Proposal of Experiment

Dynamics of Spectator Fragmentation Studied with the INDRA Multidetector

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ABSTRACT

We propose a study of the dynamics of spectator fragmentation at relativistic energies with the INDRA 4-π multidetector. The exclusive measurement of double-differential cross sections and correlations for identified light charged particles and fragments of intermediate mass is expected to resolve current open questions concerning preequilibrium and collective effects in the decay of highly excited spectator systems. In addition, these data will improve the accuracy to which the excitation energy residing in the decaying system at breakup is known. Eight days of ^{12}C beams at incident energies between 0.6 and 2 GeV per nucleon and four days of ^{40}Ar beams at 1 GeV per nucleon are requested.

1 Physics motivation

The experimental study of the nuclear liquid-gas phase transition has made considerable progress in recent years. In particular, the first reports of a caloric curve [1] and of values for critical point exponents [2] have received wide interest and stimulated further work. These results suggest that signals of the nuclear liquid-gas phase transition may be revealed by studying reactions of finite nuclei (Fig. 1). At present, however, the experimental methods have not been assessed and confirmed to a point which would permit quantitative interpretations on the desired level. It is, therefore, very important that the new methods for measuring thermodynamic properties of excited nuclear systems will be subjected to further critical examination. The systematic errors will have to be reduced, which seems feasible with improved experiments and model calculations.

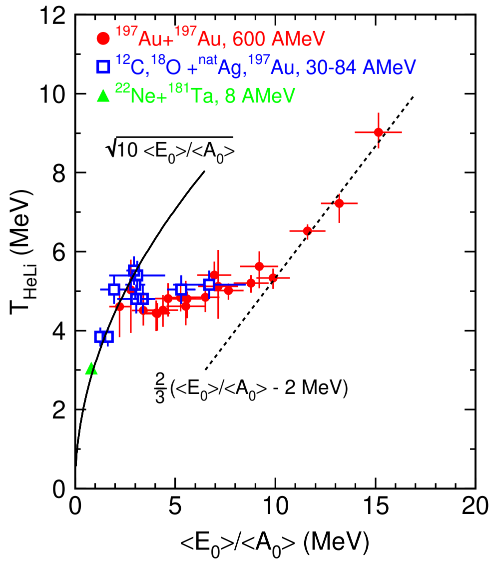

Figure 1: Caloric curve of nuclei as constituted by the temperature T_{HeLi} as a function of the excitation energy per nucleon (from Ref. [1]).

The ALADIN collaboration is actively involved in present activities in this direction. In 1995 a second experiment devoted to the measurement of breakup temperatures for *target* spectators in ^{197}Au + ^{197}Au collisions has been conducted (experiment S117). Concerning the isotope temperatures, the new data confirm the earlier results. The obtained temperatures, measured for the target spectator and involving additional combinations of isotopes, are in good agreement with those measured previously in the projectile frame [3]. At the same time, however, unexpected new results were obtained. Temperatures for central collisions at bombarding energies of 50 up to 200 MeV per nucleon obtained with two different methods, from isotopic yield ratios and from the population of particle-unstable resonances, were found to deviate in a systematic fashion (Fig. 2). These data are intriguing as they may require modifications of the concept of a common breakup, possibly along the line suggested by recent theoretical work [4, 5, 6]. However, a good understanding of the effects of sequential decays of excited fragments is a prerequisite of their interpretation [7, 8]. The experimental program of the INDRA collaboration, in their upcoming experiments at GSI (experiment S185), will particularly address these questions.

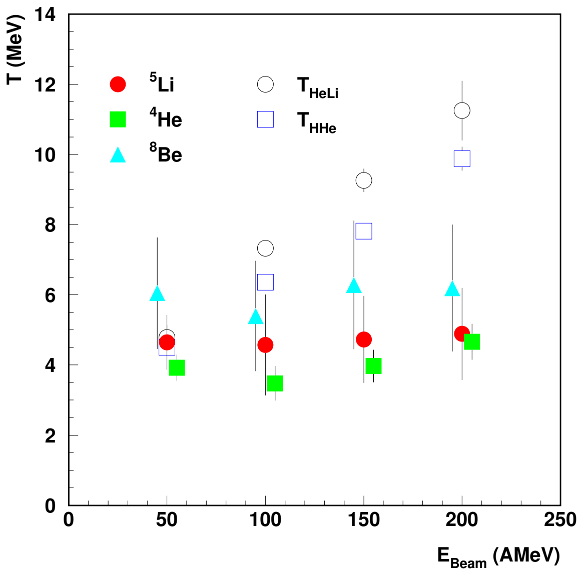

Figure 2: Temperatures from double ratios of isotopic yields (open symbols) compared to temperatures from particle unstable states (closed symbols).

