THE N/Z RATIO EQUILIBRATION IN DEEP–INELASTIC COLLISIONS*,**

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From the γ-γ coincidence data and radioactivity analysis nearly complete distributions of products for ^{208}Pb + 350 MeV ^{64}Ni and ^{130}Te + 275 MeV ^{64}Ni reactions were established. The results are discussed in terms of the equilibration of N/Z ratio in deep-inelastic (massive transfer) processes. Comparison with model calculations suggests a significant deformation of nuclei at the scission point.

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We have studied the equilibration of N/Z ratio in heavy ion deep-inelastic collisions at energies slightly above the Coulomb barrier. In this report we present data obtained from two experiments: the ^{208}Pb + 350 MeV

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^{64}Ni reaction studied with the OSIRIS setup at the HMI Berlin and the ^{130}Te + 275 MeV ^{64}Ni collision investigated with GASP array at the INFN Legnaro.

The idea of measurements and details of analysis were presented in a number of previous reports [1-3]. We measured in-beam and off-beam coincidences of gammas emitted from the reaction products stopped in thick targets. The quality and statistics of the coincidence data made possible the identification of most of the products including those arising in very weak reaction channels. After experiments γ-rays from radioactive decays were measured providing additional accurate information on the production yields. Altogether, the combined information from γ-γ coincidences and from the radioactivity measurements allowed us to reconstruct almost complete distribution of products.

Yield distribution of reaction products for ^{208}Pb + ^{64}Ni system is presented in Fig. 1. Along with contribution from quasi-elastic processes concentrated in the vicinity of target and projectile a major part of the cross section is located in two broad symmetric bumps that contain mostly deep-inelastic reaction fragments. Almost no symmetric binary products have been observed confirming that at the used beam energy of 5.5 MeV/A the fusion-fission channel is almost absent [2, 4].

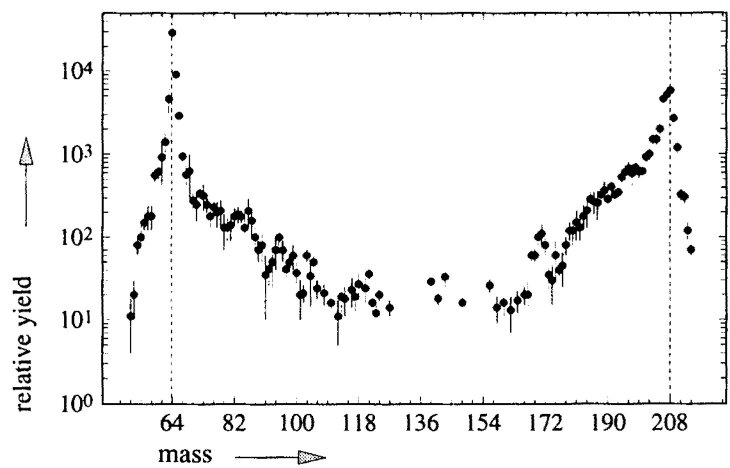

Fig. 1. Mass distribution of ^{208}Pb + 350 MeV ^{64}Ni reaction products.

The observed yield distribution represents secondary nuclei that arise after evaporation of particles from the excited primary products. In order to calculate the N/Z ratio for the primary fragments we tried to reconstruct the pre-emission distribution [3]. Since both, target and projectile nuclei are rather neutron-rich practically only neutrons are emitted from hot primary products. Thus, the number of protons in the colliding system is always conserved and in the reaction exit channel pairs of complementary elements with $Z_1 + Z_2 = Z(\mathrm{Pb}) + Z(\mathrm{Ni}) = 110$ appear as partners (*e.g.* Pb–Ni, Tl–Cu, Hg–Zn). The sum of average masses calculated from the isotope yield of each pair of elements is always smaller than the $A = 272$ total mass of the system. The obtained difference is attributed to the neutron evaporation and is shown in Fig. 2 as a function of transferred proton number.

