SUMMARY TALK

A. Bialas

M. Smoluchowski Institute of Physics, Jagellonian University
Reymonta 4, 30-059 Kraków, Poland
e-mail: bialas@th.if.uj.edu.pl
and
H. Niewodniczański Institute of Nuclear Physics, Kraków, Poland

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Following the obvious (although not explicit) intention of the organizers, I shall not present a real SUMMARY of the workshop. This would be impossible, anyway, given the fact that I am an *amateur* rather than an expert in the field. Moreover, we have heard already 15 summary reports from the working groups (not counting the excellent summary of QCD calculations by Dick Roberts), so that one more summary would be rather pretentious and certainly superfluous. Therefore I am restricting myself to just some comments which came to my mind while sitting here and listening to many excellent contributions. Needless to say, this selection reflects my personal interests and should not be interpreted otherwise.

1. "Geometrical" scaling

It was proposed by Golec-Biernat, Kwiecinski and Stasto [1] who realized that it is a feature of the Golec-Biernat and Wuesthoff model [2] which may be more general than the model itself. It states that the virtual photon total cross-section, generally a function of two variables, is actually a function of only one scaling variable τ. In the original version (suggested by [2])

$$\tau \equiv Q^2 R^2 \; ; \quad R^2 = R^2(x) = Q_0^{-2} \left(\frac{x}{x_0}\right)^{\lambda} \; ; \quad \lambda = 0.29 \tag{1}$$

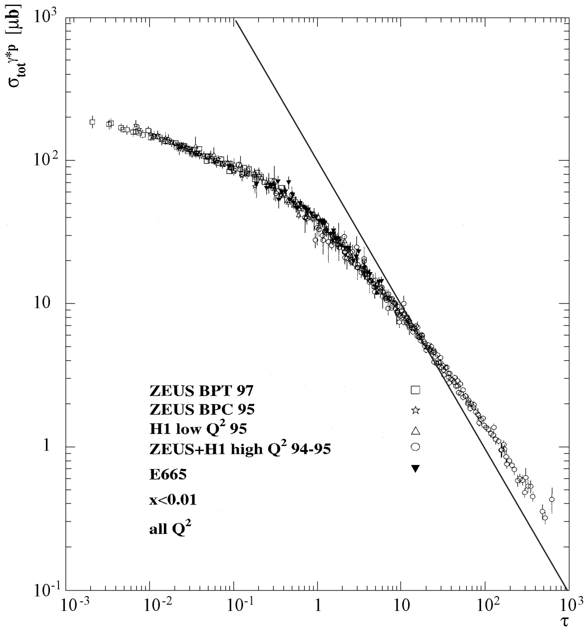

Fig. 1. Scaling from [1].

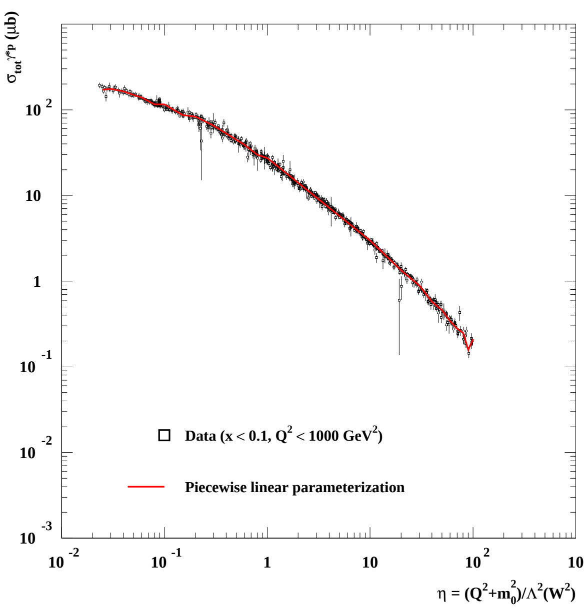

Fig. 2. Geometrical scaling from [4].

($Q_0 = 1$ GeV) and scaling works pretty well, as seen in Fig. 1. This need not be, however, a best choice: one may seek other scaling variables. Such an attempt was indeed undertaken [3] and presented during this meeting [4]. These authors propose the scaling variable of the form (1) but with R^2 which is a function of the total energy rather than x. The result is excellent, as is seen in Fig. 2.

