FEW REMARKS ON WŁADYSŁAW ŚWIĄTECKI PHYSICS*

Krzysztof Pomorski

Institute of Physics, Theoretical Physics Department
Maria Curie-Skłodowska University, Lublin, Poland

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Numerous highlights from the rich scientific attainments of the late Professor Władysław Świątecki are presented. The influence of his main achievements on the development of nuclear theory is shown on a few examples.

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1. Introduction

Professor Władysław Jerzy Świątecki, called by his friends and co-workers Władek, was born in 1926 in Paris. He grew up in Lublin, a Polish city, where young Władek attended primary and secondary schools. The second world war insisted family Świątecki to emigrate to Great Britain, where he completed his education. At the age of 19, he defended his master's thesis in physics and at the age of 20 in mathematics at the University of London. In 1950, he defended his Ph.D. Thesis *The Surface Energy of Nuclei* written at the University of Birmingham under Rudolf Peierls supervision. Subsequently, he worked in Denmark, Sweden (among others under the direction of Niels Bohr) and from 1957 at the University of California in Berkeley at the Lawrence Berkeley National Laboratory. He retired in 1991. He was a member of the Danish Royal Academy of Sciences and the Polish Academy of Arts and Sciences. In 1990 he was awarded the Marian Smoluchowski Medal and in 2000 he obtained the honorary doctorate of the Jagiellonian University in Cracow. He passed away in 2009 in Berkeley in the USA.

Professor Świątecki always kept close contacts with Poland and Polish physicists. Since the middle 70ties he visited several times the physics institutes in Warsaw, Cracow and Lublin. He attended almost every second Workshop of Nuclear Physics, held every year in Kazimierz Dolny.

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Fig. 1. W.J. Świątecki at the X Nuclear Physics Workshop in Kazimierz Dolny.

2. W.J. Świątecki's research main topics

It is not easy to classify the scientific works done by Władek Świątecki. Many of his papers have played a major role in the development of nuclear physics in the second part of the 20$^{\text{th}}$ century. One can mention here the following main topics risen in his research:

— Nuclear mass formulas and backgrounds of the macroscopic–microscopic (mac–mic) model:

finding of the role of shell effects,

liquid drop and droplet models,

finite range nuclear Thomas–Fermi model;

— Spontaneous fission theory:

spontaneous fission lifetime systematic,

fission barrier height and topographical theorem,

deformation-dependent congruence energy;

— Shape evolution of rotating nuclei and astrophysical objects;

— Damped nuclear collisions, in particular the introducing of:

nuclear proximity force,

mechanism of one-body damping, wall and window friction,

nuclear dynamics, optimal bombarding energy, extra push model,

transition state method,

high-energy nuclear collisions,

coalescence and reseparation models;

— Chaos theory: role of symmetries in the nuclear shape dynamics;

— Synthesis and properties of super-heavy nuclei.

The above list is a personal choice of the author and it surely does not cover the whole scientific activity of professor Świątecki.

3. Selected contributions of Świątecki to theory of atomic nuclei

We would like to present here a few topics which, in our opinion, were very important for the nuclear structure and nuclear fission, and characterize well the style of Władek's works and his deep understanding of physics.

3.1. Shell energy and macroscopic–microscopic model of nuclei

Already since the formulation of the nuclear liquid drop model by Weizsäcker in 1935 [1], it was clear that the proton–neutron mater in nuclei behaves like charged liquid drop (LD) with its binding energy proportional to the number of particles and the surface tension which arises from the fact that particles at the surface of nucleus are less bounded. The nuclear part of the binding energy in the Weizsäcker LD is additionally diminished by the Coulomb electrostatic energy arising from the proton repulsion. The LD model has reproduced the nuclear bindings energies, known at that time, with astonishingly good precision. Unfortunately, similarly like ancient astronomers, Weizsäcker and his first continuators assumed that nuclei are spherical. An important extension of the LD model was proposed by Meitner and Frisch in 1939 [2] who forced to let nuclei to be deformed in order to explain some strange experimental results obtained by Hahn and Straßmann [3] when bombarding uranium with neutrons. The model of Meitner and Frisch assumes that a nucleus can deform like normal liquid drop and split into two parts. They called this process nuclear fission per analogy of fission of cells in biology. Further backgrounds to the macroscopic model of deformed nuclear liquid drop were formulated by Bohr and Wheeler [4] in order to describe more quantitatively the nuclear fission phenomenon. The success of the macroscopic model in the reproduction of the binding energies and the fission phenomenon has proven that the short-range correlations between the nucleons in nuclei are dominant. On the other hand, one has observed that nuclei having 2, 8, 20, 28, 50, 82 protons or neutrons (with an additional number 126) are more bound than the LD model predicts. The origin of these so-called *magic numbers* was first clarified in papers written by Jensen [5] and Goeppert–Mayer [6] who formulated the nuclear shell model. It assumes that nucleons move independently in an average spherical mean-field potential in which they act in addition to the spin–orbit forces. The magic numbers correspond to the closed orbitals in this nuclear shell model. The next important step in evolution of the shell model was done by Nilsson [7] who introduced the deformed mean-field potential. The shell and the LD models, which at first sight are contradictory, have described simply different aspects of the same nuclear structure.

