Vol. 10 (2017) *Acta Physica Polonica B Proceedings Supplement* No 1

WILCZYŃSKI PLOTS FOREVER?[*]

W. Gawlikowicz

Cardinal Stefan Wyszyński University
Faculty of Biology and Environmental Sciences
Dewajtis 5, 01-815 Warszawa, Poland

J. Błocki

National Centre for Nuclear Research
Hoża 69, 00-681 Warszawa, Poland

(Received January 10, 2017)

Correlations between the energy and the deflection angle of the projectile-like fragments were studied for the ^{136}Xe + ^{209}Bi reaction at $E/A = 28$ and 62 MeV. Experimental correlations were compared with model calculations performed by QMD code, including only one-body and both one- and two-body dissipations — only in the latter case an agreement with experimental data was obtained. It is shown that at a bombarding energy of 62 MeV/nucleon, the reaction cross section is still dominated by dissipative binary reactions involving the survival of well-defined projectile- and target-like fragments.

DOI:10.5506/APhysPolBSupp.10.81

1. Introduction

At low bombarding energies, the mean-field interaction (one-body dissipation) is largely responsible for the dissipation of the initial kinetic energy into the thermal energy [1]. On the other hand, at high energies (few hundreds MeV/nucleon), the nucleon–nucleon collisions (two-body dissipation) play dominant role [2]. It is hence expected that the reaction mechanism will undergo significant changes at higher bombarding energies [3].

The interplay between one- and two-body dissipation leads to appearance of a balance energy, where the attractive mean-field scattering is balanced by the repulsive nucleon–nucleon scattering [4] — in that case, one expects vanishing of Wilczyński plots [5], which are characteristic for dissipative orbiting at low bombarding energies.

---

[*] Presented at the XXIII Nuclear Physics Workshop "Marie and Pierre Curie", Kazimierz Dolny, Poland, September 27–October 2, 2016.

The purpose of this work is to understand the influence of one- and two-body dissipation in dissipative orbiting mechanism.

2. Experimental setup

The experiments were performed at the National Superconducting Cyclotron Laboratory of Michigan State University. Beams of ^{136}Xe ions with energies $E/A = 28$ and 62 MeV were focused on a self-supporting 3.5 mg/cm^2 thick ^{209}Bi targets — for details, see Ref. [6].

In this paper, we are presenting experimental data measured by silicon-detector telescopes placed at an angular region close to the grazing angle. The silicon telescopes were position-sensitive, anticipating laboratory grazing angles $\theta_{\mathrm{gr}} = 6.65^\circ$ (for $E/A = 28$ MeV) and $\theta_{\mathrm{gr}} = 2.96^\circ$ (for $E/A = 62$ MeV), with laboratory angular coverage for $\theta = (3.07^\circ, 5.89^\circ)$ and $\theta = (2.01^\circ, 3.81^\circ)$ for energies $E/A = 28$ and 62 MeV, respectively [7].

3. Theoretical modeling

The typical theoretical modeling of heavy-ion reactions is based on a two-step process, with the first step describing the collision dynamics and the second one describing the deexcitation of the created reaction products [8].

In the present study, the interaction stage was modeled using the Quantum Molecular Dynamics (QMD) code CHIMERA [9], with the deexcitation phase simulated by dynamical version of the GEMINI code [10], assuming an equilibrium-statistical decay of excited reaction products [11].

In the QMD calculations, the reaction evolution is determined by the nuclear potential (one-body dissipation) and the particle dynamics leading to nucleon–nucleon collisions (two-body dissipation). The collisions are determined by the nucleon–nucleon cross section, which is energy- and isospin-dependent. Any two nucleons are considered candidates for a collision, whenever their spatial separation is smaller than the distance related to nucleon–nucleon cross section — the collisions may be, however, blocked due to the Pauli principle.

We assume here a soft equation of state ($K \approx 200$ MeV) with symmetry energy strength coefficient corresponding to an ASY-STIFF equation of state ($C = 31.4$ MeV).

In order to study the reaction evolution for different dissipation mechanisms, the CHIMERA code was used in two alternative versions:

(i) including one-body dissipation only (mean-field effects only),

(ii) including both one- and two-body dissipation (mean-field plus nucleon–nucleon collisions).

4. Wilczyński plots

The logarithmic contour plots of the fragment yield as a function of the energy and the emission angle of the projectile-like fragments (PLFs) are presented in Fig. 1 for bombarding energies of $E/A = 28$ and 62 MeV. The top panel shows the results for QMD calculations for one-body dissipation only, while the bottom panel presents results with one- and two-body dissipation. The final deexcitation was simulated with the equilibrium-statistical decay code GEMINI. Additionally, the crest lines of experimental distributions in the measured angular range are shown. As one can see (the upper panels), the one-body dissipation does not reproduce the experimental trend especially for higher bombarding energy. The ratio of the collective velocity to the average speed of particles is equal to 0.425 for $E/A = 28$ MeV and 0.632 for $E/A = 62$ MeV. So the condition that this ratio should be small is not fulfilled and, therefore, the applicability of the one-body dissipation only becomes questionable. Including two-body dissipation mechanism (the bottom panels) improves very much the comparison with an experiment.

As seen in the top panel of Fig. 1, the calculations performed with one-body dissipation only (mean-field effects) describe the general collision scenario, showing dissipative orbiting with a subsequent statistical decay of the

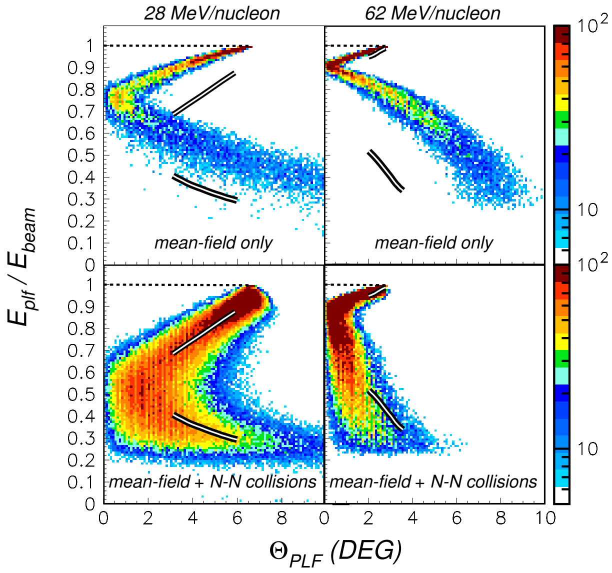

Fig. 1. (Color online) PLF yield as a function of the energy and the emission angle (LAB system) for bombarding energy $E/A = 28$ and 62 MeV, as obtained from QMD + GEMINI simulation (see the text). Dashed lines — results for elastic and quasi-elastic reactions. White solid lines — crest line of experimental distributions [7].

primary PLF. It appears that the reaction picture for peripheral collisions is essentially the same at $E/A = 62$ MeV as it was earlier found at lower bombarding energies [5].

Introduction of nucleon–nucleon collisions (bottom panel) adds an extra dissipation, what is seen in lowering of energy of the PLF residue. As an additional effect, one observes broadening of observed distributions, what can be understood taking into account the random nature of nucleon–nucleon collisions. For bombarding energy $E/A = 62$ MeV, one can notice a pronounced reduction of deflection angle for lower branch of distribution (high dissipation region) caused by introducing nucleon–nucleon collisions (two-body dissipation). This effect will grow with increase of bombarding energy, causing a vanishing of Wilczyński plots for a certain value of balance energy [4].

Consequently, in a view of the above study, the presence of Wilczyński plots for energy as high as $E/A = 62$ MeV shows that the transition to a high-energy scenario dominated by two-body interactions and two-body dissipation must be occurring at higher bombarding energies.

5. Summary and conclusions

In the performed analysis, the projectile-like fragment deflection function was found as a sensitive signature for one- and two-body dissipations modeling. While the one-body dissipation seems to be responsible for general features of dissipative orbiting, only an inclusion of nucleon–nucleon collisions (two-body dissipation) gives proper reaction description.

The correlations between the energy and the emission angle of projectile-like fragments shows that peripheral collisions, for energies as high as $E/A =$ 62 MeV, are still governed by dissipative orbiting — a characteristic feature of low bombarding energies (Wilczyński plots forever?).

REFERENCES

[1] J. Błocki *et al.*, *Ann. Phys.* **113**, 330 (1978); W.J. Świątecki, *Phys. Scr.* **24**, 113 (1981).
[2] P. Danielewicz *et al.*, *Phys. Rev. C* **38**, 120 (1988).
[3] H.M. Xu, *Phys. Rev. Lett.* **67**, 2769 (1991).
[4] G.D. Westfall *et al.*, *Phys. Rev. Lett.* **71**, 1986 (1993).
[5] J. Wilczyński, *Phys. Lett. B* **47**, 484 (1973).
[6] W. Gawlikowicz *et al.*, *Phys. Rev. C* **81**, 014604 (2010).
[7] W. Gawlikowicz *et al.*, *Acta Phys. Pol. B* **46**, 1025 (2015).
[8] W. Gawlikowicz, *Acta Phys. Pol. B* **40**, 1695 (2009).
[9] J. Łukasik *et al.*, *Phys. Rev. C* **55**, 1906 (1997).
[10] W. Gawlikowicz, *Acta Phys. Pol. B* **28**, 1687 (1997).
[11] W. Gawlikowicz *et al.*, *Nucl. Phys. A* **681**, 295c (2001).