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FAST PROCESSES INDUCED BY HEAVY PROJECTILES AT INCIDENT ENERGIES
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Abstract: Collisions between heavy nuclei ($A \geq 86$ u) are investigated at relative velocities which are 7.5 to 10.5 MeV/u in excess of the Coulomb barrier. Information on charge equilibration, preequilibrium light particle emission and projectile splitting is presented. Evidences in favour of collective modes of excitation are discussed.

1. Introduction

Heavy ion reactions confronted us with a complex mechanism in which a large number of internal degrees of freedom of the nucleus are excited. It is, however, a rather difficult task to follow and disentangle the evolution of each of them. As a consequence one considers the most important collective degrees of freedom associated with the dynamics of a large number of nucleons and their interaction with the large number of internal degrees of freedom. Such collective degrees of freedom are: the kinetic energy of relative motion, the charge and mass asymmetry, the relative and internal angular momenta of the fragments and the deformation. The coupling between the collective and intrinsic degrees of freedom is a source of irreversible processes in the nucleus; heavy ion reactions have opened the possibility to study such processes in small quantum-statistical systems.

The macroscopic variables are characterized by different relaxation times. Using the connection between scattering angle and interaction time in deep inelastic collisions, one has the possibility to study the nuclear system at different stages during the relaxation process. The energy loss can be explained by incoherent particle-hole excitation and collective excitations. The collective excitations are expected to be enhanced with an increase of the momentum associated with the coherent motion of the nucleons of the projectile relative to those of the target. As a consequence, at higher incident velocities (≥ 10 MeV/u) we expect an enhanced excitation of collective modes which could be 'doorway' states for deep inelastic reactions or couple to other types of exit channels.

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In this contribution we will concentrate on fast processes such as charge equilibration, preequilibrium light particle emission and projectile splitting which are important at this higher incident energy.

In Sect.2 we describe the experimental set-up specially designed for complete kinematical coincidence studies at large bombarding energies. In Sect.3 we will present experimental results for the N/Z equilibration process and discuss possible quantum fluctuations effects. A comparison with a recently developed model for a quantum treatment of the charge asymmetry degree of freedom is presented. In Sect.4 experimental evidences are presented for non-equilibrium charged particle emission. Results which speak in favour of the presence of a fast fragmentation of the projectile-like product into two heavy products ('splitting') at these higher incident energies are shown in Sect.5.

2. A new set-up for experiments above 10 MeV/u

Since the beginning of this year energies in excess of 12 MeV/u are available at the UNILAC accelerator in Darmstadt. At such energies three and four-body processes are expected to become increasingly important (the term two, three or four-body is used to specify the number of heavy fragments in the exit channel). For this reason our kinematic coincidence set-up, which originally was designed and optimized for the selection of two-body processes has been modified and consists by now of the following elements:

- a) A large-area position-sensitive ionisation chamber, 130 cm deep, with a parallel-plate timing counter in front of it, both attached from the outside to a spherical scattering chamber of 130 cm diameter. Nuclear charge and mass as well as the velocity of the products can be identified.
- b) A new series of 12 position sensitive parallel-plate counters with an active area of $20 \times 30 \text{ cm}^2$, placed inside the spherical chamber (see Fig.1a). The velocity vectors of the products are determined with a resolution of 4 mm both in x and y and a time resolution of about 0.8 ns.
- c) A series of solid state telescopes and a 100 cm^2 plastic scintillator for the identification of light charged particles.
- d) Three γ -ray detectors each consisting of a $4 \frac{1}{2}'' \times 5''$ NaI - crystal.

Although two, three and four body processes can be reconstructed just from the measured velocity vectors, the described detection system is designed to measure for one of the outgoing products, namely the one detected in the ionisation chamber, also charge and mass. This gives the following advantages:

- a) The full (N,Z)-distribution of the products can be determined what is of particular interest at small energy losses, and
- b) the kinematic reconstruction can be improved in cases of ambiguities (as e.g. when in a three-body reaction the C.M.-velocity vectors are aligned).

In addition, the ionisation chamber covers, as compared to parallel-plate counters, a broader dynamical range what is important for the investigation of the splitting process.

Fig. 1 a) Photograph of the new kinematical coincidence set-up seen from the direction of the impinging beam.
 b) Reconstructed position of the points where the products hit the parallel-plate counters in an inclusive measurement, viewed as in the photograph from the beam axis (at $+\infty$).