The excitation energy of the system at breakup, the observable plotted along the abscissa in the representation of the caloric curve (Fig. 1), has not received the same attention so far as the breakup temperatures. Recent evaluations of the excitation energy, that have taken into account the data for hydrogen emission measured in the 1995 experiment, have resulted in corrections to the published energy values of the order of 10%. However, the deduced spectator energy was found to depend considerably on the bombarding energy. It increases by about 30% over the range 600 to 1000 MeV per nucleon which is in contrast

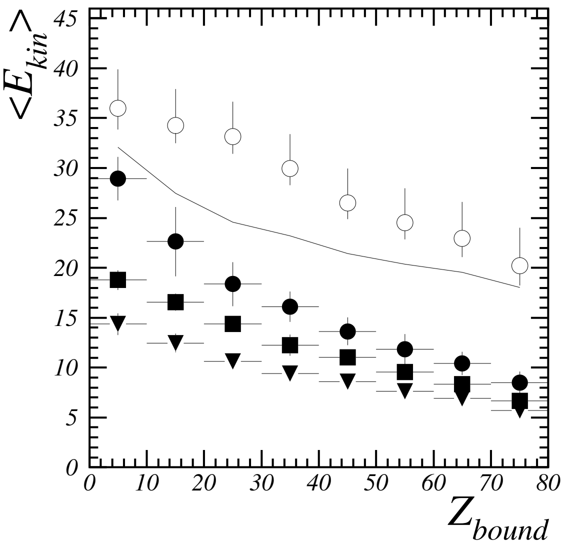

Figure 3: Mean kinetic energy of neutrons (full symbols) in the rest frame of the projectile spectator as obtained in measurements with LAND for the three bombarding energies 600 (triangles), 800 (squares), and 1000 MeV per nucleon (circles). For the case of 1000 MeV per nucleon, a comparison is made between the measured mean kinetic energies of protons (open circles) and those obtained by adding estimated Coulomb contributions to the neutron kinetic energies (full line).

to the universality observed for the products with $Z \geq 2$ of the spectator decay [9]. This rise is solely caused by the behavior of the mean kinetic energies of neutrons in the spectator frame (Fig. 3), measured by the ALADIN/LAND collaboration in 1993 (experiment S114). The measured values of the neutron energies have a large effect on the deduced total excitation energy, first, because the neutron multiplicity is large and, second, because the hydrogen isotopes, in the absence of equivalent data, were assumed to scale in the same way as the neutrons do. The kinetic energies of neutrons and hydrogens together amount to typically half the total spectator energy. It is obvious that this uncertainty represents a considerable problem for the quantitative interpretation of the caloric curve [10]. Conjectures that part of the experimentally determined energy may be due to pre-equilibrium [11] or pre-breakup emission [3] require further experimental verification.

The following questions are obvious in this situation and should be answered: What is the behaviour of the hydrogen isotopes with bombarding energy, and is there any structure in the energy spectra that may permit a distinction of equilibrium and non-equilibrium emission ? What is the level on which similar effects may be observed or excluded for

