Reaction Mo + Mo between 12 and 18.8 MeV/u: Approaching the Limits of the Deep-Inelastic Process

S. Gralla, J. Albinski,[(a)] R. Bock, A. Gobbi, N. Herrmann, K. D. Hildenbrand, J. Kużminski,[(b)] W. F. J. Müller, M. Petrovici,[(c)] H. Stelzer, J. Tōke,[(d)] and H. J. Wollersheim
Gesellschaft für Schwerionenforschung, 6100 Darmstadt, West Germany

and

A. Olmi, P. R. Maurenzig, and A. A. Stefanini
Università di Firenze and Instituto Nazionale di Fisica Nucleare, 50125 Florence, Italy
(Received 12 June 1984)

The triply differential cross sections $d^3\sigma/dA\,dE\,d\theta$ of binary exit channels in the reactions $^{92}Mo+^{92}Mo$ and $^{100}Mo+^{100}Mo$ have been measured at energies between 12 and 18.8 MeV/u. Complete relaxation is reached at energy losses up to 650 MeV, corresponding to temperatures in the fragments of up to 5 MeV; the primary mass distributions tend to spread over the full range of mass asymmetries, indicating a loss of the initial target and projectile identity and hence the disappearance of an essential feature of the deep-inelastic process.

PACS numbers: 25.70.Lm

In collisions of heavy nuclei with $A \geqslant 60$ most of the total reaction cross section is exhausted by deep-inelastic processes.[1] With very few exceptions, all previous experimental and theoretical studies of this mechanism were carried out for the limited range of incident energies below 10 MeV/u, at which the interaction barrier is exceeded by only a few MeV/u and where one-body dissipation plays a dominant role.[1] Recently, the accessible energy range for massive projectiles has been enlarged by the upgrading of existing or the advent of new accelerators. The first published results on experiments carried out at energies above 12 MeV/u have dealt with, besides the specific question of the sharing of the excitation energy among the fragments,[2] the effect of a three-body breakup of the fragments ("splitting")[3,4] which was expected to represent the natural transition from a low-energy deep-inelastic into a high-energy fragmentation regime; however, the three-body process was shown to be a sequential one, although of short half-life.[5] The results presented in this Letter seem to point toward another limitation for the deep-inelastic process at high incident energies, namely, the extreme growth of the mass distribution widths at large energy losses. Several considerations suggest that the temperature of the dinuclear complex is the relevant quantity which governs the observed increase of the mass widths and that two-body dissipation cannot be neglected any more in theoretical descriptions.

Our most complete measurement[6] in the higher-energy region concerned the reaction $^{92}Mo+^{92}Mo$ at 14.7 MeV/u; primary and secondary triply differential cross sections $d^3\sigma/dA\,dE\,d\theta$ were determined for two- and three-body exit channels. The yield of ternary events was found[7] to represent about one-tenth of that of the binary ones at the highest energy losses (and in total less than 3%–5% of the two-body cross section). No evidence for any fragmentation was found. For peripheral collisions the inclusively measured charge variances[8] were in good agreement with a model ascribing the energy loss to stochastic single-particle transitions.[9] The influence of the detector geometry and of the sequential particle emission on the mass variances has been studied in extensive Monte Carlo simulations.[7]

The present results deal with more central collisions in *binary* reactions, which were selected by conditions on coplanarity and center-of-mass collinearity. Figure 1(a) shows the diffusion plot $d^2\sigma/dE^*_{K\,\mathrm{tot}}\,dA$, where $E^*_{K\,\mathrm{tot}}$ denotes the total kinetic energy corrected for the difference between Coulomb energies in entrance and exit channels.[10] The broadening of the mass distributions with increasing total kinetic energy loss ($\Delta E^*_{K\,\mathrm{tot}}$) is clearly seen to take place until full relaxation is achieved around $E^*_{K\,\mathrm{tot}}=180$ MeV. Independent of the energy loss, the mean mass stays fixed at $A=92$, the mass of target and projectile. Together with the coplanarity and collinearity distributions this is a verification that the *primary* reaction step was a binary one.[7] Striking is the strong increase of the widths of the mass distributions at large energy losses, which tend to spread between zero and the total mass of the system; extreme mass asymmetries ($A \leqslant 30$, $A \geqslant 150$) are difficult to measure and are missed by the present detection system.

