WOUNDED NUCLEONS, WOUNDED QUARKS: A PERSONAL STORY*

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(Received January 20, 2020)

One of the authors of the idea of "wounded" nucleons and quarks recalls the origin and development of this concept.

DOI:10.5506/APhysPolB.51.1023

This article is based on a talk given during the ceremony of awarding Peter Seyboth the honorary doctorate of the Jan Kochanowski University in Kielce. When I learned that my long-time friend, Peter Seyboth is receiving this great honour, I could not resist to come and to express my gratitude for many years of fruitful collaboration and great help I received from him on numerous occasions. I followed suggestion of Marek Gazdzicki to present a story of the concept of wounded nucleons and wounded quarks, hoping that it may remind Peter old days when we were both relatively young and eagerly exploring the processes of multi-particle production on elementary and nuclear targets. I also hope that the wounded nucleons story will be of interest for my younger colleagues, potential readers of this special volume of *Acta Physica Polonica B*.

First, a warning: this is not an attempt to present a *history* of this concept. This would require searches in libraries and studies of many papers written by numerous authors contributing to the development of the idea. I am not able to do that. I can only try to search my own memory and construct a very *personal story* which surely is not complete and is lacking the objective value. It may perhaps be interesting, however, to follow the meanders of the long and complicated road which — seen from outside — may appear short and straight.

* Based on talk given at the Jan Kochanowski University in Kielce at the celebration of the Honorary Doctorate presented to Peter Seyboth (MPI, Munich).

For me the story started in early sixties of the last century, when I joined the experimental group of Professor Marian Mięsowicz in Cracow. The group was engaged in extensive measurements of events observed in nuclear emulsion irradiated by the cosmic rays at high altitudes. The events were mixtures of collisions of high-energy cosmic rays (mostly protons) with protons and with other nuclei presented in the nuclear emulsion, such as oxygen, silver and bromium. The measurements showed a strange effect: the observed multiplicity of particles produced in collisions with heavy nuclei was much lower than originally expected. Indeed, if one thinks about the process of collision with nucleus as a sequence of collisions with nucleons, the first Idea coming to one's mind is that it must lead to a sort of cascade depicted in Fig. 1: Particles created in the first collision should interact again, producing new particles and so on.

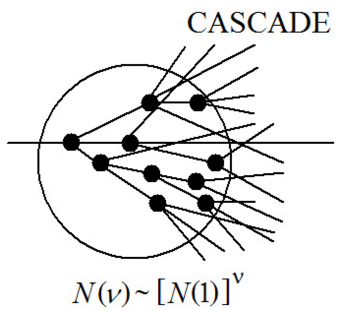

Fig. 1. Intra-nuclear cascade.

Such a mechanism leads to very large multiplicities, growing roughly exponentially with the number of collisions. In the simplest form we have, at least for the fast particles,

$$N(\nu) \sim [N(1)]^{\nu}\,, \tag{1}$$

where ν is the number of collisions inside nucleus, and $N(1)$ is the multiplicity of the fast particles produced in one collision. This simple formula must be of course corrected for dissipation of energy in subsequent collisions. Corresponding calculations were performed but the reduction was by far not enough to explain the observed multiplicities.

The inevitable conclusion was that apparently there is no intra-nuclear cascade. It looked as if the newly produced particles were inactive and did not produce the new ones.

The explanation of this strange phenomenon was given by Mięsowicz himself, who (using the argument proposed by Landau and Pomeranchuk who discussed electromagnetic cascades) introduced the concept of the "formation zone", suggesting that these newly created high-energy particles do not interact inside the nucleus because they are produced not *inside* but *outside* of the nucleus, as shown in in Fig. 2. Why?

