REFLECTIONS ON WILCZYŃSKI'S SCIENTIFIC WORK IN GRONINGEN*

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Remembering Janusz Wilczyński, means for the authors looking back at the most successful work of the KVI in the field of heavy-ion reaction studies. We will review some of the high-lights, focusing on the most important concepts Wilczyński introduced.

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1. Introduction

Janusz Wilczyński and Krystyna Siwek-Wilczyńska stayed two extensive periods at the Kernfysisch Versneller Instituut in Groningen. This was from 1977–1979 and 1989–1991, in addition, there were several visits of shorter periods. In the first period, mostly the reaction mechanism of asymmetric reactions was explored, leading to the concept of generalized critical angular momentum and the Sumrule model. The second period considered the large scale motion associated with fission-like exit channels, in particular, the time scale of this decay process. The articles written about work in the KVI periods are [1–18]. We will follow the notation used in [8] throughout this article.

2. Generalized critical angular momentum

A binary nuclear reaction can be written as

$$A_{\mathrm{P}} + A_{\mathrm{T}} \rightarrow (A_{\mathrm{P}} - n + m) + (A_{\mathrm{T}} + n - m) = A_{\mathrm{PLF}} + A_{\mathrm{TLF}} \,, \qquad (1)$$

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where n nucleons are transfered from the projectile (P) to the target (T) and m nucleons from the target to the projectile. Discussing mostly mass asymmetric reactions, we assume the light nucleus to be the projectile with mass number $A_{\rm P}$ and the target to be heavy with mass number $A_{\rm T}$. Although the Sumrule model was formulated allowing mass transfers both ways, in practice the dominant channels have $m = 0$ as can be observed from the emission of projectile-like fragments (PLFs) with beam velocity. Using the proximity force, Wilczyński showed in his earlier work [19] that at $l_{\rm crit}$, there is no attractive force any more between nuclei touching at saturation density, *i.e.* the Coulomb plus centrifugal potential are larger than the nuclear attraction. Only if there is a pocket in the overall potential, it is assumed that fusion can occur. Therefore, fusion is limited to entrance angular momenta $l_i < l_{\rm crit}$. The approximate expression for $l_{\rm crit}$ is given by

$$\left(l_{\rm crit} + \frac{1}{2}\right)^2 = \frac{\mu(C_1 + C_2)^2}{\hbar^2}\left[4\pi\gamma\frac{C_1C_2}{(C_1 + C_2)}\right] \tag{2}$$

with C_1 and C_2 — the half-density radii, Z_1 and Z_2 — the charges, and μ — the reduced mass of the two nuclei. γ is the isospin-corrected surface-tension coefficient. The parametrization of C_i and γ are given in [8]. An important aspect of Eq. (2) is that it does not depend on energy. This allows discussing many aspects of the reaction without considering the actual beam energy.

The concept of generalized critical angular momentum states that if fusion cannot take place, the next largest fraction of the projectile will fuse. Requiring also that this fraction, consisting of n nucleons and carrying an angular momentum $l_n = \frac{n}{A_{\rm P}} l_i$, obeys its critical angular momentum for fusion, *i.e.* $l_n < l_{\rm crit}(n + T)$, (taking $m = 0$ for clarity of argument). The entrance angular momentum is thus partitioned between the target-like fragment (TLF) and PLF such that $l_i = \frac{A_{\rm P}}{n} l_{\rm crit}(n+T)$ and $l_{\rm PLF} = l_i - l_{\rm crit}(n+T)$. The latter is carried off by the PLF with beam velocity and the TLF will have gained spin $l_{\rm crit}(n + T)$. This produces a very simple partition of cross section, where with increasing l_i the projectile fraction absorbed reduces and the PLF mass increases. This may appear similar to a reaction picture based on geometrical overlap but by placing it in angular momentum space, the process of (incomplete) fusion is made more physical, *i.e.* it relates directly to the actual mean-field potential.