This diffusion plot is used to deduce the mass variances σ_A^2 as a function of $E^*_{K\,\mathrm{tot}}$; we prefer in the following to present the quantity $\sigma_A^2/(A/Z)^2$ which is assumed to be equivalent to the charge variance σ_Z^2 especially at high energy losses. Figure 1(b) shows the resulting values (solid triangles), plotted as proposed by Wollersheim *et al.*[11] as a function of $E^*_{K\,\mathrm{tot}}/l_{\mathrm{gr}}$, together with the results of similar reactions ($^{92}Mo+^{92}Mo$ at 18.2 MeV/u, $^{100}Mo+^{100}Mo$ at 12,

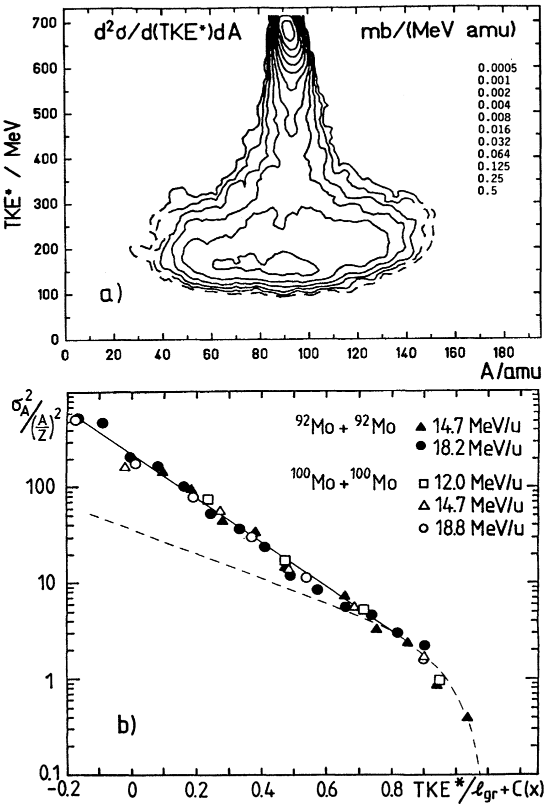

FIG. 1. (a) Double-differential cross section $d^2\sigma/dE^*_{K\,\mathrm{tot}} \times dA$ (diffusion plot) of binary fragments produced in the ^{92}Mo + ^{92}Mo reaction at 14.7 MeV/u. The values of the contour lines are given in units of mb/MeV·amu on the right-hand side; dashed lines indicate beginning cuts due to detector inefficiency. (b) Mass variances σ_A^2 [in units of $(A/Z)^2$] as a function of $E^*_{K\,\mathrm{tot}}/l_{\mathrm{gr}} + C(x)$ of all measured systems. The system-dependent shift $C(x)$, which may lead to even negative values, allows for a direct comparison between these. The dashed line is a stochastic single-particle-model (Ref. 9) calculation for ^{92}Mo + ^{92}Mo at 14.7 MeV/u. For details see text.

14.7, and 18.8 MeV/u); l_{gr} denotes the grazing angular momentum. At low $E^*_{K\,\mathrm{tot}}/l_{\mathrm{gr}}$ (i.e., high energy losses) all systems show the same exponential growth of the variances; a linear fit of all data yields an exponential slope of -5.27 $\hbar$/MeV. This value differs slightly from the average constant -6.07 which has been shown to describe a number of reactions at lower incident energies[11]; it is nevertheless still within the fluctuations revealed there by the different systems. Therefore, we will use the present value in the following; adopting the value of Ref. 11 would not affect the conclusions to be drawn.

