NONEQUILIBRIUM FEATURES OF THE NUCLEAR LIQUID-GAS PHASE TRANSITION***

B. Zwieglinski[g] for the ALADIN Collaboration:
T. Odeh[a], C. Gross[a], C. Schwarz[a], R. Bassini[b],
M. Begemann-Blaich[a], T. Blaich[a], H. Emling[a],
A. Ferrero[b], S. Fritz[a], S.J. Gaff[h], G. Immé[c],
I. Iori[b], U. Kleinevoss[a], G.J. Kunde[h], W.D. Kunze[d],
V. Lindenstruth[a], U. Lynen[a], M. Mahi[a], A. Moroni[b],
T. Möhlenkamp[e], W.F.J. Müller[a], B. Ocker[a],
J. Pochodzalla[f], G. Raciti[c], Th. Rubehn[a], H. Sann[a],
M. Schnittker[a], A. Schüttauf[d], W. Seidel[e],
V. Serfling[a], J. Stroth[a], W. Trautmann[a],
A. Trzcinski[g], G. Verde[c], A. Wörner[a], H. Xi[a],
and E. Zude[a]

[a] Gesellschaft für Schwerionenforschung, D-64220 Darmstadt 11, Germany
[b] Dipartimento di Fisica, Università di Milano and I.N.F.N., I-20133 Milano, Italy
[c] Dipartimento di Fisica dell'Università and I.N.F.N., I-95129 Catania, Italy
[d] Institut für Kernphysik, Universität Frankfurt, D-60486 Frankfurt, Germany
[e] Forschungszentrum Rossendorf, D-1314 Dresden, Germany
[f] Max-Planck Institut für Kernphysik, D-69029 Heidelberg, Germany
[g] Soltan Institute for Nuclear Studies, 00-681 Warsaw, Hoża 69, Poland
[h] NSCL, Michigan State University, East Lansing, MI 48824, USA

(Received December 2, 1998)

Energy spectra of protons emitted by the target residue in Au + Au collisions at 1 GeV/u were measured for different excitation energy bins. They reveal two components with different slopes attributed to preequilibrium and equilibrium emission. The relative contribution of the latter decreases rapidly with excitation energy, so that its presence becomes not apparent for the highest energy bins. It is argued therefore, that equilibrium may not be reached on the gas branch of the caloric curve.

PACS numbers: 25.70.Pq

* Presented at the XXXIII Zakopane School of Physics, Zakopane, Poland, September 1–9, 1998.

** This work was supported in part by the European Community under contract ERBFMGECT950083 and by the BMBF (Bonn) — KBN (Warsaw) Collaborative Agreement in Science and Technology under contract POL-196-96.

There is an increasing amount of evidence [1,2] that multifragmentation (MF) in peripheral to semicentral relativistic heavy-ion collisions is a three-stage process. A residue with an average excitation energy $\langle E_0 \rangle$ and mass number $\langle A_0 \rangle$ is formed in the initial contact stage of projectile-target interaction. A fraction of $\langle E_0 \rangle$ and $\langle A_0 \rangle$ are then removed in the second stage by light-particle (LP; $A = 1 \div 4$) emission. A breakup into intermediate-mass fragments and LP's occurring on a short-time scale terminates the third stage and the residue's history. The applicability of thermodynamical concepts, such as liquid-gas phase transition, to MF requires that the residue is in thermal and chemical equilibrium at the instant of its disassembly. Implicit to this requirement is an assumption that the residue's lifetime, throughout which the constituent nucleons form a self-bound system, is sufficient for equilibration to occur.

In the present contribution we examine the validity of this assumption in the three domains of residue excitation energy per nucleon $\langle E_0 \rangle / \langle A_0 \rangle$, corresponding to the liquid ($\langle E_0 \rangle / \langle A_0 \rangle \leq 3$ MeV), liquid-gas coexistence ($3 \leq \langle E_0 \rangle / \langle A_0 \rangle \leq 10$ MeV), and the gas ($\langle E_0 \rangle / \langle A_0 \rangle \geq 10$ MeV) branches of the caloric curve [3]. The notion of a self-bound system is particularly difficult to reconcile with the residue decaying predominantly into LP's, the situation encountered at excitation energies corresponding to the gas branch of the caloric curve.

