Future of Baryons

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A personal view upon the future of baryon studies is presented, with an emphasis on the quark–pion dynamics, in relation with new hadron spectroscopy triggered by arrival of pentaquarks, as well as at the baryon structure as revealed in proton scattering/production processes in hadron and heavy ion collisions.

1. PREFACE

I was kindly asked by the Organizing Committee of the Baryon Structure Workshop to give a Concluding talk rather than a Summary talk. This decision was wise in two respects. Firstly, addressing such a vibrant and exciting field it looks proper to talk about puzzles and pending problems rather than summarizing results. Secondly, by so formulating my task, the organizers tried to help me to do a stress-free presentation. If that was indeed their intention, it failed miserably. In the time allocated, I barely made it through a half of what I was planning to discuss. Fully accepting responsibility for this failure, I still feel that I have an excuse: the audience was so receptive that I got carried away. Having spent too much time elaborating on the issues touched upon in the first half of the talk (pentaquarks and pions, versus asymptotic freedom and confinement) I had to jump to conclusions. By so doing I skipped the whole topic of the structure of baryons as probed in scattering processes, and the hot subject of "baryons in a QCD medium" in particular, which undermined the very logic of the presentation. In this writeup I will attempt to restore that logic.

All preceding talks presented at the last session of the Workshop had a key word "Future" in the title. Therefore, the title of this presentation. Immediate future of baryon studies in my opinion can be described as a two-stream flow: settling the issue of new hadron spectroscopy triggered by pentaquarks and scrutinizing baryon structure in proton scattering/production processes.

2. ARE PENTAQUARKS REALLY THERE?

They better be. And for aesthetic reasons in the first place. Well established notions of the hadron world — *Constituent–Non-Relativistic–Additive* quarks as building blocks for hadrons and their interactions — hardly ever received beating at a comparable scale.

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2.1. Weird aspects of pentaquark states

Today we seem to be witnessing *spectacular inadequacy* of the conventional constituent quark picture. In good old days mass splittings between the members of the baryon decuplet obediently followed the strangeness content, without much imagination:

$$M_\Omega > M_\Xi > M_\Sigma, M_\Lambda > M_N .$$

Now, in the new multiplet $\overline{\mathbf{10}}$, a hadron carrying an **anti**strange quark, Θ^+, is *lighter* than its strangeness-free counterpart $N(1710)$. It is also double-split from the $\Sigma(1890)$ state — the one with the *same* number of strange bricks. (Looks *as if* constituent mass of the strange **anti**quark inside Θ^+ were negative …) Then, an amazingly small decay width which remains to be qualitatively explained (not mentioning quantitatively understood). Finally, an apparent elusiveness of Θ^+ in high energy reactions provokes nightmarish thoughts. (A programme for systematic experimental studies of potential *production mechanism dependence* was recently formulated by Marek Karliner and Harry Lipkin [1].)

It would be premature to pronounce the conventional quark picture dead, however. Playing with *diquarks* may well come to rescue.

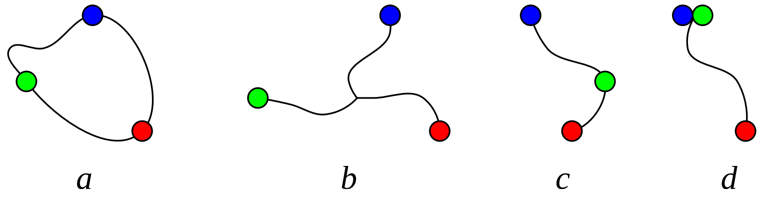
2.2. Diquarks, rediscovered & redeployed

Revival of diquarks in purely theoretical QCD context dates back 1999 when Vladimir Braun, Sergey Derkachov, Gregory Korchemsky and Alexander Manashov have observed a diquark emerging in the problem of the light-cone proton wave function as a state with the smallest anomalous dimension that dominates its asymptotic behavior (distribution amplitude). They found that in the $Q^2 \to \infty$ limit the *exact* solution for the light-cone wave function has a structure [2]

$$\psi(x_1, x_2, x_3) \implies \psi(x_1, \frac{x_2 + x_3}{2}) + \text{symm}\,, \tag{1}$$

with x_i a longitudinal momentum fraction of a valence quark. This means that three-quark configurations collapse into $q + d$: independence of the relative momentum $x_2 - x_3$ implies a point-like (spin 0) diquark, corresponding to $\delta(z_2 - z_3)$ in the longitudinal coordinate z.

