FRAGMENT HEATING IN ^{40}Ar+^{159}Tb COLLISION AT 9.5 MeV/NUCLEON

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The target-like fragment excitation energy in ^{40}Ar (9.5 MeV/nucleon) +^{159}Tb reaction has been obtained by applying a neutron evaporation calculation to data resulting from coincidence measurements of projectile-like fragments and neutrons. The comparison between the data and results of statistical evaporation simulations with different assumptions of the excitation energy sharing between the reaction partners confirms an equal temperature hypothesis in describing of fragment heating.

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1. Introduction

In recent years the question of the excitation energy partition between reaction products has been of great interest for peripheral, partially and nearly full damped heavy ion collisions in low energy domain. Many approaches have been studied to determine the excitation energy sharing, to find the dependence of the excitation energy acquired in the course of the collision on the direction of the net nucleon transfer and to establish the time in which thermal equilibrium is reached.

Results of earlier measurements were interpreted in terms of an intermediate dinuclear system reaching thermal equilibration during the collision [1–6]. It was found that even in fast, partially damped collisions, thermal equilibrium of the system is reached, resulting in the mass proportional division of the excitation energy of primary fragments. After these early studies experimental evidence has been accumulated, showing that in the initial stage of the damped collision, where the inelastic excitation and/or few nucleon transfer govern the course of the reaction, two fragments have distinctly different temperatures if their masses are different. It was found that the time evolution (there is the correspondence between interaction time and energy loss) of the experimentally obtained excitation energy division proceeds from nearly equipartition to the thermal equilibrium [7–9].

On the other hand there is an experimental evidence for the asymmetry between the energies generated in nuclei which gain or lose some mass. A strong channel dependence of the excitation energy partition producing the net receptor fragment significantly more excited than the donor nuclei was found. Even for peripheral collisions characterized by a short interaction time the excitation energy deposited in two reaction fragments was found to be nonequal. Results of studies of Schmidt *et al.* [10] and Sohlbach *et al.* [11, 12] demonstrate that fragments absorbing the transferred mass acquire almost all of the excitation energy leaving nearly cold the donor nucleus. Correlations between the excitation energy and the mass flow were also observed for less distant collisions by several authors [13–17]. For almost fully damped collisions this dependence is found to be very weak and the excitation energy partition is close to the equal temperature limit. It was found that the donor target-like fragment (TLF) is excited in accordance to the evolution from the excitation energy equipartition at low energy loss to mass proportional division at the highest energy losses. Receptor TLF at all the energy losses takes a large fraction of the excitation energy corresponding approximately to the equal temperature value, leaving projectile-like fragment (PLF) relatively cold.

The aim of this work was to determine the excitation energy sharing between two binary products of ^{40}Ar (9.5 MeV/nucleon)+ ^{159}Tb collisions on the base of mean multiplicity of neutrons cooling down the hot target-like fragments in the broad range of excitation energy.

2. Experimental setup

The experiment was done at Hahn-Meitner-Institut Berlin using 9.5 MeV/nucleon ^{40}Ar beam from the VICKSI accelerator, focused on the 524 μg/cm^2 ^{159}Tb target. Neutron multiplicity as a function of charge and energy of projectile-like fragments detected below the grazing angle were measured (Fig. 1). PLF's with charge number $7 \leq Z_{\rm PLF} \leq 20$ were detected at 14.5° using conventional ΔE–E Si telescope consisting of 25μ and 1000μ

thick detectors. The PLF detection signal was used as a trigger signal for neutron registration in 4π scintillator tank of 1 m diameter, filled with 500 l of Gd-loaded toluene. The average detection efficiency of neutron coincident with projectile-like fragments was determined to be 82%. The detection system allowed to identify $Z_{\rm PLF}$=7–20 and neutron multiplicity measurement subtended the range of M_n=0–14. The scintillator tank provided no information on the energy and angular distribution of registered neutrons. A detailed description of experimental setup and results is presented in Refs [18–19].

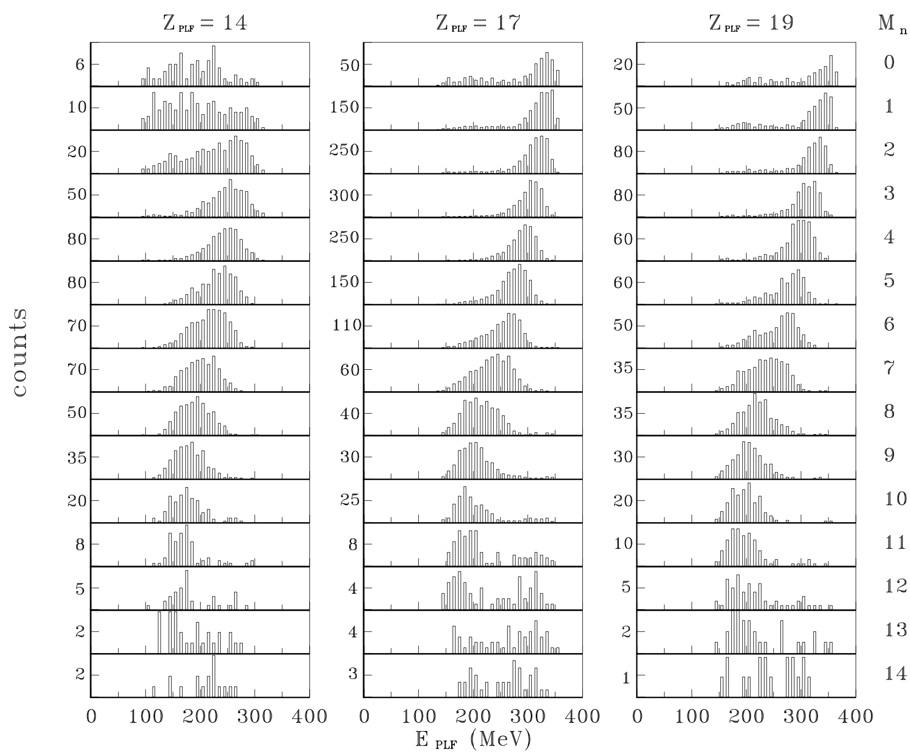

Fig. 1. Laboratory energy spectra summed over 10 MeV wide energy intervals of selected ejectiles sorted according to the number of detected neutrons M_n.

3. Analysis and interpretation of the results

Considerations concerning the behavior of the PLF energy spectra, the dependence of the mean neutron multiplicities, $\langle M_n\rangle$, on $Z_{\rm PLF}$ and PLF atomic number distributions in the total kinetic energy loss intervals indicate on the two body nature of ^{40}Ar+^{159}Tb collisions producing in exit channels fragments with 14$\leq Z_{\rm PLF} \leq$ 20 [19–20]. These projectile-like fragments originate in peripheral or less peripheral collisions with small and significant energy dissipation, respectively. The total kinetic energy loss, $E_{\rm loss}$, corrected for the ground state Q-values of the reaction is converted into the excitation energy of both primary fragments carrying almost all the nucleons of the entire system ($E^*_{\rm tot} = E^*_{\rm PLF} + E^*_{\rm TLF}$). Primary excited projectile-like fragments and target-like fragments cool down in the sequential statistical decay evaporating mainly neutrons which are the most abundant decay products. Projectile-like fragments with $Z_{\rm PLF} \leq 13$ are out of scope of this paper because mostly they do not originate directly from binary collisions.

The first assumption made in this analysis concerns the identification of the prevailing source of registered neutrons. The neutron detection efficiency is energy dependent and decreases with increasing velocity of the measured neutrons. The laboratory velocity of neutrons is directly related to the laboratory velocity of emitter and to the velocity of the emission. In most cases neutrons evaporated from the moving forward PLF have velocities considerably higher than that originating from the slowly moving TLF. Therefore the detection of neutrons emitted from PLF is less effective in comparison with the detection of neutrons emitted from TLF. Another circumstance which makes difficult to detect neutrons originating from PLF's is a strong kinematical focusing of all emitted fragments into the direction of flight of PLF's. Some part of these neutrons escapes from the detector through the outlet of the beam. In contrary, the slow heavier partner, TLF, has a nearly isotropic pattern of emitted neutrons in the laboratory frame. For those reasons total neutron yields obtained in the experiment using 4π neutron detector may be considered to be close to that originating from TLF's only. Simulation of the detection efficiency for registration of neutrons emitted by TLF and PLF performed for Ar + Au collision at 27.2 MeV/nucleon using the same 4π neutron detector as used in the present work, allowed to estimate that 96% of the detected neutrons originate from slowly moving source, *i.e.* target-like fragment [21]. In conclusion: *(i)* the energy dependence of the detection efficiency, *(ii)* the possibility of escape through the beam tube of neutrons emitted in forward direction, *(iii)* the asymmetry of the system — the heavy partner in contrast to the lighter one is more neutron rich and decays mainly via neutron evaporation (due to the lower Z the lighter emitter has a smaller Coulomb barrier and proton or alpha emission may compete with neutron evaporation), allow to admit the assumption that for the ^{40}Ar (9.5 MeV/nucleon)+^{159}Tb reaction the 4π neutron detector accepts neutrons preferably from the TLF evaporation and hence the neutron multiplicity data provide the information on the excitation energy deposited in TLF [19]. Hence in further analysis, calculations of the evaporation from heavier reaction partner were done and compared with experimental data. The mean experimental neutron multiplicities were corrected taking into account limitations of the experimental set up in order to estimate the real neutron multiplicities. These values were compared with theoretical predictions.

In order to obtain the information about the excitation energy sharing between fragments the dependence of experimental mean neutron multiplicity on total excitation energy was compared with the statistical model calculations simulating the TLF deexcitation. A comparison of the experimental results with calculations assuming different types of the energy sharing (see Fig. 2) demonstrates that the average neutron multiplicity is strongly dependent on this sharing and appears as a good measure of the excitation energy acquired by the fragments.

The sequential decay of the excited fragments was simulated by means of the Monte Carlo technique using the standard statistical code PACE II [22] based on the Hauser–Feshbach formalism [23]. Decay channels subtended by the code concern the statistical emission of γ-rays, neutrons, protons and α-particles. Some default settings of parameters inherent to this kind of calculation were similar to that used successfully by other authors [24–25].

The initial parameters used in the code PACE II correspond also to properties of the primary nucleus prior to the evaporation. These are the nuclear charge, mass, spin and excitation energy.

In the first approach simulations were performed taking into account the following conditions:

(1) the charge and mass of deexciting nucleus was calculated according to the assumption of a binary scenario of the reaction as:

$$
\begin{aligned}
Z_{\rm TLF} &= Z_{\rm proj} + Z_{\rm T} - Z_{\rm PLF}\,,\\
A_{\rm TLF} &= A_{\rm proj} + A_{\rm T} - A_{\rm PLF}\,,\\
A_{\rm PLF} &= 2Z_{\rm PLF} + 1\,,
\end{aligned}
$$

(where $Z_{\rm proj}, Z_{\rm T}, Z_{\rm PLF}, Z_{\rm TLF}, A_{\rm proj}, A_{\rm T}, A_{\rm PLF}, A_{\rm TLF}$ are the charge and mass number of projectile, target, PLF and TLF, respectively), accepting that the measured PLF charge number is the primary value,

(2) total kinetic energy loss corrected for the ground state Q-value of the reaction is fully converted into the excitation energy of the fragments.

Because a statistical emission of neutrons is only slightly sensitive to the spin of the parent nucleus, the estimation of the spin imparted to the nucleus was done according to the centrality of the collision determined from the total kinetic energy loss and the obtained values were used in simulations [19]. For most peripheral collision, at angular momentum $l{=}l_{\max}$

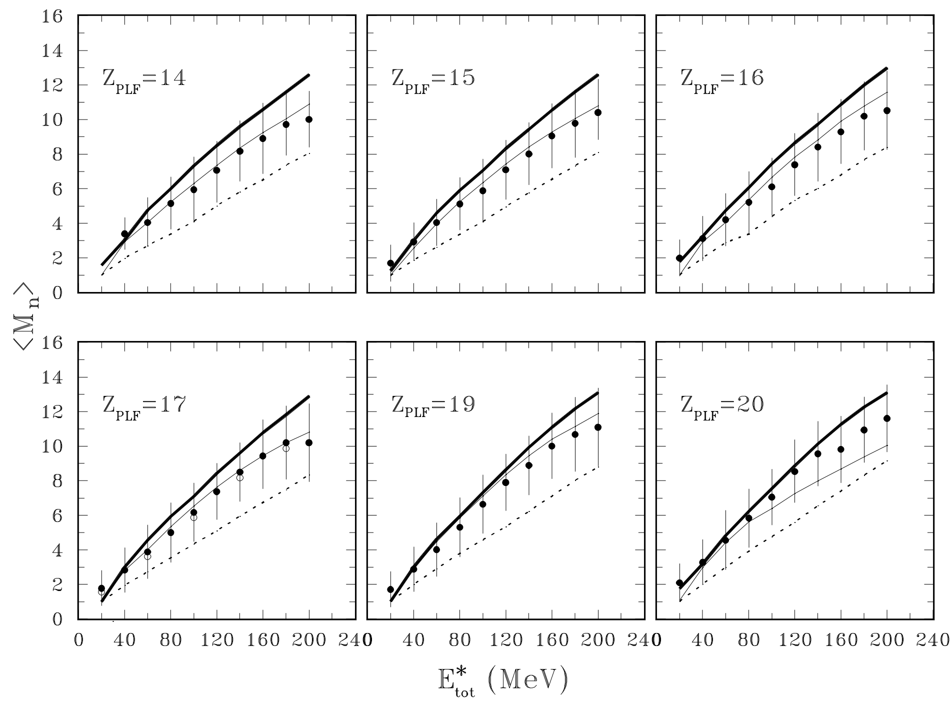

Fig. 2. Mean neutron multiplicity (with efficiency correction) as a function of total excitation energy $E^*_{\rm tot}$ for $14 \leq Z_{\rm PLF} \leq 20$ (full dots). $E^*_{\rm tot}$ refers to the centroid of 20 MeV-wide energy interval for which the mean neutron multiplicity was obtained. The dashed and solid lines represent the results of statistical model calculations assuming equal and mass proportional sharing of the total excitation energy, respectively. The empty circles at selected $E^*_{\rm tot}$ for $Z_{\rm PLF}$=17 correspond to the experimental results assuming $A_{\rm PLF}$=39. The detailed description of symbols used for various model assumptions is given in the text. The bars denote the FWHM values of neutron multiplicity distributions.

(the grazing limit) the total kinetic energy loss was assumed to be equal to 0. With decreasing value of angular momentum collisions become more central, reaching at l=$l_{\rm cr}$ the fusion limit. Between these two limits the intermediate angular momenta corresponding to given values of $E_{\rm loss}$ were obtained by linear interpolation. Further, the fraction of the angular momentum imparted into nuclei as a spin for intermediate values of l was obtained by linear interpolation between zero transfer at the grazing limit, and the value of classical sticking at the fusion limit.

In the light of the above considerations the excitation energy used as an input parameter in statistical model simulations plays a crucial role in changing the calculated neutron multiplicity. Simulations of the TLF deexcitation were performed with two limiting assumptions that either the total excitation energy is shared equally between PLF and TLF ($E^*_{\rm PLF} = E^*_{\rm TLF}$) or in proportion to the mass of fragments, what means that the equal temperature limit is assumed ($T_{\rm PLF} = T_{\rm TLF}$). A comparison of the experimental mean multiplicities with results of the evaporation calculations is presented in Fig. 2 as a function of the total available excitation energy for various $Z_{\rm PLF}$, corresponding to appropriate target-like fragments. The bold lines represent the neutron yield corresponding to the equal temperature limit and the dashed lines result from calculations assuming that the available excitation energy is divided equally. Fig. 2 demonstrates the common behavior of all mentioned TLF's, independently on the direction and amount of net nucleon transfer. Calculations of equal energy division underestimate the experimentally obtained neutron yield, while the simulations assuming equal temperature limit overestimate the experimental results for medium and high values of total excitation energy.

A significant improvement of the description of data is achieved by using in calculations with the hypothesis of equal temperature the TLF masses of less neutron-rich isotopes (thin lines in Fig. 2). It corresponds to the production of primary PLF's which are more massive than the most abundant stable isotopes. Indeed, these phenomena were confirmed experimentally in ^{40}Ar+^{68}Zn [26] and ^{40}Ar+^{197}Au [27] reactions, where the strong abundant isotopes of K, Cl, and S were found to have masses $A_{\rm PLF}$=41,39,36, respectively. These masses were used in further calculations, while for P and Si fragments the extreme mass limits were assumed taking into account the N/Z equilibration. It was experimentally observed that the measured N/Z ratio of final fragments is strongly correlated to that of the combined system, and when the composite system is neutron-rich, the neutron-rich fragments are produced [3], [28–33]. The neutron-to-proton ratio is expected to be equilibrated during the initial stage of heavy ion reaction at interaction times of the order of 10^{-22} s. For phosphorus and silicon ions the values of $A_{\rm PLF}$= 36, 33 were used, respectively, according to N/Z value of the composite system ($\simeq$1.4). As is shown in Fig. 2 the results of calculations for $14 \leq Z_{\rm PLF} \leq 19$ (thin lines) reproduce the magnitude of neutron yields and the change of a slope of the experimental data observed at energies $E^*_{\rm tot} \geq 140$ MeV. For Ca ions measured in the exit channel the calculation results reflecting the N/Z equilibration ($A_{\rm PLF}$=48) underestimate significantly the data (thin line). A better agreement, particularly at medium $E^*_{\rm tot}$, is achieved for assumed in calculations $A_{\rm PLF}$=41 ($A = 2Z + 1$ prescription) (thick line). The underestimation of calculation results for $A_{\rm PLF}$=48 and the overestimation for $A_{\rm PLF}$=41 may indicate on a strong Ca production of mass equal to 44 amu, resulting from an α particle transfer from the projectile (^{40}Ar) to the projectile-like fragment (^{44}Ca). Similarly, in the case of production of PLF's lighter than the projectile, transfer of an α particle in the opposite direction (α is removed from ^{40}Ar) may be responsible for creation of strong abundant ^{36}S ions in the exit channel.

The choice of mass parameters used for transformation of experimental data influences the obtained experimental mean neutron multiplicity for given $E_{\rm loss}$ (or $E^*_{\rm tot}$) interval. A comparison of experimentally obtained mean neutron multiplicity assuming for $Z_{\rm PLF}$=17 the mass equal to 35 amu (corresponding $A_{\rm TLF}$=164) and 39 amu ($A_{\rm TLF}$=160) is presented in Fig. 2 as full and empty dots, respectively. The change of mass values used for a transformation of experimental data does not affect the outcome of this analysis.

Under above considerations one can state that the dependence of the energy division on the mass flow direction is justified by experimental results obtained for ^{40}Ar (9.5 MeV/nucleon)+^{159}Tb reaction for events where the mass is transferred from the projectile to the target. The underestimation of neutron multiplicity by thermal equilibrium calculations at low excitation energies ($E^*_{\rm tot} < 40$ MeV) indicate that almost all of the excitation energy is generated in heavier receptor nucleus, which is able to emit more neutrons than predicted by mass proportional energy partition. For intermediate and high excitation energies the excellent agreement with calculations assuming the equal temperature limit and mass values of strongly abundant neutron-rich isotopes of PLF is obtained.

In the case of transfer in the opposite direction, *i.e.* from the target to the projectile, the expected evolution from nearly all of the excitation energy deposited in PLF at low energies to the achievement of equal temperature limit is not obtained. The continuous trend of the energy sharing proportional to the mass ratio in the whole range of energy is observed. Results of calculations assuming the thermal equilibrium limit describe the experimental data well, although the interpretation of such behavior may be difficult. At low excitation energy the reaction products seem to be separated with almost the same nuclear temperature.

The amount of uncertainty of the calculations does not allow the stringent conclusions, however one can state that the experimental results confirm the dependence of the excitation energy division on the direction of nucleon transfer at least for collisions with mass flow from the projectile to the target. The experimental data indicate that the most part of the excitation energy is generated in TLF, which gains nucleons during the collision, independently on the losses of the total kinetic energy.

4. Summary

The experimentally obtained neutron multiplicities accompanying PLF's with $14\leq Z_{\rm PLF} \leq 20$ were compared with the statistical model calculations. Accepting the scenario of a binary mode of the reaction calculations using the statistical code PACE II have been performed assuming two limiting hypotheses for the excitation energy sharing. Calculations using the thermal equilibrium limit and the PLF masses of strongly abundant neutron-rich isotopes describe the data most convincing. Results of the experiment seem to be in disagreement with the nucleon exchange model [34] predicting the transition from the equal excitation energy division at low $E_{\rm loss}$ to the equal temperature limit for damped collisions. On the contrary there are experimental evidences of nearly equal temperature partition in the whole range of $E_{\rm loss}$, confirming the dependence of energy partition on the direction of mass transfer. The underestimation of the experimental results for quasi-elastic events for $Z_{\rm PLF} < Z_{\rm proj}$ may indicate, that nearly all of the excitation energy is deposited in receptor nucleus (TLF). The similar trend observed for $Z_{\rm PLF} > Z_{\rm proj}$ is rather surprising. Due to the mass flow from the TLF to PLF the deposit of the excitation energy at low and medium $E_{\rm loss}$ is expected in the lighter fragment, involving the decrease of multiplicity of neutrons evaporated from the TLF. For nearly fully damped collisions the agreement of the experimental data with thermal equilibrium calculations is observed, following the common experimental conclusions.

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