Intermediate mass fragment emission in heavy-ion collisions: Energy and system mass dependence

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(Received 14 February 2000; published 24 January 2001)

Emission of intermediate mass fragments (IMFs) ($Z \geqslant 3$) from central collisions of ^{40}Ar+^{45}Sc ($E/A = 35$–115 MeV), ^{58}Ni+^{58}Ni ($E/A = 35$–105 MeV), and ^{86}Kr+^{93}Nb ($E/A = 35$–95 MeV) was studied. For each system, the average number of IMFs per event increased with beam energy, reached a maximum, and then decreased. The beam energy of peak IMF production increased linearly with the combined mass of the system. The number of IMFs emitted at the peak also increased with the system mass. Percolation calculations showed a weaker dependence of the peak beam energy and the number of IMFs on the total mass of the system.

DOI: 10.1103/PhysRevC.63.027602 PACS number(s): 25.70.Pq

Nucleus-nucleus collisions can lead to highly excited systems that form hot compressed nuclear matter [1]. These systems expand due to thermal pressure [2]. The expansion can cause density fluctuations which recover to normal density [3] or expand indefinitely, leading to the onset of multifragmentation. This behavior is governed by the incompressibility of nuclear matter, which is determined by the low-density nuclear equation of state [4]. With increase in available energy, the system can develop from evaporation to multifragmentation to vaporization, signifying the liquid-gas phase transition of nuclear matter [5–8]. Several experimental and theoretical investigations of the liquid-gas phase transition and critical phenomena of nuclear matter have been carried out [9–15]. The process of multifragmentation has been successfully treated in terms of equilibration hypotheses and statistical approaches [14–16]. To investigate the critical region of phase transition experimentally, one must study the decay from a single source over a wide range of beam energies. One way to achieve this goal is to study central collisions of symmetric systems. Emissions from such collisions are expected to be isotropic, supporting the idea that central collision events can be regarded as ''single-source'' events.

The formation of the various phases of nuclear matter in heavy-ion collisions has been investigated by measurements of nuclear species emitted from the excited systems. Theoretical studies indicate that it is most feasible to study the liquid-gas phase transition by observing multifragment emission from nucleus-nucleus collisions [17–20]. Statistical nuclear multifragmentation is a signature of the transition of nuclear matter from a liquid phase into a phase of several nuclear fragments with a broad mass distribution. Numerous investigations of multifragment emission from excited nuclear systems have been carried out [21–30]. The probability of multifragment emission is expected to increase as the excitation energy increases because of available phase space and barrier penetration probability [14,31–34]. However, a peak in the fragment multiplicities is expected to occur at some intermediate energy, followed by a decrease due to the transition to a nuclear gas phase [18,19,35].

The emission of intermediate mass fragments (IMFs), defined as those particles with $3 \leqslant Z \leqslant 20$, in nuclear collisions has been studied for more than a decade. de Souza *et al.* [26] showed that as the beam energy increased from 35 to 110 MeV/nucleon for ^{36}Ar+^{197}Au collisions, the IMF multiplicity for central collisions showed a steady increase with incident energy. Also the IMF multiplicity decreased as the collisions moved from central to peripheral. On the other hand, Tsang *et al.* [28], in their investigation of ^{197}Au+^{197}Au from 100 to 400 MeV/nucleon, found that the IMF production peak shifted from near central towards peripheral as the beam energy was increased. For central collisions, where the excitation energy is best defined, they found a rapid decrease of the IMF multiplicity with increase in energy. A more comprehensive study was carried out by Peaslee *et al.* [29] in their studies of the ^{84}Kr+^{197}Au from 35 to 400 MeV/nucleon, where they found that the IMF multiplicity increased with increasing energy to a maximum around 100 MeV/nucleon and then decreased slowly. Stone *et al.* [30] used a more symmetric system of ^{86}Kr+^{93}Nb from 35 to 95 MeV/nucleon to obtain IMF multiplicity distribution as a function of beam energy by selecting central events.