Using the new set-up we performed two measurements: (i) The reactions ^{86}Kr on ^{166}Er and ^{98}Mo on ^{154}Sm were measured at 12.5 and 12 MeV/u, respectively, (ii) recently beams of ^{92}Mo and ^{98}Mo were used to bombard at 14.8 MeV/u targets of ^{92}Mo , ^{98}Mo , ^{147}Sm , ^{154}Sm and ^{238}U . The software programs necessary for the data calibration, for the data reduction and for Monte Carlo simulation have been completed. From the experiments at 14.8 MeV/u only one-particle inclusive results of the ionisation chamber for the different target-projectile combinations were analyzed until now. Since the charge equilibration process is considered particularly interesting and since the physical information on it can be already gained from the less complex binary reactions data, this aspect will be discussed first.

3. Charge equilibration

Early experiments [1,2] have shown that the charge or N/Z equilibration process occurs in a time comparable with the relaxation time of intrinsic degrees (10^{-22}sec). It is therefore probable that during the contact time the out of phase vibration of neutrons against protons may play an important role. As a consequence one of the fastest processes in the kinetic-energy dissipation could be the collective resonant excitation of an isovector dipole vibration. In order to elucidate this question a few experiments have been undertaken [3-5]. Such experiments measure the triple differential cross section $d^3\sigma/dE.dA.dZ$ in order to study the evolution of the isobaric distribution as a function of the energy loss. Some difficulties in performing such experiments are evident:

- a good mass resolution for a given Z value is required,

- a precise determination of the time evolution of the dinuclear system,
- the measured values of A,Z refer to the secondary products, therefore one has to correct for evaporation in order to obtain the primary Z and A values.

The effects of sequential evaporation on the moments of the isobaric distribution for different energy losses are quite important [6] and the appropriate corrections have to be made if one is interested in the effects connected with the primary N/Z equilibration process.

a. Experimental results

If the diabatic processes play an important role in the collective resonant excitation of modes associated with the isospin degree of freedom, they should be more pronounced at higher incident velocities. At higher energies, however, the results can be obscured by the presence of nonbinary processes even at relatively low energy losses. We have therefore undertaken a kinematic coincidence measurement of the binary products for the $^{98}\text{Mo} + ^{154}\text{Sm}$ reaction at 12 MeV/u. The projectile-like fragments were identified in charge, mass and velocity vector by the position sensitive-ionisation chamber (IC) while the velocity vector of the recoil product was detected by one of 4 parallel plate avalanche counters placed in the plane defined by the IC and the beam axis. The double differential cross sections $d^2\sigma/d\theta_{\text{cm}} \cdot dE_{\text{cm}}$, $d^2\sigma/dZ \cdot dE_{\text{cm}}$ and $d^2\sigma/dZ \cdot d\theta_{\text{cm}}$ obtained with a width of $\Delta\phi=4^\circ$ around 180° in coplanarity are shown in Fig.2. The main trends observed in these representations are generally similar to those observed at lower incident energies, except for the enhanced production of elements lighter than the projectile. With such a narrow window on coplanarity the contribution from nonbinary events is negligible within the first 150-200 MeV of energy loss. It still remains to clarify to which extent primary products heavier than the projectile are excluded due to the presence of a fast sequential fragmentation process. The

Fig. 2

Contour plots of the cross sections

$d^2\sigma/d\theta_{\text{cm}} \cdot dE$, $d^2\sigma/dZ \cdot dE$ and

$d^2\sigma/dZ \cdot d\theta_{\text{cm}}$ in the case of the

reaction $^{98}\text{Mo} + ^{154}\text{Sm}$ at 12 MeV/u

for selected coplanar events ($\Delta\phi = 4^\circ$).

triple differential cross sections $d^3\sigma/d\text{TKEL} \cdot dA \cdot dZ$ for bins in total kinetic energy loss (TKEL) of 20 MeV width are represented in Fig.3. The mass is derived from energy and time-of-flight; evaporation (for deriving TKEL and masses) is taken into account in an iterative way. Within the first 120 MeV of energy loss the mean Z value decreases by about 2 units while the mass remains almost unchanged, as expected from an N/Z equilibration process. With increasing energy loss, the distributions spread and follow the slope of the bottom of the valley in the potential energy surface (indicated by a dashed line in Fig.3). In Fig.4 the double differential cross sections $d^2\sigma/dZ \cdot dE_{\text{cm}}$ are presented: a) With no condition on mass asymmetry; b) with a window of ± 3 mass units around the projectile mass (which represents the lower limit of our experimental resolution) and c) with a window of ± 2 mass units around the projectile mass. The difference in the evolution of the charge distribution width as function of TKEL is evident. While the width of the charge distribution without condition on mass asymmetry shows the expected trend,

Fig. 3

Contour plot of the cross section represented in a (N,Z) plane for energy-loss bins 20 MeV wide ranging between 10 and 130 MeV. The contour lines are located at 95, 75, 50 and 25 % of the maximum yield.

