CRITICAL POINT*

M.I. Gorenstein

Bogolyubov Institute for Theoretical Physics, Kyiv, Ukraine
and
Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe University
Frankfurt, Germany

(Received February 16, 2017)

My friend and collaborator Marek Gaździcki celebrates his 60$^{\rm th}$ in 2016. It is my great pleasure to present this report. It shows a small part of Marek's scientific achievements connected to his theoretical results. My presentation will be even more restricted, I will only consider several selected topics — those which we studied together.

DOI:10.5506/APhysPolBSupp.10.851

1. Introduction

It is my pleasure to present a talk connected to the 60$^{\rm th}$ birthday of my friend Marek Gaździcki. Let me start with a short summary of his scientific achievements. Marek Gaździcki is a prominent scientist who works in the field of high-energy physics. He was a member of the following collaborations: Dubna SKM 200 (1982–1986), CERN NA35 (1987–1995), CERN NA49 (1996–2010), CERN NA61 (from 2011). Besides, during some shorter periods of time, Marek participated also in the STAR BNL and ALICE CERN collaborations. The total number of his publications is 350, the total number of citations 15000, H-index 65. The majority of scientific results of these impressive records were obtained in the field of experimental high-energy physics of nucleus–nucleus, proton–proton, and proton–nucleus collisions. However, Marek made also an essential contribution to the development of the theoretical description of these processes. My presentation will be rather personal, and I touch only a small part of Marek's scientific results: the part which corresponds to his theoretical achievements presented in our joint publications on high-energy phenomenological models.

* Presented at the "Critical Point and Onset of Deconfinement" Conference, Wrocław, Poland, May 30–June 4, 2016.

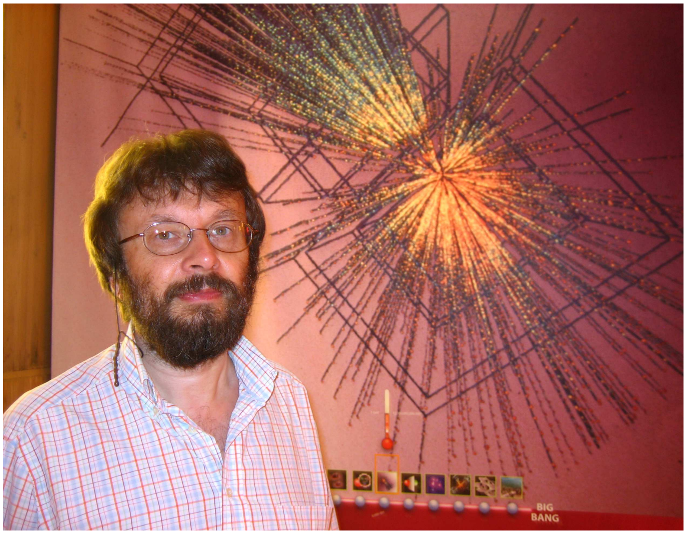

Fig. 1. Marek Gaździcki.

First time I met Marek was in Dubna in 1983. Marek Gaździcki and Stanisław Mrówczyński were Ph.D. students at the Joint Institute of Nuclear Research in Dubna. The second time we met in 1988 in Frankfurt. Marek was working at the Institute of Nuclear Physics of Frankfurt University, and I was visiting the Institute of Theoretical Physics of this University. Then, we were meeting many times in Frankfurt during my numerous visits and spent a lot of time together discussing mostly scientific problems. Our basic topic was a search for the quark–gluon plasma (QGP) signatures in relativistic nucleus–nucleus collisions. However, our first joint paper was prepared only in 1998, *i.e.* 10 years of joint discussions were needed. After 1998, we regularly met in Frankfurt and continued our scientific collaboration in rather productive way: 36 joint papers have been published during these 18 years.