The full straight line in Fig. 1(b) represents an exponential of our fitted slope; its absolute height is given by a continuous matching to the result of a calculation with the mentioned stochastic single-particle

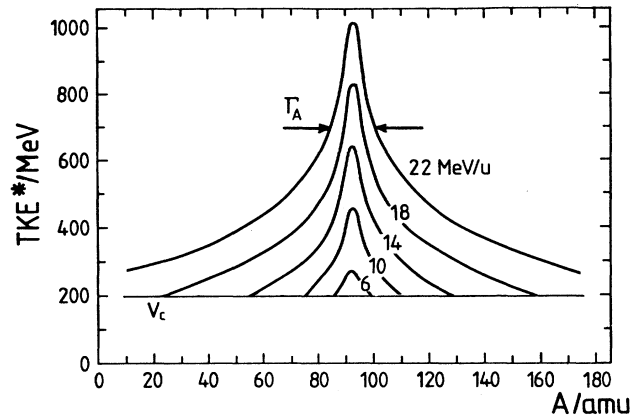

FIG. 2. Expected shape of the diffusion plots for the ^{92}Mo + ^{92}Mo system at different bombarding energies. Each curve joins the points at which the mass yield has dropped to half of its maximum at a given $E^*_{K\,\mathrm{tot}}$. As an example, the arrows indicate the full width at half maximum Γ_A at $E^*_{K\,\mathrm{tot}} = 700$ MeV reached in a reaction at 22 MeV/u.

model[7,9] at low energies (dashed line), which, at higher energy losses underestimates the experimental variances by far. In the notation of Ref. 11 the formula for the straight line reads

$$\frac{\sigma_A^2}{(A/Z)^2} = \exp\left[-5.27\left(\frac{E^*_{K\,\mathrm{tot}}}{l_{\mathrm{gr}}} - 1 + C(x)\right)\right]. \tag{1}$$

In our case the constant $C(x)$ has been derived for each system and incident energy from a stochastic model calculation; it turned out that it can be expressed universally by $C(x) = -E_0/l_{\mathrm{gr}} + 1.090$ for all considered reactions (E_0 is the incident center-of-mass energy). $C(x)$ has been taken into account by a shift of the abscissa in Fig. 1(b), which leads to a universal representation.[11] Insertion in Eq. (1) leads to

$$\frac{\sigma_A^2}{(A/Z)^2} = \exp\left[5.27\left(\frac{\Delta E^*_{K\,\mathrm{tot}}}{l_{\mathrm{gr}}} - 0.09\right)\right]. \tag{1'}$$

By means of this parametrization one can easily demonstrate how Γ_A varies as a function of $E^*_{K\,\mathrm{tot}}$ for different bombarding energies (Fig. 2): It decreases for a given energy loss, but increases for a fixed $E^*_{K\,\mathrm{tot}}$ if the bombarding energy is raised.

At lower incident energies the increase of the variances was attributed[11] to an exponential increase of the interaction time as a function of decreasing angular momentum ($-l/l_{\mathrm{gr}}$). The present results seem to contradict this explanation: For that purpose we can study the interaction-time dependence of the variances by keeping $E^*_{K\,\mathrm{tot}}$ (and hence[11] approximately l) fixed but varying the incident velocity over a broad range. The increase of σ_A^2 at higher bombarding is considered at fixed $E^*_{K\,\mathrm{tot}}$ and hence fixed relative velocity of the outgoing products (cf. Fig. 2). We select a $E^*_{K\,\mathrm{tot}}$ above the fully relaxed component, e.g., 250 MeV; this is a situation, where a multiple rotation of a long-lived fusion-fission-type system can be excluded not only by the selected $E^*_{K\,\mathrm{tot}}$ value, but also by the Wilczinski pattern, where at the present high bombarding energies products are only observed at forward angles. This forward focusing and the corresponding straight trajectories (ingoing and outgoing velocity vectors are nearly parallel to the beam axis) make it very unlikely that the strong increase of the mass variances as a function of bombarding energy at constant $E^*_{K\,\mathrm{tot}}$ can be the result of an increase of the interaction time.

