Determination of the Freeze-out Temperature by the Isospin Thermometer

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Abstract: Previous data on isotopic distributions of heavy projectile fragments, measured at the FRS with ^{238}U and ^{208}Pb beams, give some indication that the initial temperature of the last stage of the reaction, the sequential decay, is limited to a universal value. We are interested to obtain more conclusive data with a dedicated experiment with ^{124}Xe and ^{136}Xe beams. Xenon allows for a large variation of the neutron excess of the projectile and avoids problems of the previous data due to large fission competition. We expect that this detailed information that we will get from the high-resolution spectrometer FRS, combined with the global information from large-acceptance set-ups like ALADIN, will give a new experimental access to determine the freeze-out temperature in the fragmentation process.

Introduction

With the SIS accelerator and the fragment separator FRS, GSI has unique experimental equipment to determine the full nuclide production in relativistic heavy-ion collisions. An experimental program, dedicated to obtain basic data for the incineration of nuclear waste, has generated isotopic distributions of the reactions ^{238}U + Pb [1], ^{238}U + Ti [2], and ^{208}Pb + Ti [3], all at 1 A GeV, as a by-product.

An overview on these data for fragmentation-evaporation residues is given in figure 1, where the mean neutron-over-proton ratio of the isotopic distributions of the different reactions studied is shown for the different elements. Contributions from fragmentation-fission residues have been suppressed as shown in reference [1]. The isotopic distributions of the heaviest elements, down to about 20 units below the projectile, not included in the figure, show the expected behaviour: With increasing loss of protons, the neutron excess of the projectile is gradually lost by neutron evaporation, until the universal "evaporation-residue corridor" is reached, which is situated at the neutron-deficient side of the valley of beta stability. It is the

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basic assumption of the EPAX parameterisation [4] that the location of the evaporation-residue corridor on the chart of the nuclides does not depend on the projectile. The isotopic distributions of the lighter elements, however, show an unexpected feature: they do not follow the evaporation corridor any more as predicted by EPAX, but are again shifted to the neutron-rich side. They even tend to cross the beta-stability line. In addition, this shift depends on the neutron excess of the projectile. While the use of the more neutron-rich projectile ^{238}U leads to more neutron-rich products, the target does not seem to have any influence. (We would like to stress that the isotopic distributions of the fragmentation-evaporation residues below Z = 70 are expected not to be influenced by fission, which is not considered in EPAX.)

