NEUTRON-RICH NUCLEI POPULATED IN DEEP-INELASTIC COLLISIONS: NEW STUDIES OF THE REDISTRIBUTION OF PROTONS AND NEUTRONS*

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The redistribution of protons and neutrons between nuclei in deep-inelastic collisions is discussed in terms of the N/Z ratio equilibration. Experimentally established product yield distributions are used for comparison with two sets of model predictions. The present and perspective use of deep-inelastic reactions for spectroscopic studies of exotic neutron-rich nuclei is discussed.

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Deep-inelastic heavy ion collisions are nowadays used in gamma spectroscopy studies of nuclei that cannot be populated in fusion-evaporation reactions [1]. The planning of these experiments was initially guided by general understanding of the reaction mechanism of deep-inelastic collisions acquired in earlier investigations which employed fragment detection techniques. However, it was early recognized that the knowledge of kinematics and dynamics of the colliding systems was not satisfactory for practical application of deep-inelastic reactions to nuclear spectroscopy. In particular, it was not straightforward to predict yields of populated fragments in order to select optimal experimental conditions such as the target-projectile combination and the collision energy.

First experiments in which products of deep-inelastic reactions have been studied by discrete gamma-ray spectroscopy were performed in the 1990s using early implementations of Germanium detector arrays: Argonne/Notre

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Dame Array, OSIRIS and GASP. In one of the first of such measurements γ–γ cross-coincidences of gammas emitted from two excited nuclei that appeared as partners in the reaction exit channel were observed [2]. This provided full identification of the reaction, including direct information on the number of nucleons transferred between the target and projectile and evaporated from the excited primary fragments. Moreover, it proved that gamma coincidence studies of such collisions are possible and can contribute complementary information on the reaction mechanism.

We have investigated the distributions of products for three following heavy-ion reactions: ^{208}Pb + 350 MeV ^{64}Ni [3], ^{130}Te + 275 MeV ^{64}Ni and ^{208}Pb + 345 MeV ^{58}Ni [4]. The colliding energies for all three systems were selected at 12% above the Coulomb barrier. In the experiments thick targets were used to ensure that all reaction products were stopped in the target material. The multidetector arrays of Ge detectors were used to measure multifold coincidences of gamma-rays emitted from reaction products stopped in the target. It has to be noted that in these thick target measurements the kinematics of the reaction is fully integrated and moreover, also the beam energy is integrated down to the Coulomb barrier. In all cases pulsed beams were used to separate prompt and delayed events which allowed the analysis of isomeric and short-lived radioactive decays. Additionally, after the experiments we measured gamma-rays emitted in short and long-lived radioactive decays of reaction products. By combining results from the analysis of the off-beam and in-beam gamma coincidence data supplemented by the radioactivity measurements we established detailed distributions of isotopes produced in each reaction.

In Fig. 1 mass distributions obtained for ^{208}Pb + ^{64}Ni (lower panel) and ^{208}Pb + ^{58}Ni (upper panel) collisions are compared. One notices that the population of heavy target-like fragments for ^{58}Ni induced collisions is reduced, their distribution does not extend as far as for the ^{64}Ni induced reaction. Another striking feature is the appearance of a broad "island" of intermediate mass nuclei in the $80 < A < 130$ mass range. The nuclei located within this group are produced in fission of excited heavy target-like fragments arising in deep-inelastic collisions. The center of mass of the observed "island" corresponds well to the 1/2 of the average mass of heavy fragments above ^{208}Pb for which fission is expected to appear.

It is worthwhile to note that for both systems the used beam energies were significantly below the threshold needed for complete fusion and correspondingly only traces of products are observed in the region expected for the symmetric fission of the compound system. The explanation of the strong enhancement of the discussed mass $80 < A < 130$ group of products in the ^{58}Ni case compared to the ^{64}Ni is related to the N/Z equilibration process in deep-inelastic reactions. The flow of protons from the small N/Z ^{58}Ni to the

