Thermally-induced expansion in the 8 GeV/c $\pi^-$ + $^{197}$Au reaction.

T. Lefort$^1$, L. Beaulieu$^1$, A. Botvina$^2$, D. Durand$^3$, K. Kwiatkowski$^4$, W.-c. Hsi,$^4$ L. Pienkowski$^4$, B. Back$^5$, H. Breuer$^6$, S. Gushue$^7$, R.G. Korteling$^8$, R. Laforest$^9$, E. Martin$^9$, E. Ramakrishnan$^9$, L.P. Remsberg$^7$, D. Rowland$^9$, A. Ruangma$^9$, V.E. Viola$^1$, E. Winchester$^9$, S.J. Yennello$^9$

$^1$Department of Chemistry and IUCF, Indiana University Bloomington, IN 47405
$^2$Institute for Nuclear Research, Russian Academy of Science, 117312 Moscow, Russia.
$^3$LPC de Caen, 6 Boulevard Marechal Juin, 14050 CAEN, France.
$^4$Heavy Ion Laboratory, Warsaw University, 02 097 Warsaw Poland.
$^5$Physics Division, Argonne National Laboratory, 9700 S. Cass Ave., Argonne, IL 60439.
$^6$Department of Physics, University of Maryland, College Park, MD 20742.
$^7$Chemistry Division, Brookhaven National Laboratory, Upton, NY 11973.
$^8$Department of Chemistry, Simon Fraser University, Burnaby, B.C., V5A 1S6 Canada.
$^9$Department of Chemistry and Cyclotron Laboratory, Texas A&M University, College Station, TX 77843, USA.

Abstract

Fragment kinetic energy spectra for reactions induced by 8.0 GeV/c $\pi^-$ beams incident on a $^{197}$Au target have been analyzed in order to deduce the possible existence and influence of thermal expansion. The average fragment kinetic energies are observed to increase systematically with fragment charge but are nearly independent of excitation energy. Comparison of the data with statistical multifragmentation models indicates the onset of extra collective thermal expansion near an excitation energy of $E^*/A \approx 5$ MeV. However, this effect is weak relative to the radial expansion observed in heavy-ion-induced reactions, consistent with the interpretation that the latter expansion may be driven primarily by dynamical effects such as compression/decompression.

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*Present address: Physics Division, Los Alamos National Laboratory, Los Alamos, NM 87545.
†Present address: 7745 Lake Street, Morton Grove IL 60053.
‡Present address: Washington University Medical School, 510 Kingshighway, St. Louis MO 63110.
The origin of the multifragmentation process [1], and its link to a nuclear liquid-gas phase transition in finite systems [2], is one of the most interesting and debated questions in the field of many-body nuclear dynamics. Is the fragmentation process thermally driven, initiated by an early compressional stage, or simply induced by mechanical or shape instabilities? The observation of collective expansion energy at the end of the reaction may help to shed some light on the origin of the process.

The expansion of hot nuclear matter is usually attributed to either an internal thermal pressure [3] or the response to an initial compression produced at the beginning the reaction [4]. Two stages of the expansion can be schematically defined. The first drives the nucleus up to the freezeout configuration, in competition with the restraining nuclear force. A possible second stage corresponds to an extra residual expansion energy (or radial flow) that exceeds the minimum required to reach freezeout. The collective expansion energy is proportional to the masses of the emitted particles.

The onset of extra expansion energy has been observed in heavy-ion collisions near 5-7 A MeV of available center-of-mass energy for fusion-like events ($A_{\text{tot}} > 250$) [5]. In a subsequent analysis, Bougault et al [6] showed that a pure thermal extra expansion energy, simulated with the Expanding-Evaporating Source model (EES) [7], accounts for only a small part of the measured extra expansion energy. On this basis and supported with BNV calculations, they attributed the extra expansion energy observed in their data to an early compressional stage in the collision. Thus, one can link the multifragmentation energy threshold ($\approx 5$ AMeV) to the onset of collective extra expansion energy initiated by a compressional phase [5]. In this paper, we address the possible existence of thermally-induced extra expansion energy [3] and its link to the thermal multifragmentation process.

