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BINARY AND NON-BINARY ASPECTS OF ^{159}Tb(^{40}Ar, PLF) REACTION AT ENERGIES CLOSE TO 10 MeV/NUCLEON

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Dedicated to Professor Kazimierz Grotowski on the occasion of his 70th birthday

Results of a complex analysis of ^{40}Ar + ^{159}Tb collision data obtained from inclusive and coincidence measurements are presented. The experimental results support the binary nature of projectile like fragments close in Z to the projectile. Indirect evidences for primary projectile and projectile like fragment breakup following transfer reaction and/or inelastic scattering were found.

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1. Introduction

Since the discovery of the deep inelastic collisions in low energy heavy-ion reactions, many experimental and theoretical efforts have been performed in order to understand the main features of this type of reactions, which combine properties characteristic of the two apparently opposite nuclear processes: direct reaction and compound nucleus decay [1–10]. Deep inelastic reactions are characterized by the fact that the system remains essentially binary: two heavy massive products, projectile like fragment (PLF) and target like fragment (TLF) come out of the collision carrying nearly all the nucleons (except of evaporated ones from the excited primary fragments) of the system. Theirs main characteristics are the following: *(i)* a mean kinetic energy close to the mutual interaction barrier in the exit channel, *(ii)* a broad mass distributions, centred in the vicinity of the projectile and the target, and *(iii)* nonisotropic angular distributions indicating a much shorter lifetimes than would be expected from compound nucleus formation. In the sharp cutoff approximation, quasi-elastic (peripheral) and deep inelastic (more dissipative, less distant) reactions share the range of partial waves between the angular momentum, above which there is no the compound nucleus formation, and the maximum angular momentum leading to a nuclear reaction. Simple classical calculations using the sharp cutoff approximation predict, that in the case of ^{40}Ar + ^{159}Tb collision at the energy close to 10 MeV/nucleon the fusion cross section exhausts only about 25% of the total cross section; the binary quasi-elastic (QE) and deep inelastic (DI) components are then expected to be predominant in considered reaction.

2. Experimental setup

Measurements were performed at the Hahn-Meitner Institut Berlin using 9.75 and 9.5 MeV/nucleon ^{40}Ar ion beam from the VICKSI heavy ion accelerator. In the inclusive and coincidence measurements the reaction products of $Z_{\rm PLF} = 7$–20 were detected with conventional solid state detector $\Delta E(25\mu{\rm m})-E(1000\mu{\rm m})$ telescope at laboratory angles ranging from 11° to 36° and at 14.5°, respectively. Additionally, in the coincidence measurements the scintillator tank of 1 m diameter filled with 500 l of Gd-loaded toluene was used for 4π neutron detection. Experimental technique is described in details in Ref. [11].

3. Results and discussion

The studied ^{40}Ar + ^{159}Tb reaction at 9.75 MeV/nucleon (inclusive measurements) and 9.5 MeV/nucleon (coincidence measurements) shows the signs of the binary nature of collisions at low energy domain.

The characteristic features of the ejectile energy spectra obtained at $\theta_{\rm lab} = 14.5°$ in coincident experiment ^{40}Ar + ^{159}Tb at 9.5 MeV/nucleon (Fig. 1) are as follows: for the exit channels where only few nucleons are added or removed from the projectile, two components of the energy spectra are clearly distinguished. The first one is concentrated at the energy somewhat below that corresponding to the beam velocity, the second one at energies near the exit channel Coulomb barrier. They are interpreted as peripheral collision events with small energy damping, and less distant, more dissipative events, respectively. With decreasing PLF atomic number the overlap of both components becomes more significant. In the vicinity of the projectile charge number ($14 \leq Z \leq 18$) the intensity of low energy component increases in comparison with the high energy part with decreasing Z value, indicating a more dissipative character of multinucleon exchange processes. For products with charge number far from the projectile only one component in the energy spectra is observed, spread mainly between the Coulomb barrier and the energy corresponding to the beam velocity.

