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DYNAMICS OF "BINARY" ^{197}Au+^{197}Au COLLISIONS AS A TEST OF ENERGY DISSIPATION MECHANISM*

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^{197}Au+^{197}Au collisions at 15 MeV/nucleon were studied using the multidetector array CHIMERA and heavy ion beams from the superconducting cyclotron of LNS Catania. The experiment was aimed at studying the mechanism of energy dissipation in collisions of very heavy systems. In the present contribution we report on a part of our study concentrated on a subject of basically binary damped collisions, in which only two main fragments are formed prior to secondary deexcitation processes. Such "binary" events were selected by using complete information from the exclusive-type data (including all $Z \geq 3$ fragments) obtained with the CHIMERA multidetector. Results are compared with predictions of a classical dynamical model of Błocki *et al.*, in which both scenarios of energy dissipation, one-body or two-body dissipation mechanisms, are assumed.

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1. Introduction

In the past, collisions of heavy nuclear systems at low energies (below 20 MeV/nucleon) were studied in basically inclusive experiments (see *e.g.* Ref. [1]). Later, important progress in understanding the mechanism of strongly damped reactions at this energy range was made in a series of semi-exclusive experiments, *e.g.* [2–4] based on the kinematic coincidence method, allowing to detect both, projectile and target-like fragments, but without a possibility to veto other than binary partitions. In this contribution we present results of an exclusive-type experiment on the ^{197}Au+^{197}Au reaction, carried out at LNS Catania at an energy of 15 MeV/nucleon, by using a complete 4π detection system CHIMERA. The very heavy ^{197}Au+^{197}Au system was chosen because in the absence of fusion, its complete dynamical evolution, until re-separation, can be studied for all impact parameters. Moreover, interesting phenomena characterizing transition from one-body to two-body mechanism of energy dissipation are expected [5] in ternary partitions of such very heavy systems. In the present report we concentrate only on a part of data representing nearly binary deep-inelastic reactions.

2. Experiment

The experiment was carried out at the Laboratori Nazionali del Sud in Catania. The ^{197}Au beam was accelerated to the energy of 15 MeV/nucleon with the LNS Super-Conducting Cyclotron and bombarded a 273 μg/cm^2-thick ^{197}Au target, placed inside the Charged Heavy Ion Mass and Energy Resolving Array (CHIMERA). The CHIMERA multidetector, arranged in 4π geometry, is built of 1192 two-layer $\Delta E - E$ telescopes, each telescope consisting of a planar 300 μm-silicon detector and a CsI(Tl) scintillator. Most fragments originating from the ^{197}Au+^{197}Au collisions were stopped in the silicon detectors. Mass determination of these fragments was achieved by combining energy and time-of-flight (TOF) measurements. The energy resolution of silicon detectors was in the range of 0.5–1% for typical heavy ions, and 1% for fully stopped ^{197}Au ions of an energy of about 2900 MeV.

The TOF measurements were done using the timing signal from silicon detectors relative to the timing of the cyclotron high frequency signal. An overall time resolution of $\delta t \approx 0.8$–1.2 ns (FWHM) was achieved. This resulted in the mass resolution in the range from 3% at forward angles up to 8% in the worst case of measuring the TOF on a relatively short distance of 40 cm in detectors of the "sphere" part of CHIMERA. This rather poor mass resolution at large angles is not however critical regarding the main goals of the experiment.

The fact that the detection of fragments was based exclusively on the energy and TOF measurements in the CHIMERA front-layer silicon detectors had the virtue of negligibly low energy thresholds in the data. (For

Au-like fragments an effective energy threshold was about 0.2 MeV/nucleon at forward angles and about 0.05 MeV/nucleon at large angles near 80°). The information on light charged particles of $Z \leq 2$, requiring signals from the CsI(Tl) detectors, was not used in the present analysis. For more details concerning the CHIMERA multidetector see Ref. [6] and references therein.