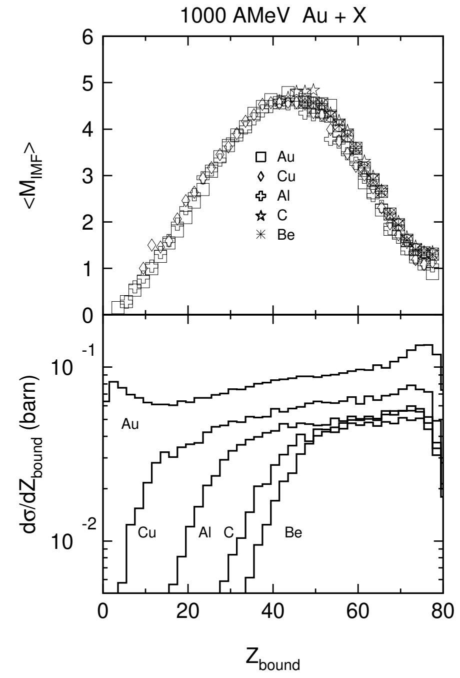

Figure 4: Top: Mean multiplicity of intermediate-mass fragments $\langle M_{IMF} \rangle$ as a function of Z_{bound} for the reactions of ^{197}Au projectiles at E/A = 1000 MeV with the five targets Be, C, Al, Cu, and Au.
Bottom: Measured cross sections $d\sigma/dZ_{bound}$ for the same five reactions. Note that the experimental trigger affected the cross sections for $Z_{bound} \geq 65$ (from Ref. [9]).

helium isotopes and the light fragments ? Are there indications of a time ordering of the emission process [12, 13, 14] ? This study should be conducted over a wide range of bombarding energies and, therefore, can best be done for the target spectator which is virtually at rest in the laboratory.

A unique possibility to start this program is given by the presence of the INDRA multidetector at the GSI in 1997/1998. It permits the exclusive study of the dynamics of multifragmentation of target spectators in asymmetric collision systems with low thresholds over the 4-π solid angle. Such data will be complementary to the existing data measured previously with the ALADIN spectrometer and by the EOS collaboration [15]. The proposed experiment will also complement the already existing INDRA program at GSI (experiment S185) by providing data for spectator fragmentation (no or very little flow) that may be confronted with the observations made for the flow-dominated central collisions in heavy systems at lower energies.

We propose to study the systems ^{12}C + ^{197}Au at three energies 0.6, 1, and 2 GeV per nucleon and ^{40}Ar + ^{197}Au at 1 GeV per nucleon. The requested time is 12 days (36 shifts). The reasoning behind the choice of the reaction systems, important experimental details, and arguments supporting the time request will be given in the next sections.

2 The collision systems

The reaction ^{12}C + ^{197}Au has the special property that maximum fragment production is reached in the most central collisions (Fig. 4). This has the consequence that the dynamics of multifragmentation can be studied with a minimum of potential complications that may arise from the bounce-off and Coulomb repulsion of the spectator system present in collisions with heavier projectiles. On the technical side, the low yield of δ electrons to be expected with such a light projectile is of great advantage and, in fact, may be essential in order to retain the full intrinsic resolution of the INDRA multidetector.

The proposed study will bridge the presently existing gap between reactions induced by light particles of high energy [16, 17] and heavy-ion induced reactions. The cross section of collisions with the carbon projectile being fully immersed into the target ($R_{proj}+b \leq R_{target}$) is large ($b \leq 4$ fm, equivalent to a cross section of 0.5 b) and the probability of observing dynamical consequences of piercing holes into the target nucleus may be at its maximum [18]. The possibilities of observing decays out of exotic nuclear shapes have been discussed widely in the literature, both for reactions induced by heavy projectiles at intermediate and light projectiles at high bombarding energies (see, e.g., [18-23] and references therein). The associated question of the resilience of nuclear matter is of considerable theoretical interest [24] and may profit from the possibility of comparing very asymmetric systems over a wider range of projectile masses (reactions induced by ^{3}He projectiles of 4.8 GeV are analyzed in Ref. [24]).

The chosen bombarding energies will include two energies studied previously in inverse kinematics [9] but will extend to the highest energies available at SIS. This will allow us to establish the behavior with bombarding energy over a large interval and into the regimes of limiting fragmentation as well as of increasing Δ production [25, 26].

Any unexpected observation will have to be scrutinized by the comparison with comparable data sets for other systems. We propose to explore the two degrees of freedom, bombarding energy and projectile mass, with a minimum number of reaction systems.

