LAST MINUTE FROM ALADIN:Temperature measurements in Au+Au reactions at relativistic energies[a]

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We report on temperature measurements of nuclear systems formed in the Au+Au collisions at incident energies of 50, 100, 150, 200 and 1000 A MeV.The target spectator matter was studied at the highest energy and the interacting zone (participants) at the lower ones.The temperature deduced from the isotope ratios was compared with the one deduced via the excited states population. An unexpected disagreement was found between the two measurements.

1 Introduction

Previous studies on the systems produced in Au + Au collisions at bombarding energies in the range 100- 1000 A MeV had shown that the decay of excited spectators proceeds independently of the entrance channel dynamics. [1,2,3,4] In addition, strong indications of collective flow [5,6] ,that characterizes the multifragmentation of the participant region, have not been found in the decay of the spectator matter. Therefore, projectile and target spectators, which are produced over a wide range of excitation energy and mass in these reactions, are well suited for the investigation of thermally driven phase transition in highly excited nuclear systems. In particular, the correlation between measured excitation energies of the decaying projectile spectator and emission temperature of the produced fragments ,measured via the double ratios of isotope yields[7], for Au+Au at 600 A MeV of incident energy, allowed us to deduce a caloric curve of nuclei [8]. The observed behaviour of the caloric curve is reminiscent of a first-order phase transition in macroscopic systems. A region of constant temperature of T $\approx$ 5 MeV separates the 'liquid' and 'vapour' regimes where the temperature rises with increasing excitation energy. These data have been subjected to a widespread discussion which addresses both, methodical aspects and questions of interpretation [9,10,11].Therefore, in order to permit a crosscomparison of two different 'thermometers' which is mandatory for a quantitative interpretation of the results, we studied collisions of Au + Au at two regimes of bombarding energies: 1 GeV per nucleon to investigate the spectator decay, and mid-central collisions at 50, 100, 150, and 200 MeV per nucleon to study the decay of the participant region which is known to exhibit a considerable collective flow.In all these studies we measured simultaneously both isotope yields and particle- particle correlations from the decay of unstable states in the emitted fragments. The latter method has been widely used at present to achieve temperature measurements[12,13,14,15,16,17]. One of the goals of the present experiment was to compare the temperature derived applying these two methods to the same class of events of the decay of the same nuclear system.

2 Experimental Apparatus

The experiment was performed at the SIS accelerator of the GSI, using the ALADiN spectrometer facility. A schematic view of the experimental setup is shown