The existence of a thermally-induced extra collective expansion is an open question. The EOS collaboration found a large amount of collective expansion, up to 50% of the total available energy, in their study of $^{197}$Au + $^{12}$C reaction at 1 A GeV [8]. On the other hand, the collective expansion observed in the spectator study of the ALADIN group is moderate [9]. In both cases, the excitation energy of the projectile should be mainly thermal, as for light-ion-induced collisions. Since the presence of collective expansion at high excitation energy may affect the isotope thermometer accuracy and hence the caloric curve shape [2], it is important to determine the extent of collective expansion in these reactions.

The advantage of using light-ion-induced collisions stems from the nature of the deposited energy in the target nucleus: the contribution of compression, angular momentum and deformation is weak and the main part of the deposited energy is thermal [10,11]. Previous studies [12] have shown that light projectiles can deposit excitation energies up to $E^*/A \approx 9$ MeV in a gold target nucleus, well above the energy threshold for multifragmentation. Thus, light-ion-induced collisions offer a powerful tool for studying the relationship between multifragmentation and collective thermal expansion.

In this letter we study fragment kinetic energy observables for the 8 GeV/c $\pi^-$ + $^{197}$Au reaction. The data are compared with different statistical models: SIMON [13] and SMM (Statistical Multifragmenting Model) [14,15], as well as with data from heavy-ion reactions. The analysis is based on experiment E900a performed at the Brookhaven AGS accelerator with tagged beams of 8 GeV/c $\pi^-$ + $^{197}$Au using the Indiana Silicon Sphere (ISiS), a 4$\pi$ detector array with 162 gas-ion-chamber/silicon/CsI telescopes [16]. Further experimental details can be found in [17].
In light-ion-induced collisions the emission spectra can be described with two components: an early pre-equilibrium emission stage that is forward-focused along the beam axis (mainly composed of energetic light charged particles) and isotropic emission from a slowly moving equilibrium-like residual source. Thermal-like charged particles are defined by the spectral shapes, from which an upper cutoff of 30 MeV for Z=1 and 9Z+40 MeV for heavier fragments is assigned [18]. The pre-equilibrium-like particles emitted above the cutoff energy are removed. Then the charge, mass and excitation energy of the equilibrated residual source are determined via event-by-event reconstruction [12,17,18]. The amount of pre-equilibrium emission increases with the excitation energy leading to a decrease of the equilibrated source average mass and charge, from \(<Z> = 76, <A> = 188\) at \(E^*/A = 1\) MeV to \(<Z> = 56, <A> = 138\) at \(E^*/A = 9\) MeV [12].

In [19,4] the shape transition of the charge distribution, from a power-law behavior to an exponential-like pattern, has been observed in coincidence with an extra collective expansion energy. Since collective expansion may shorten the time for fragment formation, this transition has been interpreted as a sign of the expansion energy presence. For the 8 GeV/c \(\pi^-\)\(^{197}\)Au reactions, a power law is able to reproduce the charge distribution of the equilibrated component [14], nonetheless, above \(E^*/A = 7\) MeV, an exponential fit provides a better result. The exponential pattern is also observed with a pure statistical scenario [15] and is enhanced by secondary decay [20]. Therefore, it is necessary to investigate other observables such as fragment kinetic energies in order to point out the existence of collective expansion.

In figure 1 the angle-integrated kinetic energy spectra for carbon nuclei (representative for all fragment spectra) are shown for three excitation energy bins. The energy of the Coulomb-like peak decreases with increasing excitation energy in agreement with the measured decrease of the source size (see above) and consistent with the onset of expanded nuclei. On the other hand the spectral slope increases with excitation energy. No evidence for a strong deformation of the spectra induced by a collective expansion is noticed, as was reported for heavy-ion-induced reactions in [21].

The mean kinetic energy of fragments as a function of their mass (charge) is also an indicator of the presence of collective expansion. One expects no dependence (flat behavior) for a pure thermal process, a slight increase due to Coulomb effects, and a steeper slope when an expansion energy is present. For a constant source size (charge) and density, the fragment mean kinetic energy is also expected to increase as a function of the excitation energy. In figure 2 the mean kinetic energy of fragments is plotted as a function of fragment charge for several excitation energy bins, transformed into the source frame. While the data are found to increase with the charge, little dependence on excitation energy is noticed. The constancy observed as a function of the excitation energy can be interpreted as a balance between the increase in thermal energy and the decrease in Coulomb repulsion of the emitting source (due to lower average source charge and possibly density) with excitation energy, consistent with the evolution of the spectral shapes in figure 1. Finally, it is worth mentioning that residues (if any), which have a lower average kinetic energy [3,22,23], are not identified in ISiS due to threshold effects.