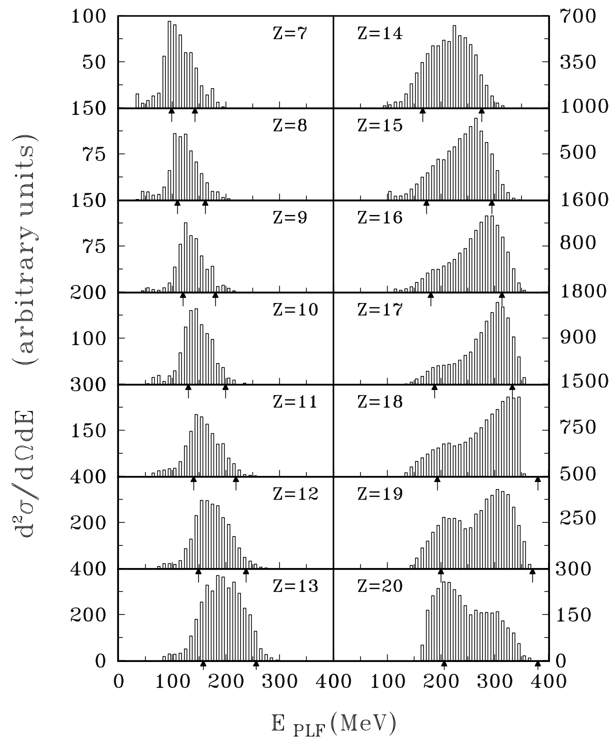

Fig. 1. Laboratory energy spectra of PLF's from ^{40}Ar(9.5 MeV/nucleon) + ^{159}Tb with Z values ranging from 7 to 20 integrated in 10 MeV bins of ejectile energy. The arrows indicate the Coulomb barrier and the energy corresponding to the beam velocity.

The angular distributions of PLF's measured in inclusive experiment with charges close to that of the projectile are peaked around the grazing angle ($\theta_{\rm lab}^{\rm gr} = 24.5°$) and they decrease at greater angles. With decreasing charge number of products maxima of angular distributions, lying in the vicinity of the grazing angle flatten, and finally disappear. For the products far in Z from the projectile the angular distributions are only weakly forward peaked and they demonstrate a gradual tendency towards the isotropy (Fig. 2). One can attach here two mechanisms which result in the similar tendency of the angular distribution. The first one may be related to the orbiting collisions which smear out the forward peaking and may theoretically introduce an isotropic component in the angular distribution. The rough estimation of lifetimes of the dinuclear systems allows to state that for PLF's with $Z \geq 14$ a considerable number of nucleons may be transferred between nuclei in fast processes, during the time shorter then the rotation period of dinuclear systems ($1 \div 2 \times 10^{-21}$ s) [11]. The second may be the pure kinematic phase space factor appearing when more than two particles are present in the exit channel. This has an effect of uncoupling of the directions of reaction products with the forward or grazing direction.

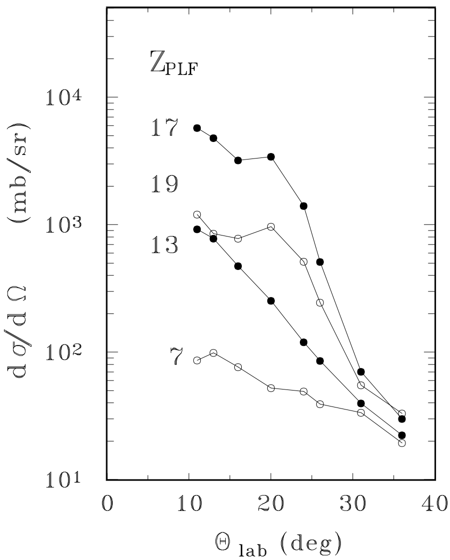

Fig. 2. Angular distributions of selected elements emitted in ^{40}Ar + ^{159}Tb reaction at 9.75 MeV/nucleon. Lines are drawn through the data point to guide eyes.