The property of scaling is important because it indicates that — at least at small x — only one scale ("saturation scale" [2]) plays a role in the process. Therefore some effort was undertaken to justify it on theoretical grounds. Two of these attempts were presented during the meeting [5,6], both starting from the non-linear QCD evolution equations discussed recently by many authors [7].

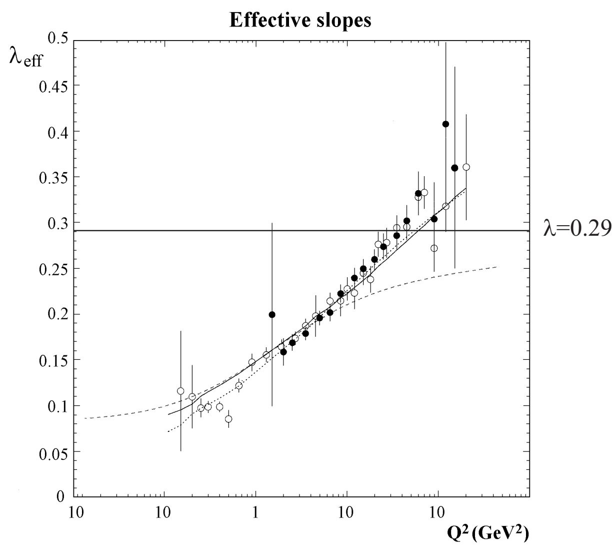

Fig. 3. Effective slope measured by H1 and ZEUS collaborations. Open circles: ZEUS, full circles: H1. Dashed line: The original Golec-Biernat and Wuesthoff model [2]. Full line: Improved model [13].

A closer inspection shows, however, that scaling is not an *exact* property of the cross-section, at least not in the form proposed in [1] and discussed in [5,6]. This follows from the analysis of the "effective" slopes in $\log(1/x)$, measured recently at HERA [8] and shown in Fig. 3. Indeed, if the cross-section is a function of τ only, then the effective slope can be expressed as

$$\lambda_{\text{eff}} \equiv -\frac{d\log[\sigma(\tau)]}{d\log x} = -\lambda \frac{d\log[\sigma(\tau)]}{d\log\tau}. \tag{2}$$

As seen from Fig. 1, the derivative $d\log[\sigma(\tau)]/d\log\tau$ is negative (guaranteeing positive $\lambda_{\rm eff}$) but its absolute value never exceeds one. This information and Eq. (2) imply that $\lambda_{\rm eff} \leq \lambda$ =0.29. One sees from Fig. 3 that this condition is badly violated by the data. We thus conclude that the geometrical scaling in the form proposed in [1] is only approximate. It would be interesting to perform an analogous test for the scaling proposed in [3].

At this point one may observe that the (almost) linear increase of $\lambda_{\rm eff}$ with $\log Q^2$ suggests that the cross-section can be represented in the form $(x/x_0)^{-a\log(Q^2/Q_0^2)}$, *i.e.* that the scaling variable may be close to $\log(x/x_0)\log(Q^2/Q_0^2)$. In fact, it was already successfully tried some time ago [9]. Also, one fit presented at this meeting [10] is not far from this. Another variable was advocated in [11]. Anyway, it seems that the hunt for the best scaling variable shall continue.

The fact that the geometrical scaling is violated was realized already by the authors of the original paper and all of them contributed to this meeting the papers on the subject. Kwiecinski and Stasto discussed violation of scaling induced by the DGLAP evolution [12], while Bartels, Golec-Biernat and Kowalski proposed an improvement to the original Golec-Biernat and Wuesthoff model [13]. This last paper is discussed in the next section.

