Determination of the freeze-out temperature with the isospin thermometer

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As a prominent signature of instabilities of highly excited nuclei, the *multifragmentation* process, i.e. the formation of several clusters in a simultaneous break-up, has extensively been studied. Efforts are being made to deduce information on the liquid-gas-type phase transition of nuclear matter [1].

In this report we describe our efforts to obtain complementary information on thermal instabilities of nuclei from an alternative approach, by measuring nuclide cross sections of heavy residues in the fragmentation of ^{238}U in a lead target [2]. The experiment was performed in inverse kinematics with the fragment separator (FRS) at GSI. With the FRS the residual nuclei can be fully identified, and their velocities can be precisely evaluated from their magnetic rigidities. In this way, fission events could be discriminated and non-fission data were used to construct the fragmentation isotopic distribution of every observed element.

In figure 1, the so-obtained values of the mean *N*-over-*Z* ratio of the fragmentation products are presented as a function of the nuclear charge, *Z*. The experimental results are compared with two "reference" lines, the position of the beta-stability valley and the expectation of EPAX [3], a semi-empirical code based on the idea that fragmentation products result from long, *sequential* evaporation chains. Surprisingly enough, the experimental data show large mean values, with a tendency to even cross the stability line for products with nuclear charge below ≈ 28. Lighter residues obviously experienced an evaporation cascade that was too short to reach the evaporation corridor. *More violent collisions seem to introduce lower excitation energies.* These apparently contradictory results can be explained assuming that the residues are formed in a *simultaneous* break-up process. This has two essential characteristics. Firstly, most of the energy acquired in the collision is consumed in the break-up stage and the remaining excitation energy is shared among the clusters. Secondly, the *N*-over-*Z* ratio of these clusters is expected to be close to the one of total decaying system. Indeed, the data can be explained assuming that the freeze-out temperature, i.e. the temperature of the clusters, at which the evaporation process starts, has a well-defined value, and it represents a limiting temperature above which no fully equilibrated compound nucleus can exist.

This idea is the basis of the *isospin thermometer* [4], a specific method used to deduce the temperature of nuclear systems from the isotopic distributions of the residues. The method consists of applying an evaporation code, with the quite well known ingredients of the statistical model, in order to deduce the temperature at the beginning of the evaporation cascade. For this purpose we have used the statistical multifragmentation model, SMM [5]. Within this model, a microcanonical ensemble of all break-up channels composed of nucleons and excited fragments of different masses is considered. It is assumed that an excited nucleus expands to a certain volume and then breaks up into nucleons and hot fragments. All possible break-up channels are considered. It is also assumed that at the break-up time the nucleus is in thermal equilibrium characterised by the channel temperature *T*. After break-up of the system, the fragments propagate independently in their mutual Coulomb fields and undergo secondary decays (evaporation-fission or Fermi break-up). In figure 1, the mean *N*-over-*Z* ratio of the isotopic distributions that results from these calculations, starting from different freeze-out temperatures, is compared to the experimental values. With increasing temperature, the mean neutron excess approaches the evaporation-residue corridor, marked by EPAX. There is a remarkable agreement found with the data when a freeze-out temperature close to 5 MeV is assumed. A similar conclusion has also been deduced from light charged particles emitted from intermediate-mass fragments in the range from Z = 2 to Z = 30 produced in central collisions of ^{129}Xe + ^{nat}Sn at 50 A MeV [6]. Thus, heavy-ion collisions in very different energy regimes show signatures of the same phenomenon.

By the use of a high-resolution spectrometer, we have revealed a new experimental signature of thermal instabilities of nuclei. A possible information on the liquid-gas like phase transition from this signature is clearly related to the liquid phase.

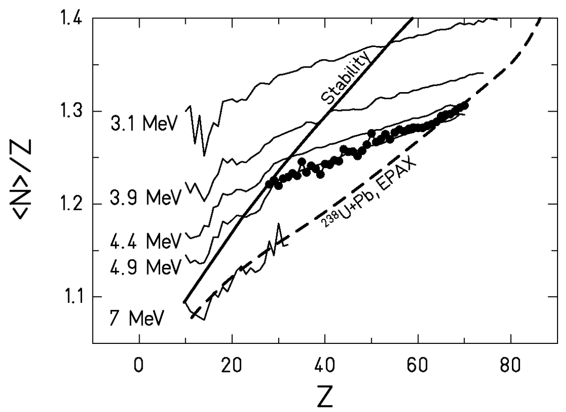

Figure 1: Experimental mean *N*-over-*Z* ratio of the fragmentation residues produced in the reaction ^{238}U on lead at $1 \cdot A$ GeV (full points), compared to the valley of beta stability and the prediction of EPAX. Fission events are not included. Mean neutron excess of the isotopic distributions of heavy residues obtained with the SMM model with different values of the freeze-out temperature show that there is a remarkable agreement with the data when a freeze-out temperature of 5 MeV is assumed.

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