In the exit channel PLF's with a moderate modification of charge in relation to the projectile charge are dominantly observed, however the distribution of produced fragments is broad and extend from the vicinity of the projectile down to the light ejectiles (Figs. 3, 4) (the range of the detected and analyzed ejectile charge numbers is extorted by the experimental conditions). Quasi elastic and deep inelastic components of elemental distributions presented in Fig. 3 were obtained using a procedure described in Refs [11], [12]. Separation was done for PLF's which energy spectra and angular distributions manifest binary nature of exit channel fragments ($Z \geq 14$). The contribution of QE and DI components to the total yield of elemental distributions depends on the PLF atomic number indicating on more damped nature of the reaction with a considerable number of transferred nucleons. The damping of the reaction depends also on the net transfer direction, the heaviest detected PLF's ($Z = 20$) originate mostly from deep inelastic collisions.

The neutron multiplicity dependence on the ejectile kinetic energy in the whole range of the measured Z-values is observed (see Fig. 4.6 in Ref. [11].

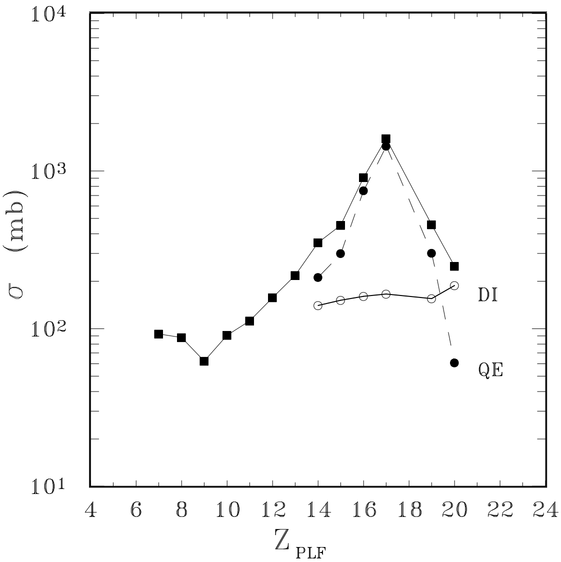

Fig. 3. Total cross section as a function of products atomic number for the system ^{40}Ar(9.75 MeV/nucleon) + ^{159}Tb (filled squares). The filled and empty circles denote the QE and DI components of the cross section, respectively. Lines are drawn to guide eyes.

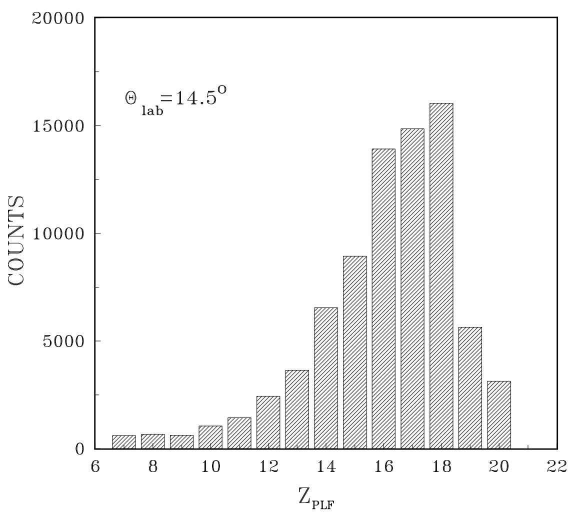

Fig. 4. The measured charge distribution for ^{40}Ar(9.5 MeV/nucleon) + ^{159}Tb collision at $\theta_{\rm lab} = 14.5°$.

The general character of this dependence is unique for products close to the projectile. The processes with small energy damping and low neutron multiplicity are overwhelming other exit channels. The mostly damped collisions consequently are accompanied by the highest neutron multiplicity. For lowest charges of ejectiles ($Z \leq 13$) events characterized by the highest neutron multiplicity, indicating on the strong energy damping, dominate quantitatively. The relative intensity of events grouped in the vicinity of the beam velocity, accompanied by the small neutron multiplicity increases with decreasing Z. The third class of events is observed at lowest kinetic energies below two-body exit channel Coulomb barrier and small neutron multiplicity and it exhibits a nearly constant relative intensity in the whole range of the charge $Z \leq 13$.

