Meson-Nucleon Physics: Past, Present and Future

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Abstract

We will present some thoughts on the following topics:
1. Major highlights in the history of strong interactions such as isospin, the pion, SU(3), quarks, the color degree of freedom, QCD.
2. Topics of high current interest such as quark confinement, the origin of mass, the search for the gluon degrees of freedom, chiral symmetry, flavor symmetry, regularities in the properties of the light-baryon families (parity doublets, clusters) decay patterns, hadronization, chiral restoration, effective Lagrangians and their degrees of freedom.
3. The input parameters for QCD and for effective models.
4. Hadron physics as a necessary aspect of precision tests of the Standard Model and of the Search for New Physics.

1 Introduction

Some of the basic questions that have been discussed at MENU-IX, our highly successful symposium which we are concluding this afternoon, are:

“Where are we in the study of Hadron Physics?”
“What has been accomplished recently in this field?”
“Which are the most interesting problems?”

I will endeavor to address these questions. In preparing this report I have been aided by the White Papers of two recent workshops, “Key Issues in Hadron Physics” [1], and the DNP meeting on Hadronic Physics [2], and two reports on the subject by James Bjorken [3,4].

We are at a momentous time in the short history of Hadronic Physics. There is a growing appreciation for the intellectual challenges presented by QCD in the non-perturbative regime, for the crucial role which it plays in precision tests of the Standard Model (SM), and in the search for New Physics beyond the SM. There is also a growing concern about the lack of a major laboratory for hadron physics with secondary beams. The practitioners of Hadron Physics are only loosely organized and they are seriously underfunded.

Our field of physics may be defined as follows [3]: “Hadron Physics is the physics of the hadronic structures and the strong - interacting vacuum”. It is a subfield of quantum chromodynamics. QCD at short distance, \( d \sim < 0.1 \text{fm} \), is a perturbative theory of pointlike quarks and gluons. Its validity in this regime is well established, e.g. the strong coupling constant \( \alpha_s \) has been determined in more than a dozen different ways [5] to an accuracy of a few percent; we also point to the very successful results coming from \( Z \) and \( W \) studies. At large distances such as \( > 2 \text{ fm} \), Hadron Physics is a theory of pions and nucleons and their strange counterparts. It is characterized by the spontaneous symmetry breaking of the approximate chiral symmetry of QCD. At intermediate distance occur a rich variety of phenomena including hadron resonances, Regge trajectories, soft diffractions and hadronization. Except for a few simple lattice - gauge calculations, the role of QCD is very limited;
it mainly justifies the use of chiral symmetry, chiral perturbation theory, the $N_c^{-1}$ expansion, and so forth. The real need for calculations of practical quantities is at intermediate energy. The mass of the proton and neutron have been measured to an accuracy of a few parts in $10^7$. The best result of a recent lattice-gauge calculation [6] for the proton mass is $878 \pm 25\,\text{MeV}$. The hadronic corrections are now the main limitation to such interesting Standard-Model tests as the new muon anomalous magnetic moment or $g-2$ experiment [7], the measurement of $CP$ violation in the $2\pi^0$ and $\pi^+\pi^-$ decay of $K_L/K_S$ (the so called $\epsilon'/\epsilon$ experiment) [8,9], the unitarity test of the CKM matrix [10] and precision determinations of $\alpha_s$. At this MENU-IX symposium much of the full spectrum of non-perturbative QCD has been under the microscope.

2 Highlights from the Rich History of Hadron Physics

It is altogether appropriate to have a short recitation of major highlights of our field. They have led to the current models and effective Lagrangians of strong interaction physics, in particular, they led to the creation of our major theory, Quantum Chromodynamics, QCD.

a) One of the oldest concepts in nuclear physics is that of isospin. Its role in the development of the theory of strong interactions is hard to overstate. Isospin was an early attempt to formulate the universality of the strong interaction at a time when only the neutron and proton had been identified. Isospin paved the way for Yang-Mills fields and it helped to usher non-abelian theory into strong interaction physics. Isospin was one of the earliest cases of a broken symmetry. Now, at the beginning of the 21st century, we know the origin of isospin breaking: it is the difference in the masses and the electric charges of the up and down quarks. The study of isospin breaking occurring in the baryons and mesons of different spin and parity continues to be of great importance. It is the only way to determine the up-down quark mass difference in various hadronic environments [11]. Isospin violation leads to meson mixing for instance $\pi^0 - \eta$ and $\rho - \omega$, also to baryon mixing such as $\Lambda - \Sigma^0$. The modern perspective is that isospin is a subgroup of a larger symmetry, the flavor symmetry of massless QCD.