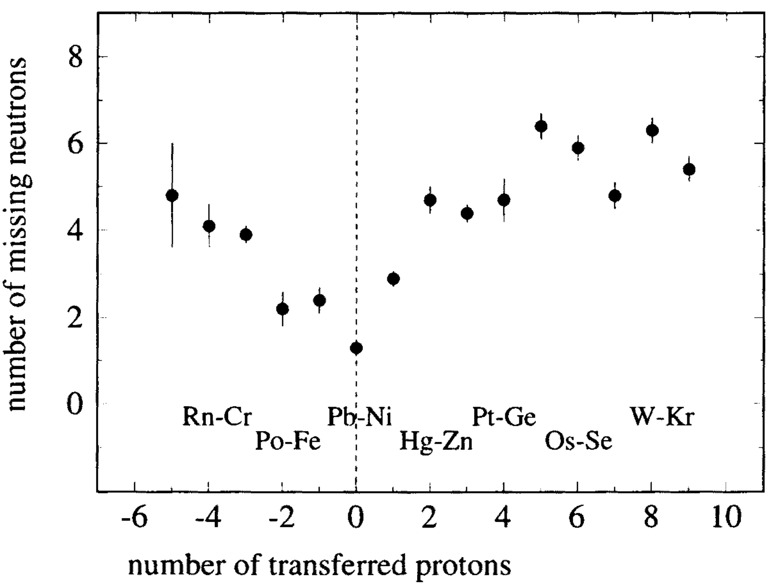

Fig. 2. Average number of neutrons evaporated from partner elements for different number of protons transferred to the projectile.

The number of neutrons emitted from both products seems to saturate at a value of 5 to 6 for charge transfers of more than 2 protons. We assumed that the excitation energy of product nuclei and in consequence number of neutrons emitted in their deexcitation is proportional to the mass. This allowed us to divide the number of missing neutrons among light and heavy fragments. For each element we corrected the isotopic distributions by appropriate shift towards more neutron-rich isotopes.

For nuclei close to the target and projectile a refined correction was needed since for those products the assumption that all isotopes of one element emit on the average the same number of neutrons is not true.

In those nuclei we looked for γ-γ cross-coincidences [1] between partner products. ¿From a detailed analysis of cross-coincidences we obtained an isotope-dependent transformation from secondary into primary distribution for products located close to the target. The reconstructed primary distribution of products was used to calculate the average N/Z ratio shown in Fig. 3 as a function of fragment mass.

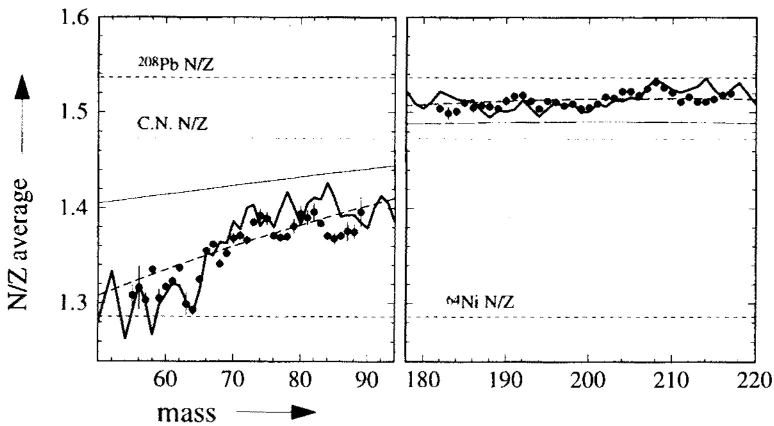

Fig. 3. Experimental most probable N/Z values for primary products of ^{208}Pb + 350 MeV ^{64}Ni reaction. The solid and dashed lines represent the results of optimum N/Z calculations [5] for two spherical touching and distant nuclei, respectively. The thick solid line corresponds to phenomenological calculations that take into account experimental nuclear masses [6].

The problem of N/Z ratio equilibration was considered already at the beginning of heavy ion physics. W.J. Swiatecki derived a formula for the expected N/Z ratio equilibration for products of heavy ion collisions from the minimization of the liquid drop energy of two touching spherical nuclei [5]. An optimum N/Z calculated within this approach (thin solid line in Fig. 3) reproduces the general trend but it significantly overestimates the equilibration effect. Since Coulomb interaction contributes decisively to the minimized energy one can artificially simulate the possible deformation effects by introducing into calculations a separation distance of two spheres. A calculation done for a system of two distant spherical nuclei with a separation distance of 10 fm (dashed line in Fig. 3) is in a much better agreement with the data. Furthermore, the observed in experiment fluctuations of the N/Z values may indicate the importance of structural effects. We tried to reproduce them by phenomenological calculations that take into account experimental nuclear masses. The results of a minimization of the reaction

