International Journal of Modern Physics E

STRUCTURAL EFFECTS IN THE NUCLIDE DISTRIBUTIONS OF THE RESIDUES OF HIGHLY EXCITED SYSTEMS

P. NAPOLITANI, F. REJMUND and L. TASSAN-GOT
IPN Orsay, IN2P3, 91406 Orsay, France

M. V. RICCIARDI, A. KELIC, K.-H. SCHMIDT and O. YORDANOV
GSI, Planckstr. 1, 64291 Darmstadt, Germany

A. V. IGNATYUK
IPPE, Bondarenko Squ. 1, 249020 Obninsk, Russia

C. VILLAGRASA
DAPNIA/SPhN, CEA/Saclay, 91191 Gif sur Yvette, France

New data from GSI on the production-cross-section for fragmentation of the systems ^{56}Fe+p and ^{136}Xe+p at 1 A GeV revealed the appearance of even-odd staggering in the cross-section distribution for chains of isotopes with given N-Z. The staggering is strongly enhanced for the chain N=Z, it reduces as the production moves away from the N=Z chain, and it reverses for the most neutron-rich odd-A residues. These phenomena, observed in the residues of rather violent reactions, are related to structural effects in the level-densities below the particle-emission threshold.

1. Introduction

Nuclear structure is extensively studied in relation to mean-field properties, by analyzing nuclear masses, binding energy, shell effects or deformation. Addidtional insight on nuclear structure is carried by other frequently investigated observables; among these are the yields of the residues in low energy fission. In this case, the fragment distribution reveals an enhanced production of the even elements, which gradually vanishes with increasing reaction energy. The disappearence of this staggering with the excitation energy seemed to constrain the study of nuclear structure to systems with low excitation energies. Though, some experiments dedicated to different and more violent reactions, like spallation or fragmentation, revealed similar structures in the yields of the residues.[1] A very complete systematics of structural effects in the isotopic distributions of highly excited systems is the result of a recent experiment: the residue cross-sections of the reaction ^{56}Fe+p and ^{56}Fe+^{nat}Ti at 1 A GeV were measured in inverse kinematics with the FRagment Separator

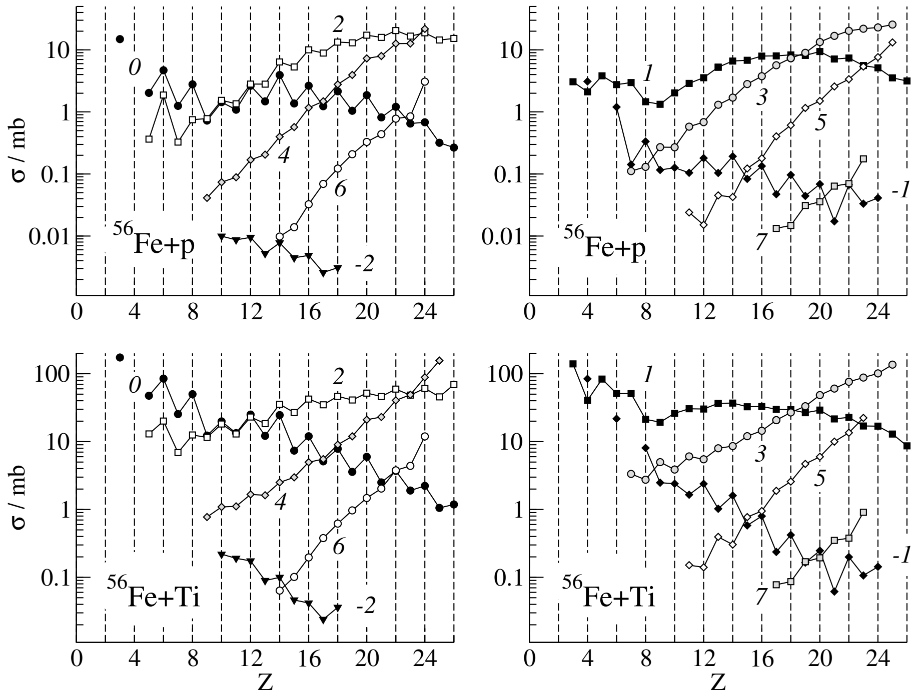

Fig. 1. Experimantal cross sections of ^{56}Fe+p (top) and ^{56}Fe+^{nat}Ti (bottom) for even-mass residues (left) and odd-mass residues (right), respectively. The cross sections are ordered in chains according to given N-Z values. The values of N-Z are marked in the figure, next to the corresponding chains.

