CORRELATION BETWEEN REACTION MECHANISM, KINETIC ENERGY RELEASE AND NEUTRON EMISSION IN ^{40}Ar+^{159}Tb COLLISION AT 9.5 MeV/NUCLEON*

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Multiplicities of neutrons using 4π detection system accompanying projectile-like fragments in ^{40}Ar+^{159}Tb collision were measured. For the system studied the results suggest a broad range of reaction mechanisms. The experimental results were compared with predictions of the random walk model supplemented by a statistical evaporation.

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1. Introduction

Last two decades of extensive investigations of heavy ion collisions have led to a good understanding of the mechanism of these reactions. In the low energy domain we have two main processes, namely compound nucleus formation for low impact parameters and a second class of binary processes for larger impact parameters. In binary processes two excited heavy products come out from the collision carrying almost all nucleons of the system. A sizable part of the entrance channel kinetic energy is dissipated and converted into internal excitation of both massive products. Similarly, the available

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orbital angular momentum is partly shared between spins of the outgoing nuclei. Later on the hot primary fragments cool down by the emission of light charged particles, γ rays and neutrons. The relative strength of these decay modes is determined by the excitation energy, spin and isospin number of the parent nucleus. As the excited fragments decay predominantly via neutron emission measurements of neutrons occurring in the reaction may provide a wealthy information about reaction mechanisms and excitation energy of the studied system.

At low energies the individual nucleon–nucleon interaction plays negligible role due to the suppressive influence of the Pauli principle. Instead, the mean field of the system induces in both directions flow of nucleons through the window opened between the target and the projectile resulting in an effective mass transfer. These phenomena are referred to one-body dissipation [1] and in the next phase are followed by reseparation of the dinuclear system into projectile-like and target-like fragments. This classical approach can provide average values for the kinetic energy, mass, charge and other exit channel observables. Moments of the distribution of these observables may be obtained after an explicit inclusion of fluctuations. In frame of the transport theory for dissipative collisions we may obtain these moments by solving the Fokker–Plank equation [2].

In the region of intermediate energies the individual nucleon–nucleon interactions as well as the mean field effects are important. The semi-classical treatment of the problem is reduced to the solution of appropriate kinetic equations. The Boltzmann–Uehling–Uhlenbeck (BUU) equation [3, 4] is an example of the transport equation which contains both the mean field and nucleon–nucleon interaction. It has also been called the Vlasov–Uehling–Uhlenbeck equation (VUU) [5] or the Landau–Vlasow equation (LV) [6]. A large number of degrees of freedom involved in these microscopic calculations causes severe numerical difficulties resulting in inevitable loss of some detailed information.

In particular great difficulties are present in describing peripheral collisions by those microscopic transport models whereas less sophisticated models were found to be quite adequate for explaining many aspects of the collisions. In this work we have applied one of these simplified methods based on the random walk model of Harvey [7] and Cole [8], supplemented with several improvements [9–11].

The paper is organized as follows: in Section 2 a brief overview of experimental setup is presented. Section 3 contains a short description of the applied model. The comparison of the model predictions and experimental data will be found in Section 4. Section 5 presents the discussion concerning the predictive power of the random walk model and Section 6 contains the conclusions.

2. Experimental setup and experimental results

The 380 MeV ^{40}Ar beam provided by the VICKSI heavy ion accelerator of Hahn-Meitner Institute was focused on the 524 μg/cm^2 ^{159}Tb selfsupporting target. The detector setup consisted of two systems with the following special destination: (1) the projectile-like fragments (PLF) conventional $\Delta E - E$ Si detector of 25 μm and 1000μm thickness, respectively, positioned at 14.5° with respect to the beam axis in horizontal plane, (2) the scintillator tank of 1 m diameter filled with 500 l of Gd-loaded toluene used for 4π neutron detection. The average detection efficiency of neutrons measured in coincidence with PLF's was determined in the present experiment to be 82%. Details of experimental setup are described elsewhere [9, 10].

The correlation of PLF kinetic energy, $E_{\rm PLF}$, ($E_{\rm min}$=30 MeV and 150 MeV for $Z_{\rm PLF}$=7 and 20, respectively) and neutron multiplicity, M_n was measured for $Z_{\rm PLF} = 7 - 20$ and $M_n = 0 - 14$. A complete description of experimental results may be found in Ref. [9].