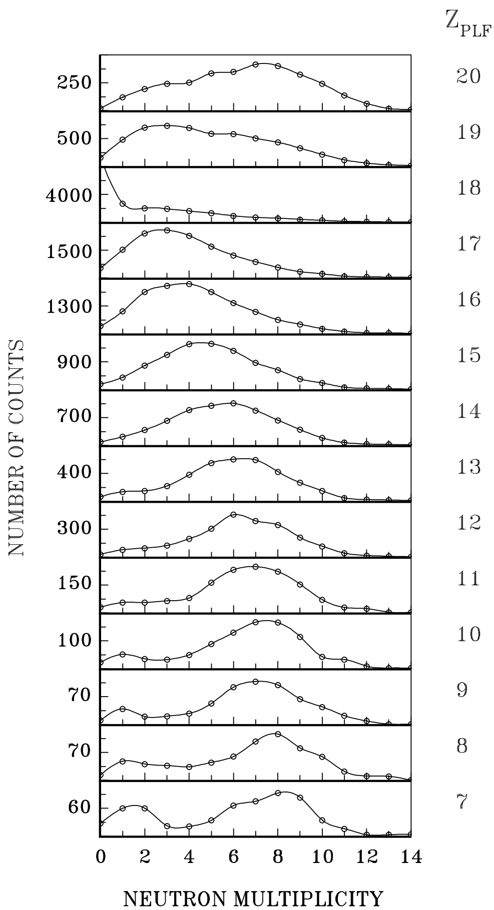

Fig. 5. Neutron multiplicity distributions for ejectiles from $Z = 7$ to $Z = 20$

The neutron multiplicity distributions obtained from coincidence measurements have approximately Gaussian shapes with noticeable drift of the maximum position towards higher values of neutron multiplicity while the coincident PLF charge number decreases (Fig. 5). It indicates that the lighter is the detected PLF the collision is more dissipative and it results in observation of the increase of the average number of neutrons evaporated by more excited reaction partners. An evolution of the shape of the neutron multiplicity distributions is seen for $Z = 13$ and it coincides with the change of general character of energy spectra and angular distributions of ejectiles. For lighter measured products one can observe an additional second component in the region of low neutron multiplicity. This class of events, for which the energy dissipation seems to be uncorrelated with the mass transfer, was assigned to projectile or PLF break-up and fission following the grazing collision. Intensities of these maxima are smaller than those at high value of registered neutron number, although the relative contributions of low multiplicity components increase with decreasing fragment charges. The drift of the high neutron multiplicity component towards higher values of neutron number with decreasing charge number of ejectiles is observed, but the shift is weaker than for PLF's close to the projectile. The change in a slope observed in the mean neutron multiplicity — charge number correlation (Fig. 6) is explained by a change of the dominating reaction mechanism. A significant part of the ejectiles with $Z \leq 13$ arises from collisions which are not primary binary in the exit channel as it is in the case of the production of PLF's close to the projectile.

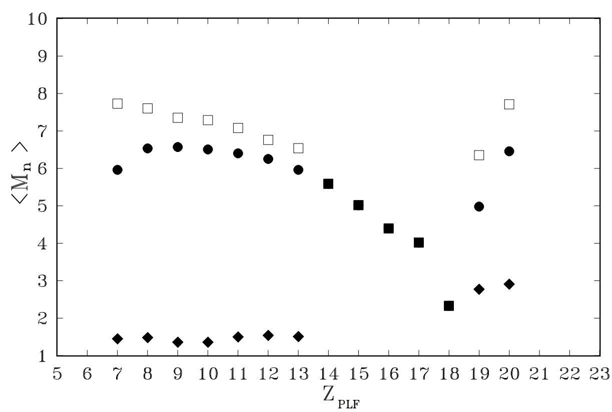

Fig. 6. Mean neutron multiplicities $\langle M_n \rangle$ coincident with fragments observed at 14.5°. The solid squares and circles represent the values calculated over the whole range of multiplicity distributions, while the empty squares and filled diamonds denote the results of calculations separating the distributions into two components.

