Proposal of Experiment at SIS

Mass and Isospin Effects in Multifragmentation

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ABSTRACT

We propose a comparative study of the multifragmentation of spectator systems formed at relativistic energies. Primary stable and secondary radioactive beams will be used in order to cover a wide range of mass and isotopic composition. Projectile fragments will be detected and identified using the upgraded ALADIN spectrometer, operated in conjunction with LAND for simultaneous neutron detection. The data are expected to serve as a general basis for the study of isotopic effects in multifragmentation and to resolve existing ambiguities in the interpretation of the caloric curve of nuclei. The tracking and mass determination with a threshold of $Z \geq 2$ will permit the study of the breakup dynamics in the spectator frame. A total of 18 days of measuring time with primary beams of ^{197}Au and ^{124}Sn, and with secondary beams ^{124}La and ^{106}Sn is requested.

1 Physics motivation

The role of isospin in multifragmentation has been explored very little up to now. This is in striking contrast to the importance of isospin, in particular for any interpretation of multifragmentation as a manifestation of the liquid-gas phase transition of nuclear matter. Müller and Serot, in their seminal paper [1], have demonstrated that the two-fluid nature of nuclear matter has very specific consequences for the phase behavior in the coexistence zone. Different isotopic compositions are predicted for the coexisting liquid and gas phases, with the gas being more neutron rich than the liquid in asymmetric ($N \neq Z$) matter. This difference stems from the decrease in the symmetry energy in nuclear matter as the density is decreased. The expected magnitude of this density dependence, however, is model dependent and very poorly constrained by existing data [2]. Furthermore, in the phase diagram of asymmetric matter, the diffusive spinodal extends beyond the adiabatic spinodal, suggesting that the adiabatically expanding system first passes through a region of instability with respect to the isotopic composition before it enters the region of mechanical instability. As a possible consequence, large fluctuations of the relative isovector density $(\rho_{\mathrm{n}} - \rho_{\mathrm{p}})/\rho$ with position may develop before breakup, provided there is sufficient time for the system to explore these instabilities [3] ($\rho_{\mathrm{n}}, \rho_{\mathrm{p}}$, and ρ denote the neutron, proton, and nucleon density, respectively).

The calculations of Müller and Serot are restricted to infinite matter with no Coulomb force included. In addition, the isotopic composition, in the calculations, is typically varied within a range of proton fractions $\rho_{\mathrm{p}}/\rho = 0.3$ to 0.5 whose limits are not easily accessible in experiments with heavy nuclei. Theoretical studies for finite systems also indicate that the sequential decay of excited reaction products has a tendency to reduce some of the expected effects [4]. Some observables are predicted to be robust with respect to sequential decay, however. If chemical equilibrium can be assumed isotopic ratios can be constructed whose exponential dependence on the ratio μ/T of the chemical potential μ and the temperature T will amplify differences resulting from the variation of μ with the isotopic composition. Measured isotopic yield ratios were found to vary strongly with the N/Z ratio of the emitting source [5], in agreement with this expectation [6, 7]. Recent experimental work by Xu et al. [8], done with ^{112,124}Sn beams and targets, has demonstrated that significant differences between neutron rich and neutron poor systems can be observed. The strong enhancement of the neutron content in the 'gas' with increasing N/Z of the system is