As an example, the relevant angular momenta for the reaction ^{20}Ne+^{159}Tb are given in Table I for the most characteristic PLFs. For example, ^{8}Be or two α-particle emissions would occur for angular momenta $57 < l_i < 63$. The only way an energy dependence comes in is the requirement that the colliding system can reach the distance $C_{\rm P} + C_{\rm T}$ defining a maximal angular momentum, $l_{\rm max}$, where this is still the case [8]. For our example, at 10 MeV/nucleon $l_{\rm max} = 89$, so that all incomplete fusion channels are open at this energy.

TABLE I

Partition of cross section over α-like ejectiles for ^{20}Ne+^{159}Tb reaction, the last two columns are discussed in Section 6.

PLF	n	$l_{\rm crit}(n+T)$	l_i	l_f(PLF)	$l_{\rm crit}$(PLF+TLF)
—	20	52	52	—	—
^{4}He	16	46	57	11	18
^{8}Be	12	38	63	25	30
^{12}C	8	29	71	43	39
^{16}O	4	17	84	67	46

The Sumrule model considers all open reaction channels and weighs them with a factor $\exp(Q_{gg}-Q_{\rm C})/T$, following an earlier finding by Bondorf *et al.* [20]. Here, Q_{gg} is the binary channel reaction Q-value and $Q_{\rm C}$ accounts for the change is the Coulomb energy at the transfer distance $R_{\rm C}$. This introduces two parameters $R_{\rm C}$ and T. The Q-value systematic modifies the original partition considerably, but on the whole, the Sumrule model gives a consistent framework to discuss incomplete fusion. A detailed comparison with experiment is, however, difficult as a PLF is not necessarily produced in a particle-stable state, and may itself be the product of a peripheral non-binary reaction. In the following, we show how this problem was tackled at the KVI.

3. Non-binary reactions and the KX-ray method

The TLFs produced in incomplete fusion are heavy-excited nuclei that will predominantly decay by neutron emission. The probability for emitting characteristic X-rays is relatively high as some transitions in the γ-ray de-excitation of the TLF will convert, leaving a K-shell hole. To check whether a PLF is produced in a (charge) binary reaction, one simply measures the coincident X-ray spectrum [9]. In the example shown in Fig. 1, only a small fraction of PLFs is (or remains) binary. The PLF-X-ray coincidences show a wealth of exit channels that, with some ingenuity, allows extracting information about the reaction. However, to further advance the understanding of reaction mechanisms, it became necessary to build complex detector systems measuring as many fragments as possible.