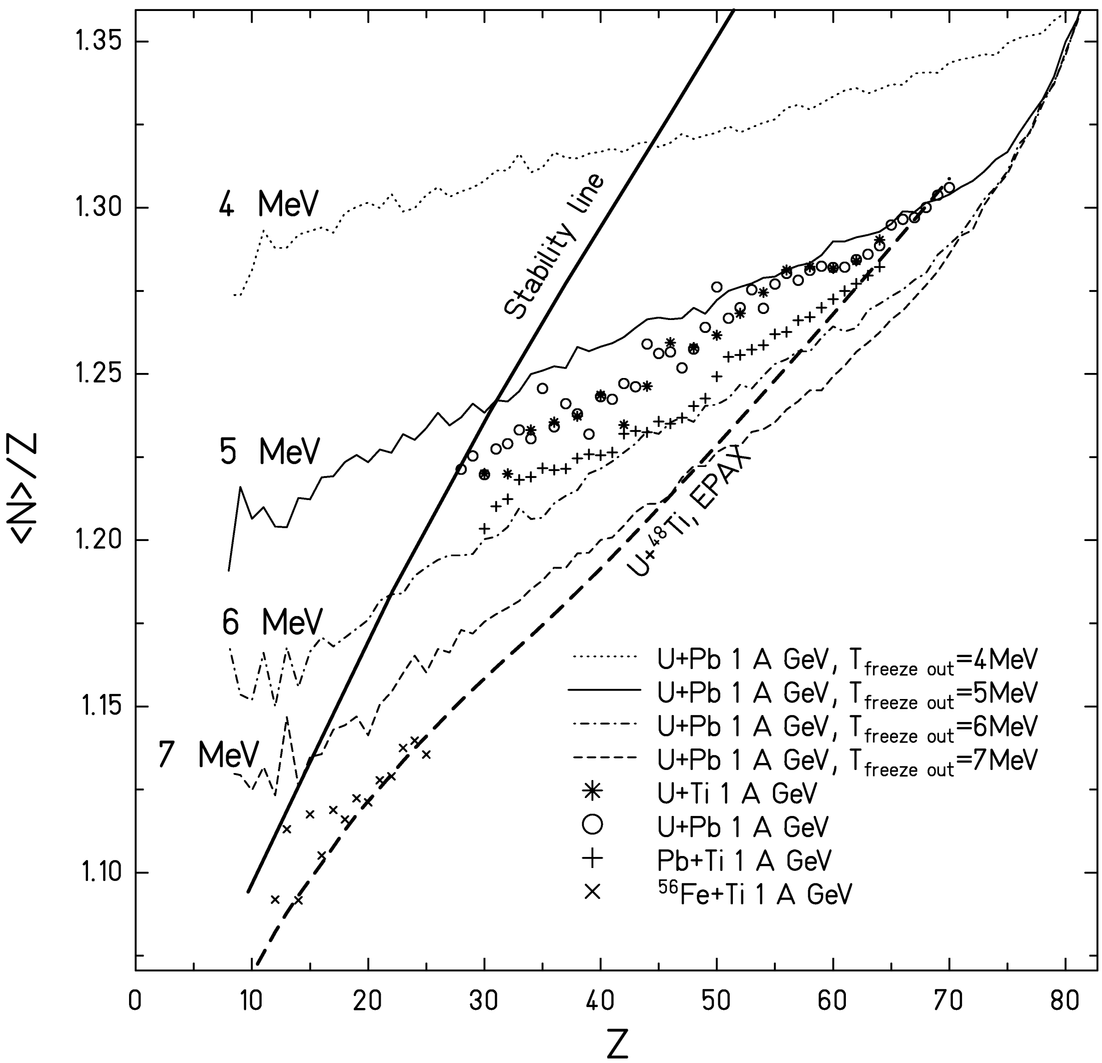

Figure 1: Experimental data on mean neutron-over-proton ratios of heavy fragmentation-evaporation residues produced in the fragmentation of ^{238}U + Pb [1], of ^{238}U + Ti [2], of ^{208}Pb + Ti [3], and of ^{56}Fe + Ti [5] in comparison with the predictions of EPAX [4]. In addition, the results of a simple three-step nuclear-reaction model for the reaction ^{238}U + Pb are given. It considers abrasion, break up and sequential decay (see text), using different values of the freeze-out temperature of the break-up stage.

Figure 2 gives a detailed view on the isotopic distribution of zirconium, produced in the fragmentation of uranium in a lead target. It is shifted to the neutron-rich side if compared to the EPAX systematics.

