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A Statistical Interpretation of the Correlation Between IMF Multiplicity and Transverse Energy


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A statistical interpretation of the correlation between IMF multiplicity and transverse energy

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Multifragment emission following ¹²⁹Xe+¹⁹⁷Au collisions at 30, 40, 50 and 60 AMeV has been studied with multidetector systems covering nearly 4π in solid angle. The correlations of both the intermediate mass fragment and light charged particle multiplicities with the transverse energy are explored. A comparison is made with results from a similar system, ¹²⁹Xe+⁹⁹Bi at 28 AMeV. The experimental trends are compared to statistical model predictions.

Highly excited nuclear matter can be produced in intermediate-energy heavy-ion collisions. In these reactions, its decay by intermediate mass fragment and light charged particle multiplicities with the transverse energy is explored. A comparison is made with results from a similar system, ¹²⁹Xe+⁹⁹Bi at 28 AMeV. The experimental trends are compared to statistical model predictions.

![Table I](image)

<table>
<thead>
<tr>
<th>$E_{\text{beam}}$/A</th>
<th>$N_{\text{IMF}}$</th>
<th>$\langle N_{\text{LCP}}\rangle_{\text{max}}$</th>
<th>$E_{\text{LCP}}^{\text{IMF}}$</th>
<th>$\langle E_{\text{LCP}}^{\text{IMF}}\rangle_{\text{max}}$</th>
<th>$\langle N_{\text{IMF}}\rangle_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 MeV</td>
<td>5 (6.5%)</td>
<td>13.9</td>
<td>220 MeV</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>40 MeV</td>
<td>7 (5.0%)</td>
<td>18.9</td>
<td>400 MeV</td>
<td>6.0</td>
<td></td>
</tr>
<tr>
<td>50 MeV</td>
<td>8 (4.3%)</td>
<td>23.1</td>
<td>530 MeV</td>
<td>6.9</td>
<td></td>
</tr>
<tr>
<td>60 MeV</td>
<td>8 (5.9%)</td>
<td>26.1</td>
<td>660 MeV</td>
<td>7.4</td>
<td></td>
</tr>
</tbody>
</table>

In recent papers, Toke et al. have offered a new interpretation regarding the origin of the correlation between $N_{\text{IMF}}$ and $E_t$. In one study [2], these authors explored the dependence of the light charged particle multiplicity ($N_{\text{LCP}}$), the transverse energy of LCPs ($E_{\text{LCP}}^{\text{IMF}}$), and the transverse energy of IMFs ($E_t^{\text{IMF}}$) as a function of $N_{\text{IMF}}$. Based upon their analysis, they concluded that a new mode of energy dissipation is present and that the resulting IMFs are formed dynamically. In another study [3], the authors examined the contributions to $E_t$ from IMFs and LCPs, and from their analysis, they ruled out statistical emission as a possible origin of the IMFs.

We have reviewed their conclusions and have found that many of their observations can be reproduced by statistical models. We have also found that the results from ref. [3] are inconsistent with measurements taken with a detector of improved dynamical range. Therefore, the interpretation in [3] is probably in error.

In what follows we report on 1) the general nature of the observations of refs. [2,3]; 2) the limited usefulness of gating on $N_{\text{IMF}}$ as an event-selection strategy; 3) experimental acceptance issues which introduce artificially features similar to those observed in ref. [3]; and 4) the reproduction of key results with statistical model calculations.

Our measurements of the LCP and IMF yields and their correlations with, and contributions to $E_t$ were made for the reaction ¹²⁹Xe+¹⁹⁷Au at 30, 40, 50, and 60 AMeV. The experiments were performed at the National Superconducting Cyclotron Laboratory at Michigan State University (MSU). Beams of ¹²⁹Xe, at intensities of about $10^7$ particles per second, irradiated gold targets of approximately 1 mg/cm². LCPs and IMFs produced in these reactions were measured with the MSU Miniball phoswich array [10]. For the bombarding en-
The average in a bombarding energy dependent fashion as well (see top panel). In contrast, the average IMF contribution to $E_t$ is approximately 4-5 at low bombarding energy to a value of 8-9 at higher bombarding energy. The value to which $N_{\text{LCP}}$ rises with increasing bombarding energy is listed in Table I and open symbols of Fig. 1, as determined by employing a high resolution Si-Si(Li)-plastic scintillator array. Details of the experimental setups can be found in refs. [13,14].