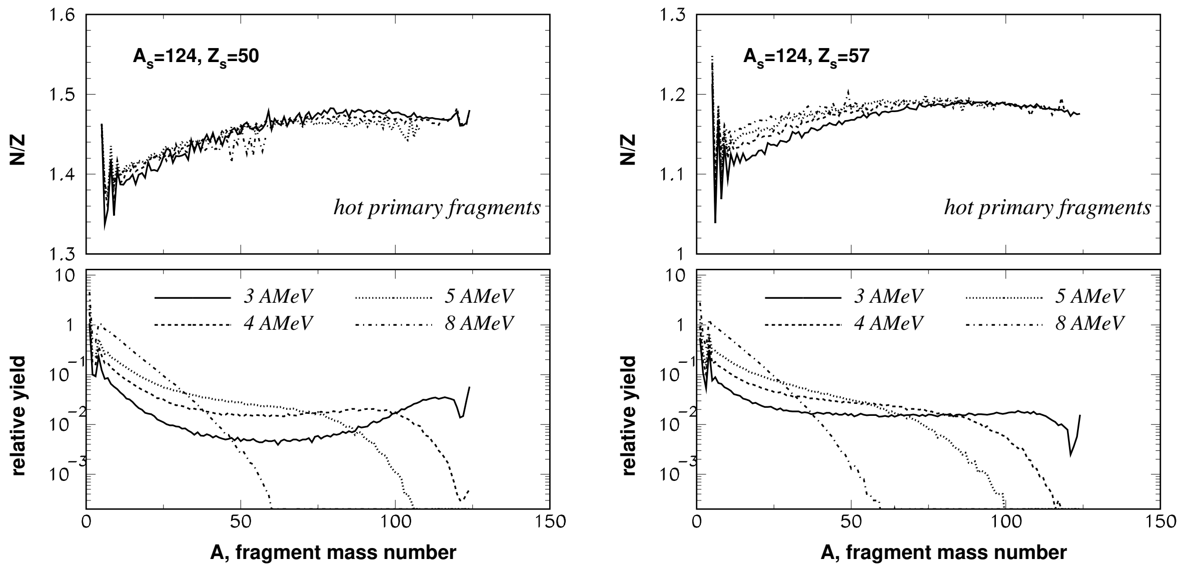

Figure 1: Neutron-to-proton ratios N/Z (top panels) and mass-yield curves (bottom panels) of the primary hot fragments produced at the breakup of two systems with fixed mass number $A = 124$ according to SMM calculations. The lines correspond to four excitation energies between 3 and 8 MeV per nucleon as indicated. Note the difference of the ordinate scales in the top panels (from Ref. [13]).

interpreted by these authors as being in qualitative agreement with the predictions of [1]. The role of the excitation energy has been emphasized by Milazzo et al. [9] who report evidence for the increased production of neutron-rich isotopes with excitation energy that is predicted by the statistical multifragmentation model (SMM, for a reference see [10]).

With the proposed experiment, we plan to investigate isotopic effects in the decay of projectile spectators at relativistic energies. Previous work has resulted in many indications that equilibrium is reached at breakup in these reactions [11]. A signature of the liquid-gas phase transition was obtained in the form of the caloric curve of nuclei [12] which, in particular, suggests that the coexistence region is explored. The isotopic composition of the excited spectator systems will be largely that of the incident projectile nuclei. By using secondary beams, the range of isotopic compositions can therefore be considerably extended beyond that accessible in reactions with stable beams and targets. This and the clean separation of the spectator sources in rapidity make this type of reaction unique for studying the isospin dependence of nuclear multifragmentation.

The SMM predictions for the fragmentation of two $A = 124$ systems, one neutron rich ($N/Z = 1.48$) and one neutron poor ($N/Z = 1.18$), are given in Fig. 1. The isotopic