Fig. 4 Contour plot of the $d^2\sigma/dz \cdot dE$ cross sections for different conditions on mass: a) no condition, b) $95 \leq A \leq 101$ u, c) $96 \leq A \leq 100$.

namely growing with increasing energy loss, an evident saturation is observed in the representations obtained for a given width in the mass asymmetry. These qualitative conclusions are supported by Fig.5 which represents $\Gamma_{\eta_z}^2$ as function of TKEL the square of the full width at half maximum, $\Gamma_{\eta_z}^2$ ($\eta_z = (Z_1 - Z_2)/(Z_1 + Z_2)$), by cutting the previous contour plots at different total kinetic energies. The value of $\Gamma_{\eta_z}^2$ increases strongly as a function of the energy loss in the first 70-90 MeV and then remains almost constant over an energy range of 80-100 MeV. Within the limits of the error bars no real difference is observed between the result obtained with a window in the mass of ± 3 units (open circles) and those with a window of ± 2 units (open triangles). Before explaining the observed trend, we refer to Fig.9 (which will be discussed in greater detail later) to show the shift of the centroid of the charge distribution for $^{98}\text{Mo} + ^{98}\text{Mo}$ at 14.7 MeV/u (open points) to see at which energies the emission of light charged particles starts to influence the distributions. Obviously a shift of two units in the mean value takes place for 135 MeV of TKEL corresponding to an average of 67.5 MeV excitation energy in each partner. If this is due to particle evaporation then this process takes probably place after reseparation of the dinuclear system, when the collective degrees of freedom are equilibrated. In the case of the $^{98}\text{Mo} + ^{154}\text{Sm}$ system the minimum value of the potential in Z for a constant A is reached at $Z=40$, indicating that after N/Z equilibration the most probable isobar has $Z=40$, two protons less than ^{98}Mo . An excitation energy of 67.5 MeV in ^{98}Mo would correspond for equal temperature to an energy loss of 174 MeV in $^{98}\text{Mo} + ^{154}\text{Sm}$ system which is close to the right limit of Fig.5. These two arguments would exclude an explanation of the observed saturation in $\Gamma_{\eta_z}^2$ values due to charged particle evaporation. To which extent this trend can be attributed to a zero point motion in an harmonic oscillator, will be analysed in the next section where a qualitative agreement with the predictions of a recently developed model for a quantum treatment of charge equilibration will be presented.

Fig.5

b. A quantum treatment of the charge equilibration process
and comparison with the experimental results.

Similar trends observed at much lower incident energies have been interpreted as evidence for quantum fluctuations corresponding to the zero point motion in an harmonic oscillator in the charge asymmetry variable. The experimental results have been compared with the predictions of linear response theory [7-9] or with the predictions of a Schrödinger equation in the charge asymmetry variable with a friction term [10,11]. In this section we will present the main results of a simple model for a quantum treatment of the charge asymmetry degree of freedom [12] and compare it with the experimental results.

In the first stage of the collision where the sudden approximation is valid, the neck radius is small compared to the nuclear radii and we can use the liquid drop potential energies of the partners to derive the potential energy of the charge asymmetry degree of freedom. For a given mass asymmetry, $(A_1 - A_2)/(A_1 + A_2)$, the potential-energy dependence on the charge asymmetry $\eta_z = (Z_1 - Z_2)/(Z_1 + Z_2)$ coordinate has a parabolic shape. Since we expect a fast evolution in N/Z for a constant mass asymmetry (an hypothesis supported by the experimental data, see Fig.2), we can in the first approximation decouple these two collective coordinates. A coupling to the relative motion is taken into account in the calculation of the energy loss as a function of time. Using a linear form in the charge asymmetry coordinate for the interaction between this collective degree of freedom and the intrinsic degrees of freedom we can write the following Hamiltonian:

$$H = H_{\text{coll}} + H_{\text{intr}} + \delta V \quad (1)$$

where

$$H_{\text{coll}} = H_{\text{osc}} = (p_{\eta_z}^2 / 2B_{\eta_z}) + \frac{1}{2} K_{\eta_z} \eta_z^2 \quad (2)$$