2. Saturation

The Golec-Biernat and Wuesthoff dipole model, postulating a simple formula for the cross-section of the dipole of the (transverse) size r

$$\sigma_d(r) = \sigma_0\left(1 - {\rm e}^{-r^2/4R^2}\right), \tag{3}$$

where $R^2 = R^2(x)$ is given by (1), was the first largely successful attempt to incorporate the idea of saturation in the phenomenology of the small-x physics. However, as we have seen, it cannot explain the recent data on $\lambda_{\rm eff}$. The authors of [13] proposed to improve the model by exploiting the relation [14]

$$\sigma_0\frac{1}{4R^2} = \frac{\pi^2}{3}\alpha_{\rm s}xg(x)\,, \tag{4}$$

where $xg(x)$ is the gluon density in the proton[1]. The obvious consequence of this formula is that R cannot depend solely on x, since both $\alpha_{\rm s}$ and $xg(x)$ depend on Q^2. In the dipole model this means that R^2 must depend on a scale μ^2 which is taken in the form $\mu^2 = c/r^2$ [14]. The resulting cross-section was then calculated using the leading order DGLAP evolution[2]. A

[1] This formula is derived by considering the limit $r^2 \to 0$.

[2] Clearly, it would be interesting to investigate in this context also the BFKL formula.

reasonable fit was obtained and, as seen in Fig. 3, the effective slopes are now much better described than in the original model.

It follows from (3) and (4) that the dipole-nucleon cross-section in the Golec-Biernat and Wuesthoff model can be rewritten as (*cf.* [15])

$$\hat{\sigma}(r/R) = \sigma_0 \left(1 - \exp\left[-\frac{\pi\alpha_{\rm s}}{3}\frac{\pi r^2}{\sigma_0}xg(x)\right]\right) = \sigma_0 \left(1 - \exp\left[-\frac{\pi\alpha_{\rm s}}{3}\langle n_g(r)\rangle\right]\right) , \tag{5}$$

where $\langle n_g(r)\rangle$ is the average number of gluons *seen by the dipole of size* r. This observation invites a natural generalization of the model [16] where the *average* $\langle n_g(r)\rangle$ is replaced by the *actual* number of gluons encountered by the dipole:

$$\hat{\sigma} = \sigma_0 \sum_{n_g} P(n_g, r) \left(1 - \exp\left[-\frac{\pi\alpha_{\rm s}}{3}n_g\right]\right) , \tag{6}$$

where $P(n_g, r)$ is the probability that a dipole of size r encounters n_g gluons in the proton.

One important consequence of (6) is that the effects of saturation should be more visible at large gluon multiplicity and thus — most likely — also at large observed hadron multiplicity. In other words, *high multiplicity events provide a trigger for saturation.* It would be interesting, I think, to investigate this feature experimentally.

Dependence of saturation on impact parameter, which is entirely neglected in the original version of the Golec-Biernat and Wuesthoff model, was studied in [17] and reported by Munier at this meeting. They looked at the *elastic* production of ρ mesons and found a fairly large degree of saturation at small impact parameters. The effect increases with decreasing Q^2, as expected. These results show, in my opinion, that there is still much room for improvements of the model.

3. Impact parameter *vs* $k_\perp$ factorization

One of the general features of high-energy scattering, crucial for the validity of the dipole model, is the conservation of the impact parameter during the collision. This follows directly from angular momentum conservation *if the transverse momenta involved in the process are small compared to the total energy of the collision.* Since this seems to be the case in the region of small x, one would expect that it should hold in general. It is therefore not surprising to see that the $k_\perp$ factorization [18], an approach derived directly from QCD, is equivalent to the dipole model at the leading order [14].

However, when the $k_\perp$ factorization formula is supplemented by the exact gluon kinematics (as is usually done when data are analyzed [19]) the result violates the principle of impact parameter conservation [20]. Obviously, introducing the exact kinematics into the leading order formula means taking into account only some part of the higher order corrections. It remains for the moment an open question whether the result of [20] implies that at higher orders very large transverse momenta enter the game (invalidating the principle of impact parameter conservation and thus also the dipole model), or that inclusion of exact gluon kinematics is not the correct way to implement higher order corrections to $k_\perp$ factorization formula. This question can only be resolved by completing the calculation of the next-to-leading order corrections to the $k_\perp$ factorization formula. Such calculations are under way [21] and were reported at this meeting by Gieseke. Although the final results are not yet ready, one may speculate that they should restore conservation of the impact parameter but — at the same time — will provide a generalization of the dipole model to the "multipole model" in which the full color-charge distribution in the incident photon is explicitly taken into account [22]. Indeed, one of the contributions in the next order involves fluctuation of the virtual photon into $q\bar{q}g$ which obviously corresponds to a more complicated structure than just a simple $q\bar{q}$ dipole.

