Origin of the even-odd effect in the yields from high-energy reactions

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In 2004, the analysis of experimental production cross-sections of relatively light nuclei (Z>6) produced by fragmentation in the reaction ^{238}U+Ti at 1 *A* GeV revealed a very strong and complex even-odd staggering [1]. The experiment was performed at the FRS, at GSI, Darmstadt. It was concluded that structural effects cannot be attributed to the surviving of nuclear structure of the colliding nuclei, as in low-energy fission; the structures appear as the result of the condensation process of heated nuclear matter while cooling down in the evaporation process [1].

Here, we want to discuss which kind of staggering we have to expect in the cold final products due to the influence of an evaporation cascade starting from hot pre-fragments. After their formation, the initial pre-fragments are definitely free of any even-odd structure, because there is no pairing above the critical energy. The number of available states from a certain total excitation energy of the decaying system is essentially determined by a mostly structureless level density above a fictive liquid-drop ground state. This structureless cloud in *N* and *Z* rains down in excitation energy and in nucleon number due to evaporation. This process is essentially deterministic, because in most cases one particle dominates and the variation of the kinetic energy of the emitted particle is small compared to the binding energy. In this way, a well-defined 3-dimensional subspace of the *N, Z ,E** initial production cloud ends up in a certain fragment. As a consequence, *the final yields will be modulated by the range of excitation energy below the lowest particle threshold*. In order to visualise this idea, in figure 1 we present the lowest particle threshold for each nuclide, calculated as the minimum value between the proton and neutron separation energies. The data are taken from ref. [3].

Recently, we performed a new systematic analysis of the even-odd effect over a large range of nuclear reactions, nuclear systems and energies. It is impressive how the staggering of the lowest particle threshold, shown in figure 1, is consistent with the even-odd staggering in the yields of ref. [1] and all other analysed data.

Hereafter, among all new analysed data, we focus on the reaction ^{56}Fe+Ti at 1 *A* GeV [2], where it was possible to extend the measurement of production cross sections down to Li isotopes. The kinematical properties of the light products (IMF) indicate that they are produced in multifragmentation events, as a consequence of a thermal instability. We will consider two possible scenarios at freeze-out. In the first scenario, the IMFs are essentially produced in their ground state; the yields are governed by Boltzmann statistics under certain conditions. This implies that the essential parameter related to the yields is the binding energy of the respective IMF. In the second scenario, the fragments at freeze-out are essentially produced with excitation energies above the critical pairing energy and will undergo the de-excitation process; the essential parameter related to the yields is the lowest particle threshold of the respective IMF. In figure 2, the measured IMF cross sections from ref. [2] are compared to the extra binding energy due to pairing (obtained by subtracting a calculated LD part from the values of ref. [3]) and to the lowest particle separation energy. The results indicate clearly that assuming that IMFs are produced cold at freeze-out is wrong, even for very light IMFs such as Li isotopes. So, it is dangerous to extract fundamental properties of hot nuclear matter assuming that the population at freeze-out is well represented by the Boltzmann factor. The situation is even more severe when these methods are extended to treat even heavier final fragments. It was recognized previously that the determination of the freeze-out temperature with the isotopic yield thermometer might be disturbed by the evaporation process. Several authors investigated this problem and proposed suitable corrections to this effect. Our analysis opens a new view on this problem showing that the fine structure observed in the yields can be explained fully by the evaporation process. This specific feature does not show any noticeable influence of the Boltzmann factor.

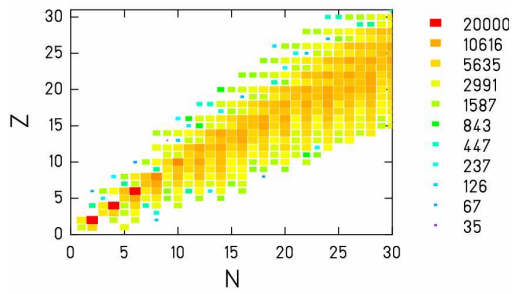

Figure 1: Lowest particle threshold (in keV).

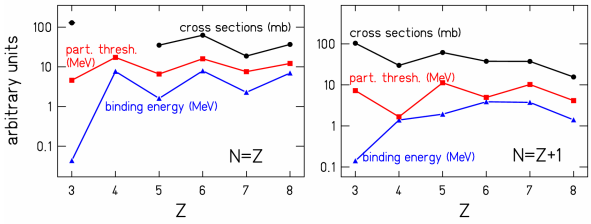

Figure 2: Staggering in the lowest particle threshold (MeV) and in the binding energies (MeV) compared to measured fragmentation cross sections (mb).

References

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[2] P. Napolitani et al., Phys. Rev. C 70 (2004) 054607.
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