It is clear from the previous studies that for a particular system the IMF multiplicity should increase with beam energy at low energies [26,29,30]. Competing with this trend would be the depletion of IMFs as a result of excess energy causing the IMFs to break up into smaller fragments. As the energy increases the latter phenomenon should become more dominant and the production of IMFs should decrease due to the transition into the gas phase of nuclear matter as observed by Tsang *et al.* Comparison of the different studies also shows that the IMF multiplicity increases with the system mass for measurements at the same energy. However, there were no systematic studies of the production of IMFs as a function of beam energy and system mass in a controlled fashion. We have therefore measured and report in this paper the IMF multiplicity distributions for ^{40}Ar+^{45}Sc from 35 to

115 MeV/nucleon, ^{58}Ni+^{58}Ni from 35 to 105 MeV/nucleon, and ^{86}Kr+^{93}Nb from 35 to 95 MeV/nucleon. In order to obtain a reliable mass dependence of the IMF multiplicity, we have chosen three systems that range in mass by a factor of 2. For each system, we made measurements over a sufficiently broad energy range so that we can observe the rise and fall of the IMF multiplicity. In all cases, we selected central collisions of approximately symmetric systems so that we can explicitly define the energy available in the center of mass. We find that the IMF multiplicity does increase with energy, reaches a peak and then decreases. We also observe that the IMF multiplicity at the peak of the distribution increases with the combined mass of the colliding system.

The experiment was carried out at the National Superconducting Cyclotron Laboratory at Michigan State University. The heavy-ion beams were accelerated in the K1200 cyclotron and momentum analyzed in the double dipole A1200 analyzing system. The beam energies were known to about 1% and the energy resolution of the beams was about 0.1%. The beam line elements were adjusted for minimal steering of the beam by the focusing quadrupoles and produced a beam spot on target of less than 5 mm in diameter. The targets were mounted at the center of the MSU 4π-Array detector system [36]. More details of the 4π-Array detector system and experimental method are given elsewhere [37,38]. For the Ar + Sc experiment, beams of ^{40}Ar ranging from 35 to 115 MeV/nucleon in steps of 10 MeV/nucleon were incident on a ^{45}Sc target. The Ni + Ni experiment was carried out with energies from 35 to 105 MeV/nucleon in steps of 5 and 10 MeV/nucleon. For the Kr + Nb experiment, 35 to 95 MeV/nucleon beams of ^{86}Kr in steps of 5 and 10 MeV/nucleon were incident on a ^{93}Nb target. To define the available energy in the center of mass of the system during the collision as accurately as possible, central collision events were selected. For the present analysis, the central events were chosen to be the 10% of all events for a given beam-target combination which had the largest transverse energy. The average number of IMFs per event $\langle N_{IMF}\rangle$ was calculated for each beam energy of the three systems under study. These are plotted as a function of center of mass energy in Fig. 1. The reported error bars include statistical as well as systematic errors.

The dependence of $\langle N_{IMF}\rangle$ on center of mass energy is similar for the three cases studied here (Fig. 1). The observed behavior can be understood in terms of chemical equilibrium. For low energies, the number of IMFs emitted is small because of the limited available energy. A large fraction of the initial energy may be carried away by the emission of pre-equilibrium nucleons, leaving the system with insufficient energy to break it up into many IMFs, resulting in relatively few IMFs. As the beam energy increases, more and more energy is available in the composite system, resulting in a larger number of IMFs. As the beam energy is increased further, even more energy is available, causing the breakup of the IMFs into nucleons and helium fragments. Thus the production of IMFs is small for low energies, increases to a maximum at some intermediate energy, and then decreases again. In order to obtain average systematics of IMF emission, second order polynomials were fit to the data. These are shown as solid curves in Fig. 1. A similar fit was made for the ^{86}Kr+^{197}Au data of Peaslee *et al.* [29]. Although these data were taken with the MSU Miniball, comparison with our measurements using the MSU 4π detector is possible because both systems have acceptances and thresholds that are very similar. We have also carried out percolation simulations [39] for comparison with our measurements. For these simulations, the bond-breaking probability for each system has been calculated as a function of the beam energy [40]. The particle distributions obtained from the percolation simulation were used to produce simulated events which were then filtered using a software model of the 4π detector. The results in Fig. 2 show a variation of $\langle N_{IMF}\rangle$ with center of mass energy, which is very similar to that found in the data. The primary exception is that, as others have observed [41], the percolation model slightly underpredicts the number of IMFs produced in all four cases.