These remarks emphasize the importance of higher order QCD calculations. They not only provide a necessary precision in *quantitative* estimates of the measurable QCD effects [23], of which numerous examples were shown during this meeting [24] but, as we have just seen, are also often necessary to understand the *qualitative* features of the problem.

4. The ρ puzzle

It is now well-known that the energy dependence of the inclusive diffraction dissociation cross-section of virtual photons measured at HERA [25] is the same as that of the total cross-section, as seen in Fig. 4(a). It was reported at this meeting [26] that the same happens for the elastic production of light vector mesons (ρ, ω and ϕ) by the virtual photons. Figure 4(b) shows the recent data.

I would like to stress the point that this simple property of the data does not find a *natural* explanation in the present phenomenology of diffractive processes. First, it simply contradicts the predictions from the Regge approach (unless, perhaps, some very complicated combination of exchanged trajectories is invoked). Although it can be accommodated in the standard analysis of structure functions [27], and in the dipole model [2] the obtained result is, in my opinion, far from satisfactory: it is a consequence of some accidental cancellations ("conspiracy" [28]). This is well illustrated by the

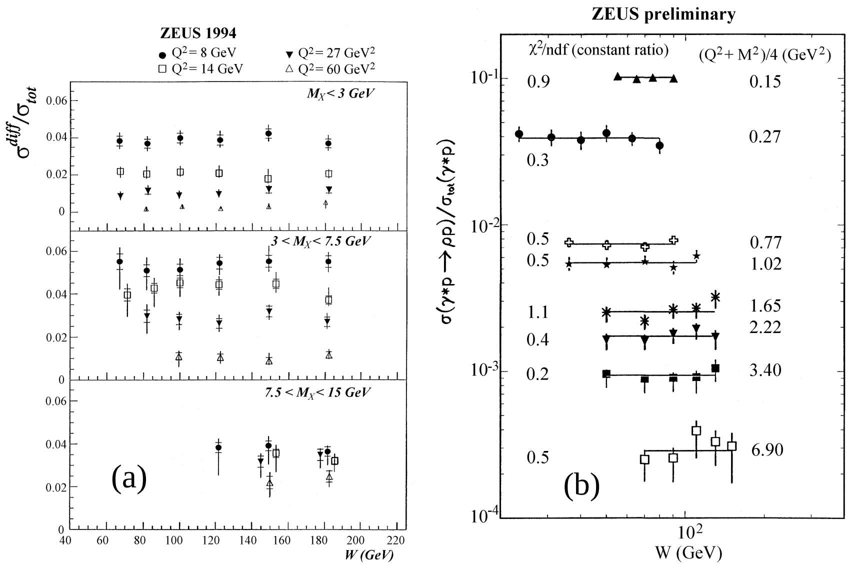

Fig. 4. (a) Ratio of the diffractive to total photon cross-sections plotted *versus* the energy of the collision [24]; (b) ratio of the cross-section for the elastic ρ production to the total cross-section, for various virtualities of the incident photon [25].

following formulae which describe the processes in question in the dipole model:

$$\frac{\sigma_{\rm dif}}{\sigma_{\rm tot}} \sim \frac{\int d^2r|\Psi(rQ)|^2\sigma_d^2(r/R)}{\int d^2r|\Psi(rQ)|^2\sigma_d(r/R)} = {\rm const}(R) \tag{7}$$

and

$$\frac{\sigma_\rho}{\sigma_{\rm tot}} \sim \frac{\left|\int d^2r\Psi_\rho^*(r)\Psi(rQ)\sigma_d^2(r/R)\right|^2}{\int d^2r|\Psi(rQ)|^2\sigma_d(r/R)} = {\rm const}(R)\,, \tag{8}$$

where $\sigma_d(r/R)$ denotes the dipole–proton cross-section, $R = R(x)$ is the saturation radius [2], $\Psi(rQ)$ the virtual photon wave function describing the fluctuation into the $q\bar{q}$ dipole and $\Psi_\rho(r)$ is the wave function of the ρ. One sees that, indeed, it requires a miracle to obtain R-independence of these ratios.