3. Random walk model

The model takes into account in a consistent way both mean field effects and nucleon–nucleon interactions with an explicit inclusion of Pauli blocking. The peripheral and less peripheral collisions are treated on the same footing so that a transition from quasi-elastic to deep inelastic collisions proceeds in a continuous way.

The model assumes that the transfer of nucleons can be decomposed into two phases. First, two potentials corresponding to the projectile and to the target start to overlap and a certain amount of nucleons is perturbed and brought from the bound state of one of the potential wells to virtual states of participants of the reaction. At this stage of the reaction three groups of nucleons are created. Two groups are composed of the undisturbed nucleons belonging to the projectile and to the target. They have no chance to leave their potential wells in course of the reaction development. The third group consists of the virtually disturbed nucleons, which belong neither to the projectile nor to the target. They may be considered as bounded by the entire system. In the second step of the reaction nucleons from the third group, common for the projectile and target, are transferred either to the projectile- or target-residua, or to the continuum. This decay is governed by the density of final states, introducing the driving factor, which depends on the available phase space. It should be noted that this scenario of the nucleon transfer can not be identified with the assumption of the two-step mechanism of the reaction. This approach is applied only in order to make feasible the introduction of all factors, which are considered to be of the greatest importance for the mass transfer in heavy ion collisions.

It is therefore a crucial task of the model to determine the number of nucleons disturbed during the collision and excited to the virtual states, $N_{\rm virt}$, and the probability of the transition from the virtual to the final states.

The dynamics of the collision, preceding the statistical deexcitation of the reaction products, is treated as a binary process. In the model the colliding heavy ions move along classical trajectories determined by the Coulomb and nuclear mean fields. When ions are sufficiently close processes occur, which modify the potential and the linear and angular momenta, according to the mass and momentum exchange. The statistical process of the random walk is assumed to take place at the distance of the closest approach to calculate the transferred mass and transferred momentum.

In the low energy domain a strong influence of the Pauli principle implies that the mean field description is the most adequate. As a consequence of a close contact between interacting nuclei the potential shape can evolve in the way which lowers the mean field barrier bounding nucleons in the projectile or in the target. Therefore the shape evolution of the self consistent field is responsible for distortion of the nucleon localization. The mean field barrier lowered by the approach of two ions creates a chance for the nucleon transition to the virtual state. The probability density of this transition evolves along the movement of the interacting ions along their trajectories.

For higher relative velocities of colliding heavy ions another mode of nucleon excitation is taking over. These are two-body nucleon–nucleon interactions, which are now not strictly prohibited by the Pauli principle. The proper treatment of this problem requires the solution of the quantum many body time dependent Schrödinger equation. Because it is practically not feasible various approximate methods are used. Following the model of Cole [8], it is assumed that the number of disturbed nucleons may be expressed by an average number of nucleon–nucleon elementary interactions at given impact parameter, b. In the present model the following modifications were made. The first refinement is the replacement of the mean cross section of the nucleon–nucleon interaction and mean densities by the local cross section and the local densities of colliding nuclei, corresponding to the local Fermi momentum. The second modification concerns the inclusion of the energy of internal motion of nucleons in addition to the energy of the relative motion of nuclei. In the case of low bombarding energy and/or of two interpenetrating nuclei at small impact parameter the Pauli blocking effect is included.

In the next step of the reaction nucleons from the virtual states (excited by means of one- or two-body interaction) are transferred either to PLF, TLF with a probability proportional to the density of the final states in both ions, or to the continuum.

According to the above prescriptions one can calculate the net mass transferred in the collision caused by one- and two-body interactions.

In the early theoretical study of the deep inelastic collisions purely macroscopic models were used. Most of them can predict the total excitation energy but not the excitation energy division between the reaction partners. For this reason the presented model invokes the fundamental microscopic processes to be responsible for the conversion of the available energy in the excitation energy of reaction products separately.