and

$$\delta V = \alpha V(x_i) \eta_z \quad (3)$$

Under the assumption that the intrinsic degrees of freedom are in a statistical equilibrium at all times, they can be described conveniently using a diagonal density matrix which in the energy representation has the following form:

$$\rho_{nm} = \delta_{nm} A \exp(-E_n/T) \quad (4)$$

where

$$A^{-1} = \sum_j \exp(-E_j/T) \quad (5)$$

A convenient assumption is that the diagonal matrix elements of $V(x_i)$ are zero whenever there is any interaction between collective and intrinsic degrees of freedom. As from the experiment we obtain the moments of the distributions for a given degree of freedom, the idea is to obtain directly the equation of motion for these quantities. In the Heisenberg representation we have two coupled equations for the operators η_z and its conjugate momenta p_{η_z} :

$$\begin{aligned}\dot{\eta}_z &= p_{\eta_z} / B_{\eta_z} \\ \dot{p}_{\eta_z} &= -K_{\eta_z} \eta_z - \alpha V(x_i)\end{aligned}\quad (6)$$

For a second order expansion in $V(x_i)$ and in the hypothesis of closely spaced levels of the internal Hamiltonian [12], the following equation for η_z is obtained:

$$\ddot{\eta}_z + \frac{\beta}{B_{\eta_z} \omega} \dot{\eta}_z + \omega^2 \eta_z = - \frac{\alpha}{B_{\eta_z}} V^{(0)}(t) \quad (7)$$

which is the differential equation for a driven damped harmonic oscillator, where:

$$\begin{aligned}\beta &= A \alpha^2 \pi B(\omega) (1 - \exp(-\hbar\omega/T)) \\ B(\omega) &\equiv \int_0^\infty dE \rho(E + \hbar\omega) \rho(E) (\tilde{V}^{(0)}(E + \hbar\omega, E))^2 \exp(-E/T) \\ \omega &= \sqrt{K_{\eta_z} / B_{\eta_z}}\end{aligned}\quad (8)$$

with K_{η_z} and B_{η_z} , the stiffness and inertia parameters associated with η_z .

For the first and second moments of the η_z distribution the following two equations are obtained:

$$\frac{d}{dt} \langle \eta_z \rangle = \frac{1}{B_{\eta_z}} \langle p_{\eta_z} \rangle \quad (9)$$

$$\frac{d}{dt} \langle p_{\eta_z} \rangle = -\beta' \langle p_{\eta_z} \rangle - B_{\eta_z} \omega^2 \langle \eta_z \rangle$$

respectively

$$\begin{aligned}\frac{d}{dt} \chi &= \frac{2}{B_{\eta_z}} \sigma \\ \frac{d}{dt} \psi &= -2\beta' \psi - 2B_{\eta_z} \omega^2 \sigma + \beta' (\omega_d) B_{\eta_z} T^* \\ \frac{d}{dt} \sigma &= -\beta' \sigma - B_{\eta_z} \omega^2 \chi + \frac{1}{B_{\eta_z}} \psi\end{aligned}\quad (10)$$

where

$$\begin{aligned}\chi &= \frac{1}{2} \langle (\eta_z - \langle \eta_z \rangle)^2 \rangle \\ \sigma &= \frac{1}{4} \langle (\eta_z - \langle \eta_z \rangle) (p_{\eta_z} - \langle p_{\eta_z} \rangle) + (p_{\eta_z} - \langle p_{\eta_z} \rangle) (\eta_z - \langle \eta_z \rangle) \rangle \\ \psi &= \frac{1}{2} \langle (p_{\eta_z} - \langle p_{\eta_z} \rangle)^2 \rangle\end{aligned}\quad (11)$$

and

$$\begin{aligned}\beta' &= \beta / B_{\eta_z} \omega \\ \omega_d &= \{1 - (\beta' / 2\omega)^2\}^{1/2} \omega \\ T^*(\omega_d) &= \frac{1}{2} \hbar \omega_d \coth \frac{\hbar \omega_d}{2T}\end{aligned}\quad (12)$$

If the oscillator in the η_z variable is centered at η_z^0 , namely $V = 1/2 K_{\eta_z} (\eta_z - \eta_z^0)^2$, taking the expectation value of the η_z operator over both the quantum-mechanical and the thermodynamical ensembles, the following result is obtained:

$$\langle \eta_z \rangle = \eta_z^0 + \frac{(\langle p_{\eta_z}(0) \rangle / B_{\eta_z}) + \frac{1}{2} \beta' \langle \eta_z(0) \rangle}{\omega_d} \sin \omega_d t \exp(-\frac{1}{2} \beta' t) \quad (13)$$

