THE TIME SCALE OF NUCLEAR REACTIONS FROM DEEP INELASTIC TO PROJECTILE–TARGET FRAGMENTATION*

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During the last fifteen years, professor Janusz Wilczyński devoted a large part of his scientific activity to Heavy-Ion (HI) experiments performed with the CHIMERA detector in the Fermi energy domain. He was an outstanding member of the international CHIMERA Collaboration. The reaction mechanism for semi-peripheral collisions at Fermi energy was carefully examined by him and his research group in close collaboration with both experimentalists and theorists in Catania. Since the earlier pioneering works in deep-inelastic collisions, the unifying concept of Wilczyński's analysis of the experimental data has been driven by the powerful notion of one-body semi-classical deflection function. Wilczyński extended in the early 1970s the application of this concept to describe in a coherent way both the energy dissipation and the time scale evolutions of dissipative collisions. In this paper, we focus mainly on the time scale of the reaction mechanism in gentle three-body reactions between two interacting heavy ions at Fermi energy.

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1. Introduction

When on January 20$^{\text{th}}$, 2016, the organizers of the XXIII Nuclear Physics Workshop, Kazimierz Dolny invited me to give a talk in memoriam of Janusz Wilczyński, I was hesitant. My hesitation derived from my difficulty to adopt the adequate perspective and attitude. Janusz, indeed, was not only a very good friend of the CHIMERA working group (so, some emotions could affect the essence of an objective work, as it should be) but, and this was the essential point for me, he was one of the most outstanding Polish scientists

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in the field of nuclear physics. He played a role of an exceptional importance in the field of HI collisions. Thus my hesitation, originated from the feeling that my background in physics was not adequate to describe even a part of his outstanding recent activity. On the other hand, I was also conscious that my efforts could be useful in view of the unique opportunity to experience and to think more about an important piece of physics, in which very good young researchers in Europe are presently involved. Consequently, after some studies, I decided to accept to give my talk at a special session of the conference. After that, I was very proud of doing it, because I have experienced there the presence of outstanding scientists coming from many countries and Polish authorities, all of them sharing with me similar attitude and emotions for Janusz: as a man, as a scientist, as a patriot and prophet of a new world with no frontiers or prejudices.

I met professor Janusz Wilczyński for the first time at the Laboratori Nazionali del Sud (LNS) in Catania in 1998, at the first annual meeting organized by the CHIMERA Collaboration [1]. Eryk Piasecki from Warsaw introduced Janusz to me and my collaborators. At that time, I was the spokesperson of the first experimental campaign (REVERSE) with the forward part of CHIMERA detector. The apparatus assembled 688 Si–CsI(Tl) telescopes and covered the laboratory angular range between 1° and 30°. The experiment was thought to investigate both peripheral (few bodies in the final state of the reaction) and central collisions (multifragmentation of the composite system in many small clusters of intermediate mass) in the ^{124}Sn+^{64}Ni, 27 Al at 25 MeV/nucleon and 35 MeV/nucleon [2]. The reaction chamber was the large LNS-Ciclope one. However, after running of a first preliminary experiment on ^{124}Sn + ^{64}Ni at 25 MeV/nucleon system, more efficient data collection was achieved in early 2000. Actually, due to the stringent experimental requirements of the REVERSE experiment concerning the timing performances of the Super Conductive Cyclotron (SCC) pulsed beams, *i.e.*, $\delta t \leq 1$ ns (in order to allow for good Time-of-Flight measurements with CHIMERA), it was suggested by the staff of the LNS–SCC to change the radial injection of the Cyclotron (this was achieved using the Tandem Beam as injector of the SCC) by a new axial injection. With a novel ECR source CAESAR, there was a hope to limit the previously observed time spread ($\delta t \simeq 2.5$ ns) of the pulsed beam on the target (flight path of the beam over about 60 m) well below values of 1 ns. The new injection was successfully installed and, following this, good timing performances of the SCC machine were obtained, and the REVERSE experiment was successfully accomplished [2]. After an important and hard analysis of the raw data acquired from the large surface n-type planar silicon detectors and the CsI(Tl) scintillators, the first CHIMERA results were discussed at the Nucleus–Nucleus International Conference in Moscow in 2003 [3, 4]. Practically, the REVERSE experiment produced the official validation of the good quality of the CHIMERA device in the domain of HI. In particular, and very importantly for me, Janusz was convinced of the high quality of the CHIMERA raw data and, consequently, he started to study a specific reaction channel with three heavy fragments in the final state: Projectile-Like Fragments (PLFs), Target-Like Fragments (TLFs) and light Fragments of Intermediate atomic number (IMFs), *i.e.*, with atomic numbers in the range of $2 < Z < 15$, with laboratory velocities very close to the CM system of the reaction, as is seen in figure 1. Evidently, the presence of IMFs of intermediate velocity strongly indicates a substantial overlap of nuclear matter of the Projectile and Target nuclei at the moment of the collision.