Therefore, accepting the fact that there is no *obvious* contradiction between the data and the accepted phenomenology, I would like to call attention to the fact that this simple feature of the data is still not really understood. It is not excluded, of course, that this energy independence of the ratios $\sigma_{\rm dif}/\sigma_{\rm tot}$ and $\sigma_\rho/\sigma_{\rm tot}$ is indeed an accident. I prefer to think, however, that simple facts demand simple explanations.

5. Exclusive hard diffraction

We all know from the high school that *absorption* of the incident wave implies its *diffraction i.e.* elastic scattering. It was first pointed out by Good and Walker [29] that to obtain *inelastic* diffraction it is necessary to consider quantum fluctuations. If the fluctuations are small, one obtains an intuitive formula for the transition $a \to a^*$ [30]:

$$\langle a^*|T|a\rangle = \varepsilon(a \to a^*)[\langle a^*|T|a^*\rangle - \langle a|T|a\rangle]\,, \tag{9}$$

where T is the scattering matrix and $\varepsilon(a \to a^*)$ is the probability amplitude for the quantum fluctuation.

When applied to some specific processes this formula gives:

(a) Vector dominance model [31]:

$$\langle\rho|T|\gamma\rangle = \varepsilon(\gamma \to \rho)\langle\rho|T|\rho\rangle\,. \tag{10}$$

(b) Dipole model [32]:

$$\begin{aligned}\langle \mathrm{JETS}|T|\gamma^*\rangle &= \varepsilon(\gamma^* \to \mathrm{dipole})\langle \mathrm{dipole}|T|\mathrm{dipole}\rangle \\ &= \varepsilon(\gamma^* \to \mathrm{JETS})\langle \mathrm{JETS}|T|\mathrm{JETS}\rangle\,. \end{aligned} \tag{11}$$

(c) Diffractive Jet production in hadronic collisions:

$$\begin{aligned}&\langle P' + \mathrm{JETS}|T|P\rangle = \varepsilon(P \to P' + \mathrm{JETS}) \\ &\langle \mathrm{JETS}|T|\mathrm{JETS}\rangle(1 - \langle P|T|P\rangle). \end{aligned} \tag{12}$$

The formulae (10) and (11) are widely used, as we have seen already in this report. One comment, however, is in order: Although Eq. (11) seems to correspond exactly to that of the Golec-Biernat dipole model, one should keep in mind that (11) can only be justified in the *impact parameter representation*. This emphasizes again the necessity of introducing impact parameters into the analysis of the saturation phenomena [17].

The formula (12), exploited for the first time in this context [33], explains breaking of Regge factorization between (b) and (c), observed recently in the data from HERA and from FERMILAB [34].

It thus seems that the old Good and Walker idea, expressed in the form of Eq. (9), is a right tool for description of diffractive dissociation in this entirely new domain.

6. Higgs production

During the meeting some attention was devoted to the possibility of Higgs production by the "Double Pomeron Exchange", two versions of which are illustrated in figure 5. The point is that, if its mass is indeed close to 120 GeV, the Higgs boson may be difficult to see at LHC because of a very large background. It is thus interesting to investigate the channels where the background is minimized. The process depicted in Fig. 5 becomes an ideal candidate, provided ... it exists, *i.e.*, that the cross-section is large enough to be observed with the expected LHC luminosity.

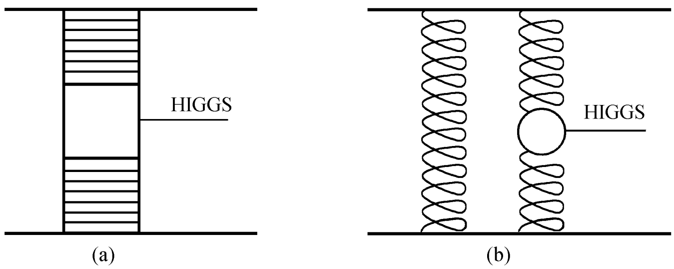

Fig. 5. Two models of the Higgs boson production by the "double Pomeron exchange": (a) factorized Pomeron; (b) two-gluon exchange.