Having as initial condition a Gaussian distribution centered at η_z^i ,

$$\psi(\eta_z, t=0) = \frac{\exp\{-\frac{1}{2}((\eta_z - \eta_z^i)/a)^2\}}{(\int_{-1}^{+1} \exp\{-((\eta_z - \eta_z^i)/a)^2\} \sqrt{B_{\eta_z}} d\eta_z)^{1/2}} \quad (14)$$

$$\int_{-1}^{+1} |\psi(\eta_z, t=0)|^2 \sqrt{B_{\eta_z}} d\eta_z = 1$$

we get:

$$\langle \eta_z \rangle = \eta_z^0 + ((\eta_z^i - \eta_z^0) \cos \omega_d t + \frac{\beta'}{2\omega_d} (\eta_z^i - \eta_z^0) \sin \omega_d t) \exp(-\frac{1}{2} \beta' t) \quad (15)$$

With the same initial conditions, the following expression for the second moment is obtained:

$$x = \frac{1}{2} \left(\frac{1}{2} a^2 (\cos \omega_d t + \frac{\beta'}{2\omega_d} \sin \omega_d t)^2 + \frac{\hbar^2}{2a^2 B_{\eta_z \omega_d}^2} \sin^2 \omega_d t \right) \exp(-\beta' t) +$$

$$+ \frac{\hbar}{4B_{\eta_z \omega_d}} \coth(\hbar \omega_d / 2T) (1 - \exp(-\beta' t)) + \frac{\hbar}{4B_{\eta_z \omega_d}} \frac{\beta'^2}{\beta'^2 + 4\omega_d^2} \coth(\hbar \omega_d / 2T) \times$$

$$x (1 - \exp(-\beta' t) \cos 2\omega_d t + \exp(-\beta' t) \frac{2\omega_d}{\beta'} \sin 2\omega_d t)$$

For two nuclei with mass numbers A_1 and A_2 the stiffness K_{η_z} is given by:

$$K_{\eta_z} = \frac{Z^2}{4} 8ka_1(1/A_1 + 1/A_2) - 8ka_2(1/A_1^{4/3} + 1/A_2^{4/3}) + 2c_3(1/A_1^{1/3} + 1/A_2^{1/3}) - \frac{2e^2}{R} \quad (17)$$

where $Z=Z_1+Z_2$ is the total charge of the composite system. The various coefficients are $a_1=15.4941$ MeV, $a_2=17.9439$ MeV, $k=1.7826$, $c_3=0.7053$ MeV and $e^2=1.44$ MeV.fm.

If we rely on the results of dipole resonance excitation, the empirical relationship $\hbar\omega=78/A^{1/3}$ MeV can be used in order to estimate the phonon energy.

As we are dealing with a system of two deformed droplets connected by a neck, a simple expression like :

$$\hbar\omega = \frac{78}{A_1^{1/3} + A_2^{1/3}} \quad (18)$$

neglects the very strong effects of the neck on the inertia of oscillations. Calculations which consider the hydrodynamical flow of protons and neutrons fluid through the neck have shown such an effect [11]. From Eq.18 one can obtain for the parameter a the following expression:

$$r_{\eta_z}^2(t=0) = 4 \ln 2 \times a^2 \quad (19)$$

Requiring a relaxation time for the η_z mode of 10^{-22} sec, using the relation:

$$\tau_i \sim \frac{1}{\beta'} \quad (20)$$

and if we approximate β given by Eq.8 as

$$\beta = c_\beta \times (1 - \exp(-\hbar\omega/T)) \quad (21)$$

one can estimate the value of c_β .

The total kinetic energy loss as function of time was obtained using a parametrisation of the deflection function [13-15] and is represented in Fig.6. The same hydrodynamical calculations [11] show that there is a retardation in the charge equilibration process for the time in which the neck radius develops enough to obtain a reasonable finite value of the inertia parameter B_{η_z} . If we consider that the temperature T is given by:

$$T = \sqrt{8E^*/(A_1 + A_2)} \quad (22)$$

then even for the higher energy losses in Fig.5 the corresponding temperature is around 2.4 MeV while the phonon energy is around 5.6 MeV (using $K_{\eta_z} = 0.8432 \cdot 10^4 \text{ MeV}$; $B_{\eta_z} = 0.8 \cdot 10^{-40} \text{ MeV} \cdot \text{sec}^2$; $c_\beta = 0.95 \cdot 10^4 \text{ MeV}$ and a retardation time of $2 \cdot 10^{-22} \text{ sec}$). From Eq.18 one can easily observe that for $\hbar\omega_d \gg T$ and $\beta't \gg 1$

$$x \approx \frac{\hbar}{4B_{\eta_z}\omega_d} \quad (23)$$

which corresponds to the quantum fluctuations in the η_z collective mode associated with the zero point motion of the oscillator in η_z with a slight frequency shift introduced by the damping. The $\Gamma_{\eta_z}^2$ as a function of TKEL obtained in the frame of the above model is represented in Fig.5 by the solid curve.

