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Structural effects in nuclide distributions from fission and fragmentation

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Abstract. A survey is given on structural effects in the nuclide production from fission and fragmentation reactions, including recent results from GSI. The prominent structural features found in low-energy fission are related to pairing correlations and shell effects as described by standard models. A complex fine structure observed in the end-products after the deexcitation of highly excited nuclei is deduced from the production yields of the system ^{238}U+Ti at 1 A GeV. Possible reasons for this structure are discussed, which go beyond the features found in low-energy fission.

Keywords: nuclear reactions; nuclide production cross sections; nuclear structure; even-odd effect; alpha clustering
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1. Introduction

Nuclear structure manifests itself in many features, which are widely investigated, e.g. in ground-state properties like binding energy, half-life, radius and deformation as well as in the properties of specific excited states. In the present contribution, we want to report on another kind of signatures of nuclear structure, appearing in nuclide distributions from different types of nuclear reactions.

These structural effects may be divided in two groups: Most of these structures only appear at low excitation energies, gradually disappearing and giving rise to smooth distributions with increasing excitation energy induced in the reaction. The enhanced production of even elements and the appearance of fission channels in low-energy fission are typical examples of this first group. More recently, another group of structural effects has been observed, which seems to be insensitive to the excitation energy induced in the reaction.

2. Survival of structural effects at low excitation energies

2.1. Even-odd structures

Already from the early radiochemical experiments it has become clear that the production of even elements is enhanced in low-energy fission [1]. The first systematic overview on even-odd structure in a continuous region of fissioning nuclei [2] has only been obtained a few years ago by studying electromagnetic-induced fission from excitation energies around 11 MeV, using secondary beams [3]. Typical examples of theses results are depicted in figure 1. In addition to the element yields of an even-Z and an odd-Z fissioning nucleus, the deduced local relative even-odd effect δ_{rel} is shown, using the following standard prescription [4]:

$$\delta_{rel}(Z+3/2) = \frac{1}{8}(-1)^{Z+1}\left[\ln\mathrm{Y}(\mathrm{Z}+3) - \ln\mathrm{Y}(\mathrm{Z}) - 3\left(\ln\mathrm{Y}(\mathrm{Z}+2) - \ln\mathrm{Y}(\mathrm{Z}+1)\right)\right] \quad (1)$$

For Y we introduce the appropriate cross-section value.

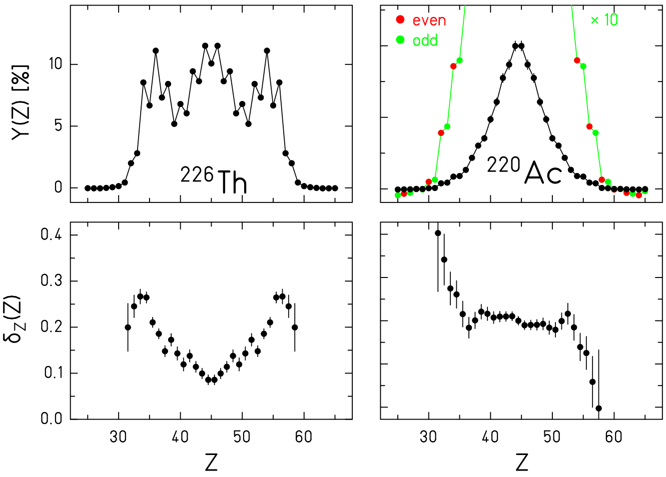

Fig. 1. Upper part: Elemental yields of fission fragments produced in electromagnetic-induced fission of ^{226}Th and ^{220}Ac [2]. Local even-odd effect, deduced from the measured yields with Eq. (1).

While the even-Z system shows an enhanced production of even elements all over the range with an increase of the local even-odd effect for asymmetric charge splits, the odd-Z system shows a positive even-odd effect in the left wing and a negative even-odd effect in the right wing of the distribution. About 70 systems have been investigated, and all reveal essentially the same features. These results could be interpreted with theoretical considerations based on the statistical model. [2] The enhanced production of fission fragments with even neutron or even proton number was quantitatively explained by the number of excited states with a completely paired configuration of the proton or the neutron subsystem, respectively, at the effective scission point, see [5]. Figure 2 shows the global even-odd effect in proton and neutron number as a function of the excitation energy at scission as calculated by this model. It becomes clear 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 [6].