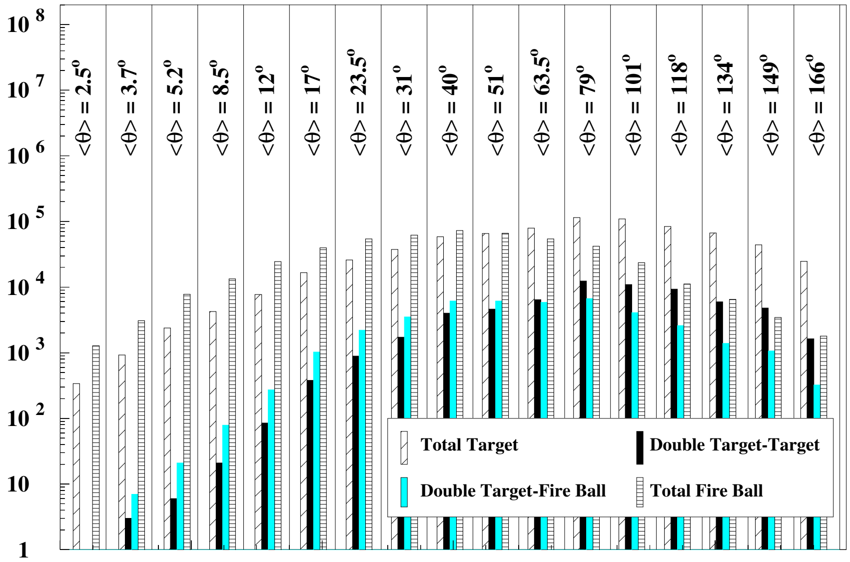

Figure 5: Relative count rates for the 17 rings of the INDRA multidetector according to FREESCO simulations for ^{12}C + ^{197}Au at 1 GeV per nucleon. The four columns in each box, from the left to the right, represent the rates from the target decay, double hits in a detector element caused by the target decay, double hits due to fireball-target coincidences, and the total rate due to the fireball decay. The data are averaged over the impact parameter.

Therefore, in addition to ^{12}C + ^{197}Au at three energies, it is proposed to study the reaction ^{40}Ar + ^{197}Au at 1 GeV per nucleon. With ^{40}Ar, maximum fragment production is expected at $b \approx 6$ fm, i.e. in moderately peripheral collisions, according to the systematics [27]. The more central collisions cover the full range of Z_{bound} which will give access to the high excitation energies for which the second rise of the breakup temperature has been observed [1, 3]. Complications due to collective effects in the entrance channel and due to the production of δ electrons are expected to be tolerable. The final choice of this heavier projectile is not crucial and may also be influenced by considerations arising from the actual SIS scheduling.

3 Specific technical details

The INDRA multidetector will be used in the same configuration as for the runs with xenon and gold beams (experiment S185). Technical descriptions are given in the pro-

