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# STRONG INTERACTION PHYSICS: FROM QUARKS TO MESONS, BARYONS AND NUCLEI*

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We summarize some of the important physics issues confronted at the NATO Advanced Research Workshop in Cracow. The topics addressed include modern challenges in understanding baryon and meson structure, hadronic interactions and hadron properties in dense matter.

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## 1. Introduction

The quest for understanding of the strong interaction presents the greatest challenge we face within the Standard Model. I would like to suggest that as the main lesson from the lectures and discussions during this Workshop we realize that the problem can only be solved if we dismantle the boundaries which so often restrict the flow of ideas. We had the pleasure to hear of progress in areas as diverse as lattice QCD, chiral perturbation theory, QCD sum-rules, nuclear many-body theory and reaction dynamics. We were able to see data from accelerators as far apart in energy as Mainz, COSY and HERA. Yet all of these diverse sources of information, some of which would traditionally be labelled particle physics, some nuclear physics and some intermediate energy physics, offer potentially vital information. Only through a synthesis of the insights offered by both traditional nuclear and traditional particle physics can we hope to fully understand the complexity and beauty of the strong interactions.

With almost fifty participants it is impossible to do justice to every contribution. I apologise in advance to those whose work could not be given

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here the attention it deserved. In order to provide a sense of coherence the issues have been grouped into just four major headings: baryon structure, meson structure, hadron–hadron interactions and finally all of the above in-medium. These topics occupy Sections 2–5 which are followed by a brief summary.

## 2. Baryon structure

The creation of the quark model, based on $\mathrm{SU}(3)_F$, was driven by the need to understand the systematics of baryon (and meson) spectroscopy. Of course, our knowledge of the baryon spectrum has steadily improved since the 60's and naive quark models have been replaced by more sophisticated treatments derived, at least in part, from QCD.

Riska reported on recent studies of the baryon spectrum which strongly favor a quark–quark interaction of the form $\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \tau_1 \cdot \tau_2$, motivated as a short-distance residue of pion exchange [1]. Certainly this interaction seems to provide a better overall description of the baryon spectrum than the traditional treatment based solely on the spin–spin interaction associated with single gluon exchange. While this is phenomenologically perfectly reasonable, from the purely theoretical point of view it is the long range pion exchange which is best under control — for example, yielding the leading non-analytic terms in a chiral expansion.

The presentations of Afnan and Speth were directly related to this long-range pionic interaction. In particular, these authors addressed the very fundamental question of which observed resonances should be viewed as predominantly three-quark states (and therefore subject to the traditional spectroscopic treatment) and which arise as a result of strong interactions in coupled meson–baryon channels. The classic case in which this issue was first seriously addressed [2] was the $\Delta(1232)$, which in the traditional Chew–Low treatment arose from strong pion–nucleon rescattering. Only within a quark model including pion couplings controlled by chiral symmetry was it possible to establish that the $\Delta(1232)$ was predominantly a three-quark state. In comparison, a similar analysis applied to the $\Lambda(1405)$ concluded that it was not a three quark state and that the $S = -1, {}^1\!/_2{}^-$, flavor singlet three-quark state which must be accommodated in quark model spectroscopy must have a mass above 1650 MeV [3] — see also Ref. [4] for recent work which reached a similar conclusion.

Speth showed an analysis of the enigmatic Roper(1440), which included coupling to the open $\pi N$ and $\pi\pi N$ channels [5, 6]. His conclusion was that this state, which has always been a puzzle as it is too low in mass (below the lowest negative parity excitation) to be a simple $2s$-excitation, is predominantly not a three-quark state. Clearly this is an extremely important conclusion and there is a great need for more systematic work of this kind — without it one cannot know which states to include in the quark model spectrum.

On a quantitative level, even if a baryon state is predominantly a three-quark state, the coupling to meson–baryon channels can induce mass shifts of 100 MeV or more. Baryon spectroscopy appears to have matured sufficiently that it is time for a unified analysis of the spectrum below (say) 2 GeV, in which both long range meson–baryon interactions (including the coupling to open channels) and quark model spectroscopy are combined.

It is vital that quark models be constrained by whatever rigorous results are available from lattice QCD. The presentation of Toki dealt with some very stimulating results from his group, in which the Abelian projection of lattice QCD provides strong support for the ideas of Dual QCD [7]. In this picture the non-perturbative QCD vacuum consists of a condensate of Dirac monopoles. It would be valuable to see a synthesis of this particular view of the QCD vacuum, within a special gauge, and the various other models in the literature which are not dependent on the choice of a particular gauge. In any case, the group has made significant progress on building phenomenological models within this framework, using Dyson–Schwinger equations to model the dynamical symmetry breaking required to understand the hadron spectrum.

Of course, understanding baryon structure involves much more than spectroscopy. One can also explore various electroweak form factors. Holstein reported on a new class of electromagnetic form factors of the nucleon — the, so called, generalised polarizabilities [8] — which can be measured in virtual Compton scattering [9]. In the particular kinematic regime where the invariant mass of the final photon and proton is below pion production threshold one is sensitive to resonance excitation without coupling to open meson–baryon channels. In the light of the preceding discussion this is clearly valuable information which should complement that obtained through direct excitation.

Unfortunately this information comes at a price. Virtual Compton scattering presents severe experimental challenges. In spite of this there are experiments proposed at MIT Bates and TJNAF. Papanicolas reported on progress at MIT/Bates (as well as on the determination of the C2/E2 amplitudes in photoproduction). Most impressive, however, was the fact that the Saclay group working at Mainz already has preliminary data of sufficient accuracy to reveal deviations from pure Bethe–Heitler scattering. We look forward to the extraction of the first generalized polarizabilities from this data.

Photon induced resonance excitation has a long history of providing important constraints on baryon wave functions. Soyeur reported on a different probe of the Roper resonance, using the $(\gamma,\omega)$ reaction. This is actively under investigation at ELSA and promises information complementary to that obtained using $\alpha - p$ scattering. In the past few years there has been a surge of interest in deep inelastic scattering (DIS) as a source of information on the **non-perturbative structure** of the nucleon (and other hadrons). Ioffe reported his recent work relating the discrepancy in the Ellis–Jaffe sum-rule to the topological susceptibility in QCD [10], using QCD sum-rules.

One of the experimental highlights of recent deep inelastic scattering work is the measurement of the $\bar{d}/\bar{u}$ asymmetry in the proton, by the E866 collaboration working at Fermilab — reported by Garvey [11]. The first, firm experimental indication of a deviation from $\bar{u} = \bar{d}$ came from the New Muon Collaboration in 1991 [12]. They established a clear deviation from the Gottfried sum-rule. This was supported by a Drell–Yan measurement by NA51, which indicated $\bar{d} > \bar{u}$ at a single value of Bjorken $x$ ($x = 0.18$) [13]. Experiment E866 followed a long series of Drell–Yan measurements specifically designed to look at the nuclear sea, with the kinematics chosen to optimise the sensitivity to the sea of the target.

Figure 1 shows a comparison between the E866 data for $\bar{d}$–$\bar{u}$ and the values extracted indirectly from the NMC data (using two standard valence quark parametrizations) [14]. The quality of the E866 data is superb, but it is clearly important to resolve the apparent discrepancy between the two experiments. As E866 was specifically designed to measure the shape of $\bar{d}$–$\bar{u}$, we concentrate on their result. In particular, we note that $\bar{d}$ exceeds $\bar{u}$ for $x$ as large as 0.25. Whether or not it then returns to zero, as the data suggests, is theoretically a crucial question. On the basis of early SLAC data [15], which hinted at $\bar{d} \neq \bar{u}$ (at the level of one standard deviation), Feynman and Field suggested that the Pauli principle might give $\bar{d} > \bar{u}$ [16]. Quantitative support for this idea first came from the bag model calculations of Signal and Thomas in 1988 [17]. Somewhat earlier it had already been realized that the pion cloud of the nucleon, arising from dynamical chiral symmetry breaking in QCD, would also give $\bar{d} > \bar{u}$ [18]. It turns out to be very difficult to make the difference go below zero on the basis of any of these models and it is therefore vital to extend the E866 measurements to higher $x$. In his summary, Garvey suggested a picture of the nucleon in which the $N\pi$ and $\Delta\pi$ components of its wave function have probabilities of order 20% and 10%, respectively [19]. These are very much consistent with the expectations within the cloudy bag model.

