Evidence for a Nonequilibrated Dinuclear System in Dissipative Collisions at 19 MeV/nucleon

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Exclusive measurements of two- and three-body events were performed for the system $^{120}Sn+^{100}Mo$ at 19.1 MeV/nucleon. Most ternary events are consistent with sequential processes in which one of the two deep-inelastic fragments fissions. For such events large differences are found between the fission probabilities of projectilelike and targetlike fragments of a given mass, this probability being larger for the nucleus which gained nucleons. This behavior demonstrates that there is a lack of equilibrium at the end of the deep-inelastic collision.

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In the study of dissipative collisions one important and not yet fully understood problem concerns the amount of nonequilibrium present in the dinuclear system at the end of the interaction. As soon as the colliding nuclei come into contact, dissipative processes begin to transport energy and angular momentum from the relative motion into internal degrees of freedom. Therefore, a certain amount of deviation from equilibrium, varying with elapsed time, can be expected to be present over the whole volume of the dinuclear system, and especially between its projectilelike and targetlike constituents.

Up to now attention has been mainly focused on the process of energy dissipation and on its partition between the final projectilelike and targetlike fragments (PLF and TLF, respectively). A complete equilibration of this degree of freedom would result in a system with the same temperature over the whole volume and thus in a sharing of excitation energy proportional to the masses of PLF and TLF.

Many experimental results [1–4], obtained from asymmetric systems mainly at low bombarding energies, point to a smooth evolution from a nonequilibrium situation, typical of events at low energy losses characterized by an equal amount of excitation energy in PLF and TLF, towards equilibrium which may be reached for the most inelastic events, attributed to central collisions with longer interactions times. The general features of this observed trend are rather well explained within the framework of nucleon exchange models (NEM) [5].

However, many recent experiments exploring a wide range of interacting systems and bombarding energies show that the situation is more complex and cannot be accounted for completely by the present NEM calculations [5]. There are indications that sometimes the system becomes very quickly equilibrated even for rather peripheral interactions in which only few-nucleon exchanges are likely to be involved [6]. In contrast to this fact, there is also evidence that in other systems nonequilibrium effects persist even for central collisions [7–10]. In many cases, and not only at bombarding energies greater than 10 MeV/nucleon, the lack of equilibrium is accompanied by features which cannot be explained within the framework of the NEM. In particular, some recent experiments [6,8–14] show a dependence of the energy partition on the net nucleon flow, which is not predicted by the nucleon exchange models. This dependence is at present a matter of debate and its evidence is controversial.

So far, knowledge about the degree of equilibration between the two reaction partners has been mostly derived from the light particles evaporated by the two fragments after the reseparation. With the aim of obtaining new information on this subject using a different approach, we performed an experiment at the UNILAC accelerator of GSI (Darmstadt). Fragments from two- and three-body ($A \geq 20$) exit channels were measured in coincidence for the collision of ^{120}Sn ions on a self-supporting ^{100}Mo target (thickness 0.22 mg/cm^2) at 19.1 MeV/nucleon. These fragments were detected with twelve gas detectors [15,16] covering more than 70% of the forward hemisphere, in which most reaction products are focused. Starting from the measured velocity vectors, primary (preevaporative) masses, angles, and kinetic energies of the reaction products were deduced for each event employing an improved version of the kinematic coincidence method [17]. The background of incompletely measured events, due to the limited solid-angle coverage and to the intrinsic efficiency of the detectors, was subtracted following the procedure described in Ref. [17]. Moreover, extensive Monte Carlo calculations [17,18], with evaporation and kinematic reconstruction included, were performed to correct all the results for the efficiency of the detectors and for possible distortions introduced by the kinematic reconstruction analysis. These Monte Carlo simulations have also shown that spurious correlations among the reconstructed variables [19] have negligible effects on the results shown in this Letter [20].

The basic idea of the present experiment was to compare the (sequential) fission probabilities of reaction products of the same primary mass A obtained in two different ways. This can be achieved with an asymmetric entrance channel because in this case PLF and TLF, both of a given mass A, have necessarily experienced different gains or losses of nucleons. The observation of different fission probabilities for a nucleus of mass A when it is a PLF or a TLF would then reveal that equilibrium between the two partners is not present at the time of their separation.