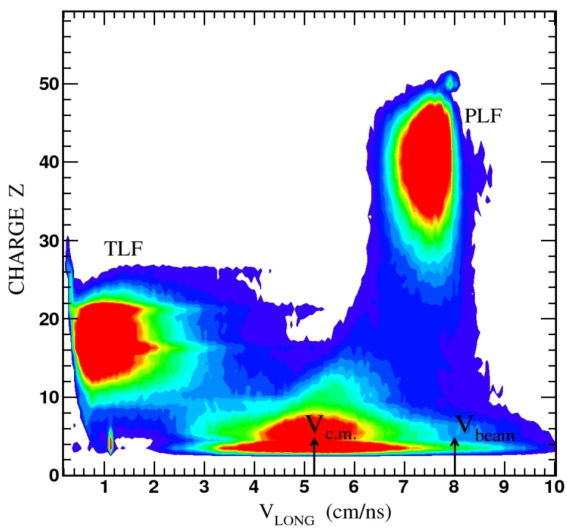

Fig. 1. Atomic numbers of the measured fragments in the reaction ^{124}Sn+^{64}Ni at the bombarding energy of $E_{\rm LAB}$ (^{124}Sn) = 35 MeV/nucleon, as obtained in the REVERSE experiment. The plot was produced by assuming a total charged multiplicity $M_{\rm tot} \leq 7$ in order to select semi-peripheral collisions. Besides PLF and TLF nuclei, a pronounced bump of IMFs indicates a substantial overlap between the Projectile and the Target Interacting systems.

After a number of discussions with the CHIMERA working group in Catania, including both experimentalists as well as theorists [5], Prof. Wilczyński suggested a very powerful representation of the relative kinetic observable thorough a new correlation plot, which was named the Wilczyński2 plot or WILC2-plot, because it was ideally linked with the famous and well-established "Wilczyński plot" related to deep-inelastic HI collisions [6]. Soon, the new plot revealed its powerful nature: it was simply a master stroke. A special international committee nominated Janusz Wilczyński as the first EMERITUS (2005) of the CHIMERA Collaboration. Figure 2 presents a collection of pictures that are still in our memory. Janusz visited CHIMERA and he was impressed by it. He also visited different places in Sicily and he was fascinated by its historical heritage and the warm hospitality of Sicilian people. His natural tendency to kindness has left a deep mark on all who knew him, both during the experimental runs or in moments of relaxation or simple tasting Italian coffee. I remember with great fondness one time that I invited him at home for a simple dinner. Eryk Piasecki was also there. My wife Rosetta cooked an excellent octopus with tomato salad and carrots. I immediately noticed the embarrass and the difficulty: Janusz and Eryk had indeed never eaten octopus. Janusz with great sense of duty tried to eat the food he did not enjoy at all. I and my wife Rosetta stopped him and, suddenly, she changed the menu: she pulled out of the fridge some meat steaks. Janusz immediately underwent an unexpected transformation and became a great cook. We all had a great dinner with grilled meat and tomato salad. I report it because Janusz liked to recall often this episode, as one of the most cheerful moments in Sicily (as his daughter Ania told me in Kazimierz).

Fig. 2. Prof. Janusz Wilczyński enjoyed Sicily. He visited Acireale, Catania, Syracuse, Noto, Caltagirone, Enna and other beautiful cities. During IWM2005 conference in Catania, he was awarded with a CHIMERA GOLD replica as the first "Emeritus Scientist" of the CHIMERA Collaboration.