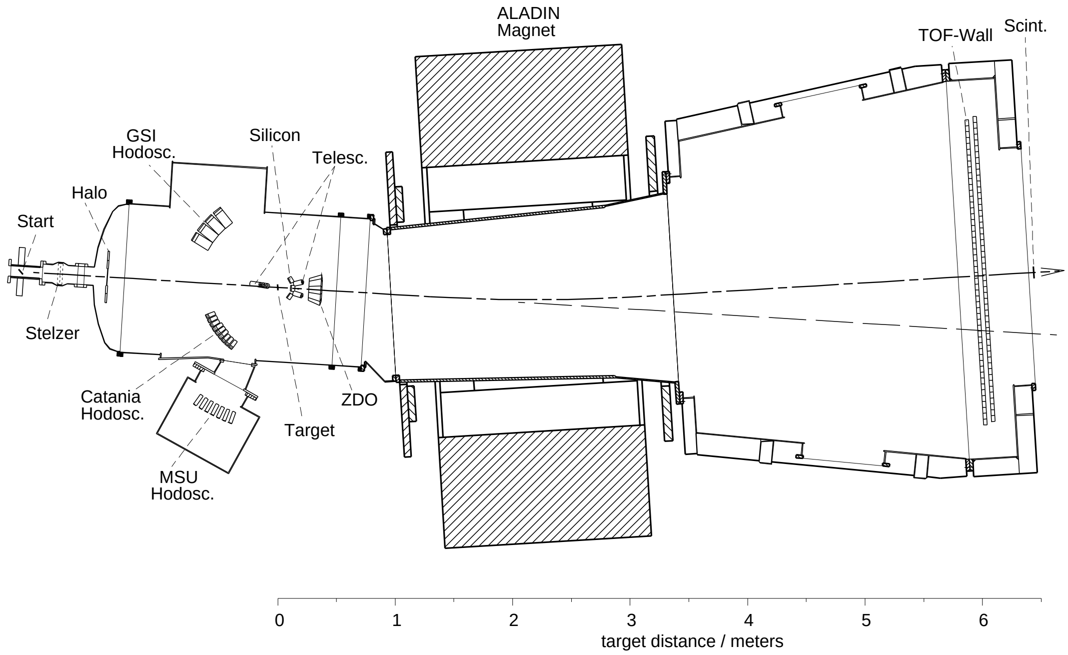


Figure 1: Schematic view of the experimental setup at the ALADIN spectrometer for the measurement with Au beams of 1 GeV per nucleon.

in Fig. 1. Three hodoscopes, from GSI (64 elements), MSU (56 elements), and Catania(96 elements), consisting of Si-CsI(Tl) telescopes(Si 3x3 cm ^{2} 300μm thick,CsI scintillators 3x3 cm ^{2} 6 cm long with photodiode readout), were set up at distances between 0.6 m and 1.1 m from the target. Their angular resolution and granularity were optimized in order to permit the identification of excited particle-unstable resonances in light fragments from the correlated detection of their decay products. For the measurements at lower energies, the hodoscopes were placed in the forward hemisphere in order to cover the angular region close to 90^0 in the center-of-mass system. At 1 GeV per nucleon(Fig.1), the hodoscopes were moved to the backward hemisphere in order to select mainly target spectator products. A set of seven telescopes, each consisting of three Si detectors with thicknesses 50 μm, 300 μm, and 1000 μm, followed by a 4 cm long CsI detector, was placed at selected angles. They served to simultaneously measure the yields of isotopically resolved light fragments.

At 1 GeV per nucleon the impact-parameter selection was achieved by measuring the quantity Z_{bound} through the forward angles time-of-flight wall of the ALADiN spectrometer. Z_{bound} is defined as the sum of the atomic numbers Z of all fragments with $Z \geq 2$[1]. Since the hodoscopes are set up at backward angles for the detection of fragments emitted by the target spectator, the method used for impact parameter selection exploits the symmetry of the collision system and avoids autocorrelations of the impact parameter selection with the temperature measurement. At lower bombarding energies the associated charged particle multiplicity was sampled, at forward angles with a set of 36 CaF_2-plastic telescopes of the phoswich type, called Zero Degree Hodoscope (ZDO) arranged symmetrically around the beam axis, and around 40^o with a set of 6 Si-strip detectors which, in total, represented 48 channels for charged-particle detection.

3 Data analysis

The calibration of more than 200 detectors was based on measurements with α and γ sources, on the observed punch-through points, and on the correlation of the responses of the Si and CsI detectors to particles of known identity and energy.

The coincidence spectra, plotted as a function of the relative momentum of the two coincident fragments, exhibit peaks due to resonance decay superimposed on the background of coincident but uncorrelated particle emission. In order to determine the background spectrum the technique of correlation functions is used. Correlation functions are created by dividing the coincidence yields by uncorrelated yields obtained from event-mixing. This eliminates the major part of non-interesting correlations, e.g. due to detector properties, which permits a more reliable estimate of the background. The background correlation function was determined with the aid of model calculations and by comparing to the correlation functions of other pairs of particles which are free of resonances in the region of small relative momenta, e.g. d + d.

Typical experimental correlation functions for p - α and d - He^3 coincidences, for the reaction Au + Au at 150 MeV per nucleon, are shown in Fig. 2. Both correspond to decay channels of ^5Li fragments, and the peaks due to the ground and excited (16.7 MeV) states are clearly visible. The solid lines represent the estimated background which, at large q, is close to one and, at small q, decreases due to the mutual Coulomb repulsion of the two charged particles.

The acceptance of the hodoscopes for a particular resonance decay depends on the properties of the resonance and on the geometry and resolutions of the detectors. Monte-Carlo simulations are best suited for the determination of the efficiency matrix. The modelling of additional effects such as multiple scattering in the target and in the detectors has been incorporated.