In the model it is assumed that the only elementary process causing the energy dissipation is the nucleon exchange between binary reaction participants. The total excitation energy is absorbed by the both primary products of the binary reaction in an a priori unknown proportion. The origin of the excitation energy was assigned in general to three sources. The first is the conversion of the kinetic energy of the relative motion into internal degrees of freedom by one-body or two-body dissipation. The other contributions come from the potential energy release and the ground state Q value of a reaction. It was assumed that each of these three forms of the energy can be divided between PLF and TLF in different, individual way.

As in the Fermi gas model the excitation energy of a nucleus is calculated as the difference between the sum of the kinetic energies of all individual nucleons in the actual state of PLF and the similar sum in the ground state. Following Siemens *et al.* [12] it is assumed that the velocities of the individual nucleons are unaffected by the transfer process. This enables the use of entrance channel momenta of the transferred nucleons for the purpose of calculating the final excitation energy. Next the correction is added to the excitation energy calculated by the above prescription. This correction is connected with the fact that nucleon is bound by the mean field of the donor nucleus so as a result of the nucleon transfer the mean field is disturbed and one can assign an additional donor nucleus excitation to this disturbance equal to the mean binding energy of nucleon in the donor nucleus. This energy, we assume, is generated from the kinetic energy of the transferred nucleons. As a consequence the excitation energy of the accepting nucleus has to be changed exactly by the same value.

The problem of the Q division was solved in frame of the liquid drop model of the nucleus. The leading term of the mass formula, the volume energy, expresses the fact that the density of the nuclear matter is approximately independent on the mass A of the nucleus. This term therefore represents the binding energy in the limiting case of the large A, isospin equilibrium $N = Z$, and no Coulomb interaction. Therefore one can divide Q in proportion to the masses of the reaction products, assuming, that the thermal capacity of a nucleus is roughly proportional to its mass.

The question of the dissipation of the potential energy was investigated adopting two extreme scenarios. In the first one it was assumed that the entire potential energy difference is not dissipated at all, but instead it is converted into the final kinetic energy of the relative motion. In a completely different approach one can assume that the entire potential energy release is totally converted into the excitation energy. This idea is supported by the opportunity of the excitation of collective states what means accumulation of the released potential energy in the deformation degrees of freedom in the exit channel. Besides, using again arguments of the proportionality of the heat capacity to the mass of the absorber, it was assumed that potential energy release is divided between PLF and TLF in proportion to their masses. The results for both extreme scenarios have been investigated for ^{40}Ar+^{159}Tb reaction at $E_{\rm in}$=380 MeV by means of numerical simulations. The observed discrepancy between both results fell below the experimental uncertainty due to the fact that the dissipation of the potential energy is much smaller than the kinetic energy damping.

4. Neutron multiplicity — PLF energy dependence

In the previous paper the description of experimental charge distribution of reaction products using random walk model was presented [10]. Another check concerning the random walk model may be provided by the comparison of experimentally obtained neutron multiplicity accompanying the PLF's with the number of neutrons predicted by the model calculations. In order to tighten constraints imposed on this comparison neutron multiplicity versus PLF kinetic energy in two dimensional space was studied.

The neutron multiplicity dependence on the ejectile kinetic energy in the whole range of the measured Z-values is observed (Figs. 1(a) and 1(b)). 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 most damped collisions consequently are accompanied by the highest neutron multiplicity. For lowest charges of ejectiles ($Z \leq 13$) the 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 $Z \leq 13$.

In contour plots (Fig. 1(a)) of experimentally obtained events as a function of the measured PLF kinetic energy, $E_{\rm PLF}$, and the neutron multiplicity,