I think it is useful to remind the readers of two papers of Janusz's important contribution to physics, just before I describe the concept of the WILC2-plot in the second part of this manuscript. The first paper (already mentioned) I would like to quote is the famous one concerning the basic explanation of deep-inelastic collisions by using the concept of semi-classical deflection function [6]. The work was strongly related with the prominent role played by the Dubna group, but it could be adopted for all the studies in deep-inelastic collisions. The idea (not discussed here in detail, because it is universally adopted) can be summarized just by the simple term of "Wilczyński Plot". Indeed, all people working in HI collisions at the pre-Fermi energies, immediately understand this term and its underlying concept: no additional comments are required. I have only to add, for an exhaustive definition of the physics connected to deep-inelastic collisions, the major role played by the concept of "nucleon mass transfer", as the dominant mechanism underlying the large dissipation of kinetic energy that occurs in deep-inelastic reactions [7]. In particular, this latter mechanism opened the real possibility to produce exotic nuclei. The second paper is linked with Janusz's activity in Groningen [8]. In that paper, an exhaustive proof of the coexistence of different projectile break-up mechanisms as uncorrelated (direct), sequential decay and incomplete fusion was given. The paper is one of the first application of the "correlation" method applied to double differential cross sections obtained in experiments where both single and coincident data were studied. The differential cross section was factorized in terms of the product of two single cross sections (in the case of one particle–one particle coincidence experiments) and, consequently, a correlation coefficient was determined. The cross sections for direct break-up, sequential ones and incomplete fusion were accurately determined by a careful fitting analysis of the integrated (in energy) angular distribution of the lightest fragments taken in coincidence with the PLF fragments that were measured at a fixed angle. The paper was an excellent demonstration of the efficacy of the coincidence method (relatively new at that time) to pin down nuclear properties that were not accessible by evaluating the energy spectra and angular distributions in experiments performed in a single mode. This paper also opened a new methodological approach for more efficient experiments in HI physics.

2. Time scale and neck fragmentation at Fermi energy

At the Fermi energy, the reaction mechanism in semi-peripheral HI collisions undergoes a rapid evolution with the energy characterized by a transition mechanism in projectile fragmentation [9]. The reaction is dominated by the mean-field interaction for bombarding energy close to the Coulomb barrier up to deep-inelastic pre-Fermi regime. At relativistic HI energies, projectile fragmentation is dominated by the participant–spectator model [10], and a fast break-up of the projectile (target) takes place, as described by the Goldhaber picture of projectile-like momentum dispersion [11]. In this scenario, the overlap region (the participant) between the projectile and the target becomes a hot and compressed source of exotic nuclear matter where nucleon–nucleon in medium interactions generates large entropy and high density (up to 2–3 times the normal density, $\rho_0 \simeq 0.15$ nucleon/fm^3) [10]. At the Fermi energy ($\simeq$ 20–100 MeV/nucleon) and for semi-peripheral collisions, signatures of deep-inelastic collisions (low-energy regime) and participant–spectator scenario (high-energy regime) coexist in the same pattern [9]. The precursor of the participant region assumes the characteristic of a transient expanding neck-like structure connecting (on a short time scale ≤ 100 fm/c) the PLF and the TLF nuclei [5]. The dynamic evolution of this neck-fragmentation process has been clearly elucidated in the context of CHIMERA data [12, 13]. This device [14] is unique 4π in the world for its ability to detect fragments in the full dynamic range from target-like nuclei to projectile-like ones, allowing to study in some details different correlations among various observables of the emitted fragments. Indeed, the WILC2-plot is one of these correlations and it is, at the same time, innovative and powerful, as is briefly discussed below, for its particular application in ternary reactions. In the case of ternary reactions, three fragments, a PLF, a TLF and one massive IMF are observed in the final state (as seen in figure 1) together with a few light particles (in figure 1, the total charged particle multiplicity was constrained to a value ≤ 7). Important results on the production mechanism of these three fragments were obtained from the analysis of the relative fragment–fragment velocities for selected binary sub-systems of the three-body system. In particular, the relative velocities of the IMF with respect to PLF and TLF, *i.e.*, V_{rel} (IMF,PLF) and V_{rel} (IMF,TLF), respectively, have been measured in an event-by-event analysis. The two relative velocities were normalized to the velocity corresponding to the Viola systematics [15], *i.e.* to the fragment relative kinetic energies as due to pure Coulomb repulsion between the two sub-systems (PLF–IMF and TLF–IMF) in the asymmetric split of primaries PLF* or TLF* [16]. In figure 3, a two-dimensional correlation plot of these two ratios for IMFs selected in the range of $4 \leq Z \leq 10$ for the reaction ^{124}Sn+^{64}Ni studied at the bombarding energy of E_{Lab} (^{124}Sn)$/A = 35$ MeV/nucleon is shown. It can be readily checked that the correlation between the two ratios gives information (together with simple kinematics) on the scenario of IMF formation and, particularly, on the time when the neck structure separates from the PLF* or TLF* (or from both in the case of instantaneous ternary splitting).

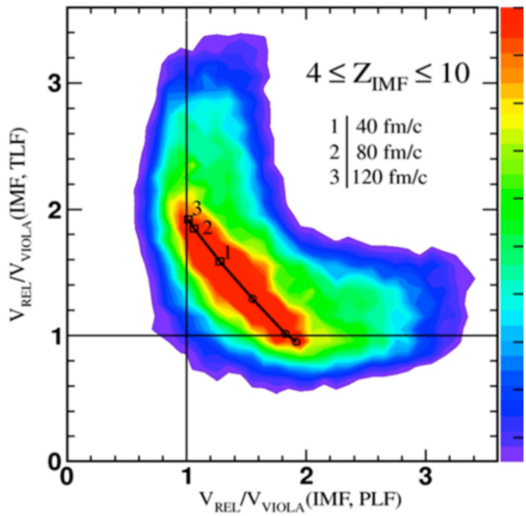

Fig. 3. Typical WILC2-plot (see the text) obtained for light IMFs of atomic number in the range of $4 \leq Z \leq 10$. Light fragments in the neck-fragmentation reaction are emitted within a short time scale, in the range of 40 fm$/c \leq$ time $\leq$ 120 fm$/c$, as indicated in the insert. Points 1, 2, 3 indicate calculations, as they were first performed by J. Wilczyński, by assuming emission of the IMF from the projectile-like fragment. Symmetrical open circles show calculations by assuming emission of the IMF from the target-like fragments. The solid line is only intended to guide the eye.

In figure 3, the calculated predictions of the time scale (see Appendix of [13] for details), assuming that the IMF separates (in a collinear configuration with the relative PLF*–TLF* velocity vector) either from the projectile- (squares) or from target-like fragments (circles) after a time interval of 40, 80, or 120 fm$/c$ from the primary (binary) PLF*–TLF* separation are shown as a solid line. Events close to the diagonal of the WILC2-plot of figure 3 correspond to prompt ternary divisions, whereas those events having a tendency to approach the values of $V_{\rm rel}/V_{\rm Viola}$ (IMF,PLF) $= 1$ and $V_{\rm rel}/V_{\rm Viola}$ (IMF,TLF) $= 1$ correspond to the sequential splitting of the primary projectile-like nucleus or the target-like nucleus, respectively. The time scales for intermediate conditions are rather short. They span the time interval in the range of 40–120 fm$/c$. Beyond that value, the predicted points of the ratio of the relative velocity correlations move no further and are indistinguishable from much slower "true" sequential decay processes ($>$ 300 fm$/c$). Sensitivity of the plot within a time scale of less than 40 fm$/c$ is limited by the relative linear momentum resolving power ($\simeq$ 50 MeV$/c$) of the used correlator (CHIMERA) largely due to the size of the detector's angular opening in the investigated region. However, the localization of the events clearly demonstrates that at least in the case of light (most probable) IMFs, the majority are emitted in almost prompt (dynamical) or "fast two-step" processes, within times of about 40–80 fm/c. The time scale calibration discussed above was an important step in the understanding of the dynamical component of the reaction mechanism, the neck-fragmentation process [12]. This new kind of Wilczyński-like plot is the most persuasive correlation to calibrate the time scale of IMF emission in semi-peripheral collisions. It demonstrates, at the same time, that the IMF emission is collinear with the relative PLF–TLF velocity vector, established at the instant of their binary separation. The analysis of the reaction ^{124}Sn + ^{64}Ni has shown for the first time a well-defined chronology: light IMFs ($Z < 15$) (as the example plotted in figure 3) are emitted either on a short time scale (within 50 fm/c) with a prompt neck-rupture mechanism or sequentially (> 120 fm/c) after the re-separation of the binary PLF*–TLF* system. To complete the picture, and in contrast with light fragment emission, heavy fragments ($Z \geq 9$, not shown here) have been proven to be emitted in a longer time scale ranging from a fast (on the time scale of $\simeq 300$ fm/c) non-equilibrated fission-like splitting to a fully equilibrated fission process of much longer time scale [17, 18]. These results were supported by different approaches of transport model simulations such as the stochastic mean-field (SMF) [5, 19] and constrained molecular dynamical model (CoMD-II) [20].