In the talk "*Minimal Strings for Baryons*" delivered at the ECT* Workshop in Trento in July 2004, Gerard 't Hooft considered quarks inside a proton as being connected by pieces of QCD string. He found that among possible string arrangements,



it is the last configuration (d) with two quarks sitting on top of each other (and thus representing a point-like diquark) that is the only one *stable* under the classical string dynamics.

The most recent hailing of diquarks is due to Frank Wilczek (September 2004), who in his contribution “*Diquarks as Inspiration and as Object*” to the Ian Kogan Memorial volume (ed. M. Shifman, to appear) have announced an extensive program of incorporating diquarks (both “*good*” and “*bad*” ones) into sort of Baryon Chemistry based upon the generalization of the Chew–Frautschi formula. [4]

3. QUARKS, QCD VACUUM AND PIONS

Charmed by the success of the relativistic theory of electron and photon fields (quantum electrodynamics) we learned to look upon the original concept of the “Dirac sea” — the picture of the negative energy fermion content of the vacuum — as an anachronistic model with little if anything to do with the physics. It was the famous Feynman $i\epsilon$ prescription that did away with the vacuum involvement in scattering processes. It is worth remembering, however, that this prescription was designed for (and applies only to) theories with *stable perturbative vacua*.

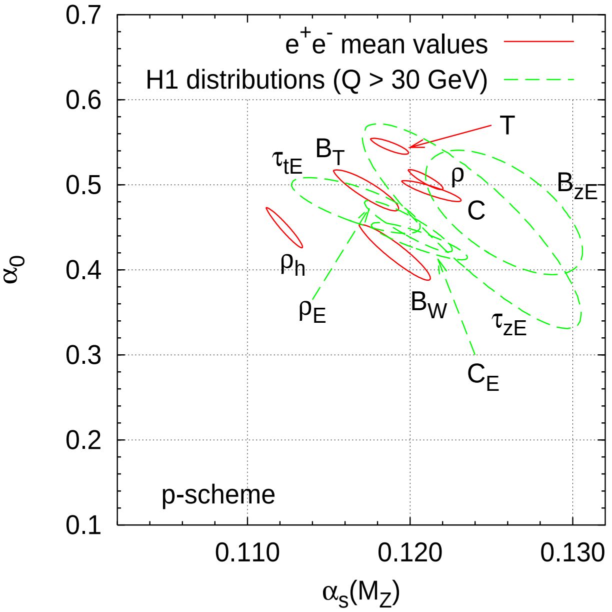
That was fine in QED where electrons and photons — the physical states of the theory — were in one-to-one correspondence with the fundamental fields put into the Lagrangian. From this point of view, the rôle of the QED vacuum can be called “trivial ”: the QED vacuum processes made the coupling $\alpha_{\text{e.m.}}$ and the electron mass operator *run*, but did not affect the *nature* of the interacting fields. Not so in QCD where response of the Vacuum is violent as it transforms the input (colored) fields *beyond recognition*.

3.1. Those mysterious pions

Pion always was, and remains, a mysterious animal. From the *weak interaction* viewpoint, it is driven into existence by spontaneous chiral symmetry breaking (SCSB) and therefore has a good reason to be treated as a fundamental (point-like) object as a Goldstone boson. On the other hand, from the point of view of *strong interaction* dynamics it is rather a loose bound state of quarks. How to reconcile the two sides of pion being? Strangely enough, this dichotomy has never been seriously addressed in the literature.

Maxim Polyakov reminded us [5] that the quarks that have gained a dynamical mass via SCSB interact with Goldstone pions very strongly, $g_{\pi qq} \approx 4$. Such a large interaction constant looks however much less scary when translated into the characteristic combination $\alpha = g^2/4\pi$ (or into α/π better still). Moreover, this number is not actually too far from the value of the standard quark–gluon coupling $g_s \equiv g_{gqq} \approx 2.5$ which translates into $\alpha_s \simeq 0.5$.