2. Quark–gluon plasma: First discovery

All scientists in our field at the late 90s awaited that the QGP should be discovered soon in experiments on nucleus–nucleus ($A+A$) collisions. To that time, the data were obtained in Au+Au collisions at the AGS BNL up to laboratory energy $E \cong 11$ A GeV and in Pb+Pb collisions at energy 158 A GeV at the CERN SPS. Marek was a member of the NA49 Collaboration at SPS. To claim the experimental discovery of the QGP, one could refer to either the *strong difference* in the data in central A+A collisions at 11 A GeV and 158 A GeV, or to observe some *characteristic differences* in central and peripheral (or in nucleon–nucleon) collisions at the same energy.

Marek Gaździcki and Dieter Röhrich [1] analyzed the data on the multiplicities of pions and strange hadrons in nucleon–nucleon and $A+A$ collisions. They found some qualitative differences between mean hadron multiplicities per nucleon participant in these reactions.

There were several theoretical predictions for the QGP signatures. In 2000, it was announced in TV and newspapers that the new state of matter — the QGP — was discovered in Pb+Pb collisions at the CERN SPS. There were 5 signatures of this new state. The most important signature (the number one) was the J/ψ *suppression* predicted by Matsui and Satz [2]. The signature number two was the *strangeness enhancement*, *i.e.* larger number of strange hadrons created in central $A+A$ collisions per nucleon participant, predicted by Rafelski and Müller [3]. Just these two signals of the QGP were the most important ones for the CERN announcement in 2000 [4]. Note that J/ψ production was not measured at the AGS energies. Thus, J/ψ suppression could not be used as the QGP signature in the AGS BNL. On the other hand, the strangeness enhancement in central Au+Au collisions at the AGS energies was much stronger than at the SPS. Thus, it is not quite clear why the QGP discovery was not announced earlier (or in 2000) at the AGS BNL. In 2000, it was the last chance for CERN to become a winner in the discovery of the QGP. In 2000, the new accelerator for Au+Au collisions, RHIC, started to operate at a much higher energy than at the top SPS one. Most people were sure that during a first few weeks of data taking at RHIC, the QGP with all already predicted signatures (and may be also with many new ones) will be observed at the RHIC BNL.

3. First joint works and general scheme

Stanisław Mrówczyński was a co-author of our first joint paper with Marek [5]. The role of Stanisław was also very important in most of our further investigations (see below). Marek is usually interested in the theoretical models which may help to understand different aspects of data obtained by his collaborations and to formulate suggestions for new experiments. Our first joint work with Marek in 1988 was made along the following scheme. This scheme appeared to be rather general and was then repeated many times.

1. As a first step, Marek formulated a new physical idea.
2. As a second step, Marek published a short theoretical paper on this subject.
3. As a third step, he published a joint, more extended paper with Stanisław Mrówczyński on this subject. The subject is almost always connected to the statistical models in high-energy physics. Marek likes the statistical physics and considers it as the most important part of theoretical physics.

4. As the last, fourth, step Marek suggested to me: "Let us do a rigorous statistical treatment of this problem". It seems that Marek considers me as a serious specialist just in statistical physics. I am always happy with such a suggestion. Very often a 'rigorous treatment' leads to unexpected and interesting results for both of us.

Fig. 2. Left: Frankfurt, 2000; Right: CPOD-3, Florence, 2006.

That time in 1988, Marek, first, suggested the idea that enhanced multiplicity of pions per nucleon participant (larger entropy density) in $A+A$ collisions at high energies is due to a formation of the QGP with larger number degrees of freedom than that in the hadron gas (the *kink*). Second, he published the short theoretical paper [6]. Third, Marek published the joint paper with Stanisław Mrówczyński [5]. That time I also participated, and this was our first joint paper with Marek. Finally, as the last fourth step, Marek proposed to me to make a 'rigorous statistical treatment' of this subject. We published the joint paper on the Statistical Model of the Early Stage (SMES) in $A+A$ collisions [7]. The paper postulated that the statistical equilibrium system was formed at the early stage of $A+A$ collision. It was also assumed that the QGP was created at the early stage in central Pb+Pb collisions at $E = 158$ A GeV and was absent in Au+Au collisions at the AGS energies. These assumptions were in agreement with the CERN announcement made two years later in 2000. The simplest equation of state with two phases — hadron gas (HG) at small temperature and QGP at high temperature — was also postulated. The model was as simple as possible and assumed the 1$^{\text{st}}$ order transition between these two phases. After these (over)simplified assumptions, our task was to calculate the consequences and find some anomalies in hadron observables as a function of collision energy. The onset of deconfinement should happen (in the SMES) somewhere between the AGS and SPS energies, *i.e.* $E = 11 \div 158$ A GeV. It should be noted that, in parallel, the NA49 Collaboration was preparing the energy scan program at the SPS: the Pb+Pb reactions at several collision energies

— 20, 30, 40, 80, 158 A GeV — were recorded in 1999–2002. Therefore, we tried to formulate predictions for the future NA49 measurements. It so happened that our predictions motivated those measurements which looked to be most sensitive to the onset of deconfinement.

What signatures of the deconfinement transition in our model formulation were found? Several signals were evidently expected from the SMES postulates. For example, the system temperature and pressure were expected to be approximately constant inside the mixed phase region. These effects known as the *softest point* of the equation of state for the system with the 1^{st} order phase transition were discussed earlier by Van Hove [8], and Hung and Shuryak [9]. This behavior indeed exists in the SMES and it is clearly seen experimentally for the inverse slopes T^* of K^+ and K^- transverse momentum spectra in central $A+A$ collisions [10]: the T^* value of K mesons increases with collision energy at both low AGS energies and high RHIC–LHC energies, but it remains approximately constant (the *step*) in the region of the SPS energies where the deconfinement transition takes place within the SMES. The most unexpected was the behavior of strangeness-to-pion ratio as a function of collision energy. This ratio was known to increase strongly with collision energy in central Au+Au collisions at the AGS laboratory energies $E = 2$–11 A GeV. Such a behavior was interpreted in the statistical hadron models as a consequence of the increase of the system temperature: the mass of the lightest strange hadrons (K mesons) is much larger than the system temperature (and than the pion mass), thus, the temperature increase leads to a much stronger (exponential) effect for the yields of strange hadrons than that of pions. In the QGP phase at a large temperature T, the total number of strange quarks and antiquarks behaves approximately in the same way as the system entropy, *i.e.*, both these quantities are proportional to T^3. Therefore, one may expect the constant value of the strangeness-to-pion ratio in $A+A$ collisions at very high energies. This was also assumed in the SMES and it was conformed later by the RHIC and LHC data for $A+A$ collisions. The open question was a behavior at intermediate SPS energies. It looked the most natural that strangeness-to-pion ratio should continue to increase with collision energy and gradually approach (from below) its asymptotic value reached at high energies. This conclusion was also supported by the data in proton–proton collisions existing at that time. The parameters of the SMES were fixed by using the Au+Au data at the AGS energies 2–11 A GeV and the Pb+Pb data of the NA49 Collaboration at the SPS energy 158 A GeV. After that, no freedom was left, and rather unexpected prediction for strangeness-to-pion ratio — a strong maximum (the *horn*) — was predicted for central Pb+Pb collisions at approximately $E = 30$ A GeV. At this energy, the onset of the deconfinement starts within the SMES. When the collision energy increases further, the QGP part of the mixed system created in central $A+A$ collisions becomes more and more profound. Quite unexpectedly this was accompanied by a *decrease* of the strangeness-to-entropy ratio in the SMES up to the end of the mixed phase at collision energy approximately located at 80 A GeV. After that, at still higher collision energies, the strangeness-to-entropy ratio remains approximately constant. This behavior is opposite to the *strangeness enhancement* [3], *i.e.*, at the fixed transition temperature the strangeness-to-entropy ratio in the SMES is larger in the HG than in the QGP. Therefore, this ratio *decreases* with collision energy while the system is transformed from the HG to the QGP.

Nobody believed in the horn structure of the strangeness-to-entropy ratio predicted in the SMES. However, after several years this prediction of the SMES was supported by the data of the NA49 Collaboration. The summary of the NA49 results with the references to the original experimental papers can be found in Ref. [11], where the relation of these experimental results to the SMES is also discussed. During several years, the NA49 data were the only ones in the energy region 11–158 A GeV. Thus, the agreement of the NA49 data with the SMES predictions remained rather suspicious: Marek was an active member of the NA49 Collaboration which supported his theoretical predictions?! Today we have at least independent confirmation of the experimental results of NA49 on the *kink, step*, and *horn* structures. Namely, the STAR Collaboration at the RHIC BNL obtained essentially the same results a few years later (the discussion of these results as well as high energy RHIC–LHC data for $A + A$ collisions are presented in [12]).

4. Event-by-event fluctuations

In recent years, event-by-event (e-by-e) fluctuations in high energy $A+A$ collisions have become the most important subject of our collaboration with Marek. It was Marek's initiative. The progress in the experimental techniques made these measurements possible in $A + A$ collisions. The data on fluctuations can be really crucially important for studies of the phase transition and the QCD critical point. And finally, these studies suggest many theoretical questions in the framework of statistical physics — Marek's beloved part of theoretical physics. First, Marek published several theoretical papers on the e-by-e fluctuations [13, 14] without me. Second, we published a joint paper [15]. This was my first paper with Marek about e-by-e fluctuations, and Stanisław Mrówczyński was a co-author. Marek was quite enthusiastic and suggested to me to 'rigourously' consider different aspects of fluctuations within statistical models. Our first finding in this area was the role of the global conservation laws on e-by-e fluctuations [16]: it was shown that fluctuation measures had different values in different statistical ensembles in the thermodynamical limit. This means that the thermodynamical equivalence between statistical ensembles (*e.g.*, between the grand canonical, canonical, and micro canonical ensemble) takes place for the first moments of the statistical distributions (like average energy, average net value of the conserved charge, *etc.*), but not for their second and higher moments, *i.e.*, any fluctuations are sensitive to the choice of the statistical ensembles. To make a comparison with data in $A + A$ collisions for the e-by-e fluctuations, one has to select a statistical ensemble which is the closest to real experimental measurements.

In Refs. [13, 14], a new measure of the e-by-e fluctuations (Φ-measure) was introduced. It has a remarkable property: Φ measure was not sensitive to the system volume and its fluctuations. Thus, this measure depends only on the local properties of the physical system. This fact leads to essential advantages for applications in the analysis of $A+A$ collisions. This property of the Φ measure was justified in [13] within the independent particle model. “Let us obtain this within the statistical mechanics”, Marek suggested. We both were sure that this proof could be done. Rather unexpectedly, many new things were discovered. For two extensive quantities A and B, there are *two* special measures, which we called the *strongly intensive* measures and denoted as $\Delta[A, B]$ and $\Sigma[A, B]$ [17]. The Σ measure appears to be connected with the Φ measure, whereas the Δ is the new one.

In Ref. [18], the *identity method* was proposed to study the chemical fluctuations in a case of incomplete particle identification. It eliminated the misidentification problem for *one* specific combination of the second moments in a system of *two* hadron species (*e.g.*, π^+ and K^+). A ‘rigorous’ study of this problem, thanks to Marek’s suggestion, led me to the extension of this method: *all* second moments were calculated in a system with an *arbitrary* number of hadron species [19]. With Anar Rustamov, we further extended the identity method for the *third* and higher moments of multiplicity distributions [20].

More details of these studies on e-by-e fluctuations can be found in Refs. [11, 21]. With Elena Bratkovskaya, we made the systematic studies of different aspects of the e-by-e fluctuations within the Hadron String Dynamics — the relativistic transport model of $A + A$ collisions. Marek was not a co-author in the published papers on this subject, but his role in these studies was quite important: he made a lot of suggestions, comments, and critical remarks. The transport model results on the e-by-e fluctuations were summarized in the review [22]. Marek also asked me many times to make any model calculations for the fluctuations in a vicinity of the critical point within the statistical mechanics. He complained that he could not find any simple formulae in the literature. These Marek’s questions stimulated me with Volodymyr Vovchenko and Dmytro Anchishkin to ‘rigorously’ consider the well-known van der Waals model adopted to a description of the nuclear matter equation of state [23]. Marek made many useful suggestions to other people to stimulate their activity. One such suggestion was the foundation of a series of the CPOD conferences in 2004, our conference in Wrocław today is already the tenth CPOD meeting.

Fig. 3. CPOD-2, Bergen, 2005.

5. Critical point

The 60$^{\text{th}}$ birthday is, in fact, a critical point in the scientific life of Marek Gaździcki. Today he is a leader of the NA61/SHINE Collaboration at CERN. This collaboration searches for the critical point of the QCD matter. At the moment, there are many more questions than answers: no one knows where this critical point is located (and whether it really exists). However, everybody knows that very *strong fluctuations* should be present in a vicinity of the critical point. In each moment, a single experimental result may dramatically change everything in these investigations, and new unexpected directions will be opened. I am sure that on his 60$^{\text{th}}$ Marek is fully ready to all scientific surprises. I expect from him new remarkable physical ideas, and I am looking forward to hearing his new suggestions to make a *rigorous statistical mechanics treatment* together. Dear Marek, I am ready. Let us do it!

REFERENCES

[1] M. Gaździcki, D. Röhrich, *Z. Phys. C* **65**, 215 (1995); **71**, 55 (1996).

[2] T. Matsui, H. Satz, *Phys. Lett. B* **178**, 416 (1986).

[3] J. Rafelski, B. Müller, *Phys. Rev. Lett.* **48**, 1066 (1982).

[4] U. Heinz, M. Jacob, `arXiv:nucl-th/0002042`.

[5] M. Gaździcki, St. Mrówczyński, M.I. Gorenstein, *Eur. Phys. J. C* **5**, 129 (1998).

[6] M. Gaździcki, *Z. Phys. C* **66**, 659 (1995).

[7] M. Gaździcki, M.I. Gorenstein, *Acta Phys. Pol. B* **30**, 2705 (1999).

[8] L. Van Hove, *Phys. Lett. B* **118**, 138 (1982).

[9] C.M. Humg, E.V. Shuryak, *Phys. Rev. Lett.* **75**, 4003 (1995); *Phys. Rev. C* **57**, 1891 (1998).

[10] M.I. Gorenstein, M. Gaździcki, K.A. Bugaev, *Phys. Lett. B* **567**, 175 (2003).

[11] M. Gazdzicki, M.I. Gorenstein, P. Seyboth, *Acta Phys. Pol. B* **42**, 307 (2011).

[12] M. Gazdzicki, M.I. Gorenstein, P. Seyboth, *Int. J. Mod. Phys. E* **23**, 1430008 (2014).

[13] M. Gaździcki, St. Mrówczyński, *Z. Phys. C* **54**, 127 (1992).

[14] M. Gaździcki, *Eur. Phys. J. C* **8**, 131 (1999).

[15] M. Gaździcki, M.I. Gorenstein, St. Mrówczyński, *Phys. Lett. B* **585**, 115 (2004).

[16] V.V. Begun, M. Gaździcki, M.I. Gorenstein, A.S. Zozulya, *Phys. Rev. C* **70**, 034901 (2004).

[17] M.I. Gorenstein, M. Gaździcki, *Phys. Rev. C* **84**, 014904 (2011).

[18] M. Gaździcki, K. Grebieszkow, M. Maćkowiak, St. Mrówczyński, *Phys. Rev. C* **83**, 054907 (2001).

[19] M.I. Gorenstein, *Phys. Rev. C* **84**, 024902 (2011).

[20] A. Rustamov, M.I. Gorenstein, *Phys. Rev. C* **86**, 044906 (2012).

[21] M.I. Gorenstein, `arXiv:1505.04135 [nucl-th]`.

[22] V.P. Konchakovski, M.I. Gorenstein, E.L. Bratkovskaya, W. Greiner, *J. Phys. G* **37**, 073101 (2010).

[23] V. Vovchenko, D.V. Anchishkin, M.I. Gorenstein, *J. Phys. A: Math. Theor.* **48**, 305001 (2015); *Phys. Rev. C* **91**, 064314 (2015).