Possibility of transient effects during the emission of intermediate mass fragments

J. Pochodzalla
Universität Frankfurt, D-6000 Frankfurt, Federal Republic of Germany

R. J. Charity, U. Lynen, H. Sann, W. Trautmann, and R. Trockel
Gesellschaft für Schwerionenforschung Darmstadt m.b.H., D-6100 Darmstadt, Federal Republic of Germany
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Multiplicity distributions of intermediate mass fragments observed in the reactions $^{18}O+^{nat}Ag$ and $^{18}O+^{197}Au$ at $E/A=84$ MeV are compared to statistical model calculations. The emission of intermediate mass fragments from a highly excited ($E_x/A \geq 6$ MeV) $A=100$ nucleus is found to be suppressed compared to the predictions of a sequential statistical evaporation model. This deficiency may be interpreted as resulting from dynamical constraints imposed by the finite time necessary to emit complex fragments.

Already since the first observation of intermediate mass fragments[1] (IMF's) in energetic nuclear reactions, the emission process of these complex clusters has been discussed within the framework of two extreme and opposite concepts. On one hand, the idea of compound nuclei and their sequential binary decay[2] has been rather successfully applied to the intermediate energy regime.[3] In contrast to this conventional decay mechanism, *true* multifragmentation, i.e., a fast, simultaneous breakup into many fragments, has been predicted to be the major decay mode of highly excited nuclear systems.[4,5] Presently, much effort—both experimentally[6,7] and theoretically[8]—is devoted to the search of observable differences between these two antipodean pictures in order to establish multifragmentation as a novel decay process. In view of the complexity of either disintegration process the inherent simplicity of statistical concepts is often used as a guidance.

Recently, Trockel and collaborators studied the IMF production in reactions of ^{12}C, ^{18}O, ^{20}Ne, and ^{40}Ar on ^{nat}Ag and ^{197}Au at bombarding energies 30 MeV $\leq E/A \leq$ 84 MeV.[6,9] In particular, they measured the mean IMF multiplicity, $\langle M_{IMF} \rangle$ (for events selected by the observation of one IMF of $Z \geq 6$, for details see Ref. 9), as a function of the average excitation energy remaining in the composite system at the end of the preequilibrium phase of light particle emission; these measured excitation energies will be denoted as $\langle E_x \rangle$ in the following. Neither a statistical multifragmentation model[4] nor multisequential statistical fragment evaporation[3] could account for the observed relationship between $\langle M_{IMF} \rangle$ and $\langle E_x \rangle$ obtained with the reactions on the Ag target.[9] Both models overestimate the associated IMF multiplicity at high excitation energies by at least a factor of 2. (It has particularly been verified that the GEMINI calculations do not underestimate the average kinetic energy of the light particles associated with the target-velocity source.[9] Therefore, the overprediction of the IMF multiplicity cannot be attributed to a too small cooling during the evaporation cascade.) On the contrary, the sequential evaporation model was in agreement with the observations made with the Au target. In this Brief Report, we will show that, in analogy to transient phenomena expected for fission-like processes,[10,11] this difference and the reduced IMF emission probability may be a consequence of dynamical constraints imposed on the emission process. More generally, our result indicates that transient effects may limit the applicability of standard statistical models to excitation energies below $E_x/A \simeq 4$ MeV.

We will concentrate our discussion on the reactions $^{18}O+^{nat}Ag$ and $^{18}O+^{197}Au$ at an incident energy of $E/A=84$ MeV because, first, these reactions result in rather high excitation energies $\langle E_x \rangle$ and associated IMF multiplicities $\langle M_{IMF} \rangle$ ($\langle E_x \rangle = 670 \pm 180$ MeV and $\langle M_{IMF} \rangle = 1.53 \pm 0.13$ for the reaction on Ag and $\langle E_x \rangle = 580 \pm 180$ MeV and $\langle M_{IMF} \rangle = 1.46 \pm 0.12$ for the reaction on Au), and secondly, because the time scale for IMF emission in these two reactions has been studied in detail in Ref. 6. In order to motivate the idea of transient phenomena we will discuss, in the following paragraphs, to what extent the initial excitation energy of the compound nucleus system, $\langle E_x \rangle$, is reflected in the observed IMF multiplicity distribution or in the IMF time scale.

The dashed lines in Fig. 1 represent the experimental reconstructed IMF ($3 \leq Z \leq 20$) multiplicity distributions determined for the reactions $^{18}O+^{nat}Ag$ (left) and $^{18}O+^{197}Au$ (right).[9] For the multiplicity distributions an exponential form was assumed since—after taking the efficiency cuts of the detector system into account[12]—it provided the best fit to the measured data. These multiplicity distributions are compared to results obtained with the statistical model code GEMINI.[3] Compound nuclei with masses $A=100$ and 190 and charges $Z=45$ and 75 were assumed to be representative for the reactions on ^{nat}Ag and ^{197}Au, respectively.[9] The calculations were performed with initial angular momenta $J=0$ (top parts) and $J=50$ (bottom parts) at various excitation energies E_x. Since the reconstructed distributions are not sensitive to the value at $M_{IMF}=0$, all multiplicity distributions are normalized at multiplicity $M_{IMF}=1$.