Fig. 6

Model predictions [13-15] for the correlation between average energy-loss and interaction time.

The general trend of the experimental data and the qualitative agreement with the results of the above quantum description of the charge asymmetry collective mode are in the favour of a possible quantum fluctuation evidence in these experimental data.

To which extent there are some other possible effects and how the excitation of possible giant modes involved in the charge equilibration process depends on the relative velocity remains an open question.

4. Preequilibrium light particle emission

At present direct evidences for preequilibrium light particle emission in collisions between heavy nuclei ($A \geq 80$) are very scarce. This is due not only to the complexity of the necessary exclusive experiments but also to the present capability of accelerators which limits the available energy above the barrier to the range where the nucleons can hardly be promoted into the continuum. To our knowledge the best founded evidences were obtained by Tserruya et al. [16] for the $^{86}\text{Kr} + ^{166}\text{Er}$ reaction at 11.9 MeV/u. This is illustrated in Fig.7 which shows the presence of a preequilibrium component of neutrons emitted mainly at forward angles on the side of the light fragment in quasielastic events. The qualitative features of the data could be reproduced by a simple model [16], which assumes that 10 % of the neutrons are knocked-out at an early stage of the collision, along the direction of the nuclear motion. The measured neutron multiplicities were found in good agreement with the predictions of evaporation model calculations.

Fig. 7
Data of Tserruya et al. showing the existence of a preequilibrium neutron emission in the $^{86}\text{Kr} + ^{166}\text{Er}$ reaction at 11.9 MeV/u.

The results on light charged particles are even more scarce than the one on neutrons. Therefore in the run at 12 MeV/u we have performed a preliminary measurement [17] of the α -particles emitted in coincidence with the binary products in the reaction $^{98}\text{Mo} + ^{154}\text{Sm}$. The velocity vectors of the two heavy products were measured using the 12 parallel-plate counters while the α -particles were identified by a solid state telescope placed at 20° . The binary events were selected by requiring collinearity in the CM-system (see Fig.8a). The kinematical reconstruction shows that the majority of the events is associated with TKE losses of several hundred MeV (Fig.8b). In the energy spectrum of the α -particles (Fig.8c) two components are seen, one peaked around 15 MeV the other around 80 MeV. The gross structure of this spectrum can be understood in terms of evaporation of α -particles as can be inferred from Figs.8d and e. The measured yield is shown in contour plots as function of the α -particle velocity v^α and emission angle Θ^α for two different frames of reference: In Fig.8d the CM-system of α and projectile-like fragment and in Fig.8e the CM-system of α and target-like fragment. Projectile- and target-like products were defined according to their laboratory velocities; the faster fragment was assumed to be projectile-like. Within the present statistical uncertainties we do not find it possible to judge

Fig. 8 Triple coincidence experiment between α -particles, measured in a telescope at $\Theta_{\text{lab}} = 20^\circ$, and the "binary" heavy products measured in 12 parallel plate counters (see text).

about the role of other possible components in the α -spectrum, e.g. the preequilibrium one.

Considering the above results on light particle evaporation it is then rather surprising to observe a strong charge drift in the element distributions at rather small energy-losses for the reactions $^{98}\text{Mo} + ^{98}\text{Mo}$ and $^{92}\text{Mo} + ^{92}\text{Mo}$ at 14.8 MeV/u (see Fig.9). Obviously some charge is missing in these collisions of identical nuclei, otherwise the element distributions of these two-body reactions would be symmetric with respect to the initial nuclear charge. Two explanations can be proposed: Light charged particle emission (preequilibrium or evaporation) or a fragmentation process (splitting). We have therefore estimated the contribution from charged particle evaporation within the framework of a statistical model [18]. As input to the evaporation code we have used the values of intrinsic angular momentum given as a function of TKEL from the diffusion model calculations of Wolschin [13-15], although it was shown by Tserruya et al. [16] that the evaporation calculation is little sensitive to the initial angular momentum distribution. The results of the calculations for the $^{92}\text{Mo} + ^{92}\text{Mo}$ and $^{98}\text{Mo} + ^{98}\text{Mo}$ reactions are given in Fig.9; they deviate significantly from the experimental observations. As the grazing angle for these symmetric combinations at this incident energy (14.8 MeV/u) is approximately 18 deg in CM and the smallest measured angle (due to geometrical efficiency of the IC) is larger than 10 deg (see Fig.12, $d^2\sigma/d\theta d\text{TKE}$ representation), appears the question if the trends observed