The choice of the reacting system was a compromise among different requirements. First, PLF and TLF must have significant fission probabilities; second, the requirement of an asymmetric entrance channel had to be matched with the capability of producing PLF and TLF of the same mass also at moderate total kinetic energy losses (TKEL), where the net mass transfer is limited. As expected from previous studies, in the chosen system the symmetric mass channel $A_{\rm PLF}=A_{\rm TLF}=110$ is populated already for TKEL$\gtrsim 200$ MeV. The steep increase [18,21] of sequential fission processes as a function of TKEL offers a sensitive tool for this kind of investigation. The fact that the two colliding nuclei have very similar N/Z (1.40 and 1.38 for ^{120}Sn and ^{100}Mo, respectively) points to a negligible role of isospin in the investigated processes.

For comparison, the symmetric system ^{120}Sn+^{120}Sn was also measured at the same bombarding energy. In this system the results concerning the fission probabilities are straightforward: No differences are expected for PLF and TLF of a given mass A, as they have both gained or lost the same number of nucleons. Therefore these data can be used for a quantitative check of the whole analysis, thus increasing the confidence in the results for the asymmetric system.

The two-body events, which exhaust about 75% of the measured reaction cross section for the collision ^{120}Sn + ^{100}Mo, can be essentially ascribed to deep-inelastic collisions.

The three-body events are found to amount to about 20% of the measured reaction cross section. A detailed phase-space analysis of these events [22] shows that about 90% of them are compatible with the sequential fission of one of the original deep-inelastic fragments. Monte Carlo simulations based on a pure sequential-fission mechanism show that in the region TKEL≤ 600 MeV less than 10% of these three-body events were incorrectly reconstructed. In this TKEL region, the original PLF and TLF can be easily separated on the basis of their angular distributions, taking as PLF the fragments emitted at $\theta_{\rm c.m.}\leq 30°$ and as TLF those for which $\theta_{\rm c.m.}\geq 150°$ (these limits being uncritical since the c.m.-grazing angle $\theta^{\rm graz}_{\rm c.m.}\approx 14°$).

From the analysis of the three-body events compatible with a sequential-fission mechanism, we can extract the numbers $N_3^{\rm PF}(A)$ and $N_3^{\rm TF}(A)$ of the original deep-inelastic fragments of mass A, respectively, for PLF and TLF, which underwent fission. Similarly, the number of events where the PLF and TLF did not fission is $N_3^{\rm PNF}(A)$ and $N_3^{\rm TNF}(A)$, respectively. Because of the relevance which has been attributed to the energy dissipation in describing the evolution of dissipative collisions [21,23,24], all results are presented for bins of TKEL.

Assuming that the three- or four-body events originate from one or two (independent) sequential-fission processes, one can obtain from the data the ratios $P^P(A)$ and $P^T(A)$ for the deep-inelastic primary fragments (PLF and TLF, respectively) of mass A. For example, for a given bin of TKEL,

$$P^P(A)=\frac{N_3^{\rm PF}(A)+N_4^P(A)}{N_2^P(A)+N_3^{\rm PF}(A)+N_3^{\rm PNF}(A)+N_4^P(A)}\,,$$

where $N_2^P(A)$ and $N_4^P(A)$ are the numbers of two- and four-body events, respectively, in which the original PLF was of mass A. These ratios are the fission probabilities weighted with the excitation energy sharing between the deep-inelastic fragments, as well as averaged over TKEL (in the chosen bin) and all other internal variables.

Because of poor statistics of the four-body events and the difficulty of unequivocally determining the true fission pairs in this case, it is worth looking for expressions not containing $N_4^P(A)$. It can be shown that

$$\frac{N_3^{\rm PF}(A)}{N_2^P(A)+N_3^{\rm PF}(A)+N_3^{\rm PNF}(A)}\leq P^P(A)\leq\frac{N_3^{\rm PF}(A)}{N_2^P(A)+N_3^{\rm PF}(A)}\,,$$

where the nontrivial right-hand-side inequality is obtained when the probability densities for fission (which are increasing functions of excitation energy) are folded with an unknown energy sharing for a given TKEL. It was verified that in the present case the two limiting expressions coincide within the experimental errors; in the following we use the simpler right-hand-side expression.

Figure 1 shows the fission probabilities $P^P(A)$ and $P^T(A)$ in two (100-MeV-wide) representative bins of TKEL for the asymmetric and symmetric systems, respectively. Apart from the steep increase of P with A (which may be due to a correlation between mass and other degrees of freedom relevant to fission), the striking new feature, reported for the first time in the present work, is that in the asymmetric ^{120}Sn+^{100}Mo system the curves for PLF and TLF do not coincide: For the same fissioning mass, the TLF has a fission probability significantly larger than the PLF, even at the highest TKEL. For example, for the central mass $A=110$, in the bin TKEL=400–500 MeV, $P^T(A)$ is about 6 times greater than $P^P(A)$. The comparison with the "reference" symmetric system, where the two curves coincide within the errors, reveals that the differences found in the asymmetric system are significant and excludes biases intro-