Energy calibration of the silicon detectors was done using elastic scattering of ^{197}Au as well as elastic scattering of ^{12}C and ^{16}O beams in additional calibration runs at different energies. Fission fragments from the $^{12}C+^{197}Au \rightarrow ^{209}At$ reaction of known average kinetic energy [7] were also used to calibrate energies of mid-mass fragments. As compared with the previous preliminary report [8], detectors in the rings covering the angular range $70° \leq \theta_{\rm lab} \leq 86°$ were added to the analysis and their calibration was done using a technique based on the in-plane Au+Au inelastic scattering coincidences.

Our method of the TOF calibration for continuous energy spectra of charged fragments (ranging from Li to Au), stopped in silicon detectors, was briefly described in Ref. [8].

3. Binary reactions

The collected data contained information on all charged particles/fragments of $Z \geq 3$ detected in the angular range $10° \leq \theta_{\rm lab} \leq 86°$. Smaller detection angles ($\theta_{\rm lab} < 10°$) were excluded in this experiment due to very intensive rate of elastically scattered Au ions. As mentioned above, information on nucleons and light charged particles of $Z \leq 2$, accompanying the heavier fragments and mostly originating from secondary evaporation processes, was not included in the data. Thus the "binary" events were selected by requiring the multiplicity $M = 2$ of charged fragments of $Z \geq 3$, having together the total mass number in the range $A_{\rm P} + A_{\rm T} - 70 \leq A_1 + A_2 \leq A_{\rm P} + A_{\rm T}$, where $A_{\rm P}$ and $A_{\rm T}$ are the mass numbers of the target and projectile, respectively. Practically this condition resulted in selection of events representing two massive fragments (projectile and target residues, PLF and TLF, respectively) and *no* other charged particles/fragments of $Z \geq 3$. The mentioned above range of the total mass accounts for the mass of *undetected* nucleons and α-particles mostly evaporated from the excited primary fragments. In order to eliminate events with one or more fragments of $Z \geq 3$ escaping detection, conditions requiring coplanarity of the two velocity vectors with the beam direction, $|\phi_1 - \phi_2| = 180° \pm 20°$, and their colinearity in the C.M. system, $|\Theta_{\rm c.m.}(1) - \Theta_{\rm c.m.}(2)| = 180° \pm 5°$ were imposed in addition to the multiplicity and total mass gates. Moreover, balance of the transversal momentum, $|\vec{p}_{\rm trans}(1) + \vec{p}_{\rm trans}(2)| < 0.04\,p_0$, where p_0 is the momentum of ^{197}Au projectiles, was required.

4. Energy-angle correlations

In Fig. 1 we show the energy-angle correlation for the class of binary events selected as described in Section 3. We would like to emphasize the importance of the exclusive character of the experiment that guarantees correct identification of the binary, ternary and multi-body events. Despite very difficult experimental conditions at large angles near $\theta_{\rm lab} = 80°$, the TLF's were detected and their energies and masses determined with reasonable accuracy. The diagram presented in Fig. 1 shows only *pairs* of PLF and TLF reaction partners detected in those events when no other particles/fragments of $Z \geq 3$ were present. The missing mass of undetected nucleons and light charged particles of $Z \leq 2$ is interpreted as originating from secondary evaporation processes, which do not significantly distort trajectories and mean velocities of the detected PLF's and TLF's.