Fig. 9

Centroid of the charge distribution as a function of energy-loss for the $^{92}\text{Mo} + ^{92}\text{Mo}$ (open triangle) and $^{98}\text{Mo} + ^{98}\text{Mo}$ reaction (open circles) both measured at an incident energy of 14.8 MeV/u. The prediction of the evaporation calculations is indicated by Δ .

above are not the result of limited geometrical efficiency. The following arguments would exclude such an effect:

- A $d^2\sigma/dZd\theta_{lab}$ representation shows the same trend toward asymmetry in the Z distribution at angles much larger than the values which correspond to the limits of the active region of the IC.
- Previous results [17] obtained in $^{86}\text{Kr} + ^{166}\text{Er}$ collision at 8.18 MeV/u shown a clear independence of the mean value of the charge distribution on the center of mass angle for a given window in TKEL.
- A result which rules out a contribution to the drift toward asymmetry from the geometry is represented in Fig.10. There are represented the double differential cross sections $d^2\sigma/dZ.dTKE$ and $d^2\sigma/d\theta_{cm}.dTKE$ together with a contour plot of the PES for the $^{98}\text{Mo} + ^{147}\text{Sm}$ system measured at 14.66 MeV/u incident energy. As the injection point is placed in the bottom of the PES the N/Z value of the composite system is already equilibrated. Nevertheless in $d^2\sigma/dZ.dTKE$ representation is observed a significant drift toward asymmetry in the first 200 MeV TKEL where the geometrical cuts are quite negligible as one can observe in $d^2\sigma/d\theta_{cm}.dTKE$ representation.

In conclusion, the observed drift toward asymmetry in the charge distribution is not affected by the geometrical cuts at list in the first 200 MeV in TKEL. However, at the moment we do not know for sure if the observed charge drift in identical nuclei collisions has to be attributed to a preequilibrium light charged particle emission. The evaluation of the two-body- α coincidences and of the three-body events should hopefully solve this specific problem of the high bombarding energies.

Fig.10

Contour plots of the cross section $d^2\sigma/dZ \cdot dTKE$, $d^2\sigma/d\theta \cdot dTKE$, and PES for $^{98}\text{Mo} + ^{147}\text{Sm}$ system measured at 14.66 MeV/u. The height of the contour lines varies in steps of a factor of two.

5. Projectile splitting

Two and a half years ago in a first experiment at 12 MeV/u using the $^{86}\text{Kr} + ^{166}\text{Er}$ reaction we have surprisingly discovered that the projectiles had a high probability to undergo a fragmentation into two heavy products [19,20]. The large probability, much higher than that expected from compound nucleus reactions made us postulate the presence of a dynamical process called "splitting". Recently, using the new set-up described in Sect.4 and in view of the upgraded energies at the UNILAC we have reconcentrated our attention on this problem. In the meantime detailed angular and mass distributions of this process have been obtained in the case of the Xe+Sn reaction in a work by Harrach, Glässel et al. as it can now be read in two recently published articles [21,22]. In order to give you the latest results we concentrate on our inclusive data obtained at 14.8 MeV/u with beams of ^{98}Mo and ^{92}Mo on targets of ^{92}Mo , ^{98}Mo , ^{154}Sm , ^{238}U and on the coincidence data [23] obtained for $^{98}\text{Mo} + ^{154}\text{Sm}$ at 12 MeV/u.

The three (possibly four-body) data on $^{98}\text{Mo} + ^{154}\text{Sm}$ of Fig.10c were selected by requiring coincidences between the ionisation chamber and the parallel plate counters placed outside the scattering plane defined by the IC and the beam axis. For a comparison we also show in the same figure the inclusive data (Fig.10a) and the two-body data (Fig.10b), the latter selected on the basis of a coplanarity of 4° . In order to present the data without the two-body kinematic assumption inherent to the usual TKE vs. Z plot the correlation between the identified nuclear charge and the associated product velocity, calculated in the CM-system is displayed. The measured quantities refer always to the IC but with different coincidence conditions. The dashed line V_1 represents the expected velocities of deformed binary fragments due to Coulomb repulsion (Viola energy). The two-body

condition selects events extending, in Fig.10b, mainly below the values for velocity and nuclear charge of the projectile and ranging down to the fully relaxed events along the V_i -line. The three (possibly four) body events of Fig.10c are mainly located below the V_i -line: They correspond to products emitted forwards resp. backwards in the moving frame of the primary products. Presumably the detection geometry favours a separation into two branches. The information of Figs.10b and 10c is particularly helpful for the understanding of the trends of the inclusive data of Fig.10a and of Fig.11 (data from the recent high energy measurement).