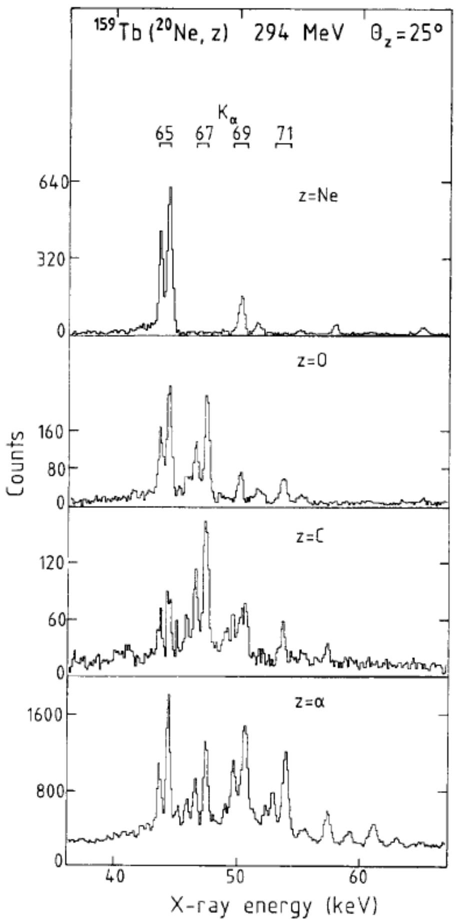

Fig. 1. Characteristic X-ray spectra, taken from [21]. The panels show characteristic KX-ray spectra measured in the reaction ^{20}Ne+^{159}Tb at 15 MeV/nucleon. Gating on Ne ejectiles, one observes two prominent peaks (K_α) and two minor peaks (K_β). This is the basic finger print for $Z_{\rm TLF} = 65 =$ Tb. The finger print shifts to higher energy with increasing the element number. With a pattern recognition program, one can determine the yield with high accuracy for the various $Z_{\rm TLF}$, even in overlapping spectra. When gating on Ne only, the target element number is found. Gating on oxygen, as seen in the second panel, one finds about equal amounts for the binary reaction channel ($Z_{\rm TLF} = 67$) and the non-binary channel (65), presumably $\rm O + \alpha$. The third panel shows that $\rm C + \alpha$ is the strongest channel, while the last spectrum shows the complementary α exit channel with a very small yield for the binary reaction channel.

4. Non-binary reactions and the partition of excitation energy

The dissipation of kinetic energy may be understood by considering that the nucleons transfered between the target and projectile deposit their kinetic energy in the receiving nucleus. Whereas the TLF will mostly emit neutrons, the light PLF will emit more charged particles, although the emission concerns both equilibrium and non-equilibrium emission [6,7]. Thus, in general, the number of exchanged nucleons, $n+m$, is not the minimal value assumed in the Sumrule model. Apart from the observation with X-rays, this was also concluded by measuring the light charged particles associated with the emission of a PLF [10] using a multi-detector system. With decreasing asymmetry in the entrance channel, the total exchange $n+m$ can become much larger than the net transfer $|n-m|$. Sufficient kinetic energy can be dissipated to include in this description deep-inelastic reaction with fragments at the Coulomb barrier.

The favorite reaction model of Wilczyński was Randrup's window–wall mechanism [22], *i.e.* an effective one-body dissipation mechanism with the constituent nucleons moving in a self-consistent mean field. Pauli blocking prevents the nucleons from colliding with each other. Only if the relative kinetic energy is sufficient to overcome Pauli blocking, nucleons can collide, which is referred to as two-body dissipation.

5. Two-body dissipation

In the 1990s, the KVI Heavy-ion group participated in the TAPS Collaboration that operated an efficient high-energy photon detector system which traveled through Europe to work in conjunction with other advanced complex systems. This gave an opportunity to consider the role of two-body dissipation, which sets in when the collision energy per nucleon approaches the Fermi-energy ($E_{\mathrm{F}} \approx 45$ MeV) of nuclei. Here, we discuss the work published in [23]. We also refer to this article if the concepts introduced below are too sketchy.

The TAPS system consisted of large barium–fluoride crystals that could efficiently measure high-energy photons ($E_\gamma \geq 30$ MeV). Photons produced in near Fermi energy collisions can be shown to originate from bremsstrahlung in proton–neutron collisions. The yield of these photons is thus a measure of the importance of this dissipation mechanism.

The reaction studied was ^{36}Ar $+^{159}$Tb at 44 MeV/nucleon. The idea of the experiment was to explore the relative role of one-body and two-body dissipation in the formation of PLFs. The setup and results are shown in Fig. 2. The asymmetry in the mass distribution of the primary PLFs indicates again that the larger target tends to absorb the smaller projectile: this is a typical mean-field effect. The linear dependence of the bremsstrahlung yield on mass transfer in either direction shows that, indeed, for larger mass transfer more nucleon–nucleon collisions take place. The bremsstrahlung dependence is stronger in the pick-up direction (increasing mass of the PLF) than in the stripping direction (decreasing mass of the PLF). This shows that nucleons can also be transfered without collisions as in one-body dissipation. For the relative importance, one needs a description in a theory exploiting the Boltzmann–Uehling–Uhlenbeck equation, which is beyond the scope of the present discussion.