In a closely related talk, Nikolaev explained that the pion cloud of the nucleon could not be ignored even in diffactive scattering at HERA at very small $x$. Indeed, he showed that one could use data in the target fragmentation region at $x \sim 10^{-3}$–$10^{-4}$ to extract information on the *pion* structure function [20].

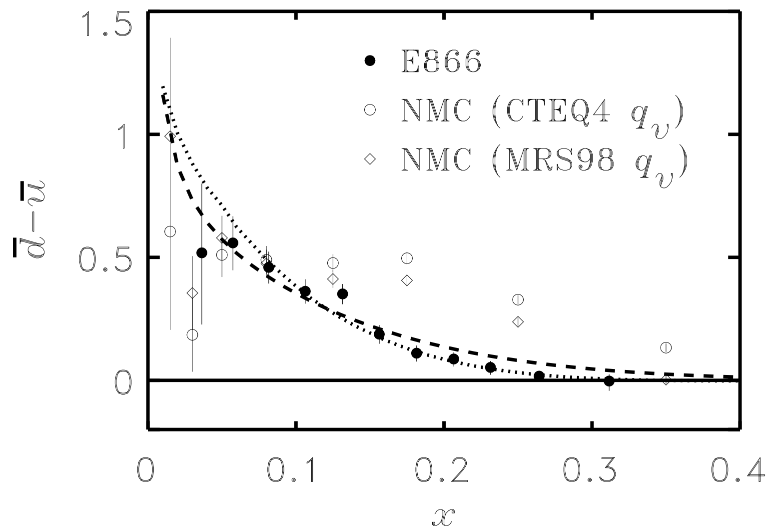


Fig. 1. Comparison of $\bar{d}$–$\bar{u}$ from the E866 experiment with the values extracted from the NMC measurement of the proton–neutron structure function difference, using the CTEQ4 and MRS98 parameterizations for the valence quark distributions. Also shown are the parameterizations of $\bar{d}$–$\bar{u}$ from CTEQ4 (dashed) and MRS98 (dotted) — from [14].

With hyperon beams developed at Fermilab in order to make magnetic moment measurements it is no longer impossible to imagine using Drell–Yan measurements to get information on their parton distributions. Henley explained some of the major surprises one might hope to find in such measurements [21]. For example, the pion cloud of the $\Sigma^+$ would lead to an even greater excess of $\bar{d}/\bar{u}$ than in the proton. In addition, one can anticipate violations of SU(3) symmetry, in comparing $\Sigma^+$ and $p$ parton distributions, as large as 100%. This would be a major shock for many who have come to rely on SU(3) symmetry.

### 3. Meson structure

Recent progress in the study of heavy quarkonia was reviewed by Zalewski. Because of the large mass of the $t$-quark, $t$–$\bar{t}$ bound states are unstable to decay to $W^+$–$W^-$ and therefore one is restricted to the $b$–$\bar{b}$ and $c$–$\bar{c}$ systems as sources of information on QCD with heavy quarks. At present, the predictions of QCD sum-rules and lattice QCD are limited to errors of 10–20 MeV, many orders of magnitude outside the experimental precision. Thus one is left with the Schrödinger equation and QCD-motivated potential models for detailed spectroscopic analysis [22]. One notable feature of the spectra, which any theoretical treatment must reproduce, is that the level spacing is independent of quark mass.

Turning to mesons composed of light quarks, Johnson reported a recent analysis of the light-cone wave function of the pion [23]. By using light-cone sum-rules he was able to constrain $\phi_\pi(x = 0.3)$ to 1.0 $\pm$0.2. Combined with other constraints, this strongly suggests that the wave function is quite smooth — consistent with the leading asymptotic form, rather than the oscillatory form favoured by some earlier analyses.

## 4. Hadronic interactions

Given the body of work produced in Jülich concerning hadron–hadron scattering, it was not surprising that this was the topic of numerous presentations. Durso reported recent studies of meson–meson scattering in the region around 1 GeV, where it is important to distinguish "molecular" states from $q$–$\bar{q}$ states. Meissner discussed the essential ingredients for building an effective nucleon–nucleon interaction within the framework of chiral perturbation theory [24].

Colour transparency is one of the more spectacular predictions of perturbative QCD. Even though a similar phenomenon arises and has been confirmed in QED, it is crucial to test it within strongly interacting systems. The essential idea is that in a hard collision, such as $(e, e'p)$ at very high momentum transfer, one would select a component of the nucleon wave function with a very small spatial extension. Yazaki reported recent work in which the on-set of colour transparency was modelled microscopically [25].

Another topic which has a checkered history, but goes to the heart of our understanding of QCD, is the search for dibaryons. As with hybrids and glueballs in the meson sector, it is crucial to establish whether or not non-perturbative QCD supports these exotic objects. Recent promising hints of the existence of a $d'$ state below 2200 MeV, which is being studied at CELSIUS, were reported by Wagner [26]. Contrary to initial indications of $I = 2$, it seems this state must have $I = 0$ to be consistent with all the present data. Clearly the experimental evidence for this state must be clarified quickly.

New experimental facilities should open new windows for us. We have previously seen the power of pionic atoms, notably the $\pi^- p$ and $\pi^- d$ atoms measured at PSI, to finally pin down the pion nucleon scattering lengths. At DAΦNE there are ambitious plans to produce comparable accuracy for the $K^- d$ atomic shift. This and other initiatives were reviewed by Petrascu. While on the topic strangeness, I should note that recent work on hypernuclei was reported by Bartke, Cieply and Dabrowski. Lack of space forces me to refer the interested reader to their individual contributions. Finally, I should also refer to the contribution of Drożdż and Wójcik on the isoscalar giant dipole resonance, which indicated that current experimental estimates most likely underestimate the centroid energy.

Baryon–baryon scattering was discussed by Nomokonov and Banerjee. The latter was concerned with the effect on the in-medium $N$–$N$ force of the strong, scalar mean field which seems an inevitable consequence of the Lorentz scalar nature of the intermediate range $N$–$N$ force [27]. The effect of replacing $m$ by $m*$ in the two-pion-exchange force has a dramatic effect on the tensor force in-medium and hence on the saturation properties of nuclear matter. This particular study is just one example of what should be a central concern for strong interaction physics. That is, why should one expect hadron masses and coupling constants not to change in hadronic medium? This brings us naturally to our last topic.

## 5. Hadron properties in matter

One of the central challenges for strong interaction physics is to understand the properties of matter at high density. On rather general grounds one expects a phase transition to a chirally restored phase above a critical density, $\rho_c$, or temperature, $T_c$. While the latter can be investigated on the lattice, the former presents formidable problems. Initial studies within the Dyson–Schwinger formalism suggest a possible first-order phase transition at $\rho_c \sim 3 \div 4\rho_0$ [28], but much more work is needed.

Enormous attention has been focused on this problem by the measurement of a large excess of $e^+$–$e^-$ pairs with invariant mass in the region 400–600 MeV in relativistic heavy ion collisions [29]. Simulations of these collisions suggest that one attains baryon densities of $2 \div 3\rho_0$ for significant time, and the data was initially interpreted in terms of a decrease of the mass of the $\rho$ meson in medium by several hundred MeV [30] — as predicted by many theoretical models. Many of the papers presented at the meeting dealt with issues raised by these results — especially those of Birse, Brown, M. Ericson, Krewald, Rho and Wambach.

Rather than attempting to summarise everything which was said, we focus on a few key issues, beginning with the question of whether chiral restoration is directly related to the average value of the quark condensate in matter. Following the arguments of Birse and Wambach, in particular, this cannot be so [31]. For example, the expectation value of $\bar{q}q$ in the pion, $\langle\bar{q}q\rangle_\pi$, is of order 10 (*c.f.* $\langle\bar{q}q\rangle_N \sim 7$). Thus a single pion moving freely in box of size 3–5 fm$^3$ is sufficient to drive $\langle\bar{q}q\rangle$ to zero. On the other hand, it is apparent that this is in no sense a region of space in which chiral symmetry has been restored. Yet the model-independent formula for $\langle\bar{q}q\rangle$ in a medium with nucleon density $\rho_N$:

$$\frac{\langle \bar{q}q\rangle_\rho}{\langle \bar{q}q\rangle_0} = 1 - \frac{\sigma_{\pi N}\rho_N}{f_\pi^2 m_\pi^2}, \tag{1}$$

has exactly the same origin.

A second question relates to the change in the effective masses of hadrons in medium, namely whether they are linked to the variation of $\langle \bar{q}q\rangle_\rho$. Birse explained that for the specific case of the nucleon this cannot be the case, as the chiral behaviour of the two quantities is necessarily different. Clearly if the result is untrue for the nucleon it cannot be a general result.

Over the past year the theoretical simulations of $e^+e^-$ production, and particularly of the response of the medium in the $\rho$-meson channel, have become much more sophisticated. Through the work of Klingl *et al.* and Friman [32] it has become apparent that the $\rho$ meson becomes extremely broad in-medium. It certainly cannot be represented by a Breit–Wigner distribution and, to the extent that one can define a mass, the dispersive effect of the low mass absorptive channels probably undo most of the attraction expected in mean-field theory. There are also numerous baryon resonances below 1800 MeV which couple strongly to $\rho N$, although the couplings are often poorly known. All of this makes the initial interpretations of the data as a simple consequence of the lowering of the $\rho$ mass in medium appear, at least at first glance, a little naive. On the other hand, Brown argued that these two views may be simply different perspectives on the same physics [33].

One very positive message to come out of these studies concerns the $\omega$ meson. Unlike the $\rho$, it seems that when one constrains the theory using known free nucleon cross sections, the $\omega$ remains fairly narrow — and certainly recognisable as a Breit–Wigner resonance. There is general agreement that the in-medium width should be of order 30–40 MeV at $\rho_0$. As a consequence, the earlier estimates of a decrease of the $\rho$ mass in-medium should be more or less correct for the $\omega$.

These considerations make the recently proposed GSI experiments to produce an $\omega$ bound to an atomic nucleus, using recoiless production in the $(d,^3\text{He})$ reaction [34], a "gold-plated" test of decreasing meson masses in medium. For example, within a relativistic mean-field theory, such as QMC, a $q$–$\bar{q}$ meson like the $\omega$, feels no vector potential (this has opposite signs for $q$ and $\bar{q}$) and hence there is only attraction from the scalar field. Thus, for example, the $^{11}\text{B}_\omega$ mesic-nucleus (in the 1$s$-state) is expected to be bound by 80 MeV [34, 35]. It is vital to our understanding of dense nuclear matter to check this prediction as soon as possible.

## 6. Concluding remarks

As I trust this brief summary has made clear, this workshop was an outstanding scientific success. The range of energies and momenta at which experiments can teach us about the strong interaction was seen to run all the way from Mainz through COSY and CELSIUS to CERN and HERA. There are only mental barriers between nuclear and particle physics when it comes to the strong interaction and this workshop helped remove many of them.

One of the key speakers was Josef Speth who in May this year has celebrated his 60th birthday. His own work has always been closely linked to state of the art experiments and has also covered the full range from giant resonance studies to diffractive scattering at HERA. Keeping in mind his significant contribution to such a diversity of subjects I find this workshop an appropriate opportunity to express my own best wishes to Josef.

Finally, no scientific meeting can succeed without excellent organisation. The local organizers are to be congratulated not only on the beautiful city which they chose as the site of the meeting but also for their superb organisational skills.

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