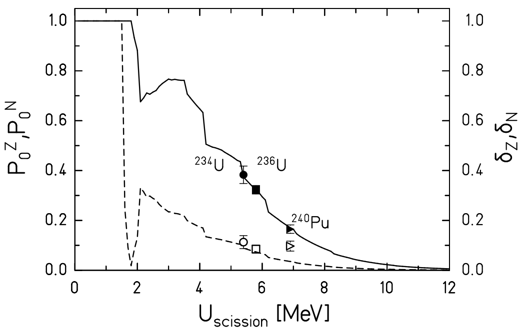

Fig. 2. Calculated probabilities for the survival of fully paired proton (P_0^Z) and neutron (P_0^N) configurations as a function of the thermal excitation energy in the effective scission point [5] compared with experimental even-odd effects (δ_Z and δ_N). Data are given at high kinetic energies of the light fragments for the systems ^{234}U (Ekin = 111 MeV) as circles, ^{236}U (Ekin = 108 MeV) as squares, and ^{240}Pu (Ekin = 111 MeV) as triangles. Full symbols are referred to protons, empty symbols to neutrons. In addition, the global even-odd effects at bins of constant averaged total excitation energies (around 7, 9, 11, 13 and 15 MeV) are shown for spontaneous fission of ^{252}Cf as asterisks. References are given in [7].

2.2. Fission channels

The influence of shell effects on the global shape of fission-fragment mass or charge distributions is known since the observation of asymmetric fission not long after the discovery of nuclear fission. Fission from low excitation energies has been investigated for about 130 systems, about 70 systems have been studied alone in the previously mentioned secondary- beam experiment [3]. The relation between the shell structure in the potential of the highly deformed system on the way from saddle to scission and the preferred mass splits has been emphasized e.g. by Pashkevich [8], Maruhn and Greiner [9], as well as by Brosa et al.[10]. The concept of fission channels has been developed [8,10,11] in agreement with the appearance of specific valleys in the potential-energy landscape. The quantitative explanation of the population of the different fission channels as a function of excitation energy has been related to the disappearance of shell effects in the level density [13–16].

3. Structural effects appearing in the end products of highly excited systems

In several experiments, where different rather violent reactions have been investigated, a fine structure in the nuclide production, manifested as an even-odd effect, has been observed [18–24]. This feature apparently does not belong to the above-mentioned types, characterized by low excitation energies, but it appears in the residues of a deexcitation process starting from highly excited precursors.

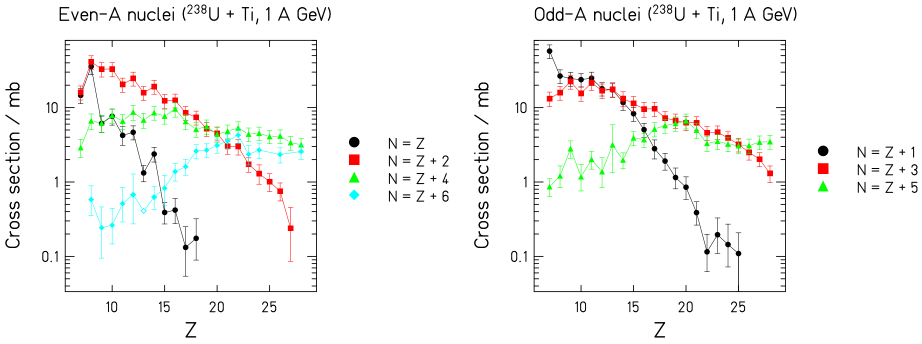

Fig. 3. Nuclide cross sections of the projectile-like reaction products from the reaction ^{238}U+Ti, 1 A GeV [25]. The data are given along specific values of $N - Z$. The chain $N = Z$ shows the strongest even-odd effect, while the chain $N = Z + 5$ shows a strong reversed even-odd effect.