The argument was based on the Heisenberg uncertainty principle. To create a particle of a rest mass m_0 requires a certain time which can be estimated from the uncertainty principle as

$$t_0 \approx 1/m_0 \,. \tag{2}$$

In the rest frame of the nucleus, however, when the particle moves with a high velocity, this time is elongated by the Lorentz factor and thus may become very large, exceeding the size of the nucleus

$$t = \gamma t_0 = (E/m_0)t_0 = E/m_0^2 \,, \tag{3}$$

where E is the particle energy. For particles with non-vanishing transverse momentum, the rest mass should be replaced by transverse mass and the formula becomes

$$t = \gamma/m_\perp = E/m_\perp^2 \,. \tag{4}$$

For 10 GeV pions with $p_\perp$ 300 MeV, this already gives about 20 fm, much more than the size of the nucleus.

The conclusion is that the newly produced fast particles do not participate in the production process and thus multiplicity should grow not exponentially but linearly with the number of collisions

$$N(\nu) \approx \nu N(1) \,. \tag{5}$$

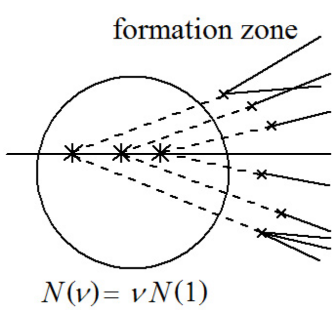

Fig. 2. Formation zone.

This was my understanding of the phenomenon until in 1976 I came to a conference in Trieste where Wit Busza presented the results from an experiment at Brookhaven [1] showing that the multiplicity does not follow the "obvious" formula (5) but rather

$$N(\nu) \approx \frac{\nu+1}{2} N(1)\,. \tag{6}$$

I was really surprised. First, by this strange but very simple result, second, when I learned that Wit Busza is a Pole, thrown by the disasters of the war to England and now working in the USA. I came to Cracow and of course immediately started to discuss the problem with my tutor and friend Wiesław Czyż. We soon realised that the Busza formula (6) can be understood if the number of particles emitted by the nucleon passing though the nucleus is *independent* of the number of collisions it underwent. It looked as if the nucleon did not care (or did not remember) how many times it scattered inside the nucleus. But why? Our — very vague — argument went like this. Nucleon is a complicated object, made of a certain amount of "stuff" which is released during the collision. This process takes time, since it is controlled by the "formation zone". Since at a given energy the amount of "stuff" is fixed by the very nature of the nucleon, the nucleon cannot emit more than it contains and thus subsequent collisions do not influence the production, Fig. 3. To explain the idea, Wiesław proposed the picture of someone hit in the face loosing all his teeth. It does not matter if he is hit again: he has no more teeth to loose. I preferred the picture of a bleeding man hit deadly by a knife. He will loose all his blood independently of number of subsequents hits. Wiesław cooked the name "wounded nucleon". Actually now I think that the better name would be "punctured nucleon", but never mind.

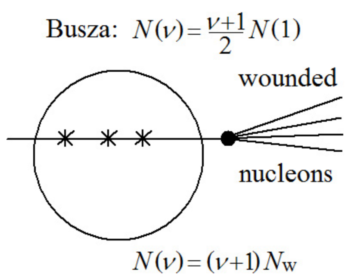

Fig. 3. Wounded nucleons.

The idea was ready but it took us more than six months before we decided to send a paper for publication. It seemed so trivial consequence of the Busza result that we were ashamed to publish this "bare" result. Wiesław engaged his student, Marek Bleszyński to perform the numerical calculations of the cross sections needed to estimate the number of collisions and other nuclear parameters. I tried to go beyond the average multiplicities and calculate the distribution of particles following from the model. I must confess that this was probably the most difficult calculation I have ever made. When these additions were ready, we finally published the paper [2]. I need not to add that nobody cared neither about our estimates of the cross sections nor about my calculation of the multiplicity distribution. I think nobody even looked into these painfully elaborated calculations hidden in the figures and in Appendix of our paper.

This looked as the end of the story. Our friends from the Męsowicz group continued the measurements, however, and it soon turned out that the Busza formula is not really exact and that the multiplicity increases somewhat faster with the number of collisions. We desperately tried to defend the idea but the data were solid and did not allow any doubt: the model must be modified. After about a year of struggle, suddenly we saw the possible rescue: the quark model. If the nucleon is made of 3 quarks which contribute independently to particle emission, then obviously number of "wounded" quarks, see Fig. 4, must increase with the number of collisions and thus multiplicity should grow faster than predicted by the Busza formula.