From the acceptance corrected yields the nuclear temperatures (emission temperature) can be calculated via:

$$\frac{Y_1}{Y_2} = \frac{2J_1 + 1}{2J_2 + 1} \, e^{-\Delta E/T}.$$

Here, Y_i, J_i are the yields and the spins of two states in the same isotope, e.g. the two states in ^5Li, separated by the energy ΔE. This assumes that the states of the decaying fragments are populated according to a Boltzmann law.

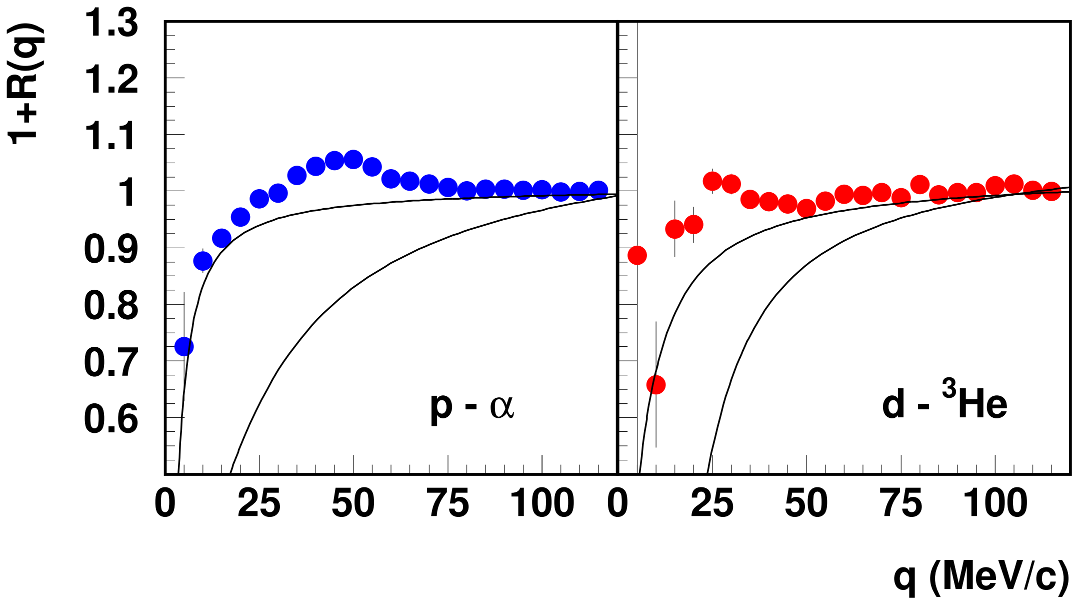
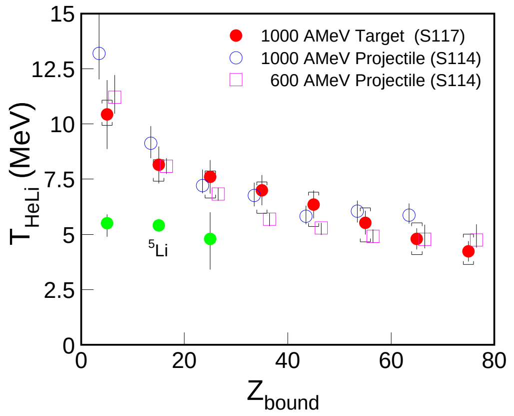


Figure 2: Correlation functions for the ^{5}Li groundstate (left side) and the 16.7 MeV excited state (right side) in Au+Au collisions at 150 AMeV. The lines show the minimum and maximum assumptions to the coulomb background.

We note that the experimentally determined yields may contain components due to the sequential decay of heavier fragments. Model calculations show, however, that the case of the proton rich nucleus ^{5}Li is particularly favourable because the distortion by sequential feeding is predicted to be small[17]. Clearly, it will be necessary to test this assumption and, more generally, to verify the assumption of a statistical population by attempting a consistent description of all observed resonance yields on the basis of sequential feeding models [14,18,19,20,21]. At the moment, the assumptions made in these models are quite crude and need some improvements.