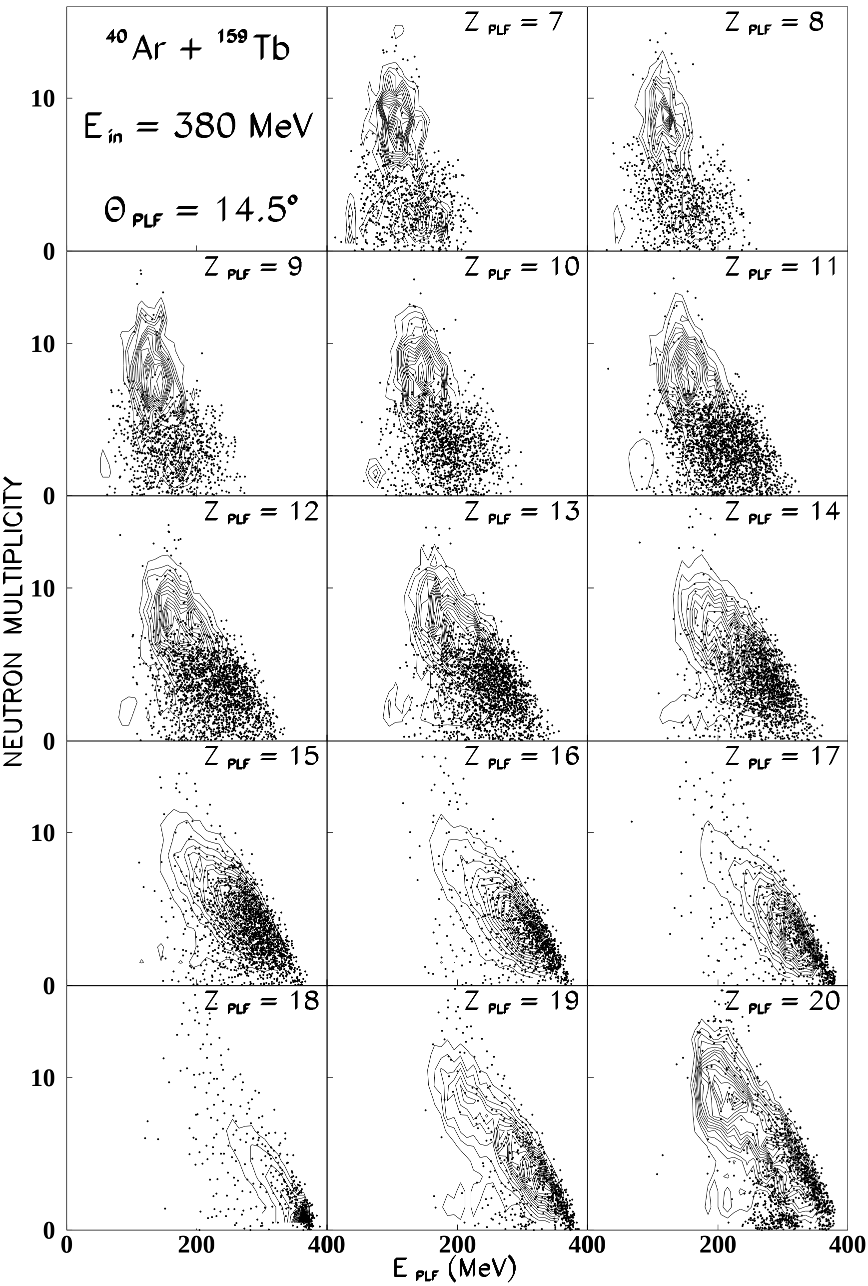

Fig. 1(a). Contour plots of counts as a function of the measured ejectile kinetic energy, $E_{\rm PLF}$, and neutron multiplicity. Dots represent results of the model calculations.