We now investigate the advantages and disadvantages of using $N_{\text{IMF}}$ as a global event selector, as employed in ref. [2], to determine the average IMF multiplicity at which the saturation occurs. As complementary evidence, the dependence of the average kinetic energy per nucleon of the projectile-like fragment is plotted as a function of $N_{\text{LCP}}$ (open symbols) and $N_{\text{IMF}}$ (solid circles). From the decrease of $(E/A)_{\text{PLF}}$ with $N_{\text{IMF}}$, the authors of ref. [2] concluded that kinetic energy of the PLF is being expended for the production of IMFs. It was also argued that for increasing $N_{\text{IMF}}$, the saturation of $(N_{\text{LCP}})$ represents a critical excitation energy value beyond which no further amount of relative kinetic energy between the PLF and TLF is converted into heat.

The trends shown in Fig. 1 for $^{129}\text{Xe}+^{197}\text{Au}$ confirm the general nature of similar observations for Xe+Bi at 28 AMeV [2]. Furthermore, a clear bombarding energy dependence is observed, with larger saturation values (as a function of $N_{\text{IMF}}$) of $(N_{\text{LCP}})_{\text{max}}$ and $(E_t)_{\text{LCP}}$ for increasing bombarding energy.

As complementary evidence, the dependence of the average kinetic energy of the projectile-like fragment $(E/A)_{\text{PLF}}$, defined as the heaviest forward-moving particle in an event, with $Z_{\text{PLF}} \geq 10$ and $\theta \leq 23^\circ$ has been studied as a function of $N_{\text{IMF}}$, an example of which is given in Fig. 2 for $^{129}\text{Xe}+^{197}\text{Au}$ at 40 AMeV (solid circles). From the decrease of $(E/A)_{\text{PLF}}$ with $N_{\text{IMF}}$, the authors of ref. [2] concluded that kinetic energy of the PLF is being expended for the production of IMFs. It was also argued that for increasing $N_{\text{IMF}}$, the saturation of $(N_{\text{LCP}})$ represents a critical excitation energy value beyond which no further amount of relative kinetic energy between the PLF and TLF is converted into heat.

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It has been argued that the saturation of the LCP observables (as opposed to the continuous rise of $(E_t)_{\text{LCP}}$) as a function of $N_{\text{IMF}}$ provides supporting evidence for dynamical fragment production. The claim is that such a saturation helps demonstrate that the IMFs do not compete statistically for the available thermal energy [2]. As complementary evidence, the dependence of the average kinetic energy of the projectile-like fragment $(E/A)_{\text{PLF}}$, defined as the heaviest forward-moving particle in an event, with $Z_{\text{PLF}} \geq 10$ and $\theta \leq 23^\circ$ has been studied as a function of $N_{\text{IMF}}$, an example of which is given in Fig. 2 for $^{129}\text{Xe}+^{197}\text{Au}$ at 40 AMeV (solid circles). From the decrease of $(E/A)_{\text{PLF}}$ with $N_{\text{IMF}}$, the authors of ref. [2] concluded that kinetic energy of the PLF is being expended for the production of IMFs. It was also argued that for increasing $N_{\text{IMF}}$, the saturation of $(N_{\text{LCP}})$ represents a critical excitation energy value beyond which no further amount of relative kinetic energy between the PLF and TLF is converted into heat.

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In other words, the IMFs no longer compete with the LCPs for the available energy — they get it all. It was this observation, together with data like those in Fig. 1, that was taken as evidence for dynamical emission [2].

One can test the consistency of such an explanation by studying the same observable, \(\langle E/A\rangle_{PLF}\), but now as a function of \(N_{LCP}\) (open symbols, top panel of Fig. 2). We observe the same dependence as that of the IMFs — a monotonic decrease of \(\langle E/A\rangle_{PLF}\) with increasing \(N_{LCP}\) which reaches a value of \(\sim 17\) MeV at the largest multiplicities. This behaviour persists whether we restrict ourselves to the saturation region \((N_{IMF} \geq 6,\) triangles) or not (open circles). It seems that the LCPs do in fact “cost” energy (as measured by the PLF) and therefore do compete with the IMFs for the available energy.

This can be seen more clearly by pre-selecting events with a better global observable, \(E_t\) [15–17], as done in the bottom panel of Fig. 2. Once a window of \(E_t\) is selected, a corresponding value of \(\langle E/A\rangle_{PLF}\) is also determined, and there is no longer any strong dependence of \(\langle E/A\rangle_{PLF}\) on \(N_{IMF}\) or \(N_{LCP}\). In fact, the resulting \(N_{IMF}\) and \(N_{LCP}\) selections both give the same value of \(\langle E/A\rangle_{PLF}\), consistent with a scenario where both species compete for the same available energy.