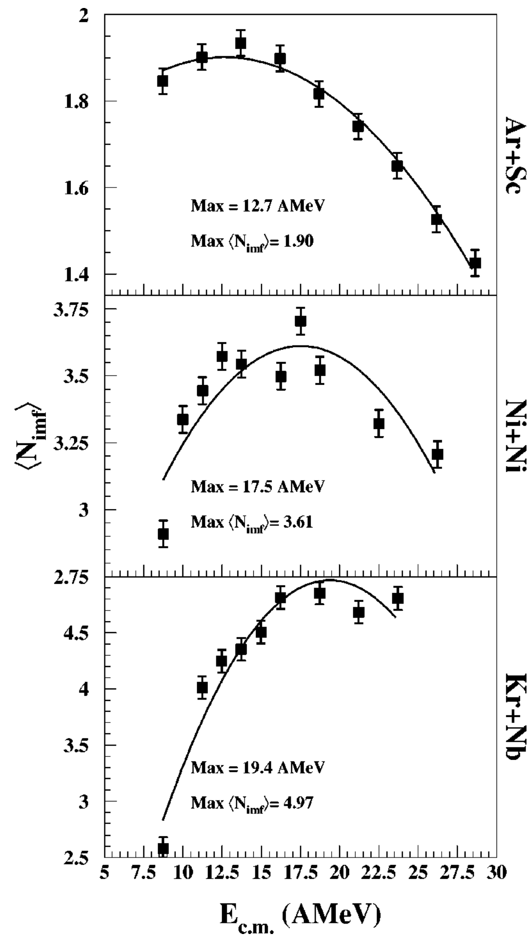

FIG. 1. Average number of IMFs emitted per event plotted as a function of available center of mass energy for collisions of ^{40}Ar + ^{45}Sc, ^{58}Ni+^{58}Ni, and ^{86}Kr+^{93}Nb. The curves are quadratic fits to the data, which determine the peak of the IMF emission and the energy at which the peak occurs.

As can be seen in Fig. 1, the average number of IMFs increases as the system mass increases, because more particles are available in a larger system. Using the fitted curves, the maximum of the average IMF emission and the energy at

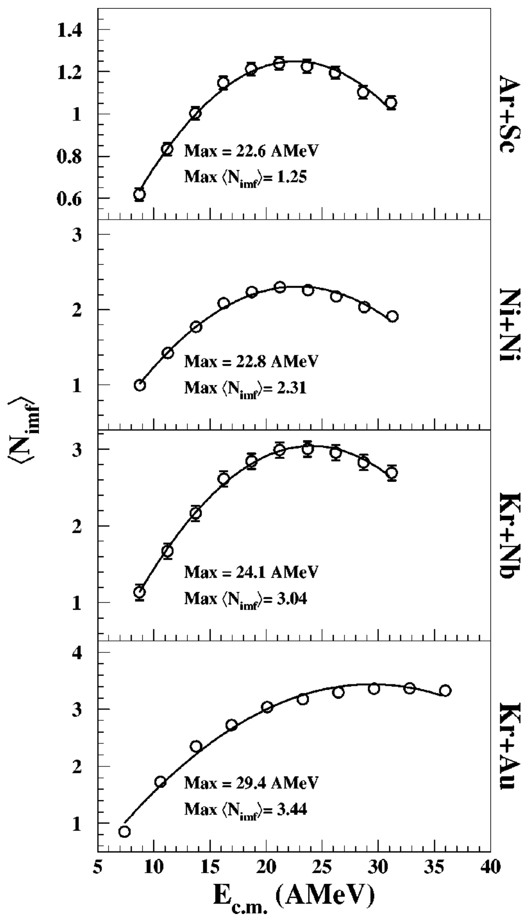

FIG. 2. Average IMF emission obtained from percolation calculations for $^{40}Ar+^{45}Sc$, $^{58}Ni+^{58}Ni$, $^{86}Kr+^{93}Nb$, and $^{84}Kr+^{197}Au$ as a function of available center of mass energy. The calculations have been filtered through the acceptances of the 4π detector. The curves are quadratic fits to the calculations; they give the peak of the IMF emission and the energy at which the peak occurs.