Concluding, behavior of energy spectra, angular, elemental and neutron multiplicity distributions confirm the binary character of projectile like fragments with $14 \leq Z \leq 20$. On the other hand there are the indirect signs that the products of ^{40}Ar + ^{159}Tb collision far in Z from the projectile do not originate in majority directly from binary deep inelastic collisions. The hypothesis that these fragments result from the decay of the excited projectile or heavier PLF by the emission of neutrons and light charged particles seems to be incorrect because of insufficient multiplicity of evaporated light particles (for instance measured neutrons). As a consequence these fragments are expected to be a result of the projectile or PLF splitting into two massive fragments, only one of which is detected. The excited primary projectile or PLF is produced in the first stage of a reaction and then it breaks-up producing massive fragments in the final state.

For PLF's with charge number $14 \leq Z \leq 20$ the statistical model (PACE II [13]) calculations have been performed and compared with experimental results. The assumption of a binary character of these collisions seems to be valid and justified by the analysis of experimental observables. The aim of the statistical treatment of the data was the determination the excitation energy sharing between exit channel nuclei. A comparison of experimental data and results of statistical calculations indicates on proportional to the mass excitation energy division between PLF and TLF in the ^{159}Tb(^{40}Ar; PLF, xn) reaction at 9.5 MeV/nucleon. Satisfactory agreement in the whole range of the excitation energy, independently on the energy loss and on the direction of the net nucleon transfer is observed between experimental and statistical calculations results.

We attempted to describe the data using another approach in which inherent features of the mass drift from the projectile to the target are especially suitable for the application to the peripheral and inner peripheral collisions, producing in the exit channel PLF's lighter than the projectile. The random walk model [14] taking into account in a proper relation to the considered energy domain, the one- and two-body dissipation seems to be suitable for our purposes. For each impact parameter the model provides the mass, the charge, the kinetic and excitation energies of PLF and TLF. In the model the heating of two partners is achieved through nucleon transfers. Model results are supplemented by the evaporation calculations (GEMINI code [15]). This procedure allows a direct comparison of calculation results with measured ones. The correlation between the neutron multiplicity and the PLF kinetic energy and charge distribution are followed by the model calculation results (see Fig. 5.2 in Ref. [11]). A good agreement is found between experimental data and model predictions for PLF's close in Z to the projectile, for which the binary nature is justified. The discrepancy for the lightest fragments registered in the ^{40}Ar + ^{159}Tb reaction is understood because the data in this region of Z are composed of variety of reaction mechanisms which partly are out of scope of the model. The other main shortcoming is related to the failure of the calculation to produce fragments heavier than the projectile. The experimental yield of PLF's heavier than the projectile is significantly underpredicted. This is caused by model assumption, that nucleons in the course of the collision of two ions are transferred in a way which reflects the size of the available phase space in nuclei involving the more favored nucleon flow in the direction from the projectile to the target.

4. Summary

In summary, the extensive experimental material obtained from the studies of ^{40}Ar(9.75, 9.5 MeV/nucleon) + ^{159}Tb collisions provide evidence for prevailing binary character of the reaction, uncovering also the non-binary aspects in creation of PLF far in Z from the projectile. The detection of more than one massive fragment in the same event may give a unique opportunity of a closer insight into reaction mechanism. Despite the extensive efforts expended in the last decade, the detailed mechanism of a production of these fragments is not yet well understood, however the break up of the lighter collision partner into two or more fragments during the interaction phase is found to set in already at about 10 MeV/nucleon and to develop fully until about 40 MeV/nucleon. A continuation of the investigation of the ^{40}Ar + ^{159}Tb reaction at the energy of about 10 MeV/nucleon by means of the precise detection of the multifragment emission is therefore expected to deliver new evidences of the reaction mechanism.

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