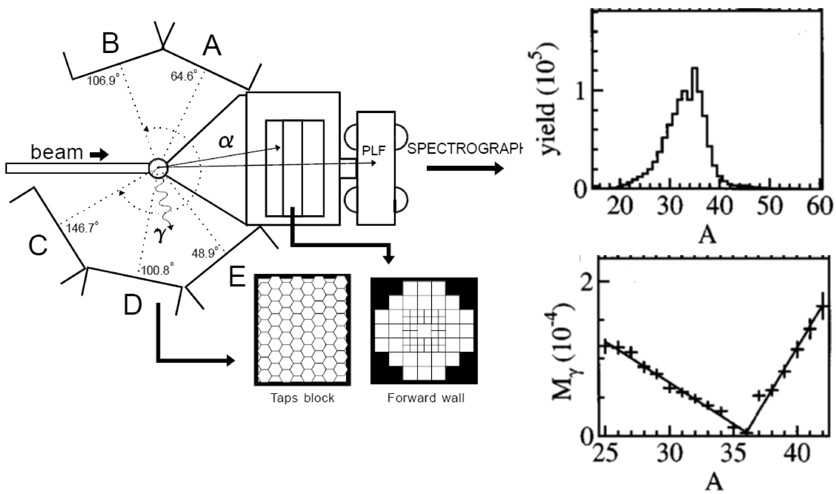

Fig. 2. The 5 TAPS blocks with BaF_2 crystals detect energetic photons from nuclear bremsstrahlung. PLFs are detected with the GANIL spectrograph SPEG. In combination with the KVI Forward wall, it is possible to reconstruct the primary PLFs. The mass distribution is shown in the top panel. The probability, of the order of 10^{-4}(!) to observe a high-energy photon together with a primary PLF is shown in the lower panel. Note the different mass scales on the horizontal axis.

6. A comment on the concept of generalized angular momentum

In preparing for this talk, we noticed that the angular momentum to be carried away by the PLF (the third column of Table I) can be lower than the critical angular momentum in the exit channel (the fourth column). This occurs for the lighter PLFs. So the question arises why these PLFs are not captured. This apparent paradox can be explained by realizing that while the fragment with mass n is inside the barrier and can fuse, the lighter fragment can remain outside. However, it really depends at which distance the PLF detaches from the projectile as it is drawn into the target nucleus. The situation is sketched in Fig. 3 for the ^{20}Ne+^{159}Tb reaction with $n = {}^{16}$O, where the PLF is an α particle. The potential for ^{20}Ne has no pocket, while for $n = {}^{16}$O, it has a shallow pocket of about 2 MeV depth. At separation $s = 0$, the density is saturated and friction is becoming strong. In order to keep the center of mass corresponding to that of the projectile, the particle to be the PLF should be placed away from the projectile center where it remains outside the barrier (as indicated by the dashed line) with respect to its potential. In this configuration, the fusing fragment will indeed transfer a maximum angular momentum $l_{\rm crit}(n+T)$, but the conversion to entrance angular momentum is different: with $l_i(P) = l_{\rm crit}(n+T) + l_f(\rm PLF)$ it is easy to show that

$$l_i = \frac{A_{\rm P}}{n} l_{\rm crit}(n+T) + A_{\rm P}\frac{\sqrt{2m_u\epsilon}}{\hbar}\left(C(P) - C(n)\right), \qquad (3)$$

where ϵ is the energy per nucleon and m_u the nucleon mass. This leads to an energy dependence that modifies the generalized concept. The effect is a small increase in both l_i and l_f(PLF) for light ejectiles. In contrast, it has a large effect for the heavy PLFs, essentially pushing these reaction channels into the realm of the grazing angular momentum. In fact, this modification may make for a more consistent view of the partition of cross sections.