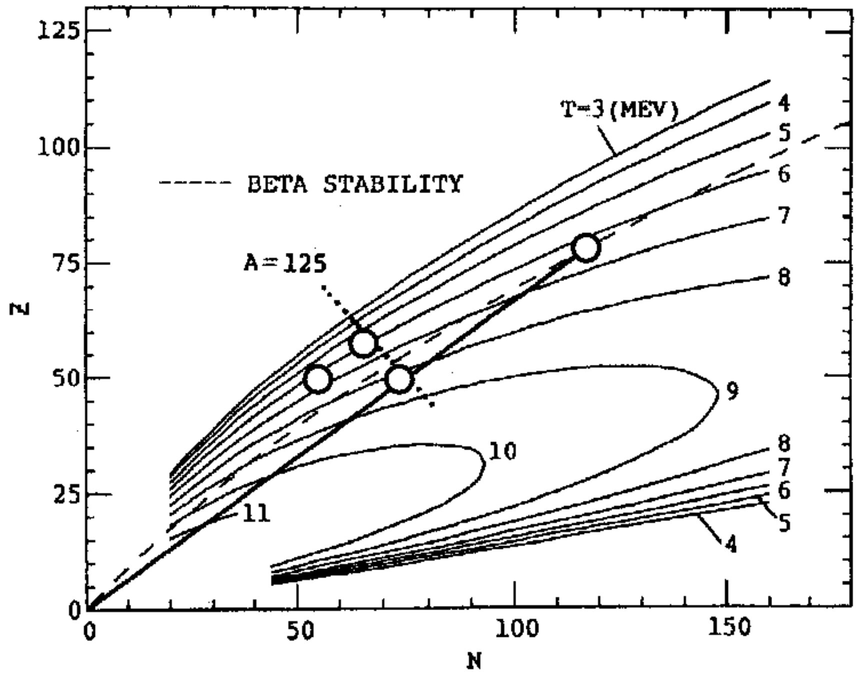

Figure 2: Location of the four projectiles in the plane of atomic number Z versus neutron number N. The contour lines represent the limiting temperatures according to Ref. [16], the dashed line gives the valley of stability, and the full line corresponds to the $N/Z = 1.49$ of ^{197}Au.

compositions of the hot fragments produced at breakup are globally very different for the two systems, close to the N/Z ratios of the primary projectiles which they approach with increasing mass number (top panels). The overall mass dependence is rather weak with a dependence on excitation energy predicted to be different for the neutron-rich and neutron-poor cases. The calculated mass yield curves are fairly similar for these systems (bottom panels of Fig. 1). Exploring these dependences experimentally will be important for our understanding of the role of phase space in the multi-fragment decays. It is also an open question whether the observed universality of spectator decays includes the invariance with isospin.

The isotopic study will be based on the fragmentation of these two nuclei with $A = 124$ and, in addition, of the proton-rich projectile ^{106}Sn with $N/Z = 1.12$. The latter, together with ^{124}Sn, forms a pair of isotopes of the same element with very different neutron numbers. Their comparison is expected to elucidate the role of neutrons in the partitioning of systems with a given number of charges. The three projectiles should provide a rather comprehensive view on potential isotopic effects in this range of heavy nuclei.

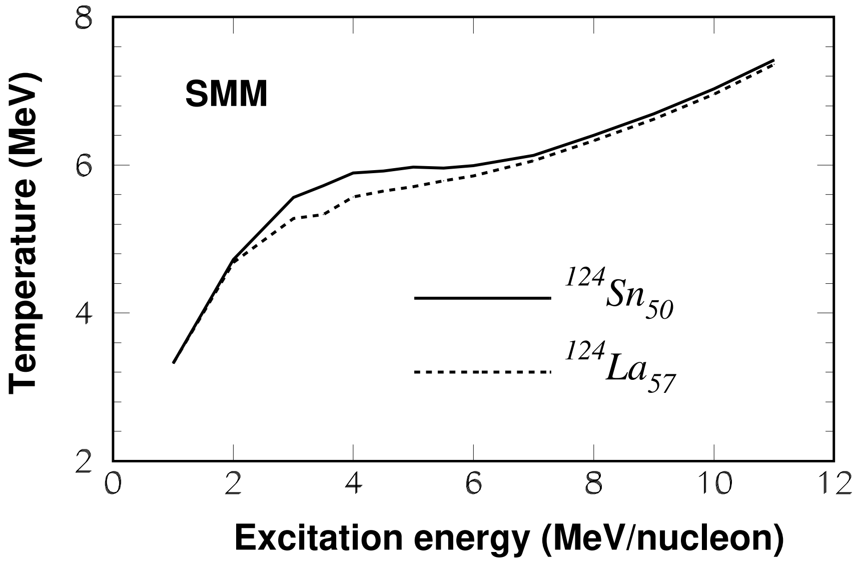

Figure 3: Caloric curves for ^{124}La ($Z = 57$) and ^{124}Sn ($Z = 50$) as calculated with the statistical multifragmentation model (from Ref. [13]).