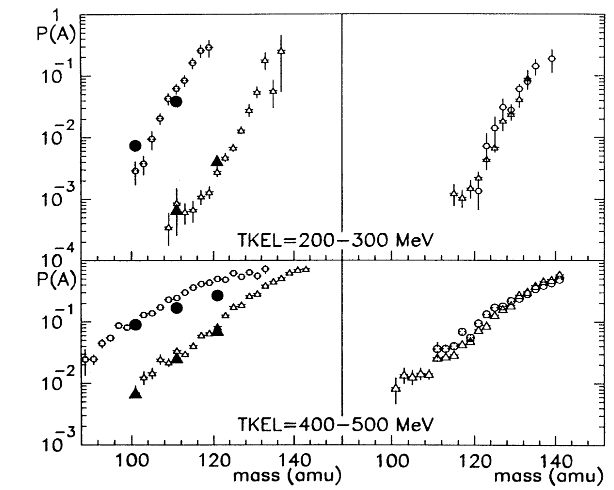

FIG. 1. Fission probabilities deduced for the PLF (open triangles) and the TLF (open circles) as a function of their primary mass in two bins of TKEL for the reactions $^{120}Sn+{}^{100}Mo$ (left) and $^{120}Sn+{}^{120}Sn$ (right) at 19.1 MeV/nucleon. For the asymmetric system the model results (solid symbols) for representative mass values are also displayed (see text). The results include Monte Carlo corrections for detection efficiencies and possible distortions due to the analysis method.

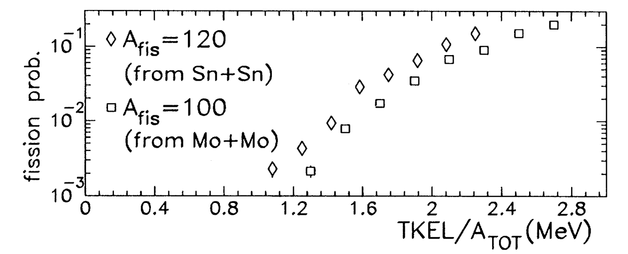

FIG. 2. Fission probabilities vs TKEL/A_{TOT} for fragments of mass $A \approx 120$ and 100 produced in the present symmetric collision $^{120}Sn+{}^{120}Sn$ (diamonds) and in the previously studied $^{100}Mo+{}^{100}Mo$ at 18.7 MeV/nucleon (squares), respectively.

duced by the detection and analysis methods. In particular, extensive Monte Carlo simulations (with evaporation and reconstruction included) showed that the experimental PLF-TLF difference cannot be reproduced by any parametrization of the fission probability in which, at a given TKEL, the mass number A is the only explicit or implicit independent variable. One definitely needs two different fission probabilities (larger for the TLF of a given mass A than for the PLF of the same mass).

Considering masses intermediate between target and projectile, one sees that the fission probability is larger when the deep-inelastic product gained nucleons, in respect to the case in which it lost nucleons. This correlation with the net exchange of nucleons clearly shows that the dinuclear system is not in equilibrium when it separates.

The observed PLF-TLF difference can hardly be understood on the basis of an overall mean-field interaction which generates excitation, angular momentum, and deformation of the fragments. The explanation should rather emerge from a model which considers explicitly the transport of nucleons. This model can be either of the incoherent (NEM) or of the coherent type (like, e.g., the random neck rupture model [25]). The first is expected to be more appropriate at small energy losses, and the second at large energy losses, when deformations are more developed. In order to verify, as in recent attempts [11-13,26], whether incoherent processes alone are able to explain the observed strong correlation with the net mass drift, a simple calculation was performed. It is based on a nucleon exchange mechanism in energy space as described in Ref. [27], complemented with the new additional assumption that, in each exchange, the recoil energy is dissipated in the receptor nucleus. In this manner a correlation between mass transfer and excitation energy is obtained even for incoherent exchanges. For a more direct comparison of the calculations with the data, no attempt was made to describe the fission step according to available fission models. Instead, the dependence of the fission probability of nuclei of mass $A=100$ and 120 on the excitation energy was deduced from the experimental data of the symmetric systems $^{120}Sn+{}^{120}Sn$ and $^{100}Mo+{}^{100}Mo$ (measured previously [28]), which are shown in Fig. 2. Fission probabilities for intermediate masses were interpolated. The calculated ratios $P(A)$ in the asymmetric system for PLF and TLF of the three representative masses $A=100$, 110, and 120 are shown in Fig. 1. The experimental PLF-TLF differences are qualitatively well reproduced by this simple model, while they are unexpected on the basis of the two most common pictures of equal temperature and equal energy sharing.