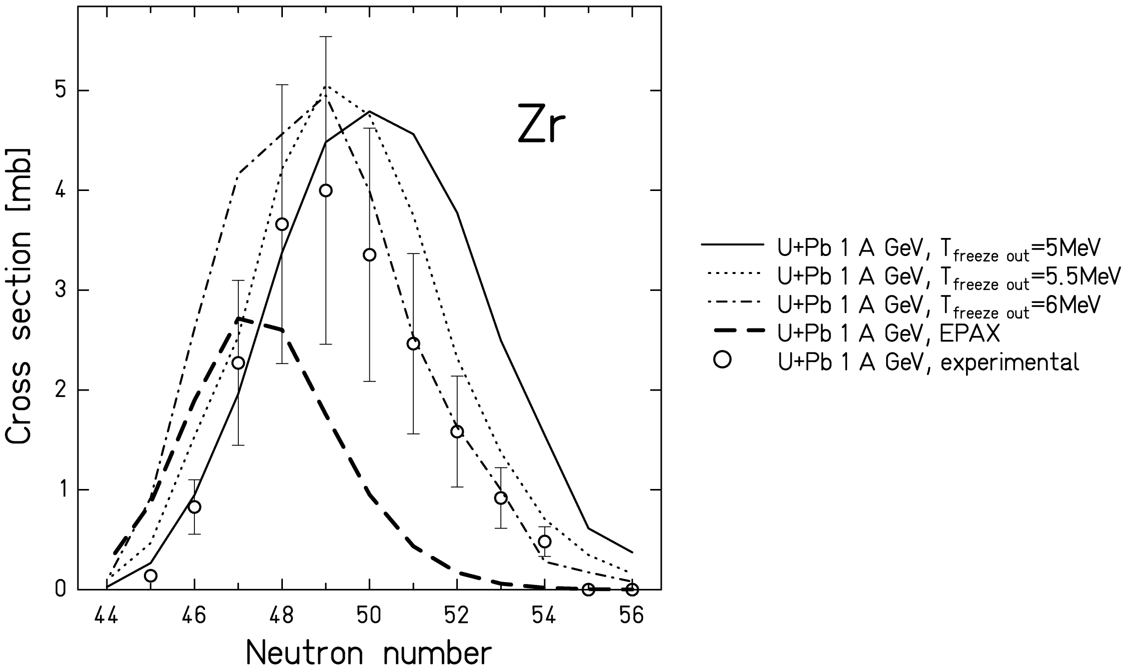

Figure 2: Cross sections of zirconium isotopes produced in the fragmentation of ^{238}U + Pb [1] in comparison with the predictions of EPAX [4], and ABRABLA, evaluated at the freeze-out temperatures 5, 5.5 and 6 MeV.

Motivation

The isospin thermometer

We think that the neutron excess of the reaction products is an important signature of the reaction mechanism. Although the full physics content can only be extracted by use of elaborate nuclear-reaction models, we would like to outline the main features of a possible interpretation in a schematic way.

High-energy nuclear reactions can roughly be divided in separate steps: the abrasion process of initial nucleon-nucleon collisions which leaves an excited projectile spectator, an eventual break-up phase, and the final sequential decay by an evaporation cascade. It is the subject of intense research to investigate the characteristics of the break-up phase, e.g. by studying multi-fragmentation (see e.g. ref. [6]). One of the main interests is its possible relation to the nuclear liquid-gas phase transition. These three reaction steps have different influence on the N-over-Z ratio. Firstly, the projectile spectator is expected to keep the neutron excess of the projectile on the average. Secondly, the influence of a simultaneous break-up on the neutron excess of the products is not so clear. Although a break-up in several fragments is not expected to lead to an appreciable variation of the neutron excess [7], it is discussed that the separation into a gaseous and a liquid phase due to spinodal instabilities [8] could lead to a reduction of the neutron excess of the liquid phase. Finally, the evaporation cascade gradually reduces the neutron excess and tends to end up in the universal evaporation corridor which is situated on the neutron-deficient side of the beta-stability valley.

If we neglect the modification of the neutron excess by the break-up phase for the moment, the neutron-to-proton ratio of the final fragments is a direct measure of the length of the evaporation chain and, with the knowledge of the relevant parameters like level densities and binding energies, it allows to determine the excitation energy at the beginning of the evaporation cascade. Thus, it gives direct information on the freeze-out temperature of the break-up phase. Including an eventual decrease of the neutron excess in the break-up phase, this analysis still gives an upper limit of the freeze-out temperature.

A simple three-stage model

We have used a three-stage model with an abrasion stage, a break-up stage and an evaporation stage for a very rough interpretation of the available data. The projectile spectator acquires an excitation energy of 27 MeV per nucleon abraded [9]. (Reference [9] demonstrates the application of the isospin thermometer for very peripheral collisions.) If this energy leads to temperatures above the freeze-out temperature, the additional energy is removed in a break-up phase. This energy reduction is connected with a mass loss in form of nucleons or light clusters, which is not specified explicitly. We assume that the N-over-Z ratio is conserved. The loss of 1 mass unit per 10 MeV energy loss is assumed on the average, but this parameter only enters into the absolute cross sections, not into the shape of the final isotopic distributions. Finally, a standard evaporation follows.

The results of such a calculation with different values assumed for the freeze-out temperature are shown in figure 1. A remarkable agreement with the data is found, if a value of 5 to 5.5 MeV is used for the freeze-out temperature in all cases.

We also performed a similar analysis using the statistical multi-fragmentation model (SMM) [10] for the last stages of the reaction which includes the effects of thermal expansion and break-up into several fragments. This analysis came to almost identical conclusions on the freeze-out temperature.