For the reactions on Au, the calculations with both $J=0$ and 50 reproduce the measured distribution when an initial excitation energy of approximately 500–600

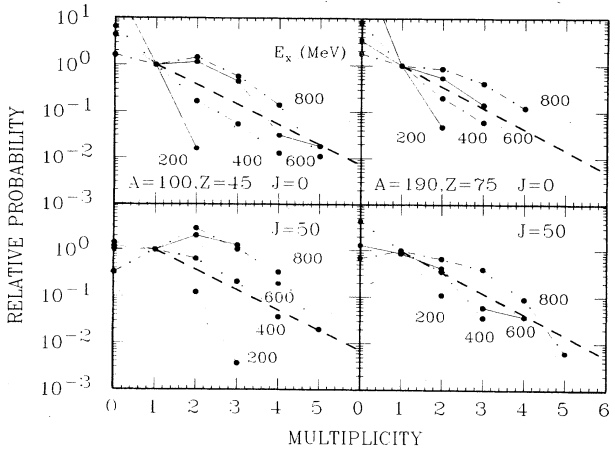

FIG. 1. Multiplicity distributions for IMF's ($3 \leq Z \leq 20$) for the indicated excitation energy E_x (in MeV) calculated with the statistical model code GEMINI (Ref. 3) for the decay of $A=100$ (left) and $A=190$ (right) compound nuclei with initial angular momenta of $J=0$ (top) and $J=50$ (bottom). The dashed lines represent the reconstructed multiplicity distributions for the reactions $^{18}O+^{nat}Ag$ (left parts) and $^{18}O+^{197}Au$ (right parts) at $E/A=84$ MeV (Ref. 9).

MeV is assumed. These values are consistent with the measured excitation energy after preequilibrium light particle (PELP) emission ($\langle E_x \rangle = 580$ MeV). Turning to the reactions on ^{nat}Ag (Fig. 1, left parts), the reconstructed multiplicity distributions suggest an excitation energy of $E_x \leq 400$ and $E_x \approx 500$ MeV for $J=50$ and 0, respectively. Thus, in line with the average associated IMF multiplicities,[9] also the *shape* of the multiplicity distributions reflects an excitation energy which is lower than the measured excitation energy after PELP emission of $\langle E_x \rangle = 670$ MeV.

Additional insight can be gained from the analysis of the time scale for IMF emission. The experimental results of Ref. 6 represent the average time *between* the emission of two IMF's of $10 \leq Z \leq 20$.[12] In order to obtain an—admittedly crude—estimate of this time, we have followed the *average* temporal evolution of the emitting nucleus based upon the decay widths given by the code GEMINI. The time difference between the subsequent steps $i-1$ and i was assumed to be given as $t_i - t_{i-1} = \hbar/\Gamma_{tot}$, where Γ_{tot} is the *total* decay width at step $i-1$. After each decay step, the mass and charge of the emitting nucleus was reduced by $\sum A_k \cdot \Gamma_k / \Gamma_{tot}$ and $\sum Z_k \cdot \Gamma_k / \Gamma_{tot}$, respectively. Here, A_k and Z_k are the mass and charge of the emitted particle in channel k. Similarly, the excitation energy was lowered by $2T+B+S$, where B and S are the average barrier and separation energy and T denotes the temperature of the emitting system. For simplicity, the angular momentum is reduced according to the classical equations given in Ref. 13. The average time between the emission of the two IMF's was then calculated as

$$\langle \tau_{IMF\text{-}IMF} \rangle = \sum_i \sum_{j>i} p_i p_j (t_j - t_i) \Big/ \sum_i \sum_{j>i} p_i p_j \, . \quad (1)$$

Here, $p_i = \Gamma_{IMF}/\Gamma_{tot}$ denotes the probability for the emission of an IMF (corrected for the reduced detection efficiency[12]) at the time step i.