The latter value — the *average* QCD coupling at small momentum scales — had been extracted from the studies of non-perturbative $1/Q$ suppressed effects in event shape observables in e^+e^- and DIS [6],



$$\alpha_0 \equiv \frac{1}{2\,\mathrm{GeV}} \int_0^{2\,\mathrm{GeV}} dk\, \alpha_s(k^2) \;\simeq\; 0.5\,. \qquad (2)$$

The pentaquark frenzy has a positive impact at least in that it invites us to look more closely into the long standing problem of quark–pion dynamics.

From the theory viewpoint, one does not necessarily need to be a chiral soliton advocate to enthusiastically greet arrival of pentaquarks. Indeed, the picture of self-consistent quark & pion fields that brings in pentaquarks in the DPP approach [7] drives home the following philosophical messages:

- pions are as important (fundamental) as are the quarks;
- dynamical chiral symmetry breaking does not reduce to a mere constant — fermion vacuum condensate $\langle\bar\psi\psi\rangle$ — used in QCD sum rules;
- Dirac sea of negative kinetic energy quarks is not an abstraction;
- non-linear collective phenomena in the broken QCD vacuum may manifest themselves in the physical spectrum of QCD as an infrared unstable QFT.

Strangely enough, this list of warning messages could have been signed by someone who was rather sceptical about the rôle of classical topology in QFTs.

3.2. Gribov light quark confinement

In 1990 V. Gribov suggested the so-called *supercritical binding* of light (u and d) quarks as a mechanism for colour confinement in the real world, see [9,10] and references therein.

Energy of a Dirac electron in an external static field created by a point-like electric charge Z becomes *complex* for $Z > 137$. This means instability. Classically, the electron "*falls onto the centre*". Quantum-mechanically, it also "*falls*", but into the Dirac sea. In QFT the instability develops when the energy ϵ of an empty atomic electron level drops, with increase of Z, below $-m_ec^2$. Then, an e^+e^- pair pops up from the vacuum, with the vacuum electron occupying the level: the super-critically charged ion decays into an "atom" (the ion with the smaller positive charge, $Z-1$) and a real positron:

$$A_Z \Longrightarrow A_{Z-1} + e^+\,, \qquad \text{for } Z > Z_{\text{crit.}}$$

Thus, the ion becomes *unstable* and gets rid of an excessive electric charge by emitting a positron [8].

Gribov found that in a system of two light fermions interacting in a Coulomb-like manner supercritical binding develops *much earlier* namely, when the coupling hits a definite critical value

$$\frac{\alpha_{\text{crit}}}{\pi} \;=\; C_F^{-1}\left[1-\sqrt{\frac{2}{3}}\right] \simeq 0.137\,; \qquad C_F = \frac{N_c^2-1}{2N_c} = \frac{4}{3}\,. \qquad (3)$$

3.2.1. Gribov approximation to the Schwinger–Dyson equation

Gribov developed a new approximation to the Schwinger–Dyson equation for the fermion (quark) Green function [9] which

- takes into account the most singular (logarithmically enhanced) *infrared* and *ultraviolet* renormalization effects,
- makes a smart use of the *gauge invariance*,
- is *local* in the momentum space,
- retains essential *non-linearity* due to quark-gluon interactions
- and possesses a rich *non-perturbative structure*.

It can be looked upon as a perturbative (leading logarithmic) approximation that allows one to penetrate into the region of *large anomalous dimensions.* [2] This equation reads

$$\partial_\mu^2 G^{-1}(q) \;=\; g\cdot\big(\partial_\nu G^{-1}(q)\big)\; G(q)\;\big(\partial_\nu G^{-1}(q)\big) \;+\;\ldots, \qquad \Big(g\equiv [C_F]\frac{\alpha}{\pi}\Big) \tag{4}$$

with … standing for *less singular* terms $\mathcal{O}\left((\alpha/\pi)^2\right)$.

If in the infrared region the coupling exceeded the critical value (3), a *bifurcation* in the Gribov equation (4) occurs, giving rise to the non-perturbative solution corresponding to the phase with *spontaneously broken chiral symmetry.*

3.2.2. Quarks and pions: feedback

Dynamical symmetry breaking brings in *Goldstone pions.* Pions, in their turn, affect propagation of quarks. The equation (4) for the quark Green function gets modified due to the pion feedback as

$$\begin{aligned}\partial_\mu^2 G^{-1}(q) \;&=\; g\cdot \partial_\nu G^{-1}(q)\, G(q)\, \partial_\nu G^{-1}(q) \\ &\qquad -\frac{3}{16\pi^2 f_\pi^2}\left\{i\gamma_5, G^{-1}(q)\right\}\, G(q)\, \left\{i\gamma_5, G^{-1}(q)\right\}.\end{aligned} \tag{5}$$

In his last paper Gribov argued that these effects are likely to lead to confinement of light quarks and, thus, to confinement of any colour states [10].