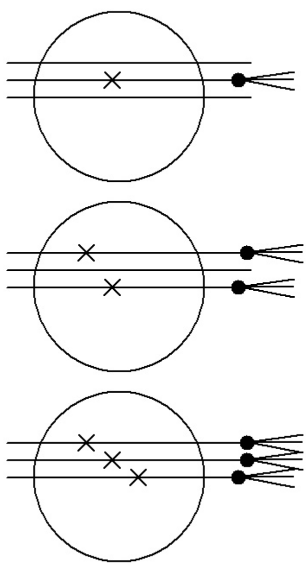

Fig. 4. Wounded quarks.

Calculations were relatively simple, we made corresponding predictions. They agreed with data but the errors were still so large that no definite conclusion was possible. The paper, written with Wiesław Czyż and Wojtek

Furmański [3] was rejected from *Physics Letters*. The referee wrote that the idea is too simple to be correct. Thus, in absence of good data, it is not worth publishing.

When I think now about this paper, I am really surprised that it took us so much time to arrive at the idea of wounded quarks. It should be realised that already since 1967 we were working heavily in Cracow on applications of the quark model to high-energy scattering (mostly to two-body processes). At some moment, Harry Lipkin even quoted our group as a "group from Jagell-Mannian University at Quarkov". Thus, from the very beginning, we have had all ingredients in our hands and still it took more than a year to arrive at the idea. Such are strange bendings of the human brain.

The first really good data came in 1982 from the Streamer Chamber experiment of the Bari–Cracow–Liverpool–Munich–Nijmegen collaboration [4]. One of the authors from the Munich group was Peter Seyboth. My role was to produce the quark model predictions (we did the calculations with Krzysiek Fiałkowski). It turned out that the model works perfectly but only in the central rapidity region, Fig. 5. The rapidity distribution was not flat, however, showing a maximum at the rapidities close to the rapidity of the nucleus and decreasing steadily towards the rapidity of the incident proton.

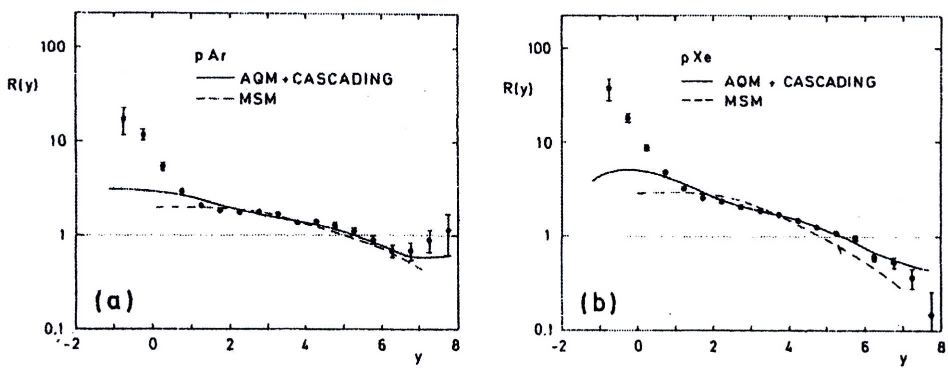

Fig. 5. Rapidity distribution in 200 GeV p–Ar and p–Xe collisions compared with the wounded quark model [4].

This was for us difficult to understand because at that time we were hooked on the idea suggested by Feynman that the rapidity distribution must be flat, at least in the region outside of the fragmentation of the target and projectile. At 200 GeV/c laboratory momentum the range of rapidity is about 5, and thus it was possible to interpret these deviations from the flat rapidity distribution as effects of the fragmentation regions and we accepted this interpretation, although I was feeling that it may be not really fully satisfactory. I did not know what to do with it, however.