As an alternative explanation we tentatively postulate the "temperature" T of the dinuclear system, which increases with the observed energy loss, to be the relevant quantity to govern the increase of the variances in central collisions; T should be regarded as a measure of the entropy of the system rather than as a temperature. Indeed Eq. (1a) can be rewritten for the special case of complete energy damping [$E^*_{K\,\mathrm{tot}} = V_c$ leads to $l_{\mathrm{gr}} \propto (\Delta E^*_{K\,\mathrm{tot}})^{1/2}$] as a function of the temperature $T = (\Delta E^*_{K\,\mathrm{tot}}/a)^{1/2}$; insertion of a level density parameter of $a = A/8$ leads for a symmetric system to

$$\frac{\sigma_A^2}{(A/Z)^2} = \exp\left(17.0\frac{T}{R_{\mathrm{int}}} - 0.48\right), \qquad (2)$$

where R_{int} is the interaction radius in femtometers. Figure 3 shows the resulting *mass* variances for the ^{92}Mo system as a function of T for the two discussed cases $E^*_{K\,\mathrm{tot}} = V_c$ and $E^*_{K\,\mathrm{tot}} = 250$ MeV [in the latter case Eq. (2) has to be slightly modified because then the argument in the exponent depends nonlinearly on T].

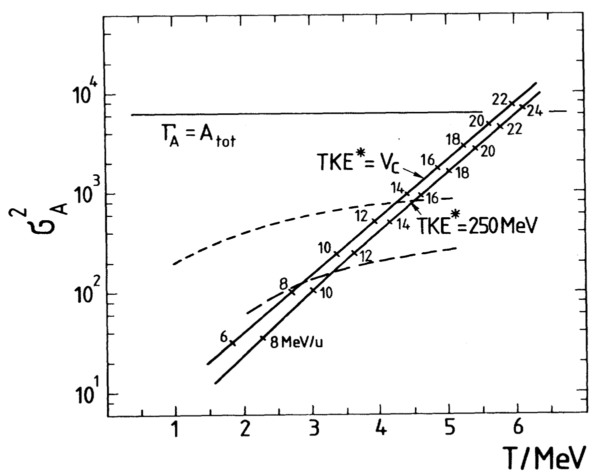

FIG. 3. Calculated mass variances σ_A^2 for ^{92}Mo + ^{92}Mo as a function of the temperature T for two given outgoing total kinetic energies ($E^*_{K\,\mathrm{tot}} \equiv V_c \simeq 200$ MeV and $E^*_{K\,\mathrm{tot}} = 250$ MeV, full lines). The long- and short-dashed lines, respectively, are explained in the text.

The curve for $E^*_{K\,\mathrm{tot}} = 250$ MeV can be compared to a diffusion-model prediction (long-dashed line), where the variances were calculated with $\sigma_A^2 \simeq 2D_{AA}\tau_{\mathrm{int}}$. The diffusion constant D_{AA} was assumed to increase proportionally to T, whereas the interaction time τ_{int} was derived from trajectory calculations. The discrepancy with the systematics is obvious. It is an open question at present whether this is due to the decrease of the nucleon mean free path[12] which becomes at temperatures of about 5 MeV smaller than the size of the involved nuclei. Additional nucleon-nucleon collisions could therefore give an extra contribution to the transport coefficient to be taken into account in a microscopic calculation.