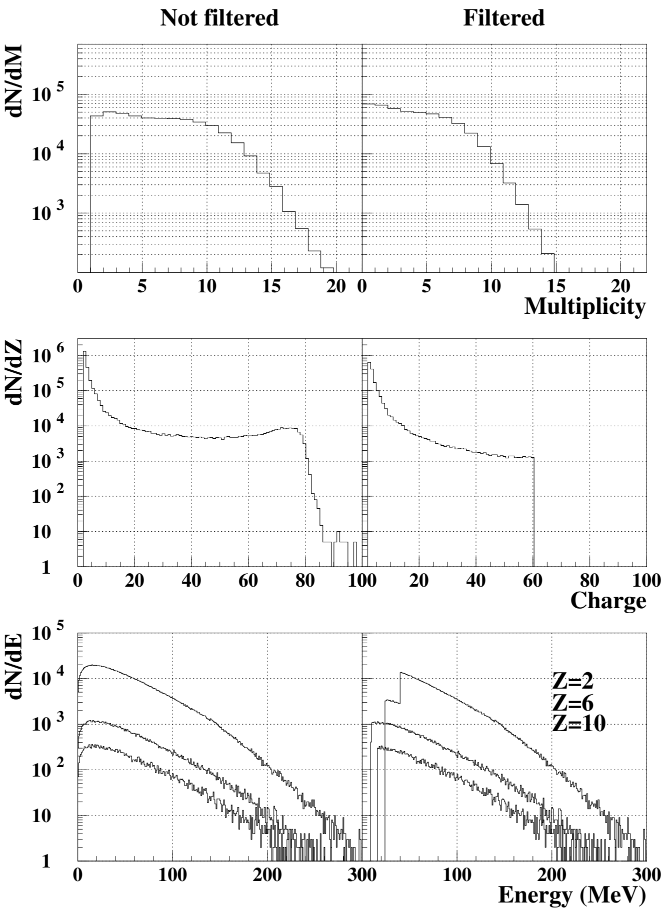

Figure 6: Result of simulations by applying the INDRA filter to a data set measured with ALADIN for the decay of gold projectiles after collisions with a gold target at 1 GeV per nucleon. The thresholds used for $Z = 2$ and for $Z = 6$,10 fragments correspond to isotopic and elemental identification, respectively. A threshold $Z_{bound} \geq 30$ was set which simulates the collision with a carbon target.

posal of experiment S185 and in Ref. [28]. The proposed experiment relies on the low detection and identification thresholds of the INDRA telescopes. This property will be even more important than in the study of central collisions at lower energies (experiment S185) because the spectator systems are nearly at rest in the laboratory and significant flow effects are not expected. The task of directing the high energetic beams through the narrow apertures of the INDRA multidetector represents an additional challenge.

The effects of the finite detection thresholds were studied in simulations taking into account the detection properties of INDRA. Using the FREESCO model [29] for the simulation of the full reaction we were able to study the effect of the midrapidity source of fast particles. The charged light particles from the initial reaction stages will be detected although not stopped in the CsI detectors. Their rate is high at the forward angles but the probability of double hits is very small, due to the high granularity of the INDRA multidetector (Fig. 5). Simulations using data files for projectile fragmentation from the ALADIN S114 experiment [9] were performed in order to assess the effect of the detection thresholds for the target source (Fig. 6). It is obvious that heavy fragments will be detected with very low probability. Therefore, for the impact parameter selection the multiplicity of light charged particles will be used. Using only the multiplicity of hydrogen isotopes, the quantity complementary to Z_{bound}, will allow the mapping onto the existing ALADIN data. The detection probability is very high for light fragments (the geometric coverage of INDRA is about 90%) and has only dropped to about 60% for $Z = 20$ fragments. We therefore expect that the measured spectra and correlations of the lighter fragments will be of very high quality.

The focussing of the beam through the narrow INDRA geometry will profit very little from the quadrupole doublet to be installed in Cave B upstream of the detector but gain from the good emittance to be expected for the carbon and argon beams of high energy, in particular, if the SIS cooler will be available. We propose a multi-step procedure in order to avoid the damaging of the detector system by irradiating it with the direct beam. The beam stopper in front of the detector, used during focussing of the Xe and Au beams at $E/A \leq 150$ MeV, will stop carbon (argon) beams with energies up to about 150 (250) MeV per nucleon. First beams of about this energy and of low intensity will be used for setting the beam line and for first directing the beam into the experimental area. After satisfying beam conditions have been achieved, the energy and intensity will be increased in finite steps chosen such that, after a scaling of the beam line elements, only minor adjustments will be required. For gaining the necessary experience with the high energy beams an extra day of beam time is requested.

4 Beam time request

The beam time request is based on the desire to collect one high statistics data set for each projectile, at the same bombarding energy, that will allow to do correlation analyses after