Besides the isospin, also the mass of the system may play an important role for fragmentation observables of the reaction. It has been suggested that the dependence of the breakup temperature on the excitation energy (caloric curve) is governed by the limiting temperature [14, 15]. This quantity represents the maximum temperature at which nuclei are found to exist as self-bound objects in Hartree-Fock calculations [16]. In lighter systems the limiting temperature is higher, mainly so because the Coulomb energy is reduced (Fig. 2). On the other hand, SMM calculations predict nearly mass-invariant temperatures for the coexistence region [10]. The comparison of two systems with different mass should therefore permit distinguishing whether the breakup temperature is determined by the binding properties of the excited hot nuclear system or by the phase space accessible to it by fragmentation. The same test can be made by varying the isospin; the calculated limiting temperatures (Fig. 2) and the breakup temperatures as predicted by the SMM (Fig. 3) depend very differently on the N/Z ratio of the system.

The collected data will be used to pursue a third important direction of research. The inverse kinematics offers the possibility of a threshold-free detection of heavy fragments and residues and thus gives a unique access to the breakup dynamics. This technique has been applied in the first ALADIN experiment from which important dynamical information has been obtained in spite of the threshold $Z \geq 8$ for the tracking and mass identification, caused by the detection properties of the MUSIC II detector [17, 18]. This threshold has been lowered by employing proportional counters in the MUSIC-III detector, and, in the subsequent experiment S114, masses were resolved with the threshold $Z \geq 2$. The isotopic identification of ^{3,4}He nuclei in this experiment was the basis of the T_{HeLi} thermometer and of the caloric curve of nuclei [12]. With the present upgrade of the MUSIC-III detector, the capability of identifying projectile fragments with a threshold $Z \geq 2$ will be extended to the full acceptance of the ALADIN spectrometer. This will, for the first time, permit the recording of the momenta of all charged fragments, including the heaviest fragments or residue nuclei. From such complete data sets, significant progress in the interpretation of fragment kinetic-energies can be expected which represent a key observable for the investigation of the fragmentation mechanism [19]. It should be possible to even detect and identify the hydrogen isotopes, although with reduced acceptance (cf. [20]).

Different targets will be mainly needed for the study of the decay dynamics. In order to reach the highest excitation energies heavy targets will be needed which, at the same time, impart high transverse momenta to the projectile system. This is not the case with carbon targets [17]. Two targets of carbon and gold, for the runs with ^{197}Au beams, will be sufficient to assess the role of the target nucleus in the deflection of the spectator system. The carbon targets will also be needed if the present results are to be related to those obtained with the INDRA detector in SIS experiment S201. There, ^{12}C + ^{197}Au was studied with carbon beams in normal kinematics. In order to identify a possible isospin transfer from the target to the projectile system (see, e.g., Refs. [21, 22]), we plan to use nickel and indium targets for the isotopic study. Of these, nickel will serve as the neutron-poor and indium as the neutron-rich target. Their masses are different but equivalent event samples can be selected by sorting according to the Z_{bound} observable.

In summary, we propose to study the decay of projectile spectators produced in collisions of ^{124}La, ^{124}Sn, ^{106}Sn, and ^{197}Au nuclei in the energy range 0.6 to 1 GeV per nucleon. Targets of carbon, nickel, indium, and gold with thicknesses equivalent to between one and three percent interaction probability will be used. The projectile fragments will be detected and identified with the ALADIN spectrometer in a configuration similar to the one used in the 1993 experiment (S114, Fig. 4), with improvements in the performance following from the present upgrade of the MUSIC-III detector. The requested time is 18 days (54 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.