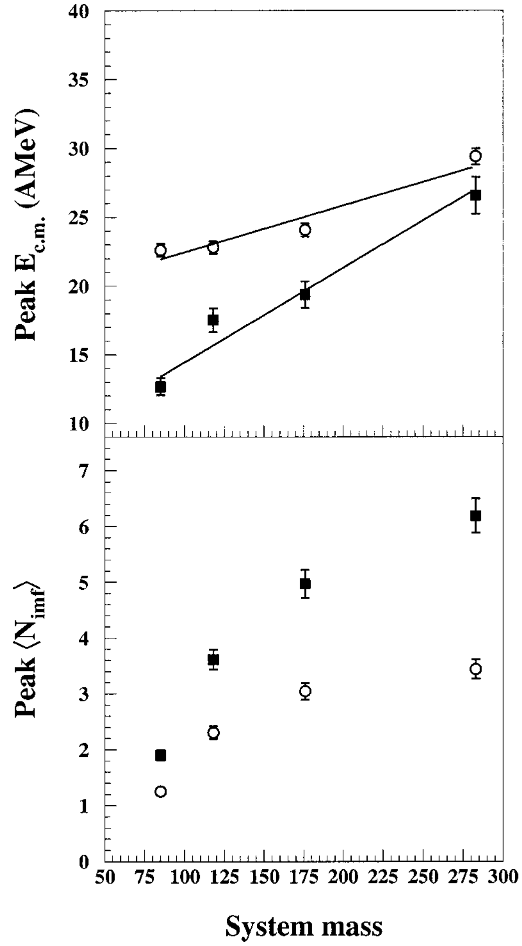

FIG. 3. Energy of peak IMF emission (top panel) and peak number of IMFs emitted per event (bottom panel) plotted as a function of system mass (solid squares) compared with percolation calculations (open circles).

which the maximum occurred were extracted for each system. These are plotted as a function of system mass in Fig. 3. For sufficiently massive systems, it is expected that the number of IMFs emitted should be proportional to the total combined mass. The maximum number of IMFs certainly increases with system mass (solid squares in bottom panel), but does not vary linearly with the mass, presumably due to surface and Coulomb effects. It appears to increase as a power of the total mass, $A^{0.7}$. An extrapolation of our results seems to limit the average maximum number of IMFs emitted per event for the heaviest systems to about 8. This nonlinear variation of peak $\langle N_{IMF}\rangle$ with system mass is also supported by percolation calculations (open circles).

The energy for the emission of maximum number of IMFs per event is shown in Fig. 3 (top panel). The energy increases by $\sim 50\%$ when the system mass is doubled. This phenomenon, requiring a much higher energy for the emission of IMFs to peak in heavier systems, is unexpected. Our raw percolation simulations did not show any significant dependence of the energy for peak IMF emission on system mass. However, after accounting for detector acceptance, a very slight increase of this energy with system mass is observed (especially for the largest system), but the effect is not as strong as in the experimental data.

In conclusion, we have made a systematic study of the IMF multiplicity as a function of both beam energy and system mass for central symmetric heavy-ion collisions. We have found that the peak in the IMF multiplicity increases with the system mass at a rate which is less than linear. In addition, we have found that the energy for peak IMF emission increases linearly with the system mass. The percolation model qualitatively reproduces the features of the data, but the dependence on the system mass is weaker. It might be interesting to compare dynamical calculations with our data in order to understand the role of effects such as radial flow in these studies.

This work has been supported by the U.S. National Science Foundation under Grants No. PHY 9971836 (UM-Dearborn) and PHY 9528844 (NSCL).

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