On the other hand we extract temperatures from the double ratios of isotope yields, measured with the telescopes. Energy spectra of the individually resolved isotopes are reproduced by using a standard three moving sources fit procedure for 1 A GeV data, and including a collective radial flow contribution for the lower energy ones. The (^{3}He/^{4}He)/(^{6}Li/^{7}Li) double yield ratios are deduced from the integrated cross sections. We want to remark that the flow parameters obtained from the fit procedure at the lower energies are in good agreement with the ones presently available in the literature.[22,23]



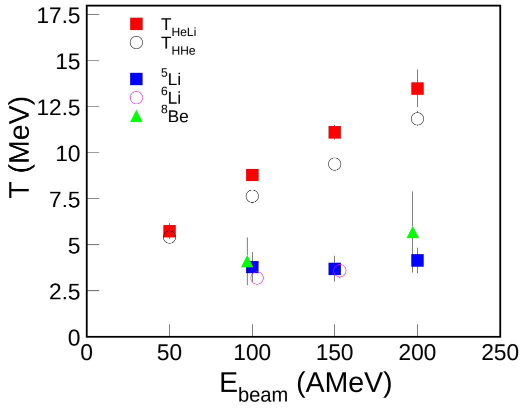


Figure 3: Target spectator isotope temperatures T_{He-Li} measured in the Au+Au reaction at 1 A GeV are shown (closed symbols) as a function of Z_{bound}. The open symbols refers to the values obtained for the projectile spectator in previous experiments.The shadowed symbols refer to the emission temperatures from ^{5}Li excited state population, measured for target spectator fragmentation at 1 A GeV.

Figure 4: Temperatures extracted from the excited states of light nuclei and the double ratio of the yields from different isotopes are shown as a function of the bombarding energy for central Au+Au collisions.The calibration of the isotope thermometers was done accordingly to Ref.26.

4 Results and discussion

The temperatures extracted from the double ratios of (^{3}He/^{4}He)/(^{6}Li/^{7}Li) isotopes (T_{He-Li}) emitted from the target spectators in the reaction Au+Au at 1 A GeV are shown in Fig. 3 as a function of Z_{bound} of the projectile spectators.They are in a very good agreement with the values obtained in a previous experiment[4] for the same system but where isotope temperatures were evaluated for projectile spectators.

Because of the Z_{bound} selection on projectile spectator products, the observed agreement between the two measurements represents an autocorrelation free methodical test.The temperatures measured for target spectators vs excitation energies associated with the selected Z_{bound} values agree well with the rising branch of the caloric curve obtained for the projectile spectators produced in the Au+ Au reaction at 600 A MeV. [24]

The values of T_{He-Li} and T_{H-He} ((^{2}H/^{3}H)/(^{3}He/^{4}He)) measured for central Au+Au collisions at incident energies of 50,100,150,200 A MeV are reported in Fig.4 versus the bombarding energy because in the present experiment excitation energies are not measured. The good agreement between the T_{He-Li} and T_{H-He} shows that the increasing behaviour of the "isotope" temperature is not very much affected by the sequential feeding.On the other hand the caloric curves for spectator and participant nuclear matter are also consistent [24]suggesting that we are dealing with similar processes. In order to crosscheck and calibrate the isotope temperatures with an alternative experimental thermometer, they are compared in Fig.3 and 4 with temperatures deduced from the relative population of states in ^{5}Li, ^{6}Li and ^{8}Be. In peripheral collisions,shadowed circles in Fig 3,we notice a slightly increasing discrepancy between the two thermometers as the excitation energy increases (lower Z_{bound} values). Both thermometers look consistent again if one apply the corrections evidenced by a systematic study on the effects of the sequential decay feeding [25]. In central collisions (Fig.4),without the corrections of Ref.25, differences up to 9 MeV between the two methods are reached at the highest bombarding energy.Such a discrepancy is independent from the particular choice of the excitation energy scale and cannot be accounted for by sequential decay because of the constancy of the emission temperature at a very low value of 4 MeV, against an increase of the beam energy of a factor of four. At present we have no quantitative explanation for the observed differences between the two methods. It could well be that the emission temperature method is insentitive to the variation of the real temperature or that the two methods select different stages of the decay process. It is particularly intriguing that the discrepancy between the two thermometers arises at beam energies where collective radial flow become important. Whether this is a pure coincidence or whether there exists some causality remains to be seen. We conclude that while the recent ALADIN experiment confirms the earlier results on the isotope temperatures, the different energy dependence of the isotope and emission temperatures seems to exclude a common freeze-out point for chemical and internal degrees-of-freedom.

Acknowledgments

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