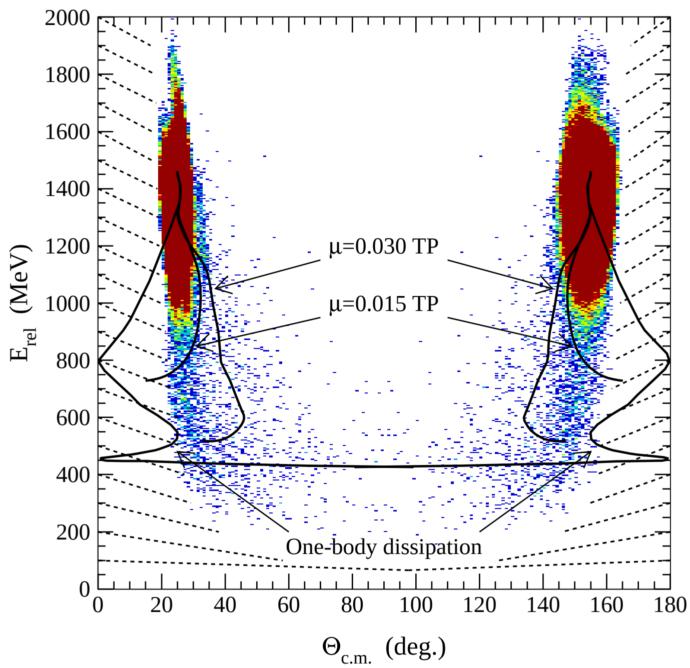

Fig. 1. Energy-angle correlation for "binary" events collected in an exclusive (nearly 2π) ^{197}Au+^{197}Au experiment at 15 MeV/nucleon. The binary events have been selected with conditions listed in Section 3. Results are compared with predictions of a classical dynamical model of Błocki *et al.* [9], assuming one-body dissipation or two-body dissipation for two different values of the viscosity coefficient μ. The dashed area shows the dynamical range inaccessible experimentally due to very high intensity of elastic scattering.

The energy-angle distribution in Fig. 1 shows two branches of the reaction partners undergoing a considerable damping of the kinetic energy. Both branches (of PLF's and TLF's) extend to the lowest relative kinetic energies corresponding to the complete damping of the available energy.

In the first stage of theoretical analysis, the measured energy-angle correlations in the ^{197}Au+^{197}Au reaction are compared with predictions of a simple deterministic dynamical model of Błocki *et al.* [9]. Such a deterministic model can predict only the most probable trajectories for a given value of angular momentum. Therefore, only localization of the "ridge" of the maximum intensity in the measured energy-angle distribution can be compared with these theoretical predictions. Calculations were done for two extreme situations regarding the nature of the energy dissipation mechanism: the one-body dissipation in form of the "wall-plus-window formula" [10, 11] and the hydrodynamic two-body dissipation [12] with the viscosity assumed to be a free parameter. In the latter case the two-body dissipation mechanism was replacing the one-body dissipation after heating up the system (in the first stage of reaction) up to a temperature of 2 MeV. Calculations were done for two values of the dissipation coefficient: $\mu = 0.015$ TP and 0.030 TP. [1 TP (terapoise) = 6.24×10^{-22} MeV s/fm^3]. The former value, $\mu = 0.015$ TP, was found [12] to be consistent with most probable kinetic energies of fission fragments, as given by the Viola systematics [7].

As seen in Fig. 1, the two different mechanisms of energy dissipation lead to qualitatively different predictions: in case of one-body dissipation a clear effect of orbiting towards negative scattering angles [13] and the second "rainbow" at $\Theta_{\rm c.m.} \approx -25^\circ$ is expected, while in case of two-body dissipation the positive-angle scattering (no orbiting) with incomplete dissipation of the available kinetic energy is predicted.

Our experimental data do not show evidence for the orbiting predicted by the deterministic one-body dissipation model [9] based on the wall-plus-window formula. However, the angular limitations of the experiment (see dashed regions in Fig. 1) do not allow us to make this conclusion firm.

More information on the dynamical evolution of the studied super-heavy system ^{197}Au+^{197}Au will be obtained from comparisons with predictions of the stochastic BNV model of Baran, Colonna and Di Toro [14] and the QMD-CHIMERA model of Łukasik [15]. Results of such an analysis will be published in a separate paper. The question of discrimination between the two extreme approximations to the mechanism of energy dissipation (one-body or two-body dissipation) can be more convincingly resolved in analysis of ternary (instead of binary) events. The analysis of ternary events in the ^{197}Au+^{197}Au reaction is under way.

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