THERMODYNAMIC OBSERVABLES IN GOLD ON GOLD COLLISIONS

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Thermodynamic observables characterizing the breakup states of spectator decays in ^{197}Au + ^{197}Au collisions at relativistic bombarding energies were deduced from data collected with the ALADIN spectrometer at SIS. The interferometry with light charged particles confirms the low density of the breakup configuration. Temperatures deduced from the new isotope thermometer T_{BeLi} exhibit a pronounced rise at high excitation energy and are consistent with the previously studied T_{HeLi}. The determination of the excitation energy at breakup with calorimetric methods is difficult because of non-equilibrium contributions to the kinetic energies of nucleons and fragments.

1 Introduction

Thermodynamic quantities such as temperature, density or pressure are commonly used to describe energetic heavy-ion collisions and they serve as principal parameters in statistical models for such collisions. The models can also provide us with realistic ideas of what values these parameters should assume. Attempts to directly measure thermodynamic variables by reconstructing them from the properties of the final decay products are based on the assumption of an equilibrated breakup state. [1,2,3] It is the temperature or density reached at this particular stage of the collision that one can hope to observe. If the reaction parameters are varied the breakup conditions may change, thereby describing a characteristic trajectory in the multidimensional parameter space. The caloric curve is an example for a trajectory in the space of temperature versus excitation energy. [4,5]

Multifragmentation reactions are of particular interest as they are expected to provide access to the region of high excitation and low density, conditions that are similar to those predicted for the liquid-gas coexistence region in the nuclear matter phase diagram. [6] For spectator reactions leading to multifragmentation, it has furthermore been shown that the degree of equilibrium at breakup is high and that the memory of the entrance channel is largely lost. [7]

In this talk new results will be reviewed that have recently been obtained in studies of spectator decays at relativistic energies conducted at SIS. The methods will be presented and, in particular, it will be discussed how the

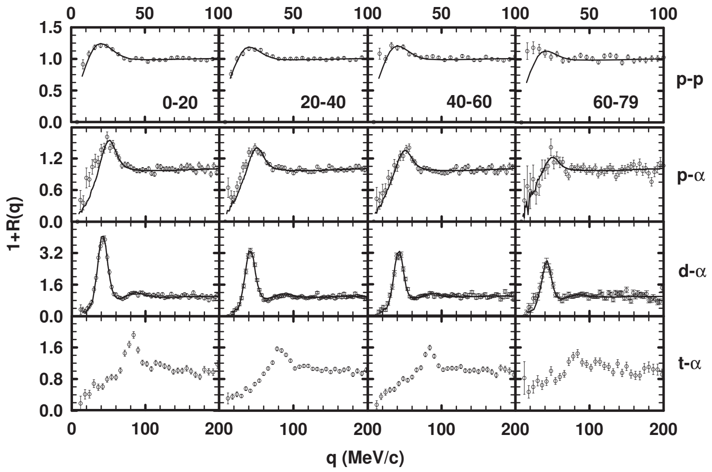

Figure 1. Correlation functions constructed from p-p, p-^{4}He, d-^{4}He, and t-^{4}He coincidences (from top to bottom) for spectator decays following ^{197}Au + ^{197}Au collisions at 1000 MeV per nucleon. The data are sorted according to Z_{bound} into four bins with limits given in the top panel of each column. The lines represent the results of the calculations used to extract source radii (see text). Note that the scales of the abscissa are different for the top row (p-p correlations) and for the remaining three rows of panels (from Ref.[8]).

directly determined quantities compare with the parameters of the statistical multifragmentation model.

The data were obtained in two recent experiments with the ALADIN spectrometer in which collisions of ^{197}Au on ^{197}Au at bombarding energies up to 1 GeV per nucleon were studied. In one experiment, the spectrometer was used to detect and identify the products of the projectile-spectator decay. The Large-Area Neutron Detector (LAND) served to measure coincident free neutrons emitted by the projectile source. In the other experiment, the target-spectator decay was studied at backward angles with three multi-detector hodoscopes and with three high-resolution telescopes, used to measure the yields and correlations of isotopically resolved light charged particles and fragments.

2 Densities from Interferometry

For the measurement of the density, correlation techniques were applied to high-statistics coincidence data, collected with the hodoscopes for ^{197}Au on ^{197}Au at 1000 MeV per nucleon. [8] Examples of correlation functions con-

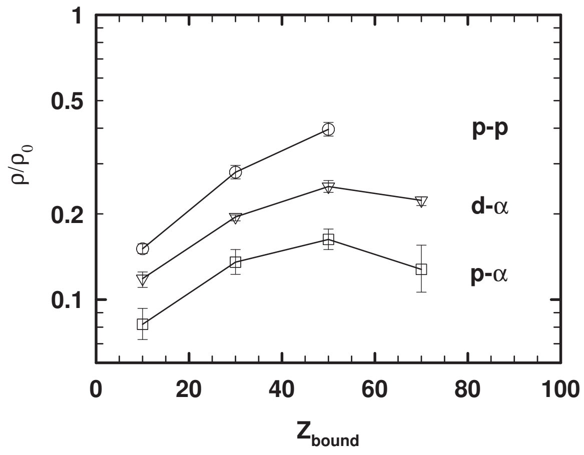

Figure 2. Breakup density ρ/ρ_0 as deduced from p-p, p-^{4}He, and d-^{4}He correlation functions for ^{197}Au + ^{197}Au collisions at 1000 MeV per nucleon. The error bars represent the statistical uncertainty (from Ref.[8]).

structed from proton-proton coincidences and from coincidences of protons, deuterons and tritons with α particles are shown in Fig. 1. The data are sorted into four bins of Z_{bound}, where Z_{bound} is defined as the sum of the atomic numbers Z_i of all projectile fragments with $Z_i \geq 2$. Z_{bound} is close to the total charge of the original spectator system and it is correlated with the impact parameter of the reaction.

The analysis of the p-p correlation functions was performed with the Koonin-Pratt formalism, [9] while for the p-α and d-α correlations the numerical results of Boal and Shillcock were used. [10] Radii were deduced in the limit of zero-lifetime for the source, and densities were calculated by dividing the number of spectator constituents (from Refs. [4,11]) by the source volume. As expected from the Z_{bound} invariance of the correlation functions, the radii change vary little with centrality. The derived densities, on the other hand, vary considerably with impact parameter, roughly in proportion to the variation of the spectator mass (Fig. 2). In the p-p case, the mean relative densities decrease from $\rho/\rho_0 = 0.4$ for the near-peripheral to below $\rho/\rho_0 = 0.2$ for the most central collisions. These values compare well with the densities assumed in the statistical multifragmentation models. [1,2] The differences between the p-p results and those from the resonances involving α particles are statistically significant. They may be partially due to the different formalisms that

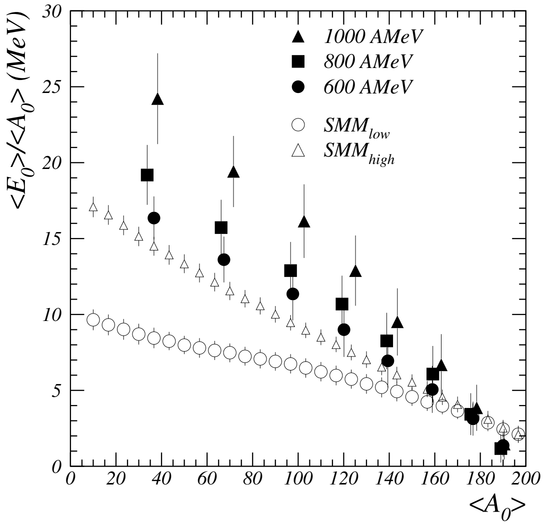

Figure 3. Mean excitation energy per nucleon $\langle E_0 \rangle / \langle A_0 \rangle$ as a function of the spectator mass $\langle A_0 \rangle$ for the reaction ^{197}Au + ^{197}Au at three bombarding energies as indicated. The open symbols denote the upper and lower limit of the mean excitation energy that may be derived from analyses with the statistical multifragmentation model (from Ref.[11]).

were used but their origin, at present, is not fully clear. [8]

3 Excitation energy from calorimetry

The determination of excitation energies and masses is based on the idea of calorimetry which requires a complete knowledge of all decay products, including their atomic numbers, masses, and kinetic energies. [12] This is difficult to achieve on an event-by-event basis, and some of the input data are only bin-wise available or based on assumptions.

The latest evaluation of the excitation energy for ^{197}Au on ^{197}Au collisions included the measured fragment and neutron data for three bombarding energies and the data for hydrogen emission from the target spectator at 1000 MeV per nucleon. [11] The spectator masses are the same for the three energies and were found to be in excellent agreement with the prediction of the geometric participant-spectator model. [13] The energy residing in the spectator source, however, depends considerably on the bombarding energy (Fig. 3). It

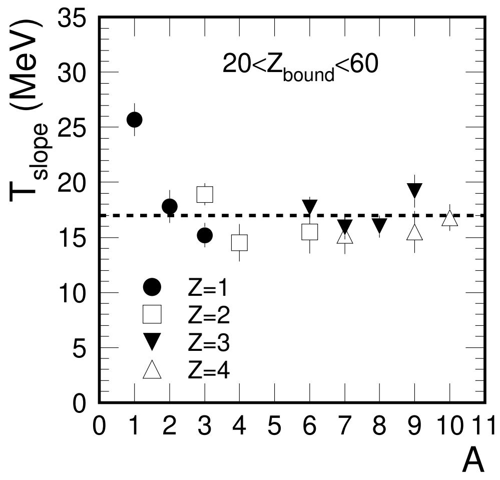

Figure 4. Slope temperatures for isotopically resolved charged particles and fragments with $Z \leq 4$ from the reaction ^{197}Au + ^{197}Au at E/A = 1000 MeV, measured at $\Theta_{lab} = 150°$ and integrated over $20 \leq Z_{bound} \leq 60$, as a function of the mass number A. For protons and α particles the value of the high-temperature component is shown (from Ref.[14]).

increases by about 30% over the range 600 to 1000 MeV per nucleon, a behaviour that is inconsistent with the universality of the spectator decay that so clearly appears in other variables. [7] Technically, this result originates in the energy dependence of the mean kinetic energies of neutrons in the spectator frame. Neutrons have a large influence on the deduced total excitation energy, first, because their multiplicity is large and, second, because the hydrogen isotopes, measured only at 1000 MeV per nucleon, were assumed to behave in a similar way. Model studies have confirmed that nucleons from the initial cascading stages of the collision may appear at spectator rapidities. [14] Their kinetic energies obviously reflect the entrance channel parameters.

For the comparison with the statistical multifragmentation model, the input parameters of the model were varied within the range compatible with the observed partitioning into fragments and light particles. [11,15] The excitation energies obtained in this way are much smaller than the measured values (Fig. 3). This is not surprising because, in the model, the equilibration of the kinetic degrees of freedom at the breakup temperature is assumed which, apparently, is not achieved for the nucleons. But also the complex particles and fragments contribute to the excess energy. Their kinetic energy spectra

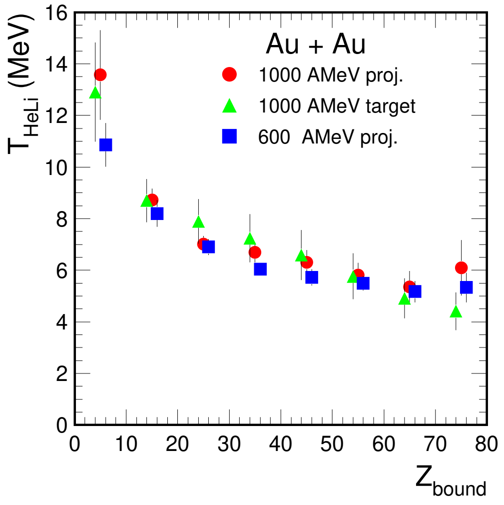

Figure 5. Temperatures T_{HeLi} for target (E/A = 1000 MeV) and projectile spectators (E/A = 600 and 1000 MeV) as a function of Z_{bound}. The data symbols represent averages over bins of 10-units width (from Ref.[14]).

are Maxwellian to a good approximation with slope parameters $T \approx 17$ MeV (Fig. 4) that are invariant with the bombarding energy [7] but much higher than the model predictions. On the other hand, an interpretation following the idea of Goldhaber for fast fragmentation [16] can satisfactorily explain the fragment kinetic energies. [14,17] They seem to be generated by the nucleonic Fermi motion within the spectator system. Calculations based on dynamical reaction models confirm this interpretation. [18,19]

4 Temperatures from Isotope Ratios

In contrast to the slope temperatures derived from kinetic energy spectra (see above) and to excited-state temperatures obtained from populations of particle-unbound states, [20] isotope temperatures seem to well reflect the breakup conditions. In particular, the invariance with respect to the incident energy has been established and a satisfactory agreement with the statistical multifragmentation model has been found. [15]

In Fig. 5 the results for T_{HeLi} in ^{197}Au on ^{197}Au, obtained in three different measurements, are shown as a function of Z_{bound}. T_{HeLi} is deduced

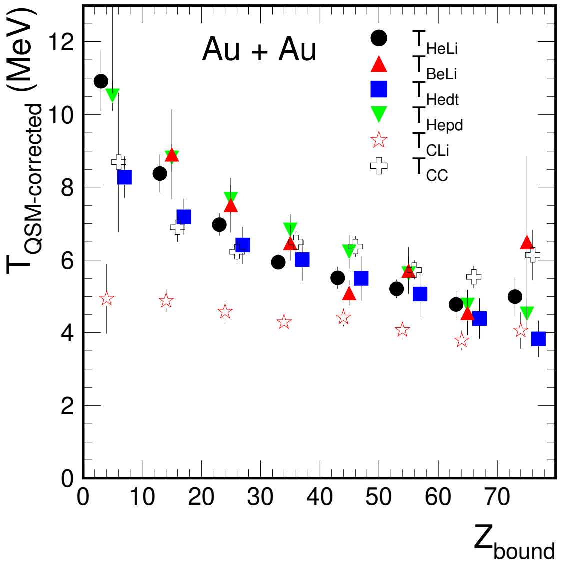

Figure 6. QSM-corrected isotope temperatures for ^{197}Au + ^{197}Au at 600 and 1000 MeV per nucleon as a function of Z_{bound} (from Ref.[14]).

from the yields of ^{3,4}He and ^{6,7}Li isotopes. Integrated yields were measured for the projectile decay where the acceptance of the ALADIN spectrometer provides full solid-angle coverage. Within the errors, good agreement is observed for the two bombarding energies 600 and 1000 MeV per nucleon. For the target spectator, isotopic yields were measured at $\Theta_{lab} = 150°$ with one of the four-element telescopes while Z_{bound} was determined for the coincident projectile decay with the ALADIN time-of-flight wall. The agreement with the measurement for the projectile decay mainly illustrates the experimental accuracy because the collision system is symmetric and large deviations from isotropy are not expected for the isotopic yield ratios.

The thermometry with isotope pairs that include the ^{3,4}He ratio benefits from the large difference of the binding energies of these two nuclei. But there are also other combinations of isotopes that will provide the necessary sensitivity for the measurement of temperatures in the MeV range. [14,21] In Fig. 6, results are given for a variety of isotope thermometers that are all characterized by a double difference of the binding energies $\Delta B > 10$ MeV. Because of the observed invariance (Fig. 5) results obtained at different bombarding energies are combined. All values have been corrected for the effect of secondary decays by using the predictions of the quantum statistical model, [22] calculated for a breakup density $\rho/\rho_0 = 0.3$. [14]

The rise at small Z_{bound}, i.e. high excitation energy, that was first observed with T_{HeLi} is well reproduced with the new observable T_{BeLi}, derived from the ^{7,9}Be and ^{6,8}Li isotope ratios. This demonstrates that the rise is not necessarily related to a particular behaviour of either ^{3}He or ^{4}He. There is overall good agreement between the different temperature observables with the exception of those containing carbon isotopes. In the latter cases, the apparent temperature values, without the correction, remain approximately constant with values between 4 and 5 MeV, a behaviour also seen in other reactions. [23] For T_{CC} (^{11,12}C and ^{12,13}C) a large correction is required according to the calculations which lifts T_{CC} into the range of values assumed by the other temperature observables.

5 Conclusion

The scenario and assumptions entering the statistical multifragmentation models have been largely confirmed by the results of direct measurements of thermodynamic variables. The densities obtained with correlation techniques and the temperatures deduced from isotopic yield ratios are in good agreement with the model predictions. Somewhat surprisingly, the bigger problems are arising for the excitation energy. The calorimetric measurement of the energy residing in the spectator source includes nucleons that originate in the initial cascading stage of the reaction. As long as their contributions cannot be quantitatively identified a universal caloric curve is not in sight. [5]

There is strong evidence in the data for equilibrium at breakup. [24] The corresponding phase space determines the partitioning into fragments and light particles and the statistical multifragmentation models describe this phase space well. The assumption of equilibration of the kinetic degrees of freedom does not seem to be justified for the present case of spectator reactions induced by heavy nuclei. The high values of the slope temperatures of complex particles and fragments are rather understood as reflecting the nucleonic Fermi motion in the equilibrated system prior to its decay. This observation seems to favour a fast fragmentation over an intermediate stage of homogeneous expansion. It is not excluded that this represents a particular property of the type of spectator decays that were the subject of this study and that different conclusions may be reached for other types of reactions. [25] This question is of considerable interest as it is related to the hierarchy of time scales for equilibration and disintegration of highly excited nuclear systems. [26]

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