The structure of (5) implies the pion–quark coupling

$$g_{\pi qq} \;=\; \frac{\{i\gamma_5, G^{-1}(q)\}}{f_\pi} \tag{6}$$

proportional to the quark mass operator, with f_π the famous pion–axial current transition constant. Dynamical nature of symmetry breaking makes f_π a dynamical object as well. It is not an arbitrary parameter (as it is in the standard effective chiral theory) but satisfies an equation containing the quark mass operator:

$$\begin{aligned} f_\pi^2 \;&=\; \frac{1}{8}\int\frac{d^4q}{(2\pi)^4 i}\,\mathrm{Tr}\left[\,\left\{i\gamma_5, G^{-1}\right\}\, G\,\left\{i\gamma_5, G^{-1}\right\} G\left(\partial_\nu G^{-1}\, G\right)^2\,\right] \\ &\quad +\;\frac{1}{64\pi^2 f_\pi^2}\int\frac{d^4q}{(2\pi)^4 i}\,\mathrm{Tr}\left[\,\left(\left\{i\gamma_5, G^{-1}\right\}\, G\right)^4\,\right].\end{aligned} \tag{7}$$

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[2] For more details see review "*Gribov conception of QCD*" [11].

Ideologically, what we are talking here is a *new bootstrap* scheme: A selfconsistent light-quark–pion theory of spontaneous chiral symmetry breaking, colour confinement, and eventually of hadron spectroscopy.

Pion-field-driven pentaquarks may have a good chance for finding their place within such a theory.

4. BARYON FUTURE

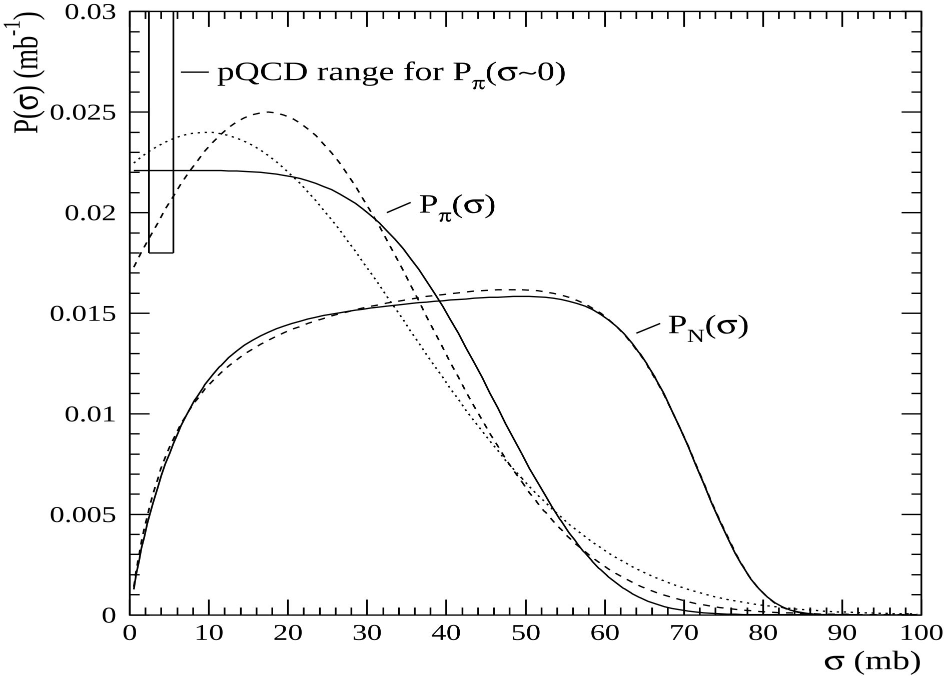
We have discussed potential *Quark Future*. Now let us have a brief look into certain aspects of immediate *Baryon Future*.