We think that the application of the isospin thermometer will contribute in a very significant way to the preceding efforts to determine the freeze-out temperature of the break-up stage, based on the spectra of emitted particles, the isobaric ratios and the population of excited levels. The new data, which can only be obtained in a high-resolution spectrometer, in connection with the large body of data obtained in large-acceptance experiments will certainly help to answer some of the open questions on the dynamic properties of hot nuclear matter.

Proposed experiment

The data presented in the introduction are very promising, but not satisfactory. First, the targets used were very thin, so that parasitic reactions in the SEETRAM current monitor and in the vacuum window, which protects the SIS vacuum against the FRS, are important. This fact introduces relatively large uncertainties in the absolute cross sections, which are certainly to be included in comprehensive theoretical interpretation. Secondly, most of the previous data have been taken for correcting the cross sections in hydrogen for the contribution of the titanium windows. Therefore, they are incomplete for the purpose of the present proposal. A third disadvantage is the large fission cross section in these reactions. Although the tracking information in the FRS allows to reconstruct the kinematics and to distinguish between the different reaction mechanism, the high precision required for the present purpose is difficult to reach. Finally, the comparison between the ^{208}Pb and ^{238}U fragmentation might not be conclusive, because these are different elements with a very different fission competition.

Therefore, we propose to perform a dedicated experiment with the two most extreme xenon projectiles, ^{124}Xe and ^{136}Xe. Xenon was chosen because ^{136}Xe is the most neutron-rich primordial isotope in this mass range. In the direct comparison, the fragments of ^{124}Xe should closely follow the evaporation-residue corridor, while the ^{136}Xe products are expected to show a similar neutron excess as those observed in the fragmentation of ^{208}Pb. As a target we propose titanium in order to introduce sufficiently high excitation energies. We intend to perform the experiment at a beam energy of 1 A GeV to obtain best conditions for the transmission of the reaction products through the FRS. The dependence of the reaction mechanism on the beam energy might the subject of future experiments.

Figure 3 shows the expected mean neutron-to-proton ratio of the fragmentation products as a function of their nuclear charge. Obviously, a clear experimental signature is expected: The isotopic distributions differ considerably over the whole range. It is essential to measure both systems in order to establish this isotopic effect experimentally and to determine the freeze-out temperature. (The sensitivity of the data to the value of the freeze-out temperature, demonstrated in figure 1, is not shown explicitely not to overload the figure.)