The spectra of LP's used to draw the conclusions presented below originate from the decays of target residues excited in ^{197}Au + ^{197}Au collisions at 1 GeV/u. They have been measured at $\theta_{\rm lab}$=150° to the beam direction for different excitation energy bins quantified with the aid of $Z_{\rm bound}=\Sigma_i Z_i$ value, where the sum extends over atomic numbers Z_i ($Z_i \geq 2$) of the products of projectile fragmentation, simultaneously detected with the ALADIN forward spectrometer [2]. Symmetry of the system with respect to the impact parameter, stemming from identity of the colliding nuclei permits to assume that excitation energies of both the target and projectile are equal on the average.

A comparison of the measured LP spectra with predictions of the Copenhagen–Moscow Statistical Multifragmentation Model (SMM) [4] revealed systematically increasing deviations from the model spectra with decreasing $Z_{\rm bound}$, *i.e.* increasing excitation energy of the residue and with decreasing particle mass [2]. These trends suggested that surplus of LP yield over the equilibrium SMM reference originates from the second (prebreakup) stage due to preequilibrium emission processes. A conclusion on their importance in ^{197}Au + C collisions at 1 GeV/u was previously reached [1] based on the presence of two distinct components of proton distributions in the transverse momentum (p_t)-rapidity plane, with the preequilibrium one extending towards much larger p_t.

Here we follow an approach alternative to [2]. The spectra of protons $\sigma_{\rm ex}(E_p)$ (see Fig. 1, left panel, open points) are fitted with a sum of two Maxwell-Boltzmann distributions with different slopes, typified by the inverse-slope parameters, $T_{\rm slope}$. An advantage of this procedure is the precise quantitative determination of the relative contributions of both components to the measured spectra. The low temperature component $\sigma_{\rm lo}$, corresponding to the equilibrium proton emission, is indicated with the dotted line, while the high temperature component $\sigma_{\rm hi}$, corresponding to the preequilibrium one, with the dashed line for the spectrum in bin $70 \leq Z_{\rm bound} \leq 80$. Solid lines represent their sum for this and the remaining $Z_{\rm bound}$ bins in Fig. 1. The total yields $Y_{\rm lo,hi}$, discussed below, result from integration of $\sigma_{\rm lo,hi}(E_p)$ over E_p. The three panels on the right-hand side of Fig. 1 sum-

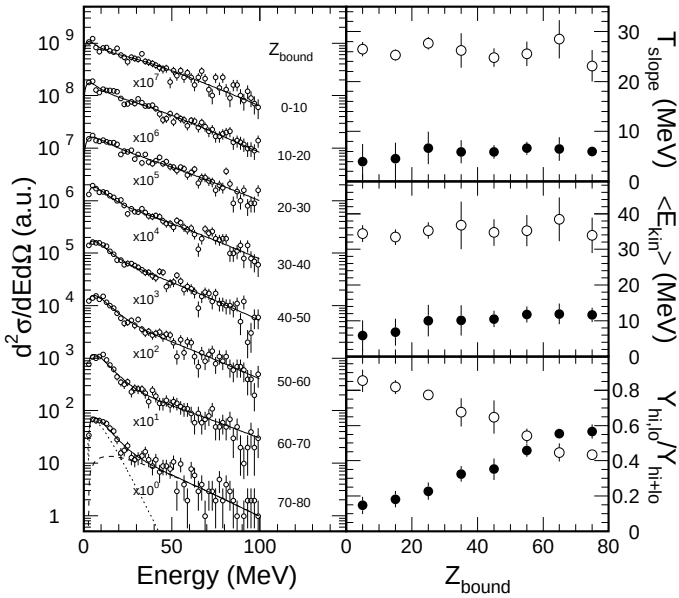

Fig. 1. Energy spectra of protons for different $Z_{\rm bound}$ bins (left panel) and temperatures, mean kinetic energies and yield ratios (right panels).

marize the parameters derived from the fits for the low- (solid points) and high-temperature (open points) components, respectively. The temperature parameters $T_{\rm slope}$ (upper panel) change very little with $Z_{\rm bound}$, while the relative intensity of the low-temperature component $Y_{\rm lo}/Y_{\rm hi+lo}$ (lower panel) decreases rapidly with decreasing $Z_{\rm bound}$, to become hardly discernible in the experimental spectra with $Z_{\rm bound} \leq 30$. The average mass number $\langle A_0 \rangle$ of a residue with which one deals for $0 \leq Z_{\rm bound} \leq 10$ is about 40 and the average excitation energy per nucleon therein $\langle E_0 \rangle / \langle A_0 \rangle \approx 24$ MeV [5, 6].