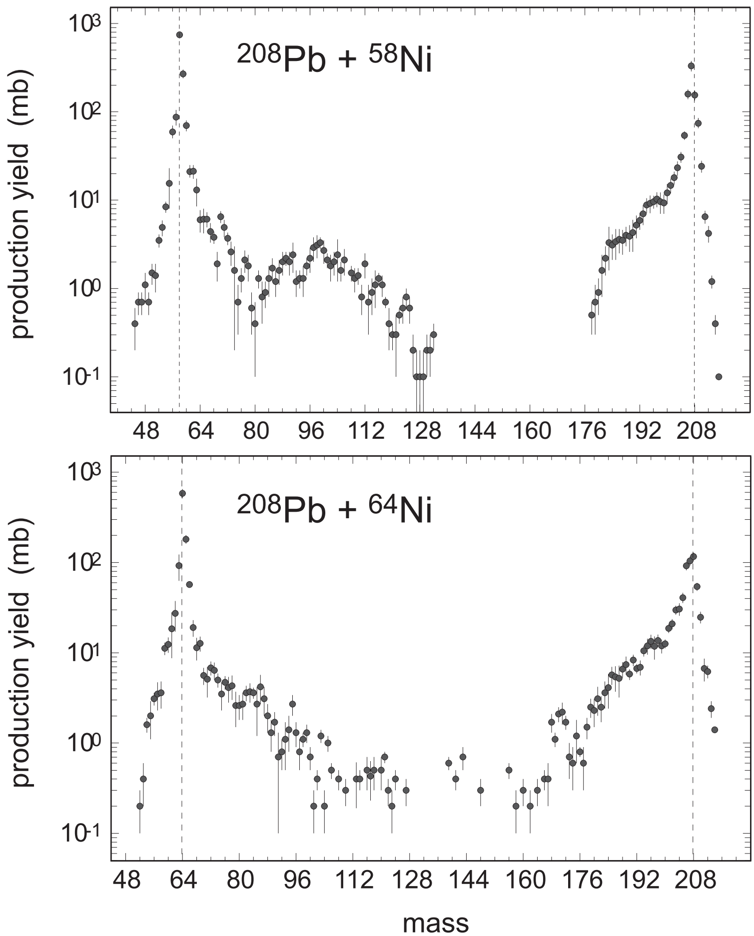

Fig. 1. Mass distributions established for ^{208}Pb + 350 MeV ^{64}Ni (lower panel) and ^{208}Pb + 345 MeV ^{58}Ni (upper panel) collisions [3, 4].

^{208}Pb target is more intense than in case of the neutron-rich ^{64}Ni projectile. This process populates heavy fragments with higher Z ($Z > 82$) which are more susceptible to undergo fission. The effect of the N/Z equilibration can be directly seen comparing heavy fragment distributions obtained for reactions of ^{64}Ni (Fig. 2) and ^{58}Ni (Fig. 3) projectiles on ^{208}Pb target. Unlike for the ^{208}Pb + ^{64}Ni system, the formation of isotopes of $Z < 82$ elements such as Tl, Hg, Au and Pt is less favored in the ^{208}Pb + ^{58}Ni system. Instead, higher production yields are found for isotopes of $Z > 82$ elements: Bi, Po, At, Rn and even Fr and Ra.