The next important step was done by Myers and Świątecki [8] who proposed a macroscopic–microscopic model in which a shell and pairing energy correction was added to the liquid-drop energy. They evaluated the shell energy for spherical nuclei by bunching the Fermi gas levels into orbitals corresponding to the magic numbers, while the pairing energy was taken into account as a mass-number-dependent correction parameter. In addition, they have assumed that the shell energy decreases exponentially with nuclear deformation. The mac–mic model of Myers and Świątecki reproduced well all measured at that time binding energies (1200), electric quadrupole moments (240) and fission barrier heights (40) of nuclei having only 10 adjustable parameters and, of course, the fixed eight magic numbers. It was a real success of this simple model which was a good example of Władek's style of working in physics.

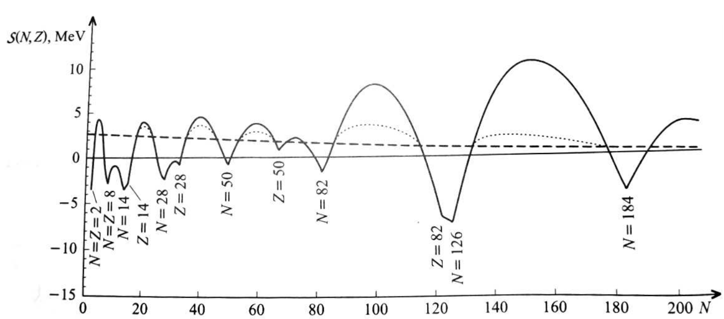

Fig. 2. Shell energy correction according to Myers and Świątecki. Figure made after Ref. [8].

Parallel to a more accurate method of evaluation of the shell energy was proposed by Strutinsky [9] which in its improved version [10] is used nowadays. It was also shown, applying the Strutinsky method, that Świątecki assumption (the shell energy decreases with nuclear deformation) was not completely true. The shell energy prefers some deformed state of nuclei which corresponds to the experimentally discovered shape isomers.

3.2. Topographic theorem of Świątecki

As mentioned in the previous subsection, the authors of the famous paper on the nuclear mass formula [8] assumed that the shell energy should play less important role when a nucleus deforms. It is not completely true as it is pointed above. Nevertheless, after thirty years, Świątecki described more precisely the role of the shell effects in the deformed nuclei. Namely, in Appendix C of Ref. [11], Świątecki formulated the following statement called by him a "topographic theorem":

> *The fission barrier is determined by a path that avoids positive shell effects and has no use for negative shell effects. Hence the saddle point energy will be close to what it would have been in the absence of the shell effects, i.e., close to the values given by the macroscopic theory! This general result of the topographic theorem — that a macroscopic theory is accurate for saddle energies — becomes exact (independently on the amplitude of the shell oscillations) in the limit where the relative range of the oscillations tends to zero.*

It means in short that "the barrier will be determined by a path that avoids positive shell effects and has no use for negative shell effects". The above statement origins from his long year experience and some general considerations on the characteristic length of the shell oscillations and the scale of the macroscopic undulations. His conclusion: "saddle point masses should be closer to a macroscopic theory that ground state masses" is not valid for nuclei which are close to lose stability against fission or nuclei in which the distance from the saddle to the ground state or to the scission point is small.

Note that "the topographic theorem does not mean that shell effect fluctuations are negligible in the neighbourhood of the saddle, or that shell effects on the saddle-point *shapes* can be disregarded".

The topographic theorem allows to evaluate the barrier height as a difference between the macroscopic saddle mass and the experimental ground-state mass of a nucleus

$$E_{\rm B} = M_{\rm macr}({\rm saddle}) - M_{\rm exp}({\rm g.s.})\,. \tag{1}$$

It was shown in Ref. [13] that the average deviation of the of the LSD saddle-point masses from the experimental ones is only 310 keV. It proves not only the validity of the above theorem but also shows that the LSD model [12] reproduces the barrier height better than the Thomas–Fermi model [11], where the similar deviation was equal to 1 MeV.

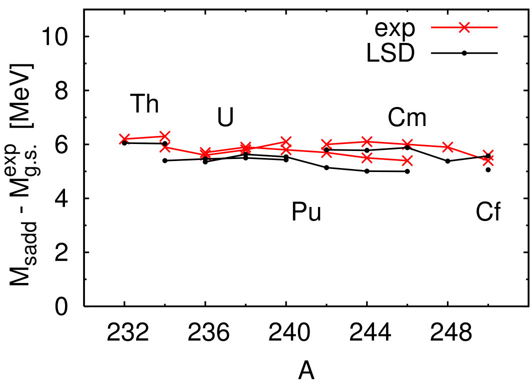

Fig. 3. Fission barrier heights evaluated using the topographical theorem of Świątecki [11] and the LSD energies of the saddle points [13].

The role of the topographic theorem is crucial in explanation of the systematic of the spontaneous half-lives found by Świątecki already in 1955 [14] what will be presented in the next subsection.

3.3. Spontaneous fission probability

Theoretical estimates of the logarithm of the spontaneous fission half-lives $T^{1/2}$ in years presented in Fig. 4 (open symbols) were obtained by Świątecki using the following phenomenological formula [14]:

$$\log_{10}\left(\frac{T_{\rm sf}^{1/2}}{y}\right) = 18.2 - 7.8\,\Theta + 0.35\,\Theta^2 + 0.073\,\Theta^3 - (5-\Theta)\delta M + \begin{cases} 6.6 & \text{o–}A \\ 0 & \text{e–e} \\ 11.5 & \text{o–o} \end{cases}, \tag{2}$$

where $\Theta = Z^2/A - 37.5$ and δM is the deviation of the experimental mass from its LD estimates measured in mili mass units.

One can ask, how such systematic works 60 years after its discovery? The answer is yes, it does well. Namely, it was found by Zdeb *et al.* [15] that all known nowadays spontaneous fission half-lives of nuclei having a finite LD barrier obey a similar systematics like that of Świątecki. It can be seen in Fig. 5 taken from Ref. [15]. All measured $\log_{10}(T_{\rm sf}^{1/2}/y)$ group around straight lines, shown in Fig. 5, when one subtracts from them the ground-state experimental microscopic energy $\delta M_{\rm exp}$ (in MeV) multiplied by an adjustable factor $k = 7.7$/MeV. This energy is defined in Ref. [15] as

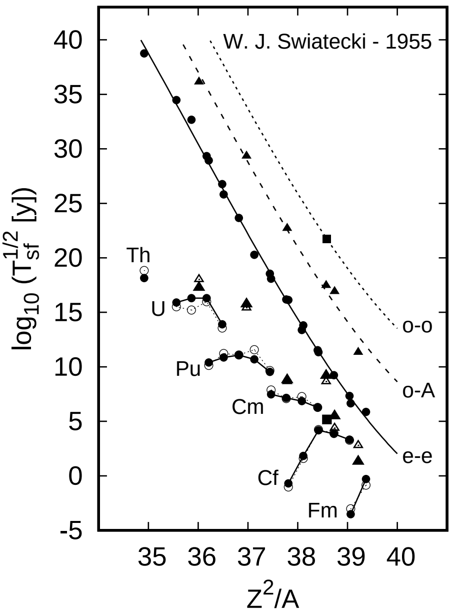

Fig. 4. Spontaneous fission half-lives for even–even (e–e, circles), odd–A (o–A, triangles), and odd–odd (o–o, squares) and the systematics found by Świątecki (lines) as a function of Z^2/A. Open symbols correspond to the estimates done with Eq. (2). Figure is prepared using the data from Table 1 in Ref. [14].