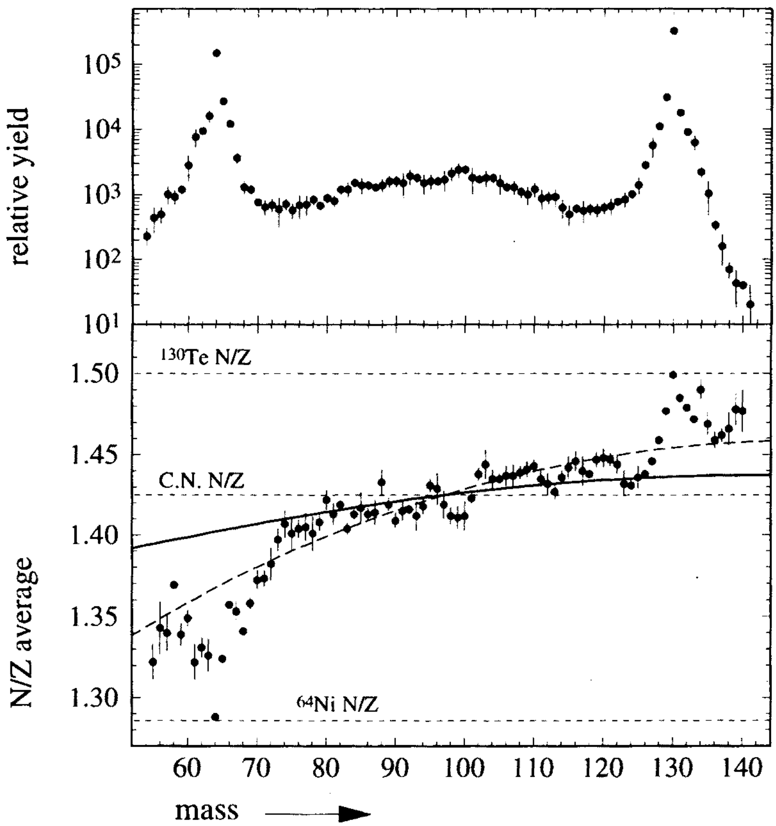

Fig. 4. Results of the ^{130}Te + 275 MeV ^{64}Ni reaction study. Mass distribution of products (upper part) and average experimental N/Z values (lower part). Results of optimum N/Z calculation [5] for touching (solid line) and for distant (dashed line) spherical nuclei are indicated.

Q-value and Coulomb interaction for two nuclei at a distance of 10 fm shown in Fig. 3 accounts for some fluctuations but the agreement is not conclusive.

The same analysis was performed for the second reaction ^{130}Te + ^{64}Ni at a collision energy 12 % above the barrier. The mass distribution of products is shown in the upper part of Fig. 4. For this system a strong fusion channel is open and most of the compound nuclei fission producing fragments in the mass range partly overlapping with the deep-inelastic products. Here, for the symmetric fragments ($A \approx 100$) the N/Z values are reproduced by the equilibration formula calculations [5] for touching nuclei (solid line in the lower part of Fig. 4). For nuclei heavier than the target and lighter than the projectile (at the limits of our distribution), that can be produced only in deep-inelastic processes the equilibration formula for distant nuclei (dashed line in Fig. 4) gives again much better agreement with the measured values.

The interpretation of the presented results is still open. In the more transparent case of ^{208}Pb + ^{64}Ni collisions the optimum N/Z of the deep-inelastic products seems to be reproduced only in calculations which invoke the deformation of nuclei at the scission point. Further modifications taking into account possible deformations (*e.g.* two nuclei connected with a neck) should clarify this question. For the ^{130}Te + ^{64}Ni reaction situation is more complex, since most of the products arise from fusion-fission processes. The obtained N/Z values in the symmetric mass range are close to equilibrium values and can be accounted by the touching spheres formula. Moving away from the symmetric mass range the contribution from the deep-inelastic products increases and affects the observed N/Z values. The general trend indicates that for those processes again the deformation at the scission point (simulated by separation of charged spheres) is important accounting for non-complete equilibration.

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