The lines in the upper parts of Fig. 2 represent the results of these calculations as a function of the initial excitation energy E_x. For the Au target, one obtains, approximately independent of the initial angular momentum J, a lifetime of 1×10^3 fm/c at $\langle E_x \rangle = 580$ MeV. This value is consistent with the measured time given in Ref. 6 (hatched regions). However, for the $A=100$ case the calculated IMF-IMF times are only in marginal agreement with the data. (Note that the momentum transfer observed in the $^{18}O+^{nat}Ag$ reaction at $E/A=84$ MeV indicates average angular momenta of the decaying systems of $J \approx 50$.[6]) Again, a reasonable agreement with the experimental IMF-IMF emission time may be obtained, if the excitation energy is reduced. Thus the IMF multiplicity and the emission time scale for IMF's in $^{18}O+^{nat}Ag$ reaction are more consistent with the GEMINI calculations if the statistical emission of IMF's starts from a compound nucleus whose excitation energy (≤ 400 MeV) is considerably lower than the measured ex-

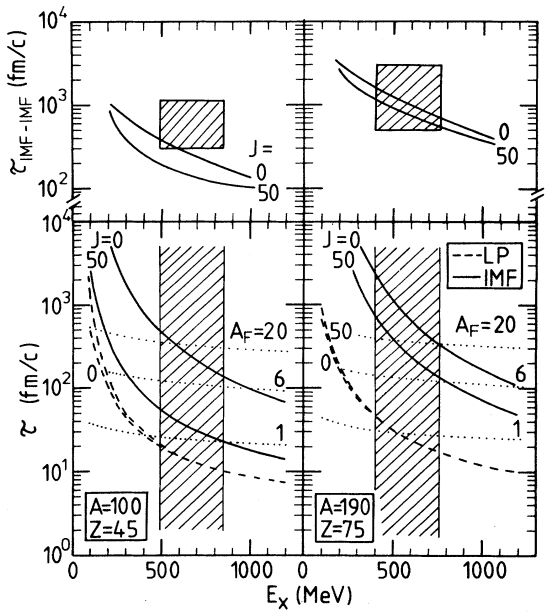

FIG. 2. Lower parts: Total mean lifetime of a $A=100$ nucleus (left) and $A=190$ nucleus (right) with respect to IMF emission ($3 \leq Z_{IMF} \leq 20$, solid lines) and light particle decay (dashed lines) as predicted by the statistical model code GEMINI (Ref. 3). The dotted lines indicate the estimated transient time for fragments of mass $A_F = 1$, 6, and 20. The hatched regions mark the excitation energy after preequilibrium light particle emission measured for the reactions $^{18}O+^{nat}Ag$ (left) and $^{18}O+^{197}Au$ (right) at $E/A=84$ MeV. Upper parts: Estimated time between the emission of two IMF's (lines) compared to the experimental values (hatched regions, Ref. 6).

citation energy after PELP emission ($\langle E_x \rangle = 670$ MeV). This would suggest that although the nucleonic degrees of freedom are (rather) equilibrated after the termination of PELP emission, it takes—in line with transient phenomena in fission processes[10]—a further time to build up the quasistationary decay probability for heavy cluster emission. This delay time may be regarded as the time which is required to populate all phase-space cells in all relevant degrees of freedoms [which is a necessary condition for the calculation of nuclear disintegration widths[14]] starting from a compact (equilibrium) configuration. Alternatively, this delay may be interpreted as the finite time which is necessary for the system to reach a certain "critical" configuration where the nucleus becomes committed to the decay. During this time, the excitation energy will be further reduced almost exclusively by light particle emission, thus decreasing the probability to reach and pass this transition state.

In order to elucidate this possible scenario, we compare in the following the lifetime predicted by the statistical model to the typical transient or relaxation time t_{IMF} of intermediate mass cluster degrees of freedom, i.e., the actual physical time that is necessary to emit a fragment. We estimate t_{IMF} by the classical relation $t_{\mathrm{IMF}} = d/v$. Here, v denotes the velocity of the (pre)fragment and d is the distance a prefragment has to move until it becomes free. For d we take for simplicity the diameter of the fragment $d = 2r_0 A_F^{1/3}$, where A_F denotes the mass number of the fragment and $r_0 = 1.4$ fm. For $1/v$ we use the average of the inverse velocity assuming a Gaussian momentum distribution[15] characterized by a temperature T:

$$\langle 1/v \rangle = \sqrt{(2/\pi)[(A_0 - A_F)A_F m_0 / A_0 T]} \,. \qquad (2)$$

Here, m_0 is the nucleon mass and A_0 is the mass number of the primary nucleus ($A_0 = 100$ and 190, respectively). The temperature T was calculated according to $T = \sqrt{E_x/(A_0/10)}$. Emission times, t_{IMF}, for $A_F = 1$, 6, and 20 fragments are indicated by the dotted lines in the lower parts of Fig. 2. Typically 100 fm/c are required to emit an $A = 6$ cluster and as much as 300 fm/c are required for an $A_F = 20$ fragment. Weighting the transient time with the observed fragment yields results in average transient times for IMF's of about 250 fm/c. Note that these times are longer than typical relaxation times for nucleonic degrees of freedom of $\simeq 20$ fm/c.[16]