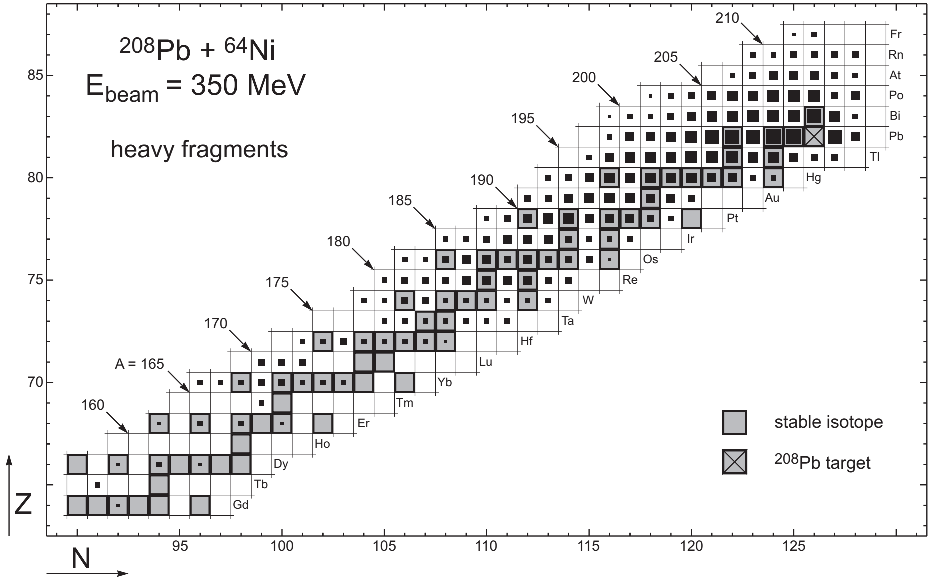

Fig. 2. Distribution of heavy fragments produced in ^{208}Pb + ^{64}Ni collisions. The size of each black square is proportional to the production yield of an isotope [3].

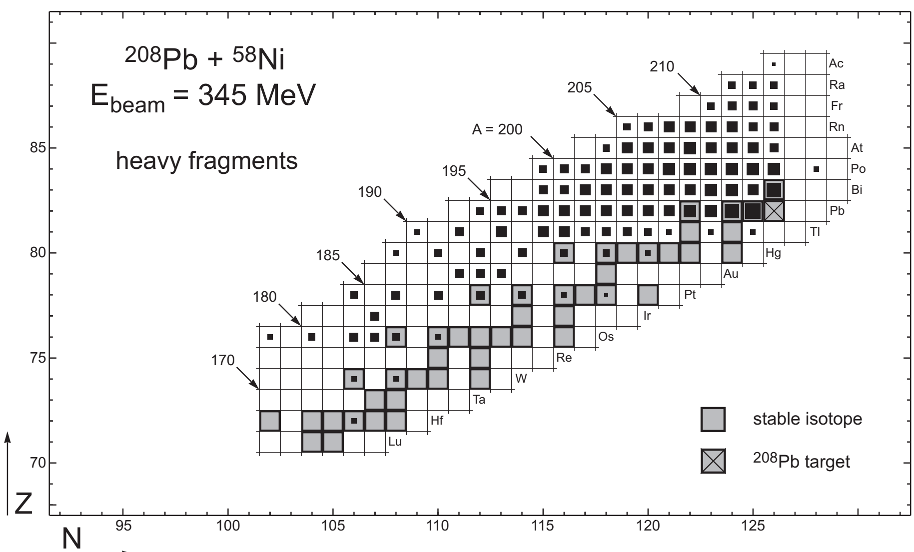

Fig. 3. Distribution of heavy fragments produced in ^{208}Pb + ^{58}Ni collisions. The size of each black square is proportional to the production yield of an isotope [4].

To investigate the equilibration of the neutron-to-proton ratio we calculated the average value of the N/Z for isobars at each mass. In Fig. 4 experimentally established N/Z values for heavy fragments produced in two reactions: ^{208}Pb + ^{64}Ni (top) and ^{208}Pb + ^{58}Ni (bottom) are presented as a function of the fragment mass. The experimental points are compared with results of an equilibration formula calculation derived from a minimization of the liquid drop energy of two spherical or deformed nuclei [5]. The dashed lines were obtained for configurations of two touching spherical nuclei at the distance between the centers equal to the sum of their radii. The solid lines are fits to the data and were obtained by allowing a considerable distance, larger than the sum of two radii, between the nuclei which imitates deformation of fragments at the time of nuclear contact. For both systems a large additional separation distance of 10 fm (for ^{64}Ni induced reaction) and 8 fm (for ^{58}Ni induced reaction) between the colliding nuclei was needed to reproduce the data. This suggests that deformation effects might be important at the time of interaction when the redistribution of nucleons takes place [6].