4.1. Baryon structure welcomes diffraction

Diffraction can be defined as a non-destructive probe with respect to the *target*. At the same time it speaks volumes about internal structure of the *projectile*. In QFT in general (and in QCD specifically) we are always dealing with *composite objects*. Our projectile is a mixture of various configurations. At high energies each of these configurations *scatters independently*, so that the structure of the projectile can be treated in *partonic terms* as a Fock wave function. Since different configurations interact with different cross sections, coherence of the projectile gets destroyed thus resulting in *inelastic diffraction*.

4.1.1. Breathing hadrons

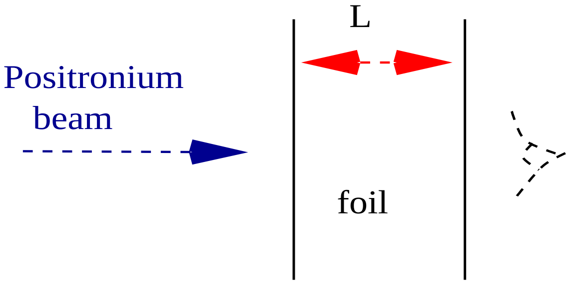
Studying inelastic diffraction allows one to picture the distribution $P(\sigma)$ that describes the probability for the projectile (pion, proton) to interact with a given cross section σ.



Collapsed hadrons = *penetrators* Swollen hadrons = *perpetrators*

The tail of the distribution (large σ) corresponds to a "swollen" hadron interacting with larger than average cross section. Its left wing (small σ) is due to small size configurations that penetrate the target easily and give rise to the so-called "colour transparency" phenomenon.

4.1.2. Inelastic break-up of pions and protons



Let us discuss what sort of final states one can expect in diffractive scattering of a composite projectile on an adsorbing target. Throw, for example, positronium beam on a foil. Fast positronium represents a dipole of transverse size $|\mathbf{b}|$ and interacts with the cross section $\sigma(\mathbf{b}) \propto \alpha^2 |\mathbf{b}|^2$. If thickness of the foil is large so that $L \gg \bar{\lambda} = 1/\rho\bar{\sigma}$ then to penetrate through, the incident positronium better be in a *squeezed* state so as to minimize the cross section and increase the mean free path to match the longitudinal size of the target,

$$\lambda(b) = \frac{1}{\rho\sigma(\mathbf{b})} \sim L \qquad \Longrightarrow \qquad \frac{1}{|\mathbf{b}|^2} \sim \alpha^2\rho \cdot L\,. \tag{8}$$

Thus we conclude that diffraction filters out *small size configurations* of the breathing projectile. Having penetrated trough the foil, a squeezed e^-e^+ system will hardly ever convert back into the bound state. The final state will normally be a *pair of "jets"* (e^- and e^+) with large relative transverse momentum

$$|\Delta\mathbf{p}_t|^2 \sim |\mathbf{b}|^{-2} \propto L. \tag{9}$$

By studying distribution of energy between these jets we can directly measure positronium wave function.

The physics of colour transparent squeezed *pions* producing two hadron jets in inelastic diffraction on nuclei [12],

$$\pi \;+\; A \;\longrightarrow\; 2\;\; \text{high–}k_\perp\, \text{jets} \;\;+\; A\,,$$

had been wonderfully demonstrated by the E–791 experiment [13]. We are eagerly awaiting the next step — diffractive dissociation of the proton into three jets:

$$p + A \to 3\;\text{jets} + A \quad (\text{RHIC}) \qquad \& \qquad p + \bar{p} \to 3\;\text{jets} + \bar{p} \quad (\text{Tevatron})\,.$$

4.2. Heavy ions and small distances

A new hope of advancing our knowledge of hadron dynamics is placed in pA and AA interactions that are being aggressively pursued nowadays by the RHIC heavy ion high energy scattering programme.