In the lower parts of Fig. 2 we have also plotted the typical lifetime $\hbar/\sum_i \Gamma_i$ for light particle ($0 \le Z_{\mathrm{LP}} \le 2$, dashed lines) and IMF emission ($3 \le Z_{\mathrm{IMF}} \le 20$, solid lines) calculated with the statistical code GEMINI as a function of the excitation energy. [Because of the low IMF multiplicity, the average lifetime with respect to light particle emission at the beginning of the decay cascade can be approximated by $\hbar/\Gamma_{\mathrm{LP}}$. For IMF's, however, cooling via light particle decay, which reduces the probability for IMF decay at later stages of the decay path, has to be taken into account. The average time for the first IMF decay estimated in line with Eq. (1) as $\langle \tau_{\mathrm{IMF}} \rangle = \sum_i p_i \cdot t_i / \sum_i p_i$ are smaller than $\hbar/\Gamma_{\mathrm{IMF}}$ by about a factor of 2 at $E_x \le 300$ MeV. However, in the excitation energy regime of interest in the present Brief Report, the time for the first IMF decay is reasonably well approximated by $\hbar/\Gamma_{\mathrm{IMF}}$.] Whereas the light particle lifetime does not significantly depend on the orbital angular momentum J or on the emitting system, the IMF lifetime decreases with increasing J and, for the $A = 100$ case, reaches for $J = 50$ in the region of $\langle E_x \rangle$ (hatched area) $\tau < 100$ fm/c. This is smaller than the transient times estimated above. The transition time of nucleons is of the order of 20–30 fm/c which is comparable to $\hbar/\Gamma_{\mathrm{LP}}$ at $\langle E_x \rangle$ and, therefore, sufficiently short to allow a significant number of light particles to be emitted. Thus, deviating from the predictions of the statistical model one might speculate that the emission of complex fragments will be suppressed in favor of light particle decay until a time of typically $t_{\mathrm{IMF}} \ge 100$ fm/c has elapsed. For $A = 190$ the lifetime for IMF emission is, even at high angular momenta, larger than 200 fm/c at $\langle E_x \rangle$. Therefore, no significant dynamical restriction for the application of the statistical model can be expected in that case.

Based on the calculations described above, one can estimate the number of light particles that will be emitted during the transient time. An $A = 100$ nucleus with an excitation energy of $E_x = 670$ MeV will emit on the average ≈ 8 light particles during the first 100 fm/c. This will cause a total reduction of the initial excitation energy by ≈ 200 MeV. Thus, only after the excitation energy has dropped to ≈ 450 MeV (which is in line with the experimental observations discussed above), we expect that IMF emission does compete with the light particle emission according to the predictions of the statistical model. For an $A = 190$ nucleus with $E_x = 580$ MeV, less than 100 MeV of excitation energy will be removed by light particles during the first 100 fm/c. Although our data are not inconsistent with such a reduction of E_x prior to IMF emission, the uncertainties of the present analysis do not permit more quantitative conclusions. For such heavy nuclei, transient effects would be clearly visible in IMF decays only at excitation energies above 1000 MeV. Since the estimated transient times scale with $A^{5/6}$—which is consistent with the observed dependence of the fission time scale on the mass asymmetry[11]—transient phenomena in heavy nuclei are more likely to be observable in fission-like processes.

Finally, we would like to point out that the estimated transient times are only weakly dependent on the excitation energy. Because of the strong dependence of the light particle lifetime on the excitation energy, a fixed time scale for the IMF decay (≈ 100–300 fm/c) results in an excitation energy at the point of IMF decay which will show only a weak sensitivity to the initial excitation energy.[17] In the range $E_x < 1000$ MeV discussed in this Brief Report, the excitation energy where IMF decay takes place is of the order of 400 MeV in the case of a mass 100 nucleus and about 500–700 MeV for an $A = 190$ nucleus. This instantaneous excitation energy will be reflected in the internal excitation energy of the emitted fragments. Indeed, intermediate mass fragments ($4 \le A \le 8$) emitted in a whole variety of nuclear reactions on ^{197}Au targets at

bombarding energies below $E/A = 100$ MeV show a characteristic emission temperature of $T \approx 5$ MeV;[18] for $A = 190$ this corresponds to an excitation energy of about 500 MeV (for $a = A/10$).

To summarize, the emission of intermediate mass fragments from a highly excited ($E_x/A \geq 6$ MeV) $A = 100$ nucleus is suppressed compared to the predictions of purely statistical model calculations. We have shown that this suppression may be a consequence of dynamical constraints imposed by the finite time which is necessary to emit a complex fragment. Our estimate of the transient times suggests that the applicability of multisequential statistical model calculations is restricted to excitation energies below 4 MeV per nucleon.

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