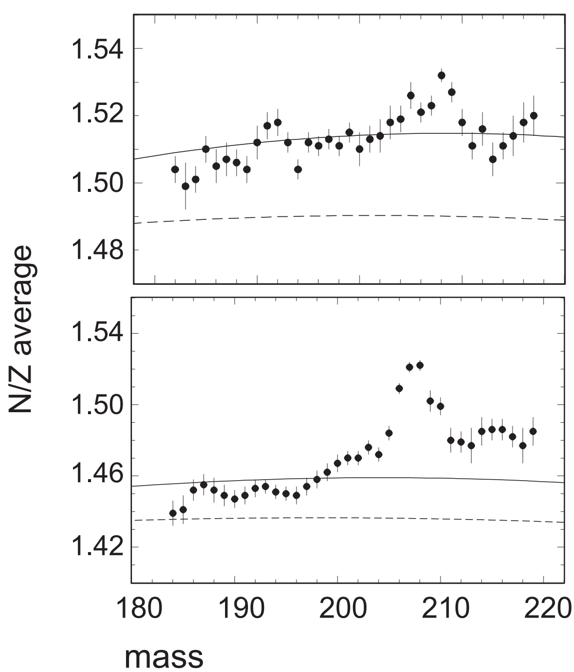

Fig. 4. Experimental average N/Z values and results of the liquid drop energy minimization for heavy fragments produced in ^{208}Pb + ^{64}Ni (top) and ^{208}Pb + ^{58}Ni (bottom) collisions. Lines are drawn for energy minimization for systems of spherical nuclei at different distances at scission point simulating possible deformation. See text for discussion.

A different, dynamical description of nucleon rearrangement in heavy-ion collisions was proposed within the framework of the Heavy Ion Phase Space Exploration (HIPSE) model [7,8]. The model consists of a three step description of the collision and identifies the approach phase, the partition formation phase and the separation phase. For the first part of the collision classical equations of motion with an interaction potential are solved for two participating nuclei which are described as collections of nucleons with momentum and space distributions. This part ends with the two partners at maximum overlap. In the partition formation phase quasi-projectile and quasi-target fragments are constituted out of nucleons outside the overlap region, while nucleons within this region are rearranged into clusters and light particles following coalescence rules in momentum and position spaces. In the exit channel the propagation of the quasi-projectile and quasi-target partition is calculated taking into account possible reaggregation effects due to nuclear and Coulomb interactions. Also, secondary decays are calculated by means of an evaporation code.

The predictions of the HIPSE model for the N/Z equilibration process for heavy fragments produced in ^{208}Pb + ^{58}Ni collisions are shown and compared to experimentally established values in Fig. 5. It is to be noted that presented results were not fitted to the data but were obtained from a three-step model calculation of nucleon rearrangement in heavy-ion collisions.

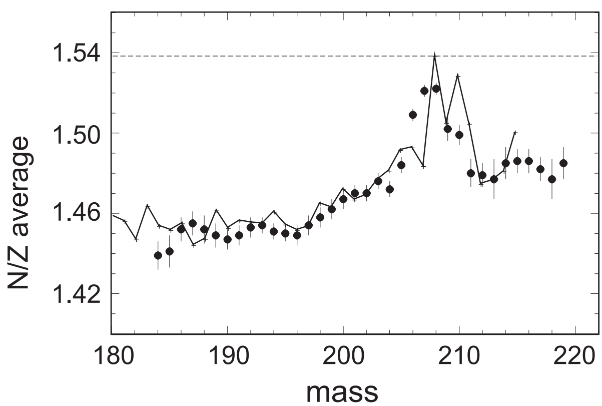

Fig. 5. Experimental average N/Z values and results of the Heavy Ion Phase Space Exploration model [7,8] for heavy fragments produced in ^{208}Pb + ^{58}Ni collisions.

The hitherto considered most probable N/Z ratios of final nuclei produced in deep-inelastic reactions define only the most easily accessible neutron richness. The real access range is determined by the experimental detection limit and depends on the variation of reaction yields for isobars around the maximum N/Z value. In Fig. 6 yield distributions for isobars of selected masses produced in ^{208}Pb + ^{64}Ni reaction are shown. A typical isobar yield distribution is rather narrow and limited to 3–4 isobars. It is also symmetrical, with the exception of isotopes close to the target and projectile.