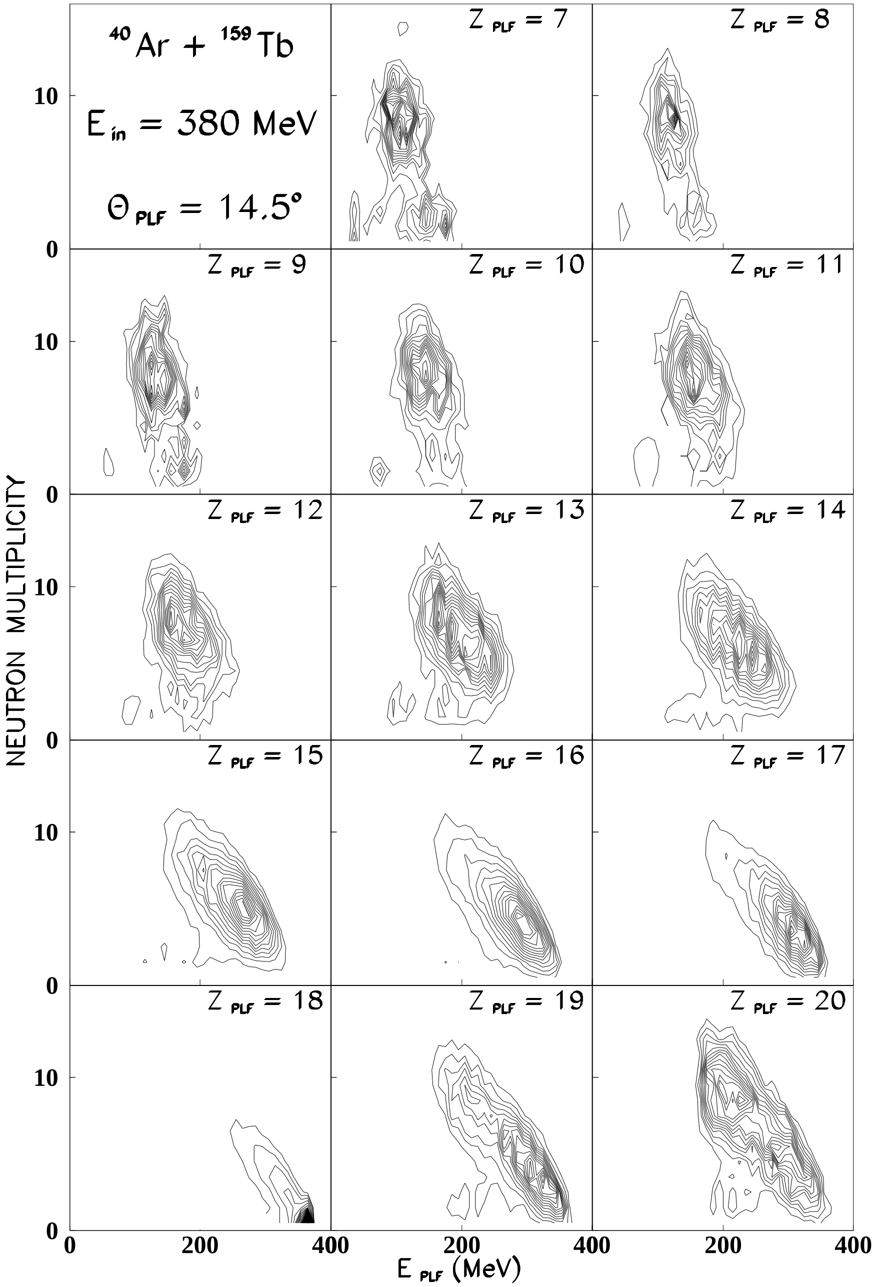

Fig. 1(b). For clarity the pure experimental dependence of the neutron fold on PLF kinetic energy is presented.

M_n, the black points denote the results obtained from the model calculations. Hot primary fragments, resulting from the random walk model, have been deexcited along the decay chain using the evaporation code GEMINI [13] where neutron, proton, α-particle, γ-ray and heavy cluster emission is taken into account. Events resulting from the calculations were filtered according to the conditions inherent to the experimental setup. The leading factors influencing this procedure were related to the limited acceptance of the PLF detector ($\theta_{\rm lab} = 14.5^\circ \pm 1.7^\circ$) and to the mean efficiency of a single neutron registration ($< \varepsilon >$=0.82), which was on-line monitored during the experiment with the ^{252}Cf calibrated fission source. The efficiency dependence on the neutron energy has been taken into account and the detection probability has been evaluated from the efficiency curve [14, 15], showing the continuous decrease with increasing energies of neutrons. This dependence (in our case the diameter of the scintillator tank was 100 cm) is significant even for large detectors, although the efficiency decreases with the energy weaker than in smaller neutron detectors. The Monte Carlo simulation was performed for each event resulting from the model calculations. The detection of any single neutron coming from the sequential decay of the TLF or PLF from the same event was considered as a statistically independent process governed by the efficiency corresponding to the neutron energy. The multiplicities obtained in this way have been used for the comparison with the experimental data.

Taking into account *(i)* the charge number of the measured ejectile, *(ii)* the main localization of experimentally obtained yield in the M_n *vs* $E_{\rm PLF}$ space, *(iii)* the conformity of the experimental data and model predictions, one can distinguish three regions of Z values.