In this letter, we focus on excitation energies above \(E^*/A = 4\) MeV, where one may expect to see evidence for collective expansion [3]. In figure 3 the fragment mean kinetic energies are compared with predictions of SIMON-evaporation [13], SIMON-explosion [13]
and SMM simulations. The inputs of all the model simulations are identical, using the source charge, mass, velocity and excitation energy distributions reconstructed from data. Then the simulations are filtered to take account of the geometry of ISiS, the energy thresholds and the energy lost in the target. In addition, the simulated events have been sorted the same as in the experimental data and the excitation energy recalculated event-by-event. The results are found to be equal to the initial input within 10%, which gives an estimate of the confidence level of the comparison. The procedure was reduced to a single geometrical filter with SIMON-explosion.

The procedure to extract the expansion energy is as follows. First we check to insure that the model reproduces the IMF multiplicity and charge distribution. If so, the thermal and Coulomb energies of fragments are calculated with the model and compared with the data. It may be necessary to add an extra collective energy (proportional to the mass of the emitted fragment) to reproduce the fragment mean kinetic energy. The extra collective energy corresponds to the expansion energy.

Above $E^*/A=3$ MeV, the evaporative model at normal density, SIMON-evaporation, underestimates the IMF ($Z=3-16$) multiplicity (by at least a factor two at $E^*/A=8$ MeV), the mean kinetic energies and produces too few heavy IMFs. This discrepancy confirms that a standard evaporative process is not able to reproduce the IMF multiplicities and the charge distributions at high excitation energy [24], although this is still debated [25]. It is therefore not relevant to use this model to estimate an expansion energy.

Since the time-dependent evaporative model is unable to reproduce the data above $E^*/A=3$ MeV, we then examined SMM and SIMON-explosion models, which assume a simultaneous break-up process. For both models the density is first set at one-third of normal density at the freeze-out stage. In our experimental event selection, we assume that the fast emission that takes place before the freeze-out is mainly removed by our cutoff energy defined above. Therefore, the experimental excitation energy determined within the energy cutoff is used as the source of thermal excitation energy at freeze-out for both models.

In order to contrast between a picture in which the fragments are emitted cold and one where they are excited, we employ SIMON-explosion to investigate the former case and SMM for the latter. In the cold fragment scenario, instead of feeding SIMON-explosion with a charge distribution of hot fragments that undergo secondary decay to produce the experimental charge distributions, the experimental charge distribution (cold fragments) is used as input. In this context, the IMF multiplicity and the charge distribution are in agreement with the data by definition. Figure 3 shows that this model reproduces the data at $E^*/A=5$ MeV but underpredicts the fragment kinetic energies at higher excitation energies.

Finally, we used SMM in which it is assumed that thermal and collective expansion are unfolded and only the thermal energy is used to generate partitions. The $Z=6-16$ multiplicity and charge distributions are well reproduced above $E^*/A=6$ MeV. For both SMM and SIMON-explosion models, it is necessary to add about 0.5 MeV/A of collective energy for the $E^*/A=6-8$ MeV bin in order to match the experimental mean kinetic energies. For SMM calculations at $\rho_0/3$, good agreement with the kinetic energy spectra is obtained if an additional collective expansion energy is included, as shown by the lines in figure 1. Except for the high kinetic energy tail, the carbon kinetic energy spectra are well reproduced at about 5 A MeV with no expansion energy (solid line) and with an added 0.5 A MeV (dashed line) for the $E^*/A=6-9$ MeV bin.
As shown in figure [1] the amount of extra collective expansion energy is low and therefore highly dependent on the Coulomb energy in the simulations, i.e. the source volume or density. In order to investigate the density dependence of the procedure used to extract the collective expansion, we have performed SMM calculations in which the density value is varied. The IMF multiplicity and the charge distribution predicted by SMM are in good agreement with such data for density values between $\rho_0/3$ and $\rho_0/2$. The two calculations, $\rho_0/3$ and $\rho_0/2$ correspond, respectively, to the upper and the lower limit of the shaded zone in the lower panel of figure [1]. Even at a higher density, an additional collective energy is necessary to match the fragment mean kinetic energy. The onset of the extra collective energy occurs at about $E^*/A=5$ MeV and increases with the excitation energy. This behavior is consistent with an increasing thermal pressure inside the nucleus as a function of the excitation energy.