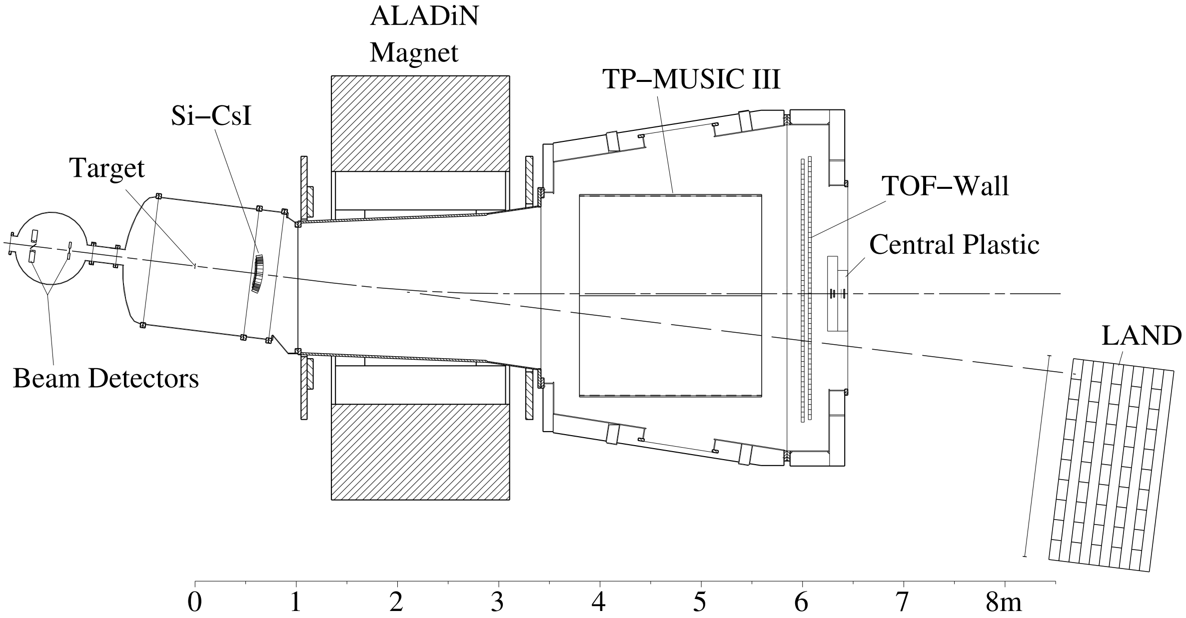

Figure 4: Cross sectional view of the ALADIN facility in the configuration of the 1993 experiment. The beam enters from the left and is monitored by two beam detectors before reaching the target. Projectile fragments entering into the acceptance of the magnet are tracked and identified in the TP-MUSIC-III detector and in the time-of-flight (TOF) wall. The Central Plastic detector covers the hole in the TOF wall at the exit for the beam. Fragments and particles emitted in forward directions outside the magnet acceptance and up to $\theta_{lab} = 16°$ are detected in the Si-CsI array. Neutrons emitted in directions close to $\theta_{lab} = 0°$ are detected with the large-area neutron detector (LAND). The dashed line indicates the direction of the incident beam. The dash-dotted line represents the trajectory of beam particles after they were deflected by an angle of 7.3°.

2 The collision systems

The four projectiles to be used in the present experiment are chosen so as to permit a study of mass and isospin effects (Fig. 2). The two projectiles ^{197}Au and ^{124}Sn have nearly the same N/Z ratio of 1.49 and 1.48, respectively, but different mass whereas ^{124}Sn and ^{124}La have the same mass but very different N/Z ratios of 1.48 and 1.18. The fourth projectile ^{106}Sn with $N/Z = 1.12$ is probably the isotope closest to symmetry in the range of heavier nuclei ($A > 100$) that is accessible for fragmentation experiments of the present kind. The comparison of two isotopes of the same element will also help to clarify the role of the neutron number N in the partition of systems with a given atomic number Z.