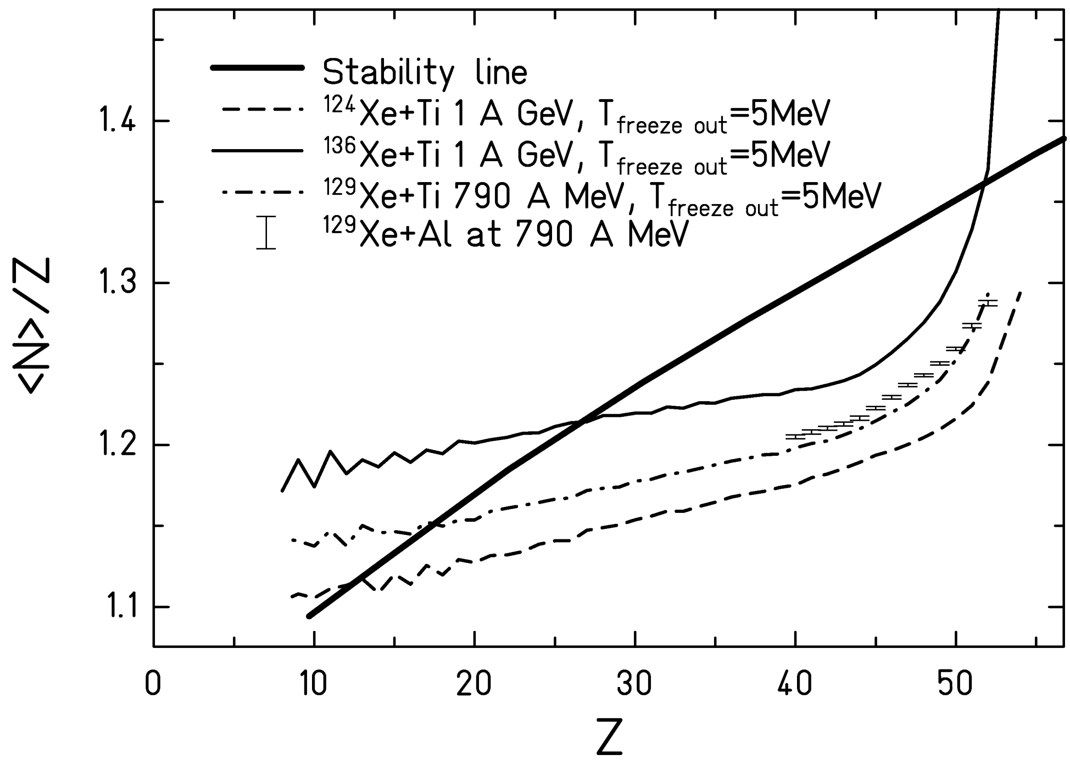

Figure 3: Calculated mean neutron-over-proton ratios of heavy residues produced in the fragmentation of ^{124}Xe + Ti and ^{136}Xe + Ti. A simple three-step nuclear-reaction model was used, which considers abrasion, break up and sequential decay (see text). The freeze-out temperature was fixed to 5 MeV. In addition we compare available data [12] on ^{129}Xe + Al with the model calculation.

Previous measurements on fragmentation of nuclei in this mass range [11, 12, 13] were dedicated to other purposes and do not yield the relevant information for the questions raised in this proposal. The available data from the system ^{129}Xe + Al are included in figure 3. They agree remarkably well with the model calculation, although they do not reach below charge 40.

We consider this experiment as an important complement of the approved experiment “Mass and isospin effects in multifragmentation” proposed by the ALADIN collaboration with the special goal of fully identifying the heaviest fragments in N and Z in a high-resolution spectrometer.

Additional interest

Without any additional effort, the proposed experiment will yield very interesting new information to an experimental program on cold fragmentation [14], using an extremely neutron-rich projectile in the fission-fragment range. (Previous data on the fragmentation of ^{136}Xe only cover a few isolated nuclides [13].)

Another point of interest is the strong even-odd structure observed previously in the cross sections of $N = Z$ nuclei in different fragmentation reactions [15,16]. Recent data on the fragmentation of ^{56}Fe [5] show this effect very clearly. A strong variation has been observed up to $Z = 20$. The fragmentation of ^{124}Xe will allow to study this effect up to about $Z = 40$. These data might stimulate progress in the understanding of alpha clustering or neutron-proton pairing, eventually connected to the Wigner term in the nuclear binding.

Beam-time request

For the measurement of the isotopic cross sections the standard configuration of the FRS will be used: this set up allows for a data-acquisition rate of *~ 2000 events/s.* To reach a statistical uncertainty of *1%* we will need *10^4 events/nucleus*. In the case of simultaneous transmission of several fragments in the same setting, we expect a ratio between the highest and the lowest cross section of about *10*. Therefore *10^5 events/nucleus* are needed to obtain a statistical uncertainty of *1%* for nuclei with lowest cross section. Since in one setting the number of transmitted isotopes is ~ *40*, we need *$4\cdot 10^6$ events/setting*. A counting time of 0.5 hour appears sufficient for one setting. In order to reconstruct the full velocity distribution for each fragment, the $B\rho$ scanning should be made in steps of *2%*. For each beam we consider two series of $B\rho$ settings, one for the lower charges (30 settings), one for the higher charges (18 settings).

Projectile	*Beam energy*	*Type of measurement*	*Number of settings*	*Beam time requested*
^{136}Xe	1·A GeV	Low Z cross sections	30	26 hours
^{136}Xe	1·A GeV	High Z cross sections	18	16 hours
^{124}Xe	1·A GeV	Low Z cross sections	30	26 hours
^{124}Xe	1·A GeV	High Z cross sections	18	16 hours

The total beam time requested to realise our experimental program of the xenon fragmentation measurement is 6 days, including time needed for FRS calibrations.

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