The use of experimental data for the fission step gives the correct normalization to the calculation and, at the same time, makes the comparison independent of the details of the fission step. Therefore, it seems reasonable to ascribe the unexpected PLF-TLF differences found in the experiment to the interaction mechanism of the deep-inelastic step. The agreement with the model indicates that incoherent one-body dissipation processes may still play an important role at these higher incident energies. However, it cannot be excluded that the present simple model is overestimating the one-body part at the cost of coherent mass transport and of two-body collisions. In fact, the present calculation is found to underestimate the mass variances by $\approx 30\%$.

In a refined nucleon exchange model one expects that each step contributes to a correlated increase of excitation energy and angular momentum (possibly deformation) in the fragments, which determine the subsequent transition to fission or particle evaporation. Therefore, the excitation energy, which is the only explicit variable in the above model, is to be considered just as representative of all internal variables describing the state of the system.

The observed correlation has been deduced in a region of energy loss (TKEL) and product mass (A), where three-body as well as two-body events are observed. However, it should be noted that the steep increase of the fission probability with excitation energy produces an enhanced sensitivity to the high-excitation-energy tail. Therefore, the present results might not be fully representative of all deep-inelastic events within a specific TKEL bin.

In conclusion, the described new experimental finding, based on a direct comparison between specifically chosen asymmetric and symmetric colliding systems, seems to be a measure of nonequilibrium generated, through the window of the dinuclear system, by the dissipation mechanisms. This result questions the validity of equal energy sharing as an initial energy perturbation in dissipative processes at high incident energies. The measurement seems to be selective among models and calls for more elaborated microscopic calculations.

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[1] T. C. Awes *et al.*, Phys. Rev. Lett. **52**, 251 (1984).
[2] R. Vandenbosch *et al.*, Phys. Rev. Lett. **52**, 1964 (1984).
[3] J. L. Wile *et al.*, Phys. Rev. C **39**, 1845 (1989).
[4] G. A. Petitt *et al.*, Phys. Rev. C **40**, 692 (1989).
[5] J. Randrup, Nucl. Phys. **A327**, 490 (1979); **A383**, 468 (1982).
[6] H. Sohlbach *et al.*, Nucl. Phys. **A467**, 349 (1987).
[7] J. L. Wile *et al.*, Phys. Rev. C **40**, 1700 (1989).
[8] K. Kwiatkowski *et al.*, Phys. Rev. C **41**, 958 (1990).
[9] R. Płaneta *et al.*, Phys. Rev. C **39**, 1197 (1989).
[10] D. R. Benton *et al.*, Phys. Rev. C **38**, 1207 (1988).
[11] K. Siwek-Wilczynska *et al.*, Phys. Rev. C **32**, 1450 (1985).
[12] H. R. Schmidt *et al.*, Phys. Lett. B **180**, 9 (1986).
[13] J. Wilczynski *et al.*, Phys. Lett. B **220**, 497 (1989).
[14] G. Beier *et al.*, Z. Phys. A **336**, 217 (1990).
[15] U. Lynen *et al.*, Nucl. Instrum. Methods **162**, 657 (1979).
[16] N. Shenhav and H. Stelzer, Gesellschaft für Schwerionenforschung Annual Report, 1983 (unpublished), p. 253.
[17] G. Casini *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **277**, 445 (1989).
[18] R. J. Charity *et al.*, Z. Phys. A (to be published).
[19] J. Toke *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **288**, 406 (1990).
[20] G. Casini *et al.* (to be published).
[21] A. Olmi *et al.*, Europhys. Lett. **4**, 1121 (1987).
[22] G. Casini, Ph.D. thesis, University of Florence, 1990 (unpublished).
[23] S. Gralla *et al.*, Phys. Rev. Lett. **54**, 1898 (1985).
[24] W. U. Schröder *et al.*, Phys. Rev. C **16**, 623 (1977); A. Olmi *et al.*, Phys. Rev. Lett. **41**, 688 (1978); G. Rudolf *et al.*, Nucl. Phys. **A367**, 109 (1981).
[25] U. Brosa *et al.*, Phys. Rep. **197**, 167 (1990).
[26] S. Chattopadhyay and D. Pal, Phys. Rev. C **42**, R2283 (1990).
[27] M. Dakowski *et al.*, Nucl. Phys. **A378**, 189 (1982).
[28] P. R. Maurenzig *et al.* (unpublished).