The limiting temperatures, according to Besprovany and Levit [16], are $T \approx 6$ MeV for ^{106}Sn, ^{124}La and ^{197}Au but considerably higher, $T \geq 8$ MeV, for ^{124}Sn. We therefore

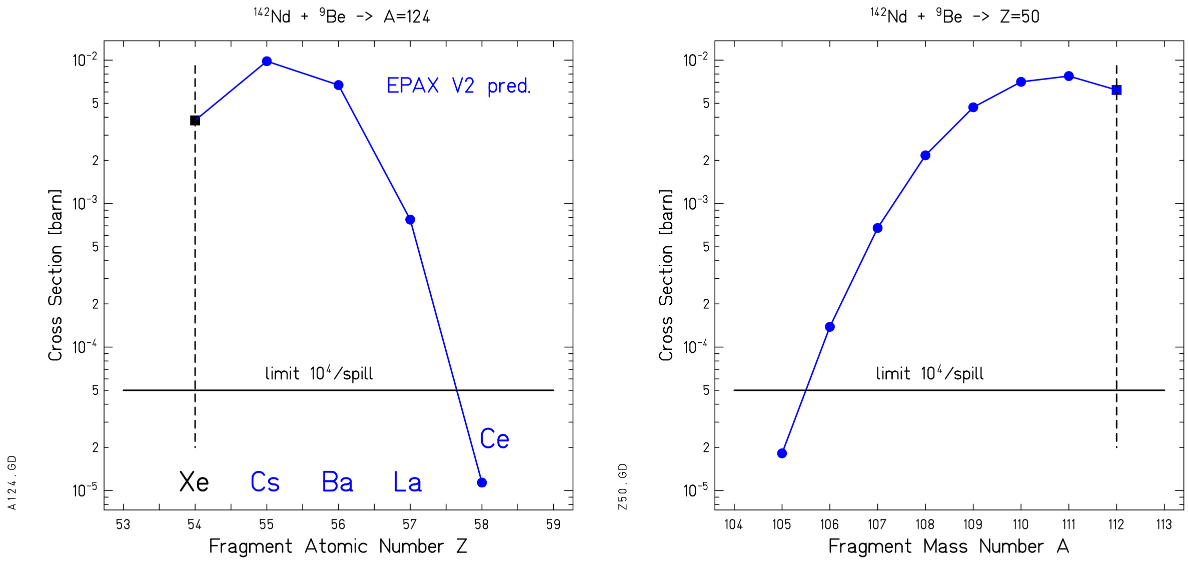

Figure 5: Expected cross sections for the production of $A = 124$ nuclei (left panel) and of $Z = 50$ nuclei (right panel) in the reaction ^{142}Nd + ^{9}Be. The count rate limit of the proposed experiment is indicated (from Ref. [23]).

expect that, with this choice of projectiles, the relative influences of mass and isospin as well as the role of the limiting temperature in multi-fragment decays can be discerned and investigated.

Rates for secondary beams with mass $A = 124$ and atomic number $Z = 50$, calculated according to the EPAX parameterization [24], are shown in Fig. 5. The primary beam ^{142}Nd and beryllium as the production target are the same in both cases. Changing between the secondary-beam species will, therefore, only require the proper adjustment of the Fragment Separator and of the beam-transport elements in the line leading to Cave B. In order to reach a sufficient selectivity, the FRS will be operated with a degrader of areal density between 5 and 10 g/cm^2, and the primary beam energy (0.8 to 1 GeV per nucleon) will be chosen so as to obtain secondary energies of 600 MeV per nucleon.

In comparison to the production cross sections, the figure also indicates the approximate upper limit of the rate that can be tolerated by the experiment. The normalization is based on typical values for the intensity of the primary ^{142}Nd beams and the thickness of the production target (several g/cm^2) but does not include the efficiency of transporting the beams to the reaction target in Cave B. The transport efficiency is unlikely to exceed 10% but, even with this low value, rates close to the acceptable 10^4 particles per spill will be reached, at least for the more favorable case of ^{124}La. The cross section is lower by a factor of 5 for the production of ^{106}Sn.

Reaction targets of natural composition and with thicknesses of several hundred mg/cm^2 will be used in order to achieve the optimum compromise between a high counting rate and a low probability for secondary reactions. Even with the stable projectiles, the rates of incident particles will have to be limited in order to keep the space charge in the MUSIC-III detector at an acceptable level, in particular during the runs with the gold beam.