As one can see in Fig. 1(a) the satisfactory agreement of model predictions with experimental data is observed for ejectiles with $14 \leq Z \leq 18$, which at most originate from binary, peripheral collisions. The positions of maxima and the ridges of experimentally obtained contour plots are well reproduced by the model. The broadening of the experimental distributions observed with decreasing Z-values in the M_n *vs* $E_{\rm PLF}$ space is also predicted by the model. For PLF's with these charge numbers the experimentally obtained yield at high kinetic energies is predominant. These PLF's are predicted by the random walk model mainly as the primary ones, the evaporation of PLF's heavier than the secondary ejectile and the evaporation of the compound nucleus and TLF contribute insignificantly into the cross section. The last two processes are predicted by the model as events at low and medium kinetic energies of fragments accompanied by the high neutron multiplicity.

The pick-up channels producing PLF's slightly heavier than the projectile show some dissimilarities to the stripping channels. The discrepancies observed between the experimental data and the model originate mainly from the general underestimation of the dissipative strength of these channels in the calculations. The ridge of the contour plot is quite well reproduced, but the position of maximum is in disagreement with experimental data. The model fails for the class of events associated with medium and high neutron multiplicity and with a noticeable energy dissipation, dominating in the experimental data, especially for $Z_{\rm PLF} = 20$. As was mentioned in the previous section the inherent features of the random walk model may extort the impossibility of the correct description of the data concerning the exit channel fragments heavier than the projectile. Due to the differences of the available phase space in the PLF and TLF primary exit channel states, the nucleon flow from the virtual states towards the heavier system is favoured. It results in the dominant production of the stripped projectiles what is distinctly pronounced by the asymmetry of the yield of the fragments lighter and heavier than the projectile. Hence, in the elemental distribution the significant underestimation of the experimentally obtained yield of PLF with Z=20 is observed. However the integrated yield of fragments with Z=19 predicted by the model is in overall agreement with the experimental data, the apparent shortcoming of the calculations is seen in the structure of energy dissipation. The region of medium and low kinetic energies suffers from an underestimation in the M_n *vs* $E_{\rm PLF}$ space, as is seen in Fig. 1(a).

For the ejectiles with $Z \leq 13$ the final yields of the predicted charge distribution contain important contribution from heavier primary fragment decays (see Fig. 3 of Ref. [10]). This contribution increases with decreasing Z value of the ejectile, whereas the contribution of the primary processes is strongly reduced. In frames of the model the primary ejectiles with $Z \leq 9$ are not predicted at all and they entirely result from a secondary evaporation of heavier, hot fragments. Results of random walk model calculations supplemented by the secondary evaporation are concentrated in the M_n *vs* $E_{\rm PLF}$ space in the region of the low and medium neutron multiplicity and they are spread over the whole considered energy range. They correspond mainly to the evaporation of two massive fragments from the hot projectile or PLF accompanied by a few evaporated neutrons (mainly from excited TLF). The results of the model calculations confirm the idea, that fragments far in Z from the projectile may origin from break-up or prompt fission of the hot projectile or PLF. The experimentally obtained yield corresponding to the highest number of neutrons is significantly underestimated by the model in the region of a small ejectile charge number. These events are predicted as a result of the compound nucleus or the TLF evaporation of massive fragment accompanied by the emission of neutrons, and they are localized in the vicinity of highest neutron multiplicity under consideration. The intensity of these events is still small and the experimentally obtained maxima in contour plots at medium kinetic energies of ejectiles and high neutron number are not generated by the model.

5. Discussion

Comparison of the model predictions with the experimentally obtained charge distribution and $M_n - E_{\mathrm{PLF}}$ correlation for ^{40}Ar+^{159}Tb reaction at 380 MeV shows that the random walk model with the phase space factors, supplemented by the evaporation code, reproduces very well the experimental results for fragments with atomic numbers $14 \leq Z \leq 18$. These fragments originate mostly from binary distant collisions as primary fragments. In peripheral collisions the overlap between potentials of the target and the projectile is small and well defined dinuclear system is formed. The reaction participants remain at the strong interaction contact for a short passage time limited by the size of the system and by the relative velocity of the nuclei. Therefore the reaction is confined to the exchange of a small number of nucleons and to the dissipation of a small fraction of the available energy. The minor mass rearrangement comparing to the size of the nuclear subsystems allows to treat the exchange process as a sequence of mutually independent single nucleon transfers. The idea which takes into account different probabilities for a nucleon going to and out of the target or the projectile is positively verified by the comparison with experimental data. These different probabilities are caused by different sizes of the available phase space in heavier and lighter ions. The flow of nucleons is favoured in the direction from the projectile to the target and PLF's lighter than the projectile are produced preferably.

The ejectiles with $7 \leq Z \leq 13$, for which with decreasing ejectile charge number the features of a binary peripheral collisions diminish, origin as well from nonbinary processes, *e.g.* projectile or PLF's break-up, as from more central binary collisions. For this class of collisions taking place at small impact parameter the interaction time (sometimes longer than the rotation period of the dinuclear system) is long enough to transfer a large amount of the mass and in outcome the significant amount of the energy is dissipated.

In the light of the above considerations discrepancies between the model predictions and the experimental data are anticipated and understood. The first shortcoming is related to the scope of the model which subtends only the binary collisions. The second one is related to the inherent feature of the model, that the nucleons are transferred in a random walk mode considering each particular nucleon transfer as a process statistically independent on any other preceding or following nucleon transfer. This assumption may be not valid for the massive transfer where more correlated processes are expected or during the sequence of transfers the donor and acceptor nuclei may gradually and significantly change their properties. This situation is analogous to the thermodynamical heat transport between two finite vessels in contact.

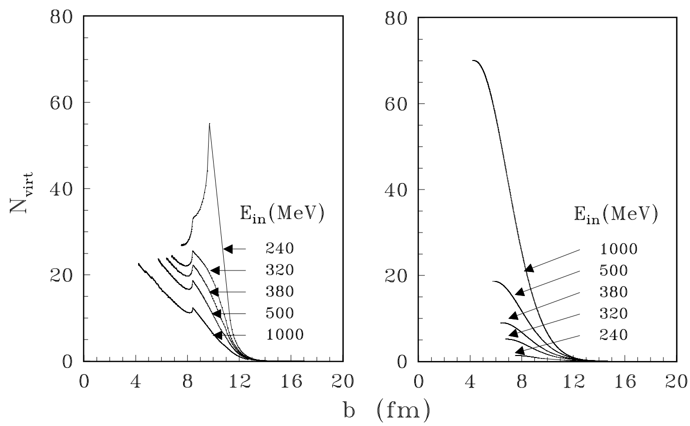

Fig. 2. Number of nucleons disturbed to the virtual states by means of one-body (left panel) and two-body (right panel) interactions as a function of impact parameter b.

In Fig. 2 the dependence of the number of nucleons disturbed to virtual states, $N_{\rm virt}$, on the impact parameter, b, given by the model is presented. The formation of long lived dinuclear system for ^{40}Ar+^{159}Tb reaction at $E_{\rm in}$=240 MeV is manifested by the rapid and enormous enlargement of the number of nucleons participating in collisions caused by mean field effects. The orbiting at given impact parameter corresponding to the angular momentum $l = l_{\rm orbit}$ allows to transfer a considerable amount of the mass and to convert a large fraction of the relative kinetic energy into the internal degrees of freedom. In frames of the model the effective potential derived from the static proximity formulas [16] does not support the necessary conditions for the orbiting scattering at energy 380 MeV, occurring at energy 240 MeV (Fig. 2). The classical deflection function for ^{40}Ar+^{159}Tb reaction at 380 MeV does not contain any singularities resulting in rather smooth dependence of $N_{\rm virt}$ *vs* b, as seen in Fig. 2. As a consequence, in the exit channel the primary fragments very far in Z from the projectile do not occur and the excitation energy deposited in primary fragments is insufficient to evaporate the high number of neutrons obtained experimentally. In fact, friction forces at the initial stages of collision may reduce the entrance channel energy and angular momentum to the level, for which the orbiting is not anymore prohibited, what is out of the model considerations. It is also neglected in the model that at violent heavy ion collisions the entrance channel deformation of the nuclei may cause the nuclear part of the potential to become virtually changed. It can result in an appearance of the potential barrier of the height matching the entrance channel kinetic energy of the relative motion, what is necessary for the orbiting.