On the theory side, with attention turned to scattering of/off nuclei, small distances persistently (and quite unexpectedly) emerged in the multiple scattering environment. As we have seen above in (9), a typical hardness of diffractive dissociation of a projectile hadron increases linearly with the size of the target, L. The same phenomenon, with exactly the same behaviour of the hardness scale $Q^2 \propto L$, had been observed elsewhere. Markedly, in the physics of

- gluon radiation accompanying propagation of a colour parton in a QCD medium, with $Q^2 \propto L$ marking the squared transverse momentum of the most energetic medium induced gluons (responsible for parton energy loss);
- McLerran–Venugopalan "Colour Glass Condensate" that was invented as a model for understanding non-linear effects in high energy QCD scattering (parton saturation) and is being extensively applied to RHIC data (with $Q_s^2 \propto A^{1/3}$ the saturation scale).

Many new intriguing things have been observed at RHIC, in particular,

- yield of pions with relatively large transverse momenta gets *strongly suppressed*,
- recoiling jets are *washed away* in central collisions.

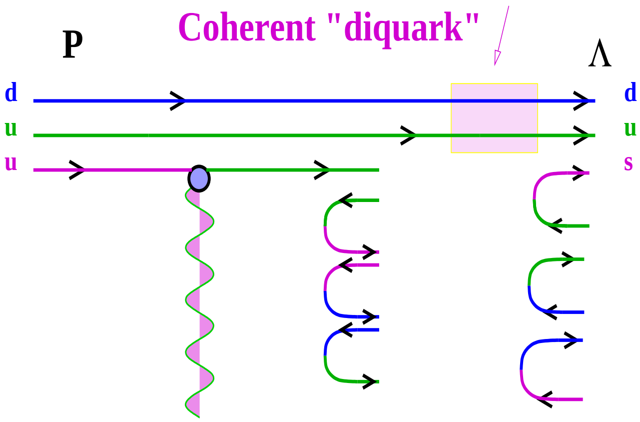
What do *baryons* have to do with all this? Quite a lot it turns out. In the multiple collision environment

1. *nucleons disappear* from the fragmentation region ("proton stopping");
2. strange hyperons become as copious as nonstrange ones, signalling lifting off the *strangeness suppression* and reaching *u-d-s* (chemical) equilibrium;
3. most unexpectedly, the yield of sea *baryons* (protons and antiprotons) with transverse momenta $p_t \gtrsim 2\,\mathrm{GeV}$ takes over that of *mesons* (pions).

It seems, something is getting "hot" in there. That *something*, by the way, is not necessarily a QGP (with the standard meaning of the word "plasma" denoting a state that develops due to reinteraction, and eventual thermal equilibration, of the system of produced particles). It may very well be the QCD vacuum itself that gets "heated" due to the presence of *stronger than usual* colour fields that develop in the course of multiple gluon exchanges between participating nucleons.

4.3. Multiple scattering, colour and baryon stopping

From the pQCD point of view, minimum bias scattering of a hadron is due to gluon exchange with one of its valence quarks. Such scattering *paints* the projectile (as well as the target) into the octet colour state and, if momentum transfer is larger than the inverse hadron size, breaks coherence of the valence quark system.