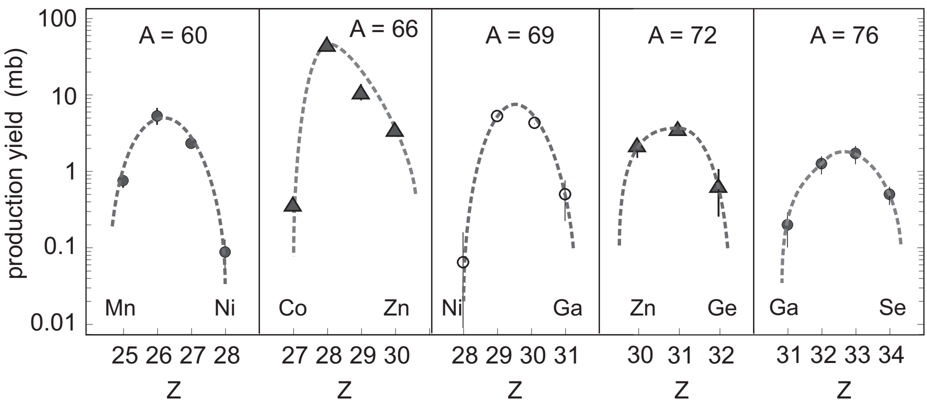

Fig. 6. Yield distributions for isobars of selected elements produced in ^{208}Pb + ^{64}Ni collisions [3]. Lines are drawn to guide the eye.

The distributions of production yields for isotopes of selected elements produced in the same reaction are shown in Fig. 7. The isotopic distributions stretch over 8 to 10 mass units. For fragments produced in processes in which larger numbers of protons are transferred, *i.e.* going from $Z = 30$ (Zn) to $Z = 32$ (Ge) and $Z = 34$ (Se) isotopes, the distributions become increasingly flat. On the other hand, for $Z = 26$ (Fe) isotopes produced in processes in which 2 protons are stripped from the Ni projectile, one notices a distinct asymmetry. Light Fe isotopes are produced with much lower yields, probably mostly by secondary neutron evaporation from more neutron-rich Fe isotopes.

In summary, the comparison of the neutron-to-proton equilibration effect observed in deep-inelastic collisions with simple calculations based on a model of two separated spheres leads to conclusion that the N/Z equilibration is significantly less effective than one would expect, possibly due to dynamical deformation of nuclei at the time of nucleon rearrangement. Furthermore, the actual ranges of observed isotopes which are useful for spectroscopic studies are determined by experimental detection limits. This poses some restrictions on access with spectroscopic experiments to exotic, very neutron-rich nuclei produced in deep-inelastic collisions. The present results are important to determine whether experiments of this type can be employed for nuclear structure studies with radioactive beams.

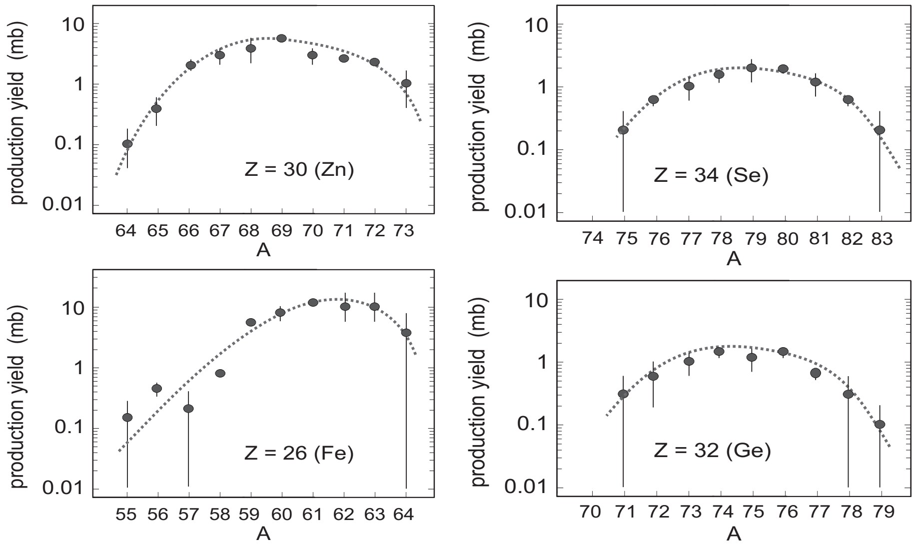

Fig. 7. Yield distributions for isotopes of selected elements produced in ^{208}Pb + ^{64}Ni collisions [3]. Lines are drawn to guide the eye.

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