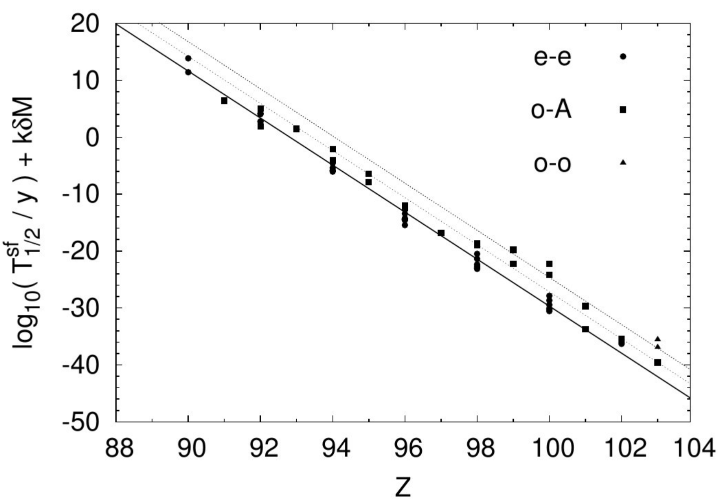

Fig. 5. Logarithms of the observed spontaneous fission half-lives [2] corrected with masses "shifts" as a function of proton number. Figure is taken from Ref. [15].

the difference of the experimental and the macroscopic LSD [12] masses:

$$\delta M^{\rm exp}_{\rm micr}(Z,A) = M_{\rm exp}(Z,A) - M_{\rm LSD}(Z,A)\,. \tag{3}$$

The fitted there to the data straight lines allow to write the following new phenomenological formula for the spontaneous fission half-lives:

$$\log_{10}\left(\frac{T^{1/2}_{\rm sf}(Z,A)}{y}\right) = -4.1\,Z + 380.2 - 7.7\,\delta M(Z,A) + \begin{cases} 2.5 & \text{o–}A\,, \\ 0 & \text{e–e}\,, \\ 5 & \text{o–o}\,. \end{cases} \tag{4}$$

which is even simpler that the original formula of Świątecki (2). The fission life-times evaluated with the new formula (4) are shown in Fig. 6.

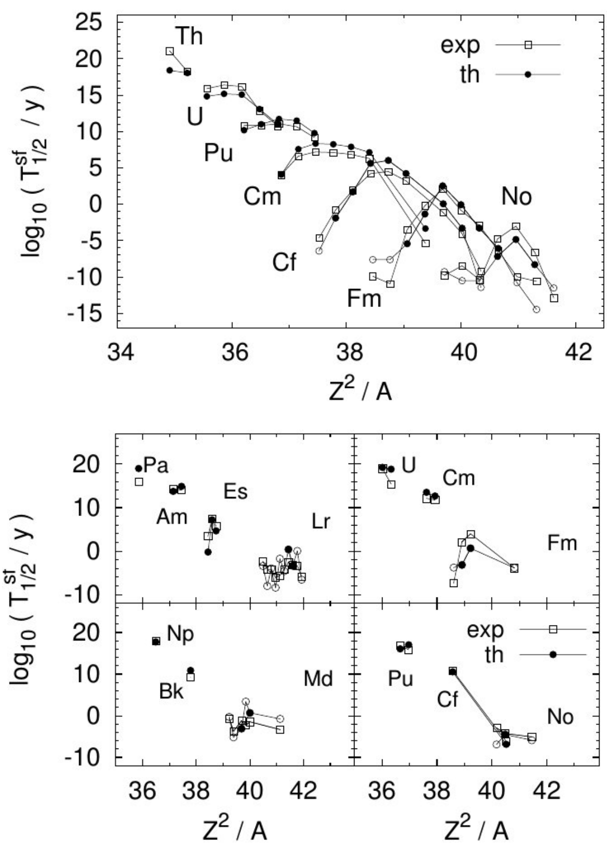

Fig. 6. Logarithms of the experimental (exp) and estimated (th) spontaneous fission half-lives of even–even (top) and odd (bottom) nuclei as a function of the fissility parameter. Figure is taken from Ref. [15].

The estimated life-times are in a good agreement with the data. Such quality of reproduction of $T_{\rm sf}$ would be rather hard to obtain even by modern macroscopic–microscopic or self-consistent models. The question rises, why such a simple formula can be so accurate? There is no explanation in the *one and half page long* original paper of Świątecki [14], where he has only written about the importance of "the shell structure in the ground-state configuration". The key to understand this puzzle lays in the discovered by him 40 years later topographic theorem (see Sec. 3.2) what was shown in Ref. [16].

4. Summary

The work of Professor Władysław Świątecki has played an important role in nuclear physics community. His papers have a significant influence on research direction both in the theoretical and experimental nuclear physics. His way of conducting scientific investigations and his deep understanding of physics as well as no rush in publication makes him an example to follow for young and not only young scientists.

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