Several estimates of this cross-section are now available [35, 37–41] but, unfortunately, there is still no consensus: different calculations give the results which are widely different, as was nicely presented by De Roeck at this meeting [42]. Three general ideas are pursued in these calculations.

The first one, applied in [41] (see also [37]), uses a "classic" picture of the factorized Pomeron [43] (Fig. 5(a)). The cross-section calculated in the two-gluon exchange approximation for the Pomeron structure is then corrected for the "gap survival probability" calculated in [38]. The resulting cross-section is very small. In view of what was said in the previous section, however, it is not entirely clear if this correction is adequate. It would thus be interesting to look if and how the Eqs (9) and (12) can be applied to this case.

Other calculations do not assume factorization but use the two-gluon exchange model (Fig. 5(b)) where the produced Higgs boson couples to one of the gluons [44]. The problem here is again the calculation of the "gap survival probability" which corrects the original cross-section for a possible exchange of "soft" gluons which — by carrying color — destroy the rapidity gap and thus imply emission of many additional hadrons. There is, however, no unique prescription how to take into account this effect, and therefore two groups which looked into this problem obtained rather different results [38, 39]. Nevertheless, they both agree that the cross-section is rather small, certainly not observable at the Tevatron and perhaps marginally at LHC.

In the original calculation in the model depicted in Fig. 5(b) [35], the gluon radiation was taken care of by introducing the concept of a "nonperturbative gluon" [45] whose propagation is restricted to small distances (less than ~ 0.2 fm). In this way the exchanged gluon remains all the time in the confinement region and does not radiate soft quanta. The prize one pays in this approach is that the "nonperturbative" coupling cannot be easily determined, thus leaving a substantial uncertainty in the estimated value of the cross-section [46]. This problem was partly removed in [40] where the "inclusive" cross-section, *i.e.* cross-section for production of the Higgs boson together with any number of hadrons in the central vertex (keeping the two rapidity gaps), was considered. In this case the result can be normalized to the existing data on production of two jets (recently measured by the CDF collaboration [47]). The cross-section for such "inclusive" Higgs production turns out rather substantial. Although the estimated background also increases, the net result is such that the prospect of finding the Higgs boson remains promising.

The most reasonable conclusion from all these considerations is that the present theoretical estimates of Higgs boson production with two large rapidity gaps are uncertain. To improve the situation, it will be necessary to normalize the calculations to the data on the "elastic" two-jet production at the Tevatron, once they are available[3].

7. Fractals

In an interesting contribution, Lastovicka suggested that the power-law fits to the structure function (in x and Q^2) may be a signal for the fractal nature of the process [10]. Obviously, I could not resist to comment on this problem.

The first remark is that fractal distributions are *natural* in the BFKL region. Indeed, when considered from the s-channel point of view [48] the BFKL behavior arises from a *cascade* of (soft) gluons. And cascades are known to be the generic sources of the fractal distributions.

My second remark is that such fractal distributions (called "intermittency" [49]) are observed in e^+e^- annihilation [50] and in hadron–hadron processes [51]. It should thus not be too surprising if they are also observed in deep inelastic scattering. Once they are seen in particle spectra, it would be interesting to check if their fractal dimensions agree with the ones determined in [10].

[3] At the moment only the upper limit exists [47].

The final remark is that, as the gluon cascade is expected to stop in the *saturation region*, one may also expect the fractal behavior to disappear when the gluon density reaches very high values (*i.e.* at extremely small x and/or in the high multiplicity events)[4].

I think it may be useful to pay more attention to these problems.

8. Nuclear targets

My last comment concerns nuclear targets[5]. It was repeatedly emphasized during this meeting that leptoproduction on nuclear targets can provide important information about the nature of strong forces which is difficult, if not impossible, to obtain otherwise (as was already proven in the past [52, 53]).

Right now the emphasis is on studies of the exciting region of saturation which should be much easier to reach in collisions with heavy nuclei [5, 6]. It is also clear that the interactions with nuclei could provide a decisive test of the dipole model. Today, however, I would like to talk about other types of measurements, related to the problem of the *formation time* of hadrons[6].