The upper panel of figure [4] shows the IMF emission probability as a function of the excitation energy. Below excitation energy of about $E^*/A=4$ MeV the light charged particle emission is the prominent decay channel. At higher excitation energy, emission with one or more IMFs takes over. The onset of multiple IMF emission occurs in the same excitation energy range as that for the onset of the thermal expansion energy. The similarity underlines the possible link between expansion energy and multiple fragment emission probability.

Finally, a comparison with heavy-ion collisions is also made in the lower panel of figure [4]. This comparison has been limited to systems with a well defined fusion source in order to avoid any problem of source separation present in the main part of the impact-parameter range. In addition, we only refer to studies performed in comparison with SMM [20,26,27]. The collective energy is expressed as a function of the freeze-out excitation energy (SMM input) instead of the available energy per nucleon used in [5]. In contrast with the small amount of thermal expansion energy found in ISiS collisions, in central heavy-ion collisions, the rise is much larger, as shown by the symbols and the two lines in figure [4] which correspond to different assumptions for extracting the collective expansion [20,26,27]. This behavior indicates that the collective expansion observed in central heavy-ion collisions cannot be explained with only a thermal component and supports the concept of an early compressional stage in central heavy-ion collisions that is not present in light-ion induced collisions.

In conclusion, a study of the fragment kinetic energies has been performed for the 8 GeV/c $\pi^- + {}^{197}$Au reactions. The sequential simulation at normal density, SIMON-evaporation, failed to reproduce the data above $E^*/A=4$ MeV of excitation energy. For the two simultaneous models, SMM and SIMON-explosion, the fragment mean kinetic energies are well reproduced if an extra collective expansion energy is added at high excitation energy. Within the context of the SMM calculation, the onset of this collective expansion energy takes place at about $E^*/A=5$ MeV of excitation energy. The expansion energy increases slightly with the excitation energy, consistent with a thermally-induced expansion scenario. This observation, consistent with a soft explosion, also suggests that the nucleus is a dilute system at the break-up stage. Multiple IMF production takes place in the same excitation energy range, underlining the possible relationship between enhanced IMF emission and expanded nuclei. Nonetheless, the thermal expansion energy is weak and much lower than that observed in central heavy ion collisions within the same excitation energy range. Therefore, the main part of expansion energy observed in central heavy-ion collisions at intermediate energies must be related to a dynamical stage (initial compression ?) that does not exist in light-ion induced collisions.
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FIG. 1. Angle-integrated kinetic energy spectra of carbon nuclei in the laboratory system for three bins of excitation energy, as indicated at the top of the figure. The lines correspond to SMM calculations \((\rho_0/3)\) with extra collective expansion energy, respectively, equal to 0 (solid line) and 0.5 A MeV (dashed line). For each bin in excitation energy, the simulated spectrum is normalized to the maximum of the experimental one.
FIG. 2. Fragment mean kinetic energy as a function of charge calculated in the source frame for 4 bins of excitation energy, as indicated on figure.
FIG. 3. Comparison between experimental and simulated fragment mean kinetic energies calculated for two bins in excitation energy. In each panel, data are shown with open and solid circles and simulations with dashed and plain lines. The corresponding bins of excitation energy are indicated on the figure. SMM and SIMON-explosion calculations have been performed without additional expansion energy.
FIG. 4. Upper panel: IMF emission probability as a function of the excitation energy. Lower panel: Comparison between central heavy-ion collisions and 8 GeV/c $\pi^- + ^{197}$Au reactions. The shaded area corresponds to the ISiS expansion energies extracted with SMM at $\rho_0/3$ (upper limit) and $\rho_0/2$ (lower limit). The dashed and plain lines set the boundaries of expansion energies extracted in central heavy-ion collisions with different assumptions regarding the source characteristics. See [5,20,26] for more details.