at GSI (Darmstadt). In fig. (1) the cross sections are presented ordered according to different chains of isotopes with given N-Z, for even (left) and odd (right) masses, respectively. Even-mass isotopes manifest an enhanced production of even elements all along the different chains. The staggering is maximum for symmetric nuclei (N=Z), and it gradually smooths down for more asymmetric isotopes. The case of odd masses is more complex: proton-rich isotopes (the chain N-Z=-1) show an enhanced production of even elements , while the staggering reverses in favour of an enhanced production of odd elements for neutron-rich nuclei. The ^{56}Fe+^{nat}Ti system, introducing appreciable higher excitation enery than the ^{56}Fe+p system on the average, shows higher cross sections, but identical features in the staggering along the chains of given N-Z. From this comparison, and from the extension to other measured highly excited systems.[1] [a], we conclude that the observed structure effect does not depend on the increase of excitation energy, and it reveals to be a general property of spallation and fragmentation residues.

[a]See also references therein.

2. A schematic explanation

A simple statistical evaporation model, where the nuclear level densities are calculated according to the Fermi-gas model.[3] would be sufficient to reproduce all the features observed in the yields, in first order.[1] This could seem to be in contradiction with the counterbalancing of the pairing gap in the nuclear masses and in the level densities. On the contrary, in each evaporation step, the probability of the possible decay channels do not only reflect the level densities of the daughter nucleus, but they also depend on the number of excited levels of the mother nucleus that could decay into the daughter. The excited levels available for the decay extend from the separation energy of the daughter nucleus down to the separation energy of the mother nucleus, increased of the Coulomb barrier in the case of charged particle emission. The separation energy of the mother nucleus corresponds to the ground state of the daughter nucleus. This is sketched in fig. (2), where the levels of some isotopes are distributed on their mass-excess parabolae. Let us consider the case of an odd-mass nucleus decaying into an even-mass nucleus. A series of even-mass isotopes (^{30}Al, ^{30}Si, ^{30}P, ^{30}S) show a smooth variation of the separation energies as a function of the element, once shifted by the pairing gap δP. The absence of