Such a situation lasted till 2004 when the data from the PHOBOS Collaboration on deuteron–gold collisions of 200 GeV/n in the c.m. system were shown, Fig. 6, together with the measurements of the number of collisions [5]. At this energy, the range of rapidity is much larger (about 10) and the data were precise enough to rule out the possibility that the distribution in the central region is flat.

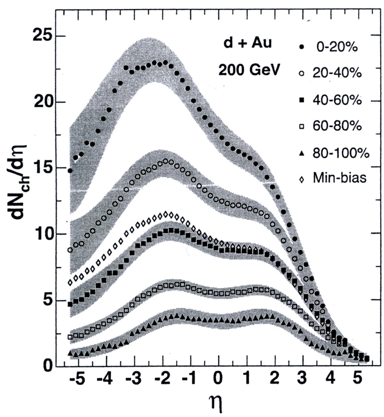

Fig. 6. Pseudo-rapidity distribution in d–Au at $\sqrt{s} = 200$ eV [5].

Discussing these results with Wiesław, we realised that, with the information on the measured number of collisions and using the wounded nucleon model, one can obtain independent information on emission from the left-moving as well as from the right-moving nucleons. To this end, it was enough to split the measured distribution into symmetric and antisymmetric parts [6], as shown in Fig. 7.

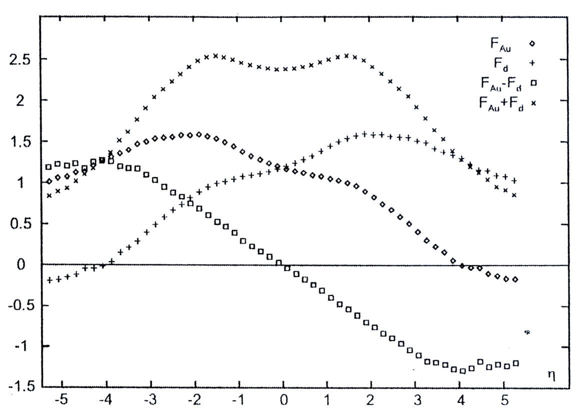

Fig. 7. Emission from a wounded nucleon at $\sqrt{s} = 200$ GeV [6] derived from the PHOBOS data [5].

The result was really spectacular: correcting for the fact that PHOBOS measured pseudo-rapidity rather than rapidity distribution, it turned out that (apart from the fragmentation region) the distribution from one nucleon is almost perfectly linear in rapidity. We were so surprised that I was even suspecting that there may be an error in the data. I was heavily thinking how to explain this effect and after some time came to the idea that it must be reflection of the flat distribution of partons (in agreement with the Feynman hypothesis). We eventually even published a paper on this (with Robi Peschanski and Adam Bzdak). I must say that I still do not understand *why* I did not immediately realised that this effect was predicted by Brodsky, Gunion and Kuhn already in 1977 [7]. I knew their paper very well (when it appeared I doubted if they may be right) but somehow it did not come to my mind at that time. Very strange and very bad for publicity of our paper. Had we quoted this old paper, certainly ours would have receive much more attention. But the human brain is apparently a mysterious object and one cannot control it as one pleases. Anyway, for me, our interpretation of the PHOBOS data meant a real breakthrough in my thinking about the idea of wounded nucleons and wounded quarks.

My last serious encounter with the wounded quarks happened when after a seminar where I presented the possibility that the nucleon may be composed of quark and diquark rather than of three uncorrelated quarks, Adam Bzdak decided to join me in confronting this idea with data. It turned out that it actually works and we could even determine the contribution for a single quark/diquark [8], as shown in Fig. 8.

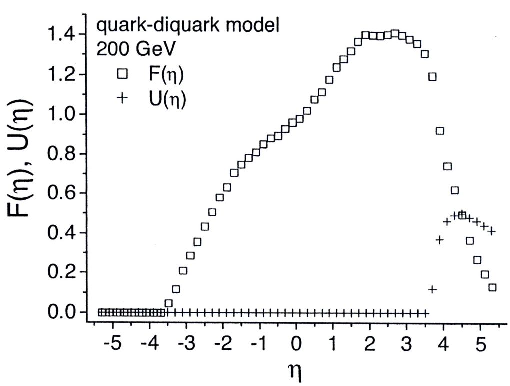

Fig. 8. Emission from a single quark/diquark; squares: wounded; crosses: unwounded [8].