Only one target, made of indium, will be used for the secondary beam experiments. With indium, the collision systems are approximately symmetric, and the channels with the highest excitations of the projectile spectator can be expected to be populated with large cross sections [11]. An areal density of ≈ 1 g/cm^2 is equivalent to an interaction probability of 2.5% and to a probability of, on the average, less than 1% for secondary reactions of a product particle or fragment with another target nucleus.

Targets made of gold and of carbon will be used for the study of the breakup dynamics. With gold, the highest spectator excitations will be reached, while carbon will allow to relate the new results in inverse kinematics to those obtained in conventional kinematics with the INDRA multi-detector. Two energies of 600 and 1000 MeV per nucleon will be used to study the dependence of the light-fragment and particle momenta on the incident energy, needed to separate the equilibrated and non-equilibrated contributions to the energy residing in the excited spectator systems.

The N/Z ratio of the thick natural targets can only be varied by simultaneously varying their mass. For the investigation of isospin effects caused by the target nucleus, a nickel target ($\langle N \rangle/Z = 1.10$) in addition to the indium target ($\langle N \rangle/Z = 1.34$) will therefore be used in the runs with stable ^{124}Sn beams.

3 Specific technical details

The detector configuration to be used resembles that of the 1993 experiments [11, 12, 25]. It will have to be adapted to the needs of secondary-beam experiments by adding a stack of silicon detectors to the system of beam detectors upstream in order to measure the atomic number of the incident projectiles with sufficiently high resolution.

The performance of the MUSIC-III detector will be significantly improved by the upgrade that is presently under way. It includes the construction of a new set of proportional counters [26] and a new readout system based on high-resolution signal recorders (sampling ADC's) and high-performance digital signal processors (DSP's). The 14-bit ADC's digitize the signals coming either from the charge-sensitive preamplifiers at the anodes of the ionization sections or from the current-sensitive preamplifiers at the electrodes of the proportional sections of the detector. The output, generated at a rate of 40 MHz, will be stored and processed by a system containing FPGA and DSP chips which are programmed to perform the necessary signal shaping as well as the determination of the collected charge and arrival time (FPGA = field programmable gate array).

It is expected that the upgraded MUSIC-III detector with this dedicated electronics system, providing high dynamic range and multi-hit capability, will represent a versatile instrument attractive also for other experiments in inverse kinematics. The proposed experiment relies on the capabilities of the system of identifying hits in the signal streams coming from the detectors on-line and with a low threshold. Test beams prior to the main experiment will be indispensable in order to determine the optimum algorithms for the specific operation conditions.

The system will be initialized by a primary interaction trigger derived from the time-of-flight (ToF) wall and/or from the CsI hodoscope at the entrance of the ALADIN magnet. A secondary trigger will be derived from the charge of the largest recorded fragment that is expected to be available as an analog signal after about 25 μs. A fast clear will be initiated and the data acquisition will be reset if this charge is above a threshold Z slightly below that of the incident beam.

The tracking in the bending plane will be based on the position information derived from the arrival times of the ionization tracks at the detector planes at both sides of the MUSIC-III chamber. The vertical positions will be obtained from the proportional counters with the method of charge division of the anode signals and from a readout of the cathode pads. The cathode pads of 1.2 cm width are modulo-five connected to five preamplifiers, so that the local position within a group of five pads (6 cm) can be determined with high precision. The coarse position is obtained from the resistive anode readout at both ends of the $\approx$ 30-cm long detector units. Three such detector units are needed to subtend the full height of the MUSIC-III chamber while four such proportional sections on either side of the chamber will provide sufficient redundancy for the tracking of the fragment trajectories.

4 Beam time request

The beam time request is based on the desire to collect high statistics data sets that will allow us to pursue the proposed investigations with the necessary accuracy. Experience from previous experiments shows that 10^6 events per system represent an absolute minimum needed to permit sorting according to $Z_{\rm bound}$ (impact parameter), $Z_{\rm max}$ (type of partition) and/or kinematic variables (see [17, 18]).