What then causes the saturation observed in Fig. 1? It is the discreteness and limited range of \(N_{IMF}\) along with its weak correlation to the deposited energy.

For example, when compared to the total charged particle multiplicity \(N_C = N_{IMF} + N_{LCP}\), it is obvious that \(N_{IMF} \leq N_C\) and therefore \(\Delta N_{IMF}/N_{IMF} \geq \Delta N_C/N_C\) where \(\Delta N_{IMF} = \Delta N_C = 1\), the base unit of change of these observables. Consequently, any measure of energy deposition or centrality of the collision based upon \(N_{IMF}\) will lead to much larger fluctuations in the deduced impact parameter scale than one based on, for example, \(N_C\) [15].

Furthermore, the values of \(N_{IMF}\) at which the observables in Fig. 1 saturate \((N_{IMF})_\text{sat}\) can be understood in terms of such an impact parameter scale. Consider the probability \(P\) of emitting \(N_{IMF}\) and its integrated yield

\[
S(N_{IMF}) = \sum_{i=N_{IMF}}^{\infty} P(i)
\]

as shown in Fig. 3 for the reaction \(^{129}\text{Xe} + ^{197}\text{Au}\) at 50 AMeV. Average impact parameter scales, as they are commonly employed, are proportional to \(\sqrt{S}\) [15]. We note that the multiplicities at which saturation occurs represent roughly 5% of the total integrated cross section (dashed line in the bottom panel of Fig. 3). The \(N_{IMF}\) value \(N_{IMF}^{\text{sat}}\) for which \(S \approx 0.05\) is listed in Table I for each of the different bombarding energies. \(N_{IMF}^{\text{sat}}\), tracks rather well the maximum average \(N_{IMF}\) \((N_{IMF})_\text{max}\) measured for the most central collisions (top 5% of events) based upon the \(E_t\) scale.

The above observations demonstrate that large IMF multiplicities \((N_{IMF} > (N_{IMF})_\text{max})\) have small probabilities and represent the extreme tails of events associated with the most central collisions. In other words, events
with increasing values of N_{IMF} in the saturation region of Fig. 1 do not come from events where more energy has been dissipated. Thus, N_{IMF} is useful as a global event selector over only a very limited range.

Consequently, it is expected that statistical models should exhibit similar trends as observed in Fig. 1. Examples of such predictions are shown in Fig. 4 for the statistical multifragmentation model SMM (open symbols) [18] and for percolation (solid symbols) [19]. In both models an excitation energy \( E \) distribution was used such that the number of events at a given \( E \) was proportional to \( (E_{\text{max}} - E) \) where \( E_{\text{max}} \) is the largest calculated excitation energy. The “excitation energy” for the percolation calculation is essentially represented by the number of broken bonds and is calculated as per ref. [19].

Both calculations show a saturation of \( \langle N_{\text{LCP}} \rangle \) when plotted as a function of \( N_{\text{IMF}} \). This behavior can be understood in terms of a simple model. Consider the statistical emission of two particle types with barriers \( B_1 \) and \( B_2 \) (and \( B_2 > B_1 \)). Assume the emission probabilities are \( p_i \propto \exp\left[-B_i/T\right] \) \( (i = 1, 2) \) with \( p_1 + p_2 = 1 \). With the temperature \( T \) characterized in terms of the total multiplicity \( n_{\text{tot}} = n_1 + n_2 = \alpha T \), and ignoring mass conservation, the solution for \( n_1 \) as a function of \( n_2 \) can be calculated for a distribution of excitation energies like that described above. The solution of this model is shown by the crossed symbols in the top right panel of Fig. 4 for \( B_1 = 8, B_2 = 24, T_{\text{max}} = 10 \) and \( \alpha = 2 \) (and \( N_{\text{IMF}} = n_2, N_{\text{LCP}} = n_1 \)). This behavior is similar to that of the other statistical models listed in Fig. 4 and to the behavior observed in Fig. 1. This behavior is a generic feature that is present in any statistical model [20]. The saturation comes about because \( N_{\text{IMF}} \) is a poor measure of the “excitation energy”, as mentioned previously.

Up to this point, we have offered alternative explanations for the similar behaviors observed in \( N_{\text{IMF}} \) selected studies of \(^{129}\text{Xe}+^{197}\text{Au} \) and \(^{136}\text{Xe}+^{209}\text{Bi} \). In the remainder of this paper we focus on the observed differences between these reactions when other event selection strategies are employed.