It should also be investigated to what extent the observed variances could be influenced by general decay properties of the unstable hot nuclear complex.[13] For that reason the variances in Fig. 3 are compared with an estimation of the statistical limits computed from the level densities as a function of mass asymmetry and excitation energy above the liquid-drop energy of the dinuclear complex. The resulting variances are shown by the short-dashed line. In comparison to this model estimation the statistical limit seems already to be reached or even surpassed in our experiment, unless additional contributions, e.g., by shape fluctuations are present.[14]

Our experiment and the systematics allow us to predict a critical incident energy E_0^{crit}, above which the deep-inelastic process loses one of its most characteristic features: As a criterion for that we use the mass width reaching the boundaries of extreme mass asymmetry at full relaxation ($\Gamma_A = A_{\mathrm{tot}}$ at V_c); Eq. (2) gives then a critical beam energy E_0^{crit} over the barrier per nucleon:

$$(E_0^{\mathrm{crit}} - V_c)/\mu = 6.9\times 10^{-3} R_{\mathrm{int}}^2 [\ln(Z_{\mathrm{tot}}/2.35) + 0.24]^2 \qquad (3)$$

For the symmetric ^{92}Mo system this limit is predicted at $\simeq 770$ MeV above the barrier, which is reached at a beam energy of 21 MeV/u (cf. Figs. 2 and 3). The deep-inelastic process nevertheless still persists for small energy losses, where up to the investigated incident energy no real evidence of the fragmentation process has been found.

Concluding, we have shown that at incident energies exceeding about 15 MeV/u one of the characteristic features of the deep-inelastic process starts to disappear: The primary binary mass distributions at large kinetic energy losses become so broad that an equipartition over all possible product masses is achieved; hence the memory of the initial target-projectile configuration is lost. A newly postulated dependence of the mass variances on the temperature seems to explain this broadening and an earlier general systematics.[11] It should be verified whether the observed trend continues at higher bombarding energies or whether a saturation in the mass variances sets in. At the present energy our experimental findings agree with the assumption of a binary process followed by sequential decay even at complete energy relaxation. The study of decay properties of nuclei created in such extreme excitation states is another exciting challenge in forthcoming studies.

We greatly appreciate discussions with J. Galin, W. Nörenberg, and V. V. Volkov.

[a]On leave from Institute of Nuclear Physics, Cracow, Poland.

[b]Now at University of Basel, Basel, Switzerland.

[c]On leave from IPNE, Bucharest, Romania.

[d]Now at Nuclear Structure Research Laboratory, University of Rochester, Rochester, N. Y. 14627.

[1]W. U. Schroeder and J. R. Huizenga, Annu. Rev. Nucl. Sci. **27**, 465 (1977); A. Gobbi and E. Nörenberg, in *Heavy Ion Collisions,* edited by R. Bock (North-Holland, Amsterdam, 1980), Vol. II, p. 129.

[2]T. C. Awes *et al.*, Phys. Rev. Lett. **52**, 251 (1984).

[3]A. Olmi *et al.*, Phys. Rev. Lett. **44**, 383 (1980).

[4]F. Plasil, Nucl. Phys. **A400**, 417c (1983).

[5]D. v. Harrach *et al.*, Phys. Rev. Lett. **48**, 1093 (1982); P. Glässel *et al.*, Phys. Rev. Lett. **48**, 1089 (1982).

[6]M. Petrovici *et al.*, Nucl. Phys. **A387**, 313c (1982).

[7]S. Gralla, Gesellschaft für Schwerionenforschung Report No. GSI-84-6 (unpublished).

[8]S. Gralla *et al.*, Z. Phys. A **310**, 345 (1983).

[9]M. Dakowski *et al*, Nucl. Phys. **A387**, 189 (1982).

[10]G. Rudolf *et al.*, Nucl. Phys. **A330**, 243 (1979).

[11]H. J. Wollersheim *et al.*, Phys. Rev. C **25**, 338 (1982).

[12]W. Nörenberg, Phys. Lett. **104B**, 107 (1981).

[13]D. Gross, Phys. Scri. **T5**, 213 (1983).

[14]U. Brosa and S. Grossmann, J. Phys. G. **10**, 933 (1984).