b) The pion has had and still has a major impact on strong interaction physics, especially on phenomenological models for nucleon-nucleon scattering. The current viewpoint is that the pion is the lightest of the 3 Goldstone bosons that are associated with the spontaneous breaking of chiral symmetry of a massless QCD.

c) SU(3) symmetry was born out of the wealth of great baryon and meson spectroscopic data. Measurements of SU(3) breaking, for instance the mass difference of the baryon octet and decuplet ground states, are the sole way for obtaining the $s-d$ quark-mass difference. SU(3) breaking is responsible for multiplet impurity such as due to $\eta - \eta'$ mixing. SU(3) is a special subgroup of the (broken) flavor symmetry of QCD.

d) Perhaps the most astonishing discovery, which was prompted by abundant new spectroscopic data, was the quark being the ultimate hadronic building block. The quark has several spectacular properties such as a non-integral electric charge and baryon number. A single, free quark cannot be observed because it is captive to the asymptotic freedom condition of QCD.

e) The latest “quantum number” to be discovered is the color charge. Again it was the well established details of baryon spectroscopy, in this case the features of the $\Delta^{++} (1232)$ resonance, together with our faith in the validity of Fermi-Dirac statistics which brought this about.

f) QCD is now considered to be the theory of all strong interactions. It has many virtues but its major shortcoming is that it cannot be solved in the non-perturbative regime. Thus, it is helpless when one needs to calculate detailed properties of the proton, neutron and complex nuclei.
3 High-Profile Subjects

Problems and topics in hadron physics which are drawing considerable attention these days include the following.

a) What is the mechanism that is responsible for the confinement of the quarks? So far no one has succeeded in deriving the confinement conditions from QCD. This is a major theoretical challenge. Help could be provided by the determination of the regularities that characterize the confined quark systems. Parity doublets dominate the $N^*$ spectra in the mass range 1600-2300 MeV [12]. Do they occur also for heavier masses? Parity doublets are also seen in in the $\Delta, \Lambda, \Sigma$ families. There is no evidence for parity doublets among the three light-quark meson families. Baryons above a certain mass appear to come in clusters as well. There is currently insufficient data to see if clusters extend to the $N^*$ mass region above 2300 MeV.

An interesting analogy can be made to the confinement of the electron in the hydrogen atom. In this case confinement does not follow from Maxwell’s equations which govern the electromagnetic interactions. Rather, confinement in the case of the hydrogen atom is the consequence of the quantization conditions from quantum mechanics. The major breakthrough to solving this historic confinement puzzle came from the interpretation of the experimentally discovered regularities in the frequencies of the spectral lines of the hydrogen atom known as the Rydberg formula. Maybe the spectra of the excited states of the light baryons could play the same role in helping to understand quark confinement.

b) What is the origin of the mass of the proton? Over 99% of the rest mass of everyone in this room and elsewhere is due to hadronic matter in the form of free and bound protons and neutrons. The proton consists of two up and one down quark for the grand total of 18 MeV and similarly for the neutron. Where does the remaining 98% come from? The missing piece is called the quark condensate, it comes from the interaction of the quarks with the vacuum. This brings up the question: “What really is the vacuum?”

c) A fascinating subject is the proposed existence of new forms of matter: hybrids, glueballs, pentaquarks, bound states of mesons and baryons, molecular-type states, etc. There is a lot of speculation about this subject. Our main theory is QCD, the theory of interacting quarks and gluons, so we might expect that confined states have quark and gluon degrees of freedom. There is no example of a certified hybrid baryon, not even a single good candidate [12]. The established baryons all obey SU(3) flavor symmetry which implies that they are $qqq$ states. There are a few candidates for a glueball and hybrid in the meson sector. Since there is no free meson target available a unique determination of the spin and parity of a candidate is hard to make and so far no polarized target data, which is very helpful, is available.

The many successes of the simple quark model (QM) are somewhat of a mystery. In the QM all baryons are $qqq$ states and they can be classified in SU(3) multiplets. This implies one antisymmetric singlet state and two mixed octets with the same $J^P$; plus one related totally symmetric decuplet. All mesons are grouped in nonets with the same $J^P$; each one consists of one singlet and 8 octet states. The QM accounts for the main features, though not the details of the masses, widths, decay branching rations, magnetic dipole moments and strength of electromagnetic couplings of all established baryons and mesons. There is as yet no compelling evidence for a gluon degree of freedom. This leads us to the important question: “Where in hadron physics at low energy is the glue?”

Recently, a new large facility was put into operation for the important goal of discovering and subsequently determining the basic properties of the quark-gluon plasma. This new state of matter is high on the list of interests of many a nuclear theorist. It is important also to make the necessary investments to enable the measurements of the properties of hadronic matter at standard density...
and temperature. As a minimum we need to measure the mass, width, and branