EQUILIBRATION AND PHASE TRANSITION IN SPECTATOR REACTIONS

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New results are reported from two recent experiments with the ALADIN spectrometer at SIS in which spectator decays following ^{197}Au on ^{197}Au collisions at bombarding energies up to 1 GeV per nucleon were studied. The evidence, obtained from these data, for the existence of an equilibrated breakup-state at low density is discussed. Particular attention is given to the kinetic degrees of freedom, and it is suggested that the slope temperatures derived from the fragment energy spectra may reflect the Fermi motion within the equilibrated spectator system prior to its decay.

1 Introduction

The observation of multifragmentation has given rise to the hope that signals of the predicted liquid-gas phase transition in nuclear matter may be identified in reactions of finite nuclei. Excited spectator systems, produced in reactions at relativistic bombarding energies, are of particular interest here as they seem to pass through highly equilibrated states of high temperature and low density before they decay. These conditions are similar to those expected for the coexistence region in the nuclear-matter phase diagram.

In this talk, the experimental evidence for equilibration at low density in spectator reactions will be reviewed. Temperatures obtained with different methods will be compared and tested for their compatibility with equilibrium at breakup. Particular attention will be given to the longstanding problem presented by the fragment kinetic energies. Their properties indicate equilibrium, however with corresponding temperatures that are much higher than those obtained from observables related to the chemical or thermal degrees of freedom. It will be shown that a consistent interpretation of these observations can be achieved if it is assumed that the fragment kinetic energies reflect the Fermi motion within the equilibrated spectator system prior to its decay.

The data were obtained in two recent experiments with the ALADIN spectrometer at SIS in which reactions of ^{197}Au on ^{197}Au in the regime of relativistic energies up to 1 GeV per nucleon were studied. In the first experiment, the ALADIN spectrometer was used to detect and identify the products of the projectile-spectator decay. The Large-Area Neutron Detector (LAND) was used to measure coincident free neutrons emitted by the projectile source.

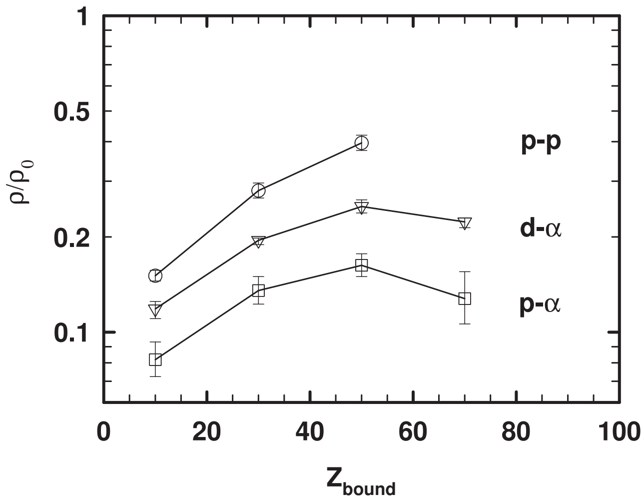

Figure 1. Breakup density ρ/ρ_0 as deduced from p-p, p-^{4}He, and d-^{4}He correlation functions for ^{197}Au + ^{197}Au collisions at 1000 MeV per nucleon. The error bars represent the statistical uncertainty.

In the second experiment, three multi-detector hodoscopes, comprising a total of 216 Si-CsI(Tl) telescopes, and three high-resolution telescopes, each consisting of three Si detectors followed by a 6-cm long CsI(Tl) scintillator, were positioned at backward angles and used to measure the yields and correlations of isotopically resolved light fragments from the target-spectator decay.

2 Density at Breakup

A breakup configuration with low density is one of the basic assumptions made in statistical multifragmentation models. [1,2] It seems supported by the fact that these models successfully reproduce the main features of multi-fragment decays. A direct experimental confirmation has now been obtained from the correlation functions constructed from proton-proton coincidences and from coincidences of protons and deuterons with α particles, measured for ^{197}Au + ^{197}Au collisions at 1000 MeV per nucleon with the multi-detector hodoscopes. [3] The analysis of the p-p correlation functions was performed with the Koonin-Pratt formalism, [4] while for the p-α and d-α correlations the numerical results of Boal and Shillcock were used. [5] 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. [6,7]) by the source volume. The results are shown in Fig. 1, plotted as a function of Z_{bound}. The sorting variable 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 is correlated with the impact parameter of the reaction.

The radii were found to be approximately constant, with values slightly larger than the radius of a gold nucleus, but the derived densities vary considerably with centrality. This is caused by the variation of the spectator masses which, in excellent agreement with the prediction of the geometric participant-spectator model, decrease with increasing centrality nearly in proportion to Z_{bound}. 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 and may be partially due to the different formalisms used. At present, their origin is not yet fully clear.[3]

3 Evidence for Equilibration

The universal features of the spectator decay, as apparent in the observed Z_{bound} scaling of the measured charge correlations, were the first and perhaps most striking indications for equilibrium. [8,9] The invariance of the fragmentation patterns with respect to the parameters of the entrance channel suggests that the memory of the dynamics governing the primary interaction of the colliding nuclei is lost.

Invariance with respect to the bombarding energy has also been established for the breakup temperature T_{HeLi} deduced from the measured ^{3,4}He and ^{6,7}Li isotopic yields. [10] In Fig. 2 the results from three measurements for ^{197}Au on ^{197}Au collisions are shown as a function of Z_{bound}. The acceptance of the ALADIN spectrometer provides full coverage for the projectile decay, and integrated yields were measured. The temperatures obtained at 600 and 1000 MeV per nucleon are found to be the same within the errors. For the target spectator, isotopic yields were measured at $\Theta_{lab} = 150°$ with a four-element telescope while Z_{bound} was determined for the coincident projectile decay with the ALADIN time-of-flight wall. The agreement with the temperatures obtained for the projectile decay at the same energy is expected from the symmetry of the collision and mainly illustrates the accuracy achieved in the experiments.

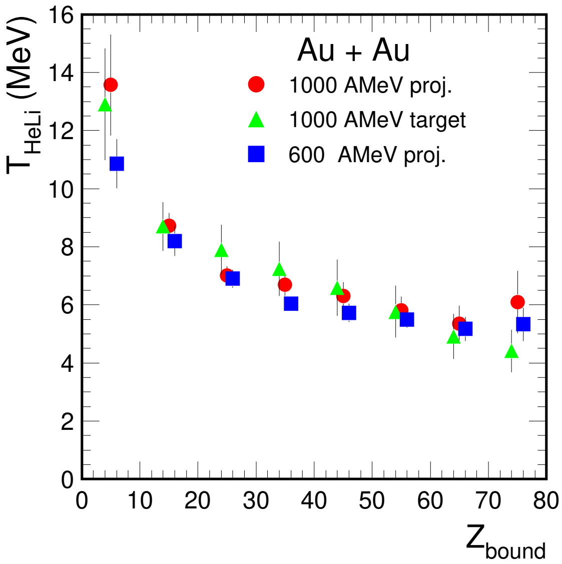

Figure 2. Temperatures T_{HeLi} for target (E/A = 1000 MeV) and projectile spectators ($E/A = 600$ and 1000 MeV) as a function of Z_{bound}. The data symbols represent averages over bins of 10-units width.

The success of the statistical multifragmentation models in describing the observed population of the partition space may be seen as a further argument for equilibration. Here the main task consists of finding an appropriate ensemble of excited nuclei to be subjected to the multi-fragment decay according to the model prescription. With empirically derived ensembles the measured correlations have been reproduced remarkably well, including their dispersions around the mean behaviour. [10,11] In addition, the equilibrium temperature obtained in this way from the model description coincides with the experimentally determined breakup temperature T_{HeLi}. [10]

The emerging picture of a statistical decay of equilibrated breakup configurations appears, at first sight, not to be supported by other temperature observables. The largest discrepancies exist with the slope temperatures, obtained from fitting Maxwellians to the kinetic-energy spectra. They are much higher than the breakup temperatures discussed above. [9,12] This is a long-standing problem and will be addressed, in the light of the new data, in the following sections. Excited-state temperatures, derived from the yields of