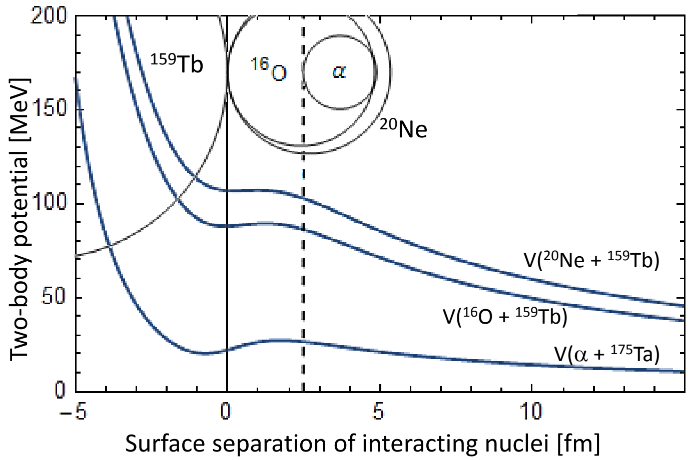

Fig. 3. Geometry of the projectile approaching the target, and the corresponding potentials ($l_i = 55$, $l_n = 44$, $l_\alpha = 11$) for the entrance channel ^{20}Ne+^{159}Tb and for the two fragments when considering the incomplete fusion reaction ^{20}Ne+^{159}Tb→ α+^{175}Ta.

7. The neutron clock for fission-like exit channels

The second period of Wilczyński at KVI concerned mostly the way kinetic energy is dissipated in nuclear reactions and how it can be observed. Here, we mention our work on the neutron clock [14, 17].

In particular, the arguments justifying the neutron clock are interesting here and still of value today. In reactions leading to fission or fission-like exit channels, the processes leading from the composite system to the scission configuration via saddle formation is a relatively slow process: The driving nuclear potential is mostly flat. The evolution of the system after the initial collision and the scission process itself are well-described by window–wall dissipation which is independent of temperature. Therefore, the temperature of the system can be decoupled from its dynamics. Experimentally, one can observe the amount of pre-equilibrium neutrons on basis of their anisotropy, removing the energy associated with this fast process ($\Delta E_{\rm pee}$). A dynamical code operating on the basis of window–wall dissipation describes then the dissipation of the available energy $Q_{\rm gs}^{\rm fusion} + E_{\rm cm} - \Delta E_{\rm pee}$. Only the potential and kinetic energy play a role in the dynamics, the excitation energy can be removed by evaporation. A simple evaporation code that includes the modest dependence on the geometrical configuration is used to calculate the loss of excitation energy as a function of time. The emitted neutrons are the ticks of the clock (ticking slower and thus becoming less accurate as excitation energy is lost). The scission process in the end heats up the fragments again, but this is on a fast time scale and does not affect the outcome concerning the number of neutrons emitted by the long-lived intermediate system. A typical example is shown in Fig. 4 for the reaction $^{16}{\rm O} + ^{197}{\rm Au}$ at 226 MeV [24]. The time spent in the shallow potential is simply extended to correspond to the number of observed neutrons. Using this clock, one can for example investigate the amount of friction in fission.

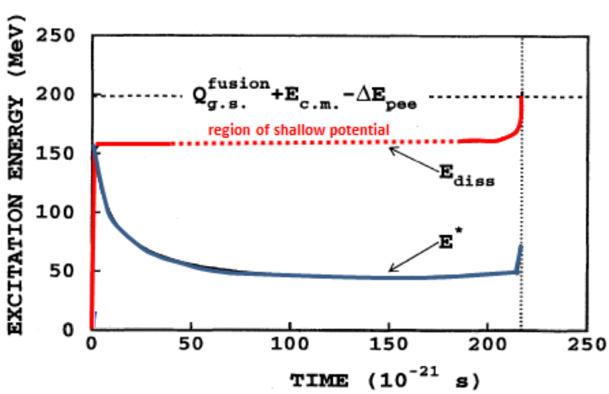

Fig. 4. Principle of the neutron clock: The time region indicated by the dashed line is adjusted to correspond to the number of neutrons emitted isotropically relative to the center-of-mass frame. Adapted from [14].

8. Conclusion

Eventually, the interest in nuclear collision dynamics could not be further pursued at KVI and the interest came to lie with more fundamental issues connected to searches for new physics, *i.e.* searches beyond the Standard Model of particles physics. This led one of the authors to search for the Lorentz invariance violation in weak interactions. A fascinating subject but outside the scope of this workshop. We give a few references here for those who may be interested [25–27].

With his sharp wit and dry humor we fondly remember Janusz Wilczyński as a person and a friend.

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