Concluding, for ejectiles close in Z to the projectile the model supplemented by the statistical evaporation gives the successful description of the data. The common feature for $Z \leq 13$ is the underestimation of the data in the region of high neutron multiplicity. The predicted excitation energy of the primary fragments is insufficient to generate with appropriate intensity the events at medium kinetic energies associated with medium and high neutron multiplicity, dominating in the experimental data. The quantitative underestimation of the theoretical yield in this region of M_n *vs* E_{PLF} space for the ejectiles lighter than Si ions may be attributed to the presence of the phenomena which are out of scope of the model. It subtends primary binary peripheral and inner peripheral collisions but does not extend to the formation of the long lived dinuclear systems at the considered incident energy. The break-up of the hot projectile or PLF is out of the framework of the model, however the results of massive fragment evaporation from the excited ejectiles follow the experimental data for the lightest measured ejectiles in the region of low neutron multiplicities in the M_n *vs* E_{PLF} space.

6. Summary

The model clearly shows up quite well agreement with the experimental charge distribution (Fig. 3 of Ref. [10]) and provides the correlation between the neutron multiplicity, M_n, and the PLF kinetic energy, E_{PLF} (Fig. 1(a)). A good agreement is found between the experimental data and the model calculations, except the lightest fragments detected in the ^{40}Ar+^{159}Tb reaction. This discrepancy 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 presented model. Because some of the ejectiles detected in the experiment can result from a binary break-up of the hot projectile or PLF's, only through more exclusive experiments the contribution to the cross section of these ejectiles may be disentangled.

The other main shortcoming is related to the failure of the prediction of production of fragments heavier than the projectile. 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 both nuclei favours too intensively the nucleon flow in the direction from the projectile to the target. This leads to the underestimation of the experimental yield of PLF's heavier than the projectile.

REFERENCES

[1] J. Błocki, Y. Boneh, J.R. Nix, J. Randrup, M. Robel, A.J. Sierk, W.J. Świątecki, *Ann. Phys.* **113**, 330 (1978).

[2] W. Nörenberg, *Phys. Lett.* **B52**, 289 (1974).

[3] E.A. Uehling, G.E. Uhlenbeck *Phys. Rev.* **43**, 552 (1933).

[4] J. Aichelin, G.F. Bertsch, *Phys. Rev.* **C31**, 1730 (1985).

[5] H. Kruse, B.V. Jacak, J.J. Molitoris, G.D. Westfall, H. Stöcker, *Phys. Rev.* **C31**, 1770 (1985).

[6] C. Gregoire, B. Renaud, F. Sebille, L. Vinet, Y. Raffray, *Nucl. Phys.* **A465**, 317 (1987); J. Cugnon, A. Lejeune, P. Grange, *Phys. Rev.* **C35**, 861 (1987).

[7] B.G. Harvey, *Nucl. Phys.* **A444**, 498 (1985).

[8] A.J. Cole, *Z. Phys.* **A322**, 315 (1985); *Phys. Rev.* **C35**, 117 (1987).

[9] E. Kozik, *Ph. D. Thesis*, Institute of Nuclear Physics, Cracow (1997).

[10] E. Kozik, J. Błocki, A. Budzanowski, J. Galin, D.Hilscher, H. Homeyer, U. Jahnke, T.Kozik, Z. Sosin, *Acta. Phys. Pol.* **B27**, 2241 (1996).

[11] Z. Sosin, private communication.

[12] P.J. Siemens, J.P. Bondorf, D.H.E. Gross, F. Dickmann, *Phys. Lett.* **B36**, 24 (1971).

[13] R.J. Charity, M.A. McMahan, G.J. Wozniak, R.J. McDonald, L.G. Moretto, D.G. Sarantities, L.G. Sobotka, G. Guarino, A. Pantaleo, L. Fiore, A. Gobbi, K.D.Hildenbrand, *Nucl.Phys.* **A483**, 371 (1988).

[14] H. Beil, R. Bergére, A. Veyssiére, *Nucl. Instr. Meth.* **67**, 293 (1969).

[15] J. Poitou, C. Signarbieux, *Nucl. Instr. Meth.* **114**, 113 (1974).

[16] J. Błocki, J. Randrup, W.J. Świątecki, C.G. Tang, *Ann. Phys.* **105**, 427 (1977).