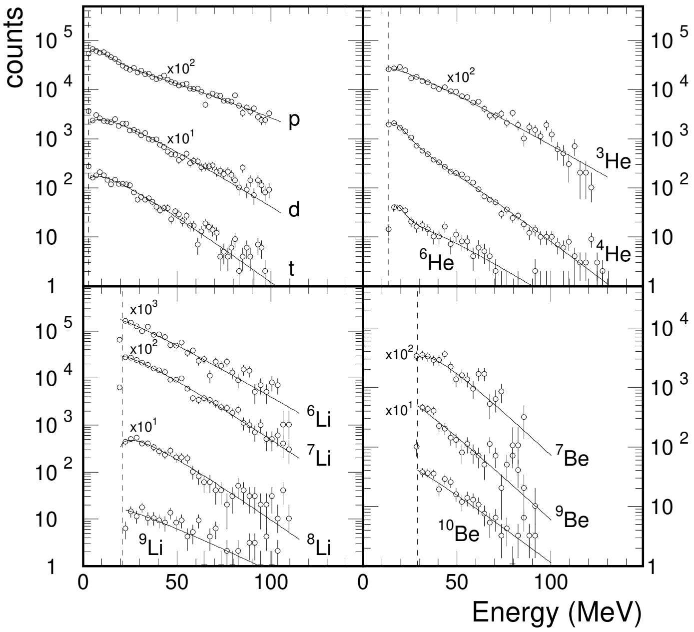

Figure 3. Energy spectra of light charged particles and fragments with $Z \leq 4$ for ^{197}Au + ^{197}Au at 1000 MeV per nucleon, measured at $\theta_{lab} = 150°$ and integrated over $20 \leq Z_{bound} \leq 60$. The full lines represent the fit results, the dashed lines indicate the identification thresholds of the telescope.

particle-unstable resonances, [13,14] are similar to the isotope temperatures for moderate excitations but then saturate at $T \approx 5$ MeV with further increasing excitation energy while the isotope temperatures continue to rise. This has been observed for several heavy-ion collisions, [15,16] including spectator reactions in ^{197}Au on ^{197}Au at 1000 MeV per nucleon. [7] Several mechanisms have been proposed as explanations (see [15] and references therein), and it is worth noticing that none of them questions the basic assumption of equilibrium at breakup. In the case of volume emission, it has to be considered that the resonances used for the temperature evaluation, even after breakup, may still weakly interact with the surrounding nuclear medium. They may not appear with their asymptotic energies and widths before they are released into vacuum. Excited-state temperatures may thus represent the internal fragment temperatures at the very final stages of the fragmentation process.

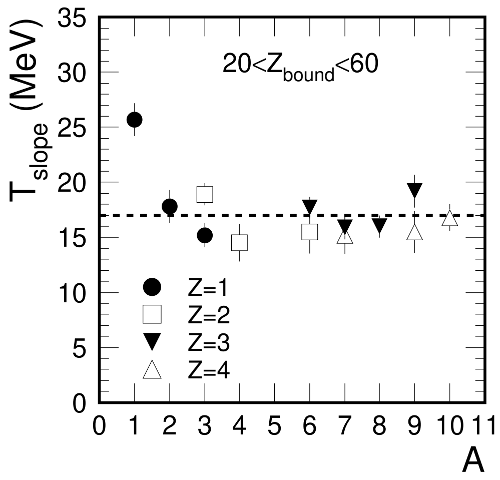

Figure 4. Slope temperatures for isotopically resolved charged particles and fragments with $Z \leq 4$ from the reaction ^{197}Au + ^{197}Au at E/A = 1000 MeV, measured at $\Theta_{lab} = 150°$ and integrated over $20 \leq Z_{bound} \leq 60$, as a function of the mass number A. For protons and α particles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

4 Fragment Kinetic Energies

Energy spectra of light charged particles and fragments were measured with the high resolution telescopes at backward angles. Examples, obtained at $\theta_{lab} = 150°$ and integrated over $20 \leq Z_{bound} \leq 60$, are shown in Fig. 3. Most spectra exhibit Maxwellian shapes to a good approximation. For protons and α particles, two individual components have been identified of which the low-temperature component has a temperature of $T \approx 5$ MeV and an intensity correlated with the production rate of heavy residues, as expected for evaporation.

The slope parameters of the high-temperature components are shown in Fig. 4. The high value observed for protons of $T \approx 26$ MeV is consistent, after Coulomb corrections, with the results obtained with LAND for neutrons from the projectile decay in the same reaction. [7] It is believed to have its origin partly in the initial cascading stages of the collision. For the other species with $A \geq 2$, the spectra exhibit temperatures that are scattering closely around a mean value of 17 MeV (dashed line).

A constant temperature and the corresponding mass invariance of the mean kinetic energies is a very general indication of equilibrium. In the present case, the effects of the mutual Coulomb repulsion after breakup and of the small but finite motion of the target spectator have to be taken into account. This was done in a model study, based on realistic partitions and including many-body Coulomb trajectory calculations, which showed that the two effects are relatively small and, at backward angles, should cancel each other to a very good approximation. [17] The measured slope parameters of $T \approx 17$ MeV (Fig. 4) may thus be directly taken as representing the thermal components of the fragment kinetic energies.

5 Modes of Fragment Formation

It was suggested many years ago by Goldhaber that the large kinetic energies of fast-fragmentation products may have their origin in the nucleonic Fermi motion within the colliding nuclei. [18] He also pointed out that the resulting behavior is indistinguishable from that of a thermalized system with rather high temperature. For the Fermi momentum $p_F \approx 265$ MeV/c of heavier nuclei the corresponding temperature is $T = 15$ MeV. This is very close to the measured slope temperatures $T = 17$ MeV.