There was one extra bonus from this analysis: by a shear accident — we discovered that such a model correctly describes not only particle production but also, and exceedingly well, the elastic proton–proton cross section [9], shown below in Fig. 9.

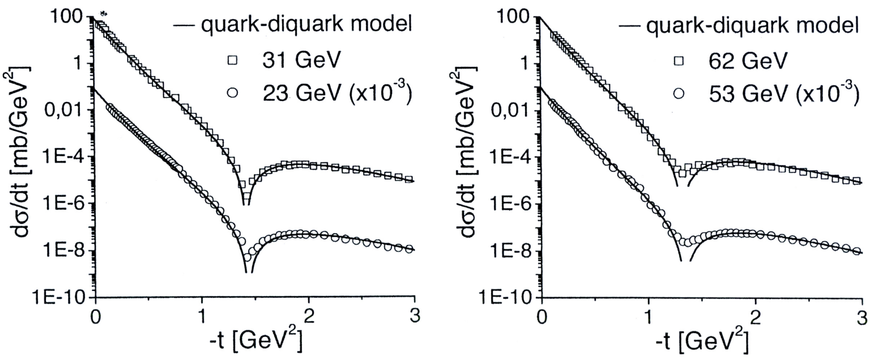

Fig. 9. Elastic scattering in the quark–diquark model [9].

This observation was later taken over by the group from Budapest participating in the TOTEM measurements at the LHC [10]. They showed that elastic scattering is very well described by the model up to highest available energies. I suspect that there must be some deeper reason for this (as I do not believe in "accidents" in physics) but I do not know where and how to look for it.

At this point, my personal story comes to the end. Further developments belong to others, particularly to Adam Bzdak and his students and to various groups working at RHIC.

REFERENCES

[1] C. Halliwell *et al.*, «Energy dependence of the pseudorapidity distributions in proton–nucleus collisions between 50 and 200 GeV/c», *Phys. Rev. Lett.* **39**, 1499 (1977).

[2] A. Białas, M. Bleszyński, W. Czyż, «Multiplicity distributions in nucleus–nucleus collisions at high energies», *Nucl. Phys. B* **111**, 461 (1976).

[3] A. Białas, W. Czyż, W. Furmański, «Particle production in hadron–nucleus collisions and the quark model», *Acta Phys. Pol. B* **8**, 585 (1977).

[4] C. De Marzo *et al.*, «Multiparticle production on hydrogen, argon, and xenon targets in a streamer chamber by 200-GeV/c proton and antiproton beams», *Phys. Rev. D* **26**, 1019 (1982).

[5] B.B. Back *et al.*, «Pseudorapidity distribution of charged particles in $d+\mathrm{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV», *Phys. Rev. Lett.* **93**, 082301 (2004).

[6] A. Bialas, W. Czyz, «Wounded nucleon model and deuteron–gold collisions at RHIC», *Acta Phys. Pol. B* **36**, 905 (2005).

[7] S.J. Brodsky, J.F. Gunion, J.H. Kuhn, «Hadron production in nuclear collisions — a new parton-model approach», *Phys. Rev. Lett.* **39**, 1120 (1977).

[8] A. Bialas, A. Bzdak, «Wounded quarks and diquarks in heavy ion collisions», *Phys. Lett. B* **649**, 263 (2007); «"Wounded" quarks and diquarks in high energy collisions», *Phys. Rev. C* **77**, 034908 (2008).

[9] A. Bialas, A. Bzdak, «Constituent quark and diquark properties from small angle proton–proton elastic scattering at high energies», *Acta Phys. Pol. B* **38**, 159 (2007).

[10] F. Nemes, T. Csörgő, M. Csanád, «Excitation function of elastic pp scattering from a unitarily extended Bialas–Bzdak model», *Int. J. Mod. Phys. A* **30**, 1550076 (2015), arXiv:1412.0813 [[hep-ph]].