The following estimate may serve as an example: yield ratios of mirror nuclei, such as ^{7}Li/^{7}Be or ^{13}C/^{13}N, are particularly robust with respect to sequential decay and, therefore, rather useful observables for isotopic studies. For the relative accuracy of such ratios, given by the counting statistics, a value of 2% is not excessive (cf. [8]), and thus about 5000 counts for each of the two species will be required. In the reaction ^{197}Au on Pb at 600 MeV per nucleon, beryllium fragments are produced with a cross section of 130 mb if collisions with $40 \leq Z_{\rm bound} \leq 49$ are selected [27]. Of these about 20% are ^{7}Be, the production cross section in this impact-parameter bin thus being about 25 mb, and, with a total reaction cross section of 6 b for ^{197}Au on Pb, a total of 1.2 Mio events will have to be collected. The bin in $Z_{\rm bound}$ chosen for this example is near the maximum of fragment production for this particular reaction. Sorting into finer bins or the study of less abundant species, as e.g. the ^{13}C/^{13}N ratio, will therefore require the collection of several millions of events.

In the most difficult case of ^{106}Sn, an incident total beam of 10000/spill may contain about 2000/spill of the desired species, corresponding to 300/s, on average. With the 2.5% target a total of 1.2 Mio events will be collected within 44 hours, not counting any extended down times of the accelerator, fragment separator or of the ALADIN spectrometer.

For the runs with the heaviest projectile, ^{197}Au, the acceptable space charge in the MUSIC-III detector limits the incident beam to about 1000/s. The expected data rates are thus typically 20 recorded events per second, corresponding to 10^6 events every 14 hours. With the measured momenta for all fragments above the $Z \geq 2$ threshold, two-particle observables such as fragment-fragment correlation functions can be constructed. Also for this purpose, about 10^6 events is the minimum statistics needed, as has been illustrated in more detail in our previous proposal for experiment S201 [28].

Counting rates larger by a factor of about three can be expected for the lighter stable beam ^{124}Sn, because of the smaller space charge generated by the $Z = 50$ projectiles in the MUSIC chamber. With this projectile, the data sets with the highest statistics can be collected, and, e.g., the effect of the isotopic composition of the target on the projectile fragmentation will only be tested with ^{124}Sn.

An overall duty cycle of 60% seems realistic for the experiments with primary beams, after SIS operation and routine checks of the experimental setup are taken into account. The secondary-beam operation may prove more difficult, however. Extra time will be needed for the tuning of the FRS, the calibration of the detectors used to measure the projectile Z, the choice of the proper slit positions at the FRS, and the transport of the low-intensity beams to the target in Cave B. We therefore estimate that high statistics data sets of possibly several million events can be collected within one day for the stable ^{124}Sn beam, while 1.5 days with ^{197}Au beam and 2.5 days with the secondary beams are needed to collect a minimum of, at least, one million events. The full program will consist of 4 runs with ^{197}Au (two energies with two targets each), 2 runs with ^{124}Sn (one energy and two targets), and of one run with each of the two secondary beams.

Provided that sufficient time with test beams has been available prior to the main experiment, the debugging of the system can be achieved within one day. Calibration runs (sweep runs with continuous variations of the ALADIN magnetic field) are needed in regular intervals. The request, therefore, consists of

control of setup	1 day	
^{197}Au @ 0.6 AGeV	3 days	targets C, Au
^{197}Au @ 1.0 AGeV	3 days	targets C, Au
switch to ^{124}Sn	0.5 day	
^{124}Sn @ 0.6 AGeV	2 days	targets Ni, In
switch to ^{124}La	2 days	
^{124}La @ 0.6 AGeV	2.5 days	target In
^{106}Sn @ 0.6 AGeV	2.5 days	target In
calibrations	1.5 days	

The total request amounts to 18 days (54 shifts).

Since new detector systems will be installed and new techniques applied, it is indispensable that sufficient test beam will be available prior to the main experiment. Part of the tests can be done with carbon beams in a parasitic mode.

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