Goldhaber's idea, initially formulated for cold nuclei, has been extended to the case of expanded fermionic systems at finite temperatures by Bauer. [19] To use the prescription given there the temperature and density of the system prior to its decay have to be specified. For the temperatures, it was assumed that they are given by the measured breakup temperatures T_{HeLi} (Fig. 2). For the breakup density two values $\rho/\rho_0 = 1.0$ and 0.3 were used which correspond to two significantly different scenarii for the process of fragment production. The higher value is expected for a fast abrasion stage that will induce fragmentation of the remaining spectators but not affect much the nucleon motion within them. The lower value is in the range usually assumed for multi-fragment breakups of expanded systems. Here the development of instabilities, as the system enters the spinodal region, may cause a rapid fragmentation, whereby the Fermi motion of the nucleons may contribute to the fragment kinetic energies. For a homogeneous system at a lower density the Fermi motion is reduced and its effect will be smaller.

The resulting slope temperatures, represented by the lines in Fig. 5, are in the range of the experimental values. They reproduce the rise with decreasing Z_{bound} which follows as a consequence of the rising breakup temperature T_{HeLi}. It also seems that a more quantitative comparison will favor the prediction for $\rho/\rho_0 = 1.0$ and a fast breakup rather than that for $\rho/\rho_0 = 0.3$ and the scenario of homogeneous expansion.

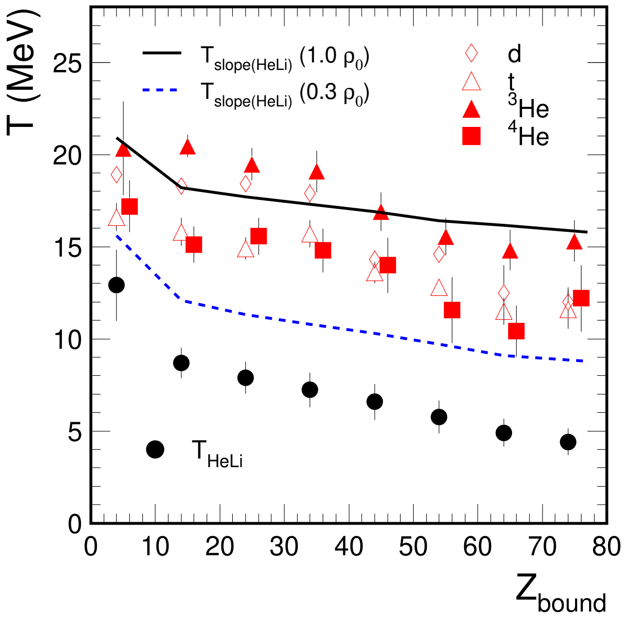

Figure 5. Slope temperatures for light charged particles of mass $2 \leq A \leq 4$ (squares, triangles and diamonds) and the isotope temperature T_{HeLi} (dots) as a function of Z_{bound}. The full and dashed lines are the slope temperatures obtained for the fast breakup of a Fermi gas with finite temperature T_{HeLi} with densities $\rho/\rho_0 = 1.0$ and 0.3.

6 Concluding Remarks

There is strong evidence in the data for the spectator systems' passing through equilibrated breakup states. The corresponding phase space determines the partitioning into fragments and light particles. The mean density is low as assumed in the statistical multifragmentation models which describe this phase space well. The measured breakup temperature T_{HeLi} is in good agreement with the equilibrium temperature of the model.

Corrections to the idealized breakup scenario result from the comparison of the different temperature observables. The temporal evolution of the system is emphasized by the saturation of the excited-state temperatures. The saturation temperatures $T \approx 5$ MeV is similar to the asymptotic temperatures obtained in dynamical models describing the reaction process. [21] The partitioning may be determined at an earlier time, as suggested by quantum or classical molecular dynamics models. [12,20]

The high values of the slope temperatures are quantitatively understood as a result of the Fermi motion of the constituent nucleons in the equilibrated system before its decay, as assumed in the Goldhaber model. This is consistent with a partitioning according to phase space but contradicts the equilibration of the kinetic degrees of freedom after breakup that is assumed in the statistical multifragmentation models.

The present data for the spectator decay in ^{197}Au on ^{197}Au collisions seem to favor a fast fragmentation over an intermediate stage of expansion of a homogeneous system. This may be different for other types of reactions. A comparison of fragment kinetic energies has shown that they may be smaller in reactions induced by light ions of high energy. [22] This question should be further investigated as it is related to the hierarchy of time scales for equilibration and disintegration of highly excited nuclear systems. [23]

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