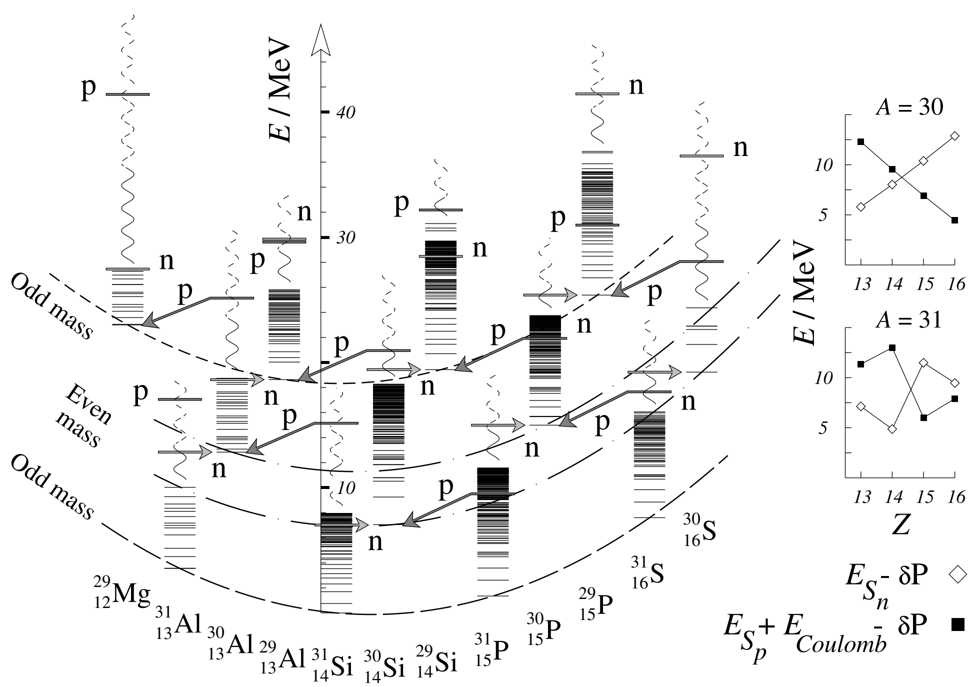

Fig. 2. Evaporation scheme. The experimental levels of a set of nuclei are ordered on their mass-excess parabolae. proton and neutron separation energies are marked with "p" and "n", respectively. On the right, the proton (S_p) and neutron (S_n) separation energies, shifted by the pairing gap δP, are presented for A=30 and A=31.

staggering in the separation energies is reflected in a smooth variation of the level density for the even-mass nuclei as a function of the element. Nevertheless, due to the pairing gap, odd-mass nuclei decaying into even-even daughters (^{30}Si or ^{30}S) have more excited levels available for the decay with respect to odd-mass nuclei decaying into odd-odd daughters (^{30}Al or ^{30}P). At the very end of the evaporation process, the decay in the ground state of the daughter nucleus becomes so relevant to determine the overproduction of even-even nuclei compared to odd-odd ones. A slightly different discussion should be dedicated to the formation of odd-mass residues (^{29}Mg, ^{29}Al, ^{29}Si, ^{29}P). As the ground states of odd-mass nuclei are all ordered along the same mass parabola, the restoring of the structure in the production yields should be determined by the separation energs that shows up as an even-odd staggering in both, proton and neutron separation energies, however with different signs, depending on the neutron excess. In odd-mass neutron-rich nuclei (^{29}Mg, ^{29}Al) the neutron separation energy, that is lower than the proton separation energy, determines the choice of the most probable evaporation channel. Thus, the residues will reflect the structure of the neutron separation energy favouring the production of odd elements. Contrarely, the yields of odd-mass proton-rich nuclei (^{29}Si, ^{29}P) reflect the structure of the proton separation energy favouring the production of even elements.

3. Conclusions and open questions

We demonstrated qualitatively that the structure observed in the nuclide cross section of spallation and fragmentation residues is a result of the very last steps of the evaporation process. It should be pointed out that the strength of the staggering is remarkably high. A study based on Tracy's analysis.[2] would reveal a strenght higher than 50% for the even-odd staggering of the N=Z chain, and up to 20% for the odd-even staggering of the odd-mass neutron rich nuclei. This is to be compared to the even-odd staggering that characterizes the low-energy fission yields, measured to reach a strength of around 40% at maximum.[4] Another interesting aspect is the much higher production of alpha-multiple nuclei (i.e. the huge staggering along the N=Z chain). If we add the remark that the hot fragments of the reaction ^{56}Fe+p or ^{56}Fe+^{nat}Ti could have spent a considerable part or their excitation energy undergoing a multifragmentation-like or break-up process.[5], we might consider alpha-cluster emission as an additional channel responsible of the restoring of the structural effects in the production yields.

References

1. M. V. Ricciardi et Al, in *Symp. on Nucl. Clusters* (Rauischholzhausen, Germany, 2002).
2. B. L. Tracy et Al, *Phys. Rev* **C5**, 222 (1972).
3. V. M. Strutinski, in *Int. Conf. on Nuclear Physics*, p. 617 (Paris, Italy, 1958).
4. Steinhaeuser et Al, *Nucl. Phys.* **A634**, 89 (1998).
5. P. Napolitani et Al, in *XLI Int. Winter Meeting on Nucl. Phys.* (Bormio, Italy, 2003).