.

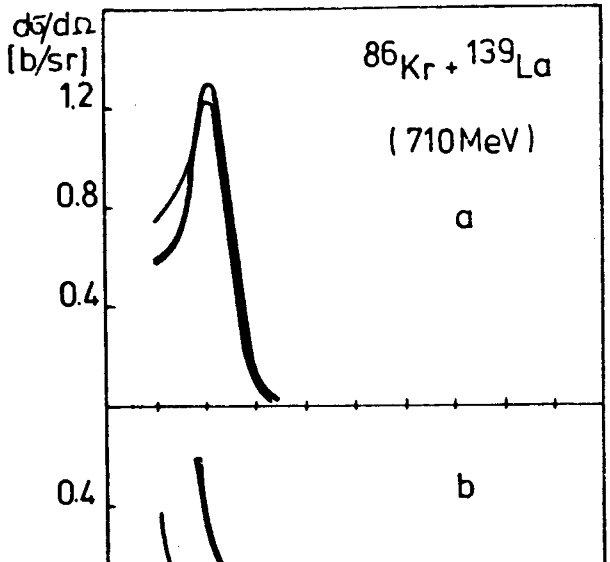
As that follows we will compare our model calculations with the avaluable experimental data. Particular interest is given to the influence of various factors such as the final kinetic energy of the products, the incident energy and the target-projectile combination on the shape of the angular distribution of the DIC. Some kinds of evolution within the angular distributions of DIC will be discussed and summarized in the evolution diagrams.

A. The influence of the kinetic energy loss on the shape of $d\sigma/d\Omega$ is illustrated for the $^{40}Ar + ^{232}Th$ reaction at two energies in *fig. 1*. It is seen that the shape of angular distributions depends considerably on the extent of the kinetic energy dissipation. With increasing



a continuous evolution between quasi elastic phenomena and completely damped ones.

In the experimental work [25] it was shown that for projectiles like Ar DIC exhibit only DITR type angular distributions up to the lowest incident energies if one takes into account an adequate loss of initial kinetic energy and (or) an appropriate charge transfer (a large charge transfer is associated with a large energy dissipation). Thus, we conclude: to analyze the shape of the angular distributions of the DIC products one should take into consideration the extent of the dissipation of the initial kinetic energy.



n components (which cor-
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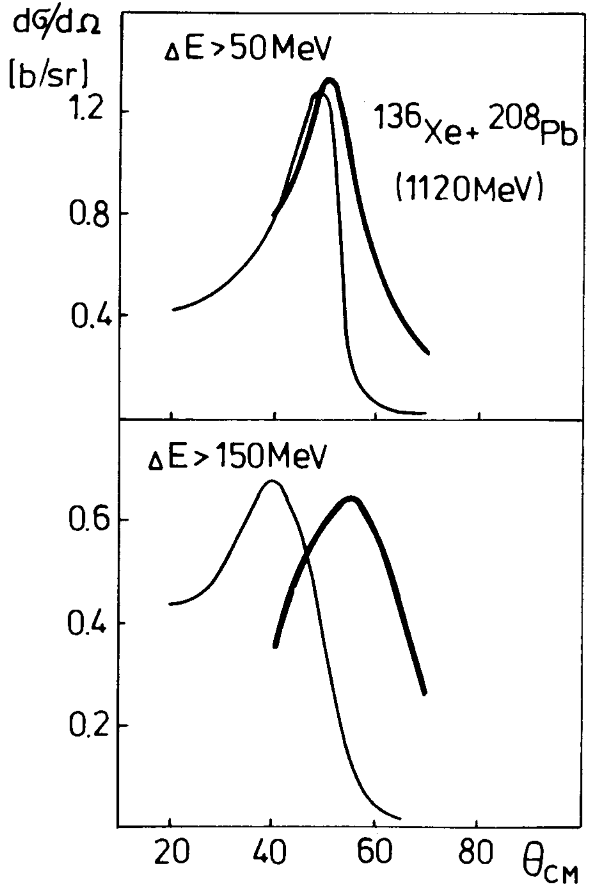

Fig. 3. Experimental (thick lines) and theoretical (thin lines) differential cross sections for all inelastic products (ΔE > 50 MeV) and products which have a kinetic energy loss greater than 150 MeV.