The latter exceeds substantially the maximum energy $\langle E_0\rangle/\langle A_0\rangle \approx 16$ MeV attained in [3] at the lower projectile energy of 600 MeV/u, thus extending the gas branch of the caloric curve towards higher excitation energies. The magnitude of the fitted ratio $Y_{\rm lo}/Y_{\rm hi+lo}$ at these low $Z_{\rm bound}$ values, where the signature of the evaporative events gradually disappears, critically depends on the assumed shape of $\sigma_{\rm hi}(E_p)$ at low E_p. In order to keep at minimum the number of free parameters in the fit, we have assumed that the latter is governed by the Coulomb barrier of the same height as the one for $\sigma_{\rm lo}(E_p)$. With this assumption we get approximately fourfold decrease of $Y_{\rm lo}/Y_{\rm hi+lo}$ (see the lower panel on the right-hand side of Fig. 1) from ≈ 0.6 for $70 \leq Z_{\rm bound} \leq 80$ to ≈ 0.15 for $0 \leq Z_{\rm bound} \leq 10$. This apparently does not contradict an equilibrium emission from the above source with $\langle A_0\rangle \approx 40$, containing about four times less protons than the target nucleus ^{197}Au. Such an interpretation for the decrease of the evaporative proton yield is offered by SMM [2, 6]. However, the effect of the Coulomb barrier may well be attenuated in the preequilibrium processes, because of their direct nature. These will allow protons to be emitted into the sub-Coulomb region, thus leaving less or no room in the fit for $\sigma_{\rm lo}(E_p)$ at low E_p.

A disappearance of the evaporative component from the proton spectra may indicate, therefore, that the residue lifetime becomes too short to reach thermalization as soon as some limiting excitation energy within the gas phase of the caloric curve is exceeded. This might be a natural consequence of disappearance of a multifragmentation barrier, created at lower excitation energies by the attractive interfragment interactions. Duration of the contact and preequilibrium stages is ≈ 50 fm/c according to different dynamical calculations, among which Ref. [7] is a representative example. We conclude therefore that above this critical energy the created systems disassemble on a shorted time scale.

In conclusion, the proton spectra emitted by the target residue in Au + Au collisions at 1 GeV/u show two components with different slopes, supporting the idea that multifragmentation proceeds in three stages at excitations covering the liquid and liquid-gas coexistence branches of the caloric curve. The observed trend of decreasing relative contribution of the evaporative component with increasing excitation energy can be understood as a consequence of decreasing size of the thermalized residue. Its disappearance above $\langle E_0\rangle/\langle A_0\rangle \approx 15$ MeV presents an alternative - either its magnitude becomes too small to be resolved from the increasing preequilibrium component or the residue lifetime becomes too short to achieve thermalization. A similar study of neutrons should shed more light on this question.

REFERENCES

[1] J.A. Hauger *et al., Phys. Rev. Lett.* **77**, 235 (1996);
J.A. Hauger *et al., Phys. Rev.* **C57**, 764 (1998).

[2] Hongfei Xi *et al., Z. Phys.* **A359**, 397 (1997).

[3] J. Pochodzalla *et al., Phys. Rev. Lett.* **75**, 1040 (1995).

[4] J.P. Bondorf, A.S. Botvina, A.S. Iljinov, I.N. Mishustin, K. Sneppen, *Phys. Rep.* **257**, 133 (1995).

[5] U. Lynen *et al., Nucl. Phys.* **A630**, 176c (1998).

[6] T. Odeh, *PhD Thesis*, Universität Frankfurt, (1998), in preparation.

[7] H.W. Barz *et al., Nucl. Phys.* **A561**, 466 (1993).