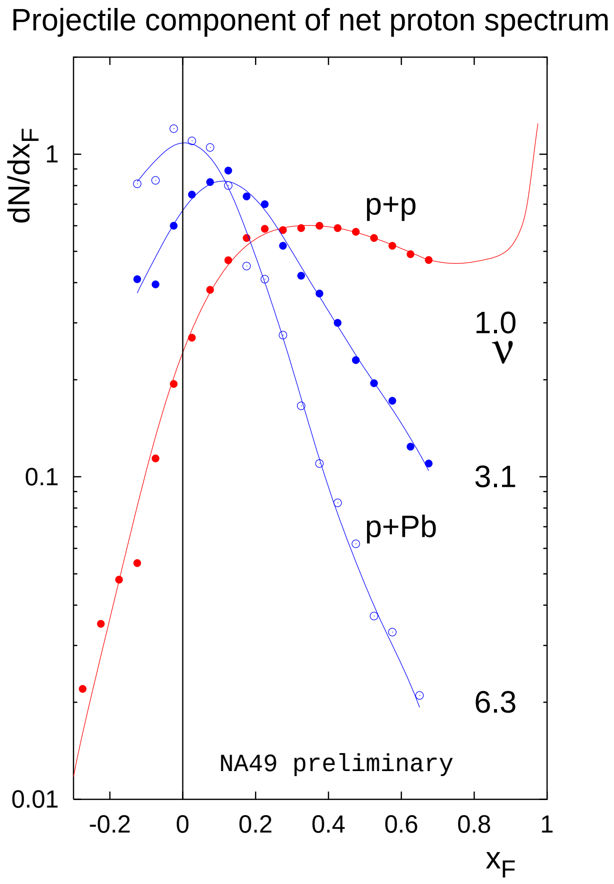


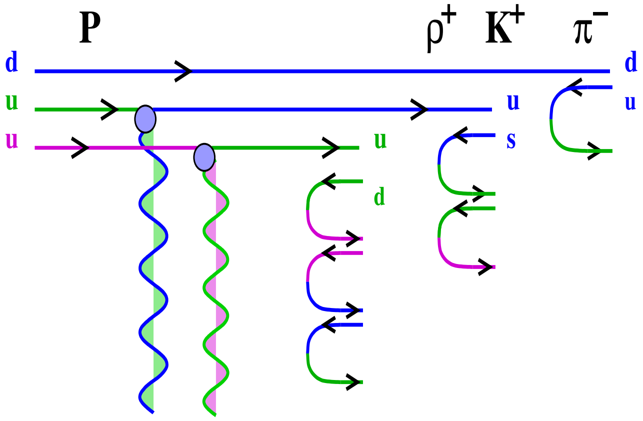
Pion projectile then breaks into a quark and an antiquark; proton dissociates into a quark and a diquark — a subsystem of two valence quarks that did not interact with the target and whose internal coherence therefore remained intact. Since two quarks in the proton are in the colour state $\bar{\mathbf{3}}$ as a whole, in both cases we have the same two colour charges ($\mathbf{3}$ and $\bar{\mathbf{3}}$) in the final state.

After the interaction, colour field builds up between the projectile and target particles separating as colour octets. Breakup of the vacuum in this increasing field produces sea $q\bar{q}$ pairs that form two Kogut–Susskind quark chains attached to the valence $\mathbf{3}$ and $\bar{\mathbf{3}}$ sources. These two quark chains is an image of a cut Pomeron describing final states in inelastic hadron scattering — the Feynman plateau.

The only difference between the pion and proton scattering is that in the latter case the valence diquark, as a rule, picks up a quark from the vacuum and forms a *leading baryon* in the final state.

The situation changes however when a nucleon experiences *multiple scattering* (be it in pA or AA environment). If the energy is high enough so that within the breathing time of the projectile more than one valence quark interacts with the target, the coherence of the valence quark system gets fully broken, and each of the three leaves behind it a personal Kogut–Susskind chain on the hadronization stage as shown on the right insert.





There is no longer a leading baryon in the fragmentation region of the incident proton. As the NA-49 study showed, the net proton spectrum $p - \bar{p}$ softens considerably with increase of the number of elementary collisions ν: the baryon quantum number "sinks" into the sea. How deep? It is not difficult to estimate using two phenomenological parameters: an average rapidity distance η_0 between successive hadronization acts in a single quark chain (inverse rapidity density of vacuum breakups), and the probability r of picking up a *diquark* (instead of a quark) from the vacuum. Then the typical rapidity distance from the projectile, at which a first baryon appears in the three-chain fragmentation can be estimated as

$$\Delta\eta \simeq \frac{\eta_0}{3\cdot r} \sim 2\text{—}3.$$

For CERN SPS energies that meant the central rapidity region.

4.4. Confinement in new environment

In the *AA* (and *pA*) environment, after the "pancakes" separate, at each impact parameter we have the field strength corresponding to $n_p \propto A^{1/3}$ "strings" per fm^2. This bring in a new, unexplored problem: How does the vacuum break up in a *stronger than usual* colour field? If those overlapping strings fragmented independently of one another, hadron abundances would have been the same as in the single inelastic scattering processes. Increase of the strange quark yield in multiple collisions may hint at deficiency of the good old picture of exchange of many non-interacting Pomerons. In a strong field, not only the overall hadron yield is proportionally larger, but the vacuum starts breaking *earlier*, at smaller distances, thus lifting off the standard massive particle production suppression (and that of strange quarks in the first place).

Scrutinizing production of strange hyperons, baryon "stopping", enhancement of the $\bar{p}/\pi^-$ ratio at moderately large transverse momenta, together with new exciting perspectives in baryon spectroscopy, offer a deep insight into the dynamics of confinement.

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