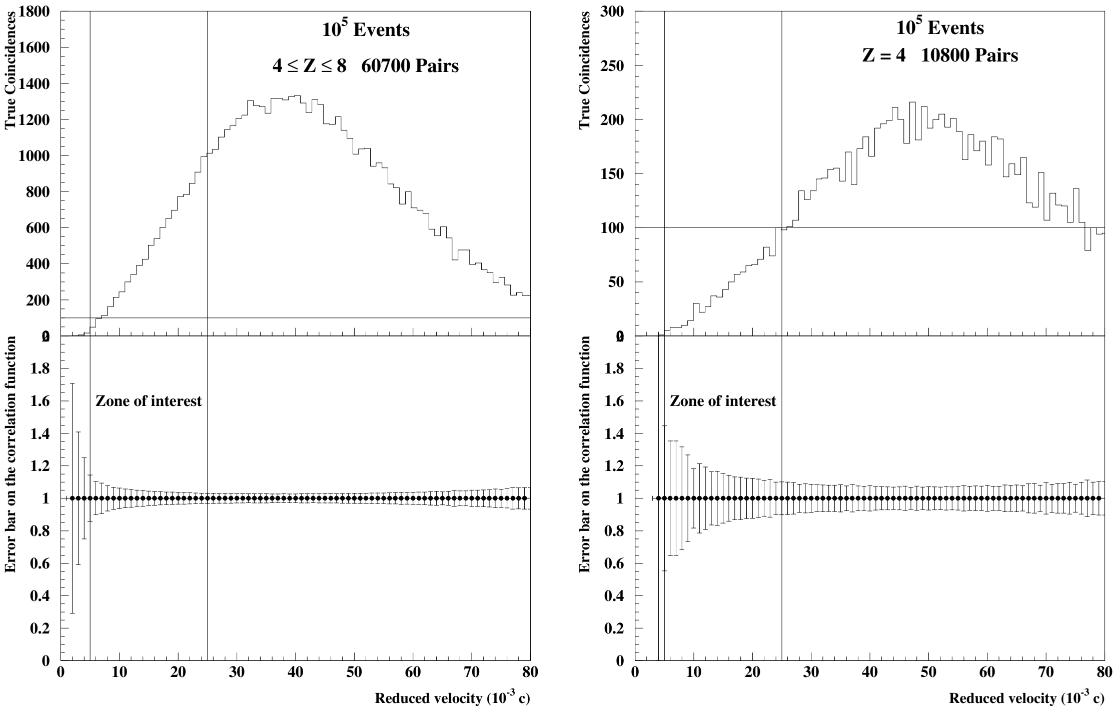

Figure 7: Result of simulations by applying the INDRA filter to a data set measured with ALADIN for the decay of gold projectiles after collisions with a gold target at 1 GeV per nucleon. Top panels: Number of fragment-fragment coincidences per 10^5 events for the given range of fragment Z as a function of the reduced velocity v_{red}.
Bottom panels: Error band of the fragment-fragment correlation function constructed from this data set. The zone of interest $5 \leq v_{red} \leq 25 \cdot 10^{-3}c$ where the correlation function is expected to depend on the emission time is indicated.

selecting on the order of 2% of the total reaction cross section. This set should contain about 10^6 events in order to permit the necessary cuts into the multi-dimensional parameter space ($\Theta_{lab}, Z, N_c, N_{IMF}$, etc.). The example of fragment-fragment velocity correlations, an observable sensitive to emission times [30, 31], is chosen in order to illustrate this requirement (Fig. 7). For a data sample of 10^5 events (Au + Au, ALADIN S114) the number of fragment-fragment coincidences (top panels) and the error bands to be expected for the correlation functions built from these data (bottom panels) are shown as a function of the reduced velocity $v_{red} = v_{rel}/\sqrt{Z_1 + Z_2}$ (v_{rel} denotes the relative velocity of two fragments with atomic numbers Z_1 and Z_2, see [31]).

The figure demonstrates that 100 events per channel (horizontal line in the top panels) is the minimum number required for a significant result and that a finer selection in Z leads to dramatic reductions of the number of coincidences. Therefore, 10^5 events may permit the construction of one meaningful correlation function (left-hand-side) but are insufficient for a study of its evolution as a function of another parameter.

The target thickness, in order to keep the thresholds low, cannot exceed 1 to 2 mg/cm^2. Beam intensities of several 10^7 particles/s are sufficient to reach the count rates of several 100/s that are suitable for the INDRA detection and acquisition system. The required total number of 2 to 5 $\cdot 10^7$ events (depending on the trigger selection) can then be collected within a period of about three days.

We expect that the INDRA multidetector will be fully debugged and operable at the time of the experiment, assuming that it will be scheduled after one of the runs with heavy projectiles of low energy. Some setup time will still be needed in order to arrive at the data taking stage. Our request, therefore, consists of

beam handling	1 day
control of setup	1 day
^{12}C @ 0.6 AGeV	1.5 days
^{12}C @ 1 AGeV	3 days
^{12}C @ 2.0 AGeV	1.5 days
change to ^{40}Ar	1 day
^{40}Ar @ 1 AGeV	3 days

The total request consists of 12 days (36 shifts).

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