calculated angular distribu-
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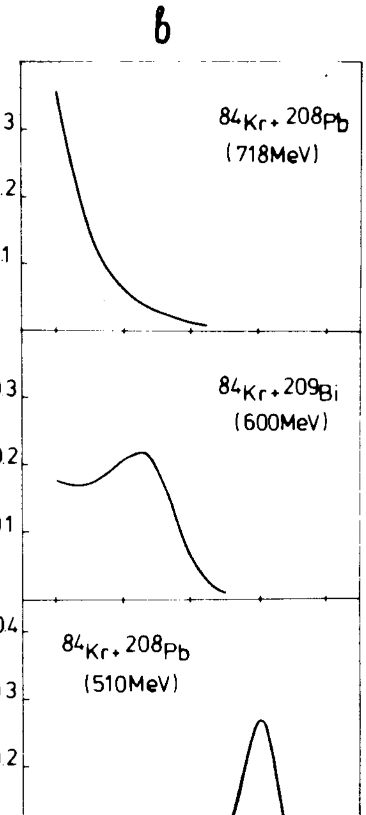

cross section in forward direction (represents orbiting in the case of bombarding energy 718 *MeV*). Both effects originate from the increasing of the total reaction time due to the deformation which keeps the system together for a longer period /24/.

It should be mentioned that such an evolution from QF to DITR for the reaction $^{84}Kr + ^{208}Pb$ and also the vanishing fusion cross section at 510 *MeV* where the reaction cross section is almost identical with that for the QF was predicted in the framework of a static fusion model /29/.

Summarizing this section we note: for heavier projectiles a continuous evolution from QF to DITR occurs with increasing bombarding energy. In addition, the predicted prototype evolution picture calculated for very inelastic products ($\Delta E > E - V_B$) seeks for further experimental analysis in order to check this.

C. The discussion of the dependence of $d\sigma/d\Omega$ *on the combination of the charge (or mass) numbers* of the colliding nuclei seems to be only meaningful if the angular distributions for equal E/V_B values (e.g., energy per entrance Coulomb barrier) are considered. This can be done approximately for the reactions $^{40}Ar + ^{232}Th$ (297 *MeV*, $E/V_B = 1.46$), $^{84}Kr + ^{209}Bi$ (600 *MeV*, $E/V_B = 1.39$) and $^{136}Xe + ^{208}Pb$ (1120 *MeV*, $E/V_B = 1.56$) and at higher energies for the combinations $^{40}Ar + ^{232}Th$ (388 *MeV*, $E/V_B = 1.91$) and $^{86}Kr + ^{139}La$ (710 *MeV*, $E/V_B = 1.99$). As one can see from comparison of the angular distributions for all inelastic reaction products ($\Delta E > 50$ *MeV*) there is a strong evolution from DITR type to QF type distributions with increasing entrance Coulomb barrier in both

nt reaction components at
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ial interest to extend this
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Ar + ^{58}Ni (280 *MeV*) and
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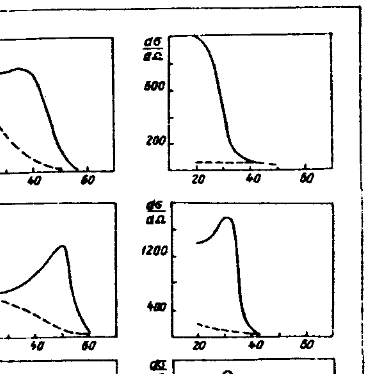

D. The evolution diagram (fig. 5) represents calculated angular distributions of DIC depending on the target-projectile combination (that means V_B) and on various bombarding energies (that means fixed E/V_B values for all reactions). This diagram is useful to illustrate all the discussed lines of evolution within the angular distributions of the DIC. We calculated the differential cross sections for three target-projectile combinations at three bombarding energies in each case (corresponding to fixed E/V_B values of 1.2, 1.5 and 2.0) and for the two kinds of reaction products: all deep inelastic events ($\Delta E > 50$ *MeV*) and those events which have a final kinetic energy less than the entrance Coulomb barrier $V_B (\Delta E > E - V_B)$. The results can be summarized as follows:

(i) $^{40}Ar + ^{232}Th$

For this system DIC occur only at sufficiently high energies where a DITR angular distribution is typical. The maximum near the grazing angle in $d\sigma/d\Omega$ at $E/V_B = 1.2$ corresponds to quasi-elastic reaction products though the final kinetic energy is less than the barrier V_B. At this energy the cross section of events with $\Delta E > 50$ *MeV* is smaller than that with $\Delta E > E - V_B$ and very small compared with the theoretical reaction cross section estimated by

$\sigma_R = \pi R_B^2 (1 - \frac{V_B}{E})$ (R_B is the radius of V_B) that

gives 830 *mb*.

(ii) $^{84}Kr + ^{208}Pb$

Here DIC exist up to the lowest energies and give the dominating contribution to the total reaction

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