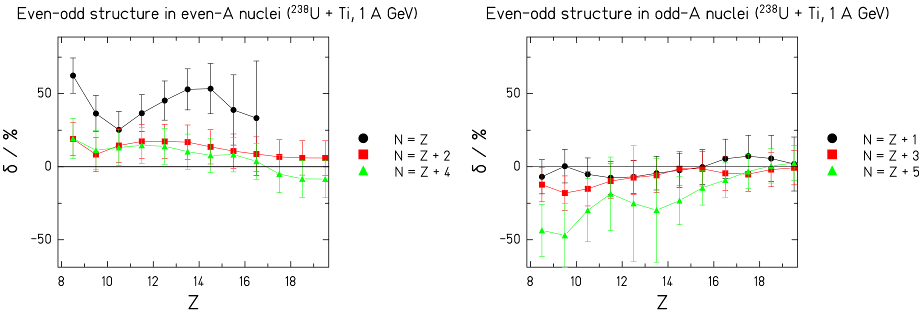

Fig. 4. Local even-odd effect deduced from the cross sections reported in Figure 3 by the use of the equation (1).

Most experiments could determine the nuclear charge of the reaction products only. With the use of mass spectrometers also the neutron number is accessible: the most remarkable finding of these previous experiments was a variation of the magnitude of this fine structure with the mean neutron excess of the reaction products [24].

In the present work, we report on new results [25] obtained in the reaction ^{238}U+Ti in an experiment at the fragment separator of GSI, which provided full nuclide identification of the projectile-like reaction products. Figure 3 gives a quantitative view on the data for cuts with given values of $N - Z$. These data reveal a complex structure, which is quantitatively evaluated as the local even-odd effect by Eq. (1) in Figure 4. In the range covered by the data, the sequence with $N = Z$ shows by far the strongest effect, reaching values in the order of 50 %. Other even-A nuclei show a much lower even-odd effect, hardly exceeding 10 %. Another remarkable feature is a very strong reversed even-odd effect for the lightest, most neutron-rich, odd-A residues. Thus, our experiment is in agreement with the results reported in ref. [24], but it provides even more detailed information.

4. Discussion

While the appearance of fission channels and even-odd effects in the fission-fragment distributions after low-energy fission is sufficiently well explained by the two most prominent nuclear-structure effects, the appearance of a fine structure after violent heavy-ion collisions needs a more elaborate discussion. This has already been stated by Ericson [26] in his famous article about nuclear level densities. There is no first-order explanation of the observation of the even-odd structure in the cross sections of $N = Z$ nuclei by pairing correlations. Recently, several complex phenomena of nuclear structure have been discussed in other context, which could also be responsible for this fine structure observed in the end-products of highly excited systems. At first, we mention the *interplay between pairing and mean-field effects* (e.g. [27]). The even-odd mass differences are understood as the sum of the variation of pairing correlations in a given potential, the blocking effect, as discussed above, and the spontaneous breaking of spherical symmetry due to the presence of unpaired particles (Jahn-Teller effect [28]). The even-odd structure in the production cross sections of $N = Z$ nuclei is particularly strong. The even-even nuclei of this class are multiples of alpha particles. Therefore it is tempting to relate the specific behavior of $N = Z$ nuclei to the phenomenon of *alpha clustering* in nuclei. Also neutron-proton pairing is discussed to play in important role in $N = Z$ nuclei. Therefore, an eventual influence of *neutron-proton pairing* on the energy of excited levels could be another explanation for the strong even-odd structure in the production yields of the $N = Z$ nuclei. The reversed proton even-odd effect in the production of very neutron-rich even-mass nuclei, which is opposite to a slight positive even-odd effect in the masses, is another interesting effect of nuclear structure.

5. Conclusion

Structural effects in the yields of the final products of fission and fragmentation reactions have been investigated. While the even-odd structure and the fission channels in the fission- fragment distribution after low-energy fission seems to be understood by standard models as manifestations of pairing correlations and shell structure, the fine structure appearing in the production cross sections of light nuclei from the decay of highly excited nuclei seems to be a signature of more complex phenomena.

It seems that a systematic investigation of the fine structure in the production yields from highly excited nuclei is a rich source of information on nuclear-structure phenomena in slightly excited nuclei found at the end of their evaporation process. It is a challenge to quantitatively interpret these results with theoretical models in order to better understand the complex nuclear-structure phenomena behind.

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