When using a different global observable \( E_t \), an unusual behavior of the \( E_t \) selected events appears in the measured \(^{136}\text{Xe}+^{209}\text{Bi} \) reaction [3]. The contribution to \( E_t \) from IMFs and LCPs is shown in the bottom panel of Fig. 5 for the reaction \(^{136}\text{Xe}+^{209}\text{Bi} \). Of particular note is the strong saturation observed for \( \langle E_t^{\text{LCP}} \rangle \) (diamonds). This was taken to indicate a decoupling or a loss of statistical competition between the IMFs and LCPs [3].

However, in a similar reaction, \(^{129}\text{Xe}+^{197}\text{Au} \), the saturation observed in \(^{136}\text{Xe}+^{209}\text{Bi} \) is not present. In Fig. 6 are plotted \( \langle N_{\text{IMF}} \rangle, \langle N_{\text{LCP}} \rangle, \langle E_t^{\text{IMF}} \rangle \), and \( \langle E_t^{\text{LCP}} \rangle \) as a function of \( E_t \) for bombarding energies between 30 and 60 AMeV. Neither \( N_{\text{LCP}} \) nor \( E_t^{\text{LCP}} \) saturate at any value of \( E_t \). And, unlike the measurement for \(^{136}\text{Xe}+^{209}\text{Bi} \), the IMFs measured in the \(^{129}\text{Xe}+^{197}\text{Au} \) reactions are never the dominant carrier of \( E_t \).
We believe that the saturation observed in ref. [3] (see bottom panel of Fig. 5) is likely due to the limited dynamic range of the detectors used. The charged particle yields from the $^{136}$Xe+$^{209}$Bi reaction were measured with the dwarf array [21] whose thin CsI crystals (thickness of 4 mm for polar angle $\theta = 55-168^\circ$, 8 mm for $\theta = 32-55^\circ$ and 20 mm for $\theta = 4-32^\circ$) are unable to stop energetic LCPs. For example, protons punch through 4 mm of CsI at an energy of 30 MeV. Consequently, their contribution to $E_t$ could be significantly underestimated.

An example of the distortions that would be caused by the detector response of the dwarf array on the similar $^{129}$Xe+$^{197}$Au reaction at 30 AMeV is given in Fig. 5. In the top panel is plotted $(E_t^{LCP})$ and $(E_t^{IMF})$ as a function of $E_t$ as measured by the MULTICS/Miniball collaboration. The thicknesses of the CsI crystals from these detectors range from 20 to 40 mm. Protons punch through 20 mm of CsI with an energy of 76 MeV. In the middle panel of Fig. 5, the $^{129}$Xe+$^{197}$Au data has been "filtered" using the dwarf array high energy cutoffs which remove prominent features observed in the $^{136}$Xe+$^{209}$Bi data set [3] (bottom panel of Fig. 5) then appear in the filtered data. Namely, $(E_t^{LCP})$ saturates to a small value and $(E_t^{IMF})$ becomes the "apparent" dominant carrier of $E_t$. These two features are likely to be instrumental in origin and therefore do not warrant a physical interpretation. Consequently, they do not represent evidence of a failure of statistical models.

For example, the SMM calculations in Fig. 4 (lower left panel) show no hint of saturation of $(E_t^{LCP})$ with increasing $E_t$. Instead, this calculation shows qualitatively the same trends as experimentally observed in Fig. 6.

In summary, the saturations observed in $(N_{LCP})$ and $(E_t^{LCP})$ as a function of $N_{IMF}$ are fundamental features of statistical decay [20] rather than evidence for dynamical emission. A bombarding energy dependence of $(N_{LCP})$, $(E_t^{LCP})$, and $N_{stat}$ IMF is expected (and experimentally observed) within the framework of statistical decay. Furthermore, it has been demonstrated that the LCPs compete with the IMFs for the available energy. By using $E_t$, a more sensitive event selection is obtained which demonstrates the limited usefulness of event classification using $N_{IMF}$. The saturation of $(E_t^{LCP})$ as a function of $E_t$ observed in ref. [3] is likely due to instrumental distortions. We can account for this saturation by filtering the present measurements of $^{129}$Xe+$^{197}$Au with the experimental thresholds present in refs. [2,3]. The resulting distortions to the data are large and induce qualitative changes in the trends of the data, causing an unphysical saturation of $(E_t^{LCP})$. Therefore, the observations listed in refs. [2,3] do not demonstrate any measurable failure of statistical models that would justify invoking dynamical IMF production by default. While the IMFs may indeed be produced dynamically, the observations listed in refs. [2,3] do not provide credible evidence for such a conclusion.

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