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Complex nuclear-structure phenomena in the cooling down of highly excited nuclear systems

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Abstract: Complex structural effects in the nuclide production from the projectile fragmentation of 1 *A* GeV ^{238}U nuclei in a titanium target, manifested as an even-odd effect, are reported. The structure seems to be insensitive to the excitation energy induced in the reaction. This is in contrast to the prominent structural features found in nuclear fission and in transfer reactions, which gradually disappear with increasing excitation energy. Most of the features of the results are reproduced using the statistical model of nuclear reactions, treating the pairing correlations in a consistent way both in the masses and in the level densities. The structures appear as the result of the condensation process of heated nuclear matter while cooling down in the evaporation process. As such, it can be considered a manifestation of the passage from the normal liquid phase of the nucleus to its superfluid phase.

Keywords: NUCLEAR REACTIONS: ^{238}U + Ti, E_{beam} = 1 *A* GeV; nuclide identification by high-resolution magnetic spectrometer; production yields of light residues. NUCLEAR STRUCTURE: complex even-odd structure in nuclide production.

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1. Introduction

Signatures of the phase transition from superfluid to normal liquid have been observed already several years ago. A beautiful example is represented by the sharp change in the moment of inertia with the increase of the temperature of low-energy fissioning polonium isotopes, shown in ref. [1]. At high temperatures the moments of inertia are high, indicating that the nucleus behaves almost like a rigid rotor. This is a condition of large viscosity. At very low temperatures the moments of inertia are low, indicating behaviour similar to an irrotational flow. This is a condition of minimum viscosity, which is what characterizes a superfluid. The passage from high viscosity to low viscosity is not continuous, but it has a sharp change around the critical point, occurring at 10 MeV excitation energy. Signatures of the superfluid phase of nuclei were also found in the production yields in specific nuclear reactions at low energies. The enhanced production of even elements in low-energy fission is a typical example of these signatures. The even-odd structure gradually disappears and transforms into a smooth distribution with increasing excitation energy induced in the reaction. The global even-odd effect in proton and neutron number as a function of the excitation energy at scission was calculated by means of a statistical model [2]. The analysis clearly showed that the observation of this kind of even-odd effect in fission is restricted to excitation energies at scission below the superfluid phase transition, which occurs around 10 MeV. In other words, structural effects do not survive above the critical point.

In this contribution, we report on the even-odd structure observed in the production cross sections from the projectile fragmentation of 1 *A* GeV ^{238}U nuclei in a titanium target, measured at GSI. This structure is systematically investigated with full nuclide identification over an extended area of the chart of the nuclides. These structural effects, appearing in the

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residual nuclei produced in a rather violent collision, cannot be attributed to the surviving of nuclear structures at very low energies. We will discuss the reason for this structure and offer our interpretation in the frame of the statistical model.

2. Experimental results

The residual nuclei were fully identified in mass and atomic number with the high-resolution magnetic spectrometer FRS, and their production cross sections were deduced. More details on the experimental technique and on the data analysis can be found in ref. [3]. In Fig.1, the data are presented according to the neutron excess *N-Z*. The production cross sections of the observed fragments, grouped according to this filter, reveal a complex structure. All even-mass nuclei present a visible even-odd effect, which is particularly strong for *N=Z* nuclei. Odd-mass nuclei show a reversed even-odd effect with enhanced production of odd-*Z* nuclei. This enhancement is stronger for nuclei with larger values of *N-Z*. However, for nuclei with *N-Z*=1 the reversed even-odd effect vanishes out at about *Z*=16, and an enhanced production of even-*Z* nuclei can again be observed for *Z* > 16. Finally, all the observed structural effects seem to vanish out as the mass of the fragment increases. A quantitative analysis of the strength of the staggering was performed by means of the equation developed by Tracy [4], which describes the local deviation of the cross sections from a Gaussian-like distribution. In the range covered by the data, the sequence with *N=Z* shows the strongest effect, reaching values of the order of 50%. Thus, this structure is even stronger than any even-odd structure observed in low-energy fission. Other even-mass nuclei show a much weaker effect, hardly exceeding 10%. For odd-mass nuclei, the intensity of the reversed even-odd effect is strongest for *N-Z*=5 nuclei (up to 40%).

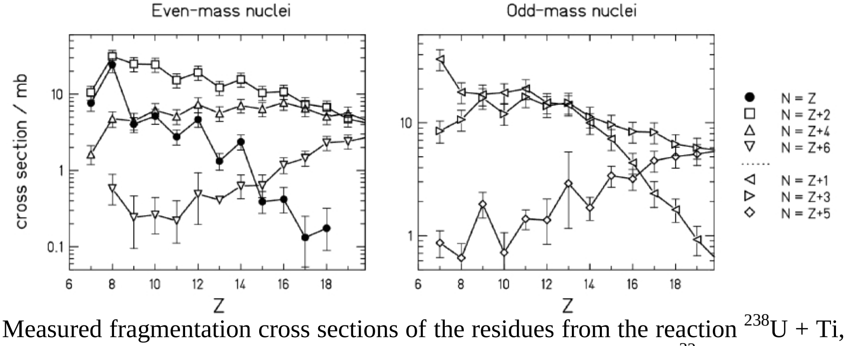

Fig. 1: Measured fragmentation cross sections of the residues from the reaction ^{238}U + Ti, 1 *A* GeV. The data are given for specific values of *N-Z*. The cross section for ^{32}Al (*Z*=13, *N*=*Z*+6) is an extrapolated value. The chain *N=Z* shows the strongest even-odd effect, while the chain *N-Z*=5 shows the strongest reversed even-odd effect.

3. Analysis with an evaporation model

In the last years, a fine structure, manifested as an even-odd effect, was found in the production yields of several deep-inelastic and fragmentation reactions (see table 1 of ref. [3]), which can be quite violent and which are expected to introduce a large amount of excitation energy in the nucleus. Most experiments could determine the nuclear charge of the reaction products, only. Consequently, only the enhancement in the production of even-*Z* elements, found in the order of a few tens per cent, could be investigated. Lately, with the use of spectrometers, also the neutron number became accessible: the most remarkable finding of