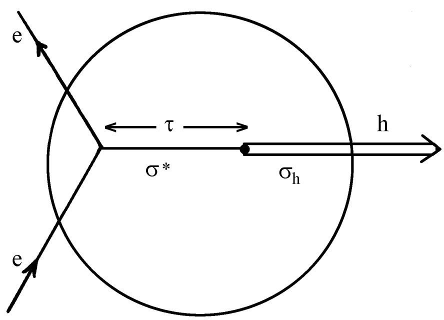

Fig. 6. A schematic picture of hadron formation in lepton–nucleus collisions.

A typical experiment of this kind is the measurement of the flux of the leading (*i.e.* $z \geq 0.2$) hadrons and compare the yields from the nucleon target with that from heavier nucleus. The idea is illustrated in Fig. 6. After the first interaction of the virtual photon, an intermediate strongly interacting system traverses the nucleus. Depending on x and Q^2, it may be a current quark, a dipole, or — perhaps — some more complicated animal. In the vacuum this system would simply change into observed hadrons with

[4] This observation is consistent with the fact that “intermittency” signal was not observed in heavy ion collisions.

[5] This is the subject I have *loved* for many years. This section is, therefore, even more than the others, biased by my own prejudices.

[6] For a review of the physics of lepton–nucleus interactions, see [54].

a characteristic time τ_h for each hadron. In the nucleus, however, both the intermediate system and the final hadrons can interact *inelastically* with the nuclear matter. Each such inelastic interaction implies an energy loss and thus eliminates the given hadron from the spectrum at large z [7]. Thus, the ratio of the hadron yield from nuclear target to that from the nucleon measures, to a good approximation, the probability P_0 that *no inelastic interaction of either the intermediate system or the final hadron took place inside the nucleus.*

As seen in Fig. 6, P_0 obviously depends on three essential parameters[8], namely the inelastic cross-section of the intermediate system $\sigma*$, the inelastic cross-section of the final hadron σ_h, and the formation time of the hadron τ_h:

$$P_0 = P_0(\sigma^*, \tau_h, \sigma_h)\,. \tag{13}$$

Thus by measuring P_0 one may obtain information about σ^* and about the formation time τ_h.

It is important to realize that such measurements do not require a very high energy beam: the formation time is boosted by Lorentz transformation and thus at very high energy hadrons are created well outside the nucleus. Consequently, in this case one can only measure σ^* and not τ_h. Taking this into account, one concludes that the HERMES experiment seems to be almost the ideal place to perform such measurements. In fact, the first data were recently analyzed [56]. The formation time of pions and protons was measured. The accuracy is not very high yet, but one important result came out already. It turns out that

$$\tau_{\rm proton} \quad > \quad \tau_{\rm pion} \tag{14}$$

in contradiction with the early estimates based on uncertainty principle [57] which suggested inverse proportionality of τ_h to the hadron mass[9]. The important consequence of this observation of the HERMES collaboration is that *the formation time depends in an essential way on the hadron structure.* This clearly opens the way to a new, very interesting area of hadronic physics. I feel that it is most worthwhile to put more emphasis on this kind of measurements. Now[10].

[7] Since the spectra of fast hadrons fall very steep at large z, this mechanism is rather effective.

[8] This is admittedly a rather simplified picture but it grasps the most essential features of the problem. For more sophisticated descriptions, taking into account, *e.g.* time-evolution of the intermediate system, its fluctuations and fragmentation functions, see [54, 55].

[9] Also the estimate based on the Lund model [58] does not satisfy (14).

[10] Although I have no illusions: the DESY management always fully agrees that it is a very exciting possibility and ... that's it.

I greatly profited from the discussions with H. Abramowicz, J. Bartels, W. Czyż, E. De Wolf, K. Golec-Biernat, K. Goulianos, L. McLerran, R. Peschanski, M. Praszałowicz, and A. Staśto. This investigation was supported in part by the Subsydium of Foundation for Polish Science NP 1/99 and by the Polish State Committee for Scientific Research (KBN) grant No 2 P03 B 09322.

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