Fig.11

Ionisation chamber results displayed on the left by contour plots of the cross section $d^2\sigma/dZ \cdot dv_{cm}$ and on the right hand side by the integrated element distribution: a) inclusive data, b) for coplanar events ($\Delta\varphi = \pm 2^\circ$) and c) non-coplanar events.

A striking feature common to the three body and to the inclusive data is the long tail of the Z -distribution towards small Z -values as it can be seen best from the projected Z -distributions of Fig.10c resp. 10a. It should be mentioned in this respect, that the yield for $Z < 20$ is heavily underestimated in these spectra and also in the corresponding contour plots since a large fraction of the light products having velocities exceeding the initial projectile velocity, are not stopped within the depth of the ionisation chamber, and therefore can not be identified by the usual dE vs. E_{rest} correlation. Work is in progress to identify such fast particles on the basis of a dE vs. v_{lab} correlation so that in the near future we should be able to display the full spectrum. At the moment we can not exclude that the product yield may even increase towards small Z -values.

Fig.12

Contour plots of the cross sections $d^2\sigma/dZ dTKE$, $d^2\sigma/d\theta_{cm} dTKE$, $d^2\sigma/dV_{cm}^1 dV_{cm}^1$ and $d^2\sigma/dV_{lab}^1 dV_{lab}^1$ for the target-projectile combinations $^{98}\text{Mo} + ^{98}\text{Mo}$, $^{92}\text{Mo} + ^{92}\text{Mo}$, $^{92}\text{Mo} + ^{154}\text{Sm}$ and $^{92}\text{Mo} + ^{238}\text{U}$ at incident energy of 14.8 MeV/u. The height of the contour lines varies in steps of a factor of two.

The newest results taken at 14.8 MeV/u are illustrated in Fig.11: For four of the investigated target-projectile combinations we display besides the usual diffusion and Wilczynski diagrams the $d^2\sigma/dZ.dv_{cm}$ and $d^2\sigma/dv^{\perp}.dv^{\parallel}$ representation, the last two plots being freed from the two-body kinematics assumption. The trends of Fig.10 are reconfirmed and appear even more drastically at the higher bombarding energy. The right hand side of the Z-distribution appears in all four reactions as strongly reduced even at rather low energy losses. The fact that this is true also for the collision between identical nuclei shows, as discussed in Sect.3, a missing charge which could have been lost by light charged particle emission (protons, alpha particles) or by heavier splitting fragments. One point which needs further attention is to measure a complete spectrum in mass asymmetry for the splitting products as a function of TKE. Although at the moment it is rather speculative, possibly for the more peripheral collision, where the perturbation is less violent and more localized, lighter products are knocked-out (large mass asymmetry) as compared to heavier products (symmetric splitting) for the more central collisions. Such a supposition is somewhat supported by the finding of Ref.[21] where the measured asymmetry increases with TKE. The measurement with the ionisation chamber should allow to measure better the large mass asymmetry values at small energy-losses. At the present stage of the investigations it appears clear that we deal here with a fast process in which the memory of the entrance channel is preserved and where during the collision, as expected from TDHF [24] calculations, strong deformations are present.

6. Conclusions

The striking features emerging from the study of collisions between heavy nuclei ($A \geq 86$ u) at a relative velocity of 12-15 MeV/u are: (i) a fast N/Z equilibration process involving possibly quantal fluctuations, (ii) a preequilibrium light particle emission and (iii) the dynamical splitting of the colliding nuclei. They suggest that at high incident energies, in the early stage of the reaction, considerable fraction of the kinetic energy is transmitted to a few degrees of freedom also of collective nature (possibly even mainly of collective nature). Such excitation modes can be seen as "doorway" states which then couple either to the other more complicated excitation modes of the nuclei, or directly to outgoing channels such as fast particle emission or projectile fragmentation.

Until now only a few pilot experiments with energetic very heavy ions were performed and therefore the evidences presented here, although quite promising, have in many respects still a preliminary character.

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