3. Conclusions

Janusz Wilczyński is a recognized world-leader in physics, a genuine thinker, a man who loved his family and friends. He was conscious of the potentials of the new millennium and enjoyed the world. He held a rigorous line of moral conduct and, therefore, helped to support the basic ideas of civil life or to change the inadequate conceptions of the world, that is, to stimulate new ways of thinking. Indeed, in this light, his genuine method has close analogy with the one adopted by E. Rutherford and collaborators at the beginning of the last century in explaining their famous experiments on the observed anomalies in elastic scattering of ^{4}He particles produced by radioactive sources and impinging on a thin gold target nuclei [21]. Janusz loved his country and at the same time, he was a citizen of the world. He was member EMERITUS of the international CHIMERA Collaboration. As an outstanding member of CHIMERA, he described the evolutionary time scale character of the fragment productions at the Fermi energy in neck-fragmentation reactions [22]. He suggested a new method of analysis in ternary reactions introducing the useful concept of "Viola systematics violation" of fragment–fragment relative energy. Recently, he also worked in Au+Au collisions at 15 and 23 MeV/nucleon [23, 24], and together with his research group in Warsaw, discovered a rapid ternary and quaternary break-up of projectile (target) nuclei at high orbital relative momenta. On the web site of Janusz's institute [25], we all recognize the vast appreciation of Polish institutions and colleagues.

I am grateful to Ania Wilczyńska and Krystyna Siwek-Wilczyńska for the careful reading of this manuscript. Thanks are also due to the organizing committee for the invitation and the warm hospitality in Kazimierz Dolny during the conference. I spent beautiful time there together with my wife Mrs. Rosa Nicotra. I met many of Janusz's colleagues and friends. I had also the unique occasion to meet Ania Wilczyńska: Janusz often recalled her in warm and unforgettable thoughts that he loved to share with me and my family. Janusz was for me a friend, a father in physics. He has a "permanent position" in our family memory.

REFERENCES

[1] First Meeting of the REVERSE Collaboration, "A CHIMERA Experiment in the Reverse Kinematics", Organizing Committee: S. Cavallaro, E. Geraci, A. Pagano, Laboratori Nazionali del Sud, Catania, February 12–13, 1998, unpublished.

[2] A. Pagano *et al.*, *Nucl. Phys. A* **681**, 331c (2001).

[3] A. Pagano *et al.*, *Nucl. Phys. A* **734**, 504 (2004).

[4] E. Geraci *et al.*, *Nucl. Phys. A* **732**, 173 (2004).

[5] V. Baran, M. Colonna, M. Di Toro, *Nucl. Phys. A* **730**, 329 (2004) and references therein.

[6] J. Wilczyński, *Phys. Lett. B* **47**, 484 (1973).

[7] J. Randrup, *Nucl. Phys. A* **383**, 468 (1982) and references therein.

[8] J. Van Driel *et al.*, *Phys. Lett. B* **98**, 351 (1981).

[9] D. Guerreau, *Nucl. Phys. A* **447**, 37c (1985).

[10] G. Peilert, H. Stocker, W. Greiner, *Rep. Prog. Phys.* **57**, 533 (1994).

[11] A.S. Goldhaber, *Phys. Lett. B* **53**, 306 (1974).

[12] J. Wilczyński *et al.*, *Int. J. Mod. Phys. E* **14**, 353 (2005).

[13] E. De Filippo *et al.*, *Phys. Rev. C* **71**, 044602 (2005).

[14] A. Pagano, *Nucl. Phys. News* **22**, 25 (2012) and references therein.

[15] V.E. Viola, K. Kwiatkowski, M. Walker, *Phys. Rev. C* **31**, 1550 (1985).

[16] D.J. Hinde *et al.*, *Nucl. Phys. A* **472**, 318 (1987).

[17] E. De Filippo *et al.*, *Phys. Rev. C* **71**, 064604 (2005).

[18] P. Russotto *et al.*, *Phys. Rev. C* **81**, 064605 (2010).

[19] J. Rizzo *et al.*, *Nucl. Phys. A* **806**, 79 (2008).
[20] M. Papa *et al.*, *Phys. Rev. C* **75**, 054616 (2007).
[21] H. Geiger, E. Marsden, *Proc. Roy. Soc. A* **82**, 495 (1909) communicated by Prof. E. Rutherford 1909; E. Rutherford, *Phil. Mag.* **21**, 669 (1911).
[22] M. Di Toro, A. Olmi, R. Roy, *Eur. Phys. J. A* **30**, 65 (2006).
[23] I. Skwira-Chalot *et al.*, *Phys. Rev. Lett.* **101**, 262701 (2008).
[24] J. Wilczyński *et al.*, *Phys. Rev. C* **81**, 024605 (2010).
[25] http://www.ncbj.gov.pl/en/aktualnosci/xxiii-nuclear-physics-workshop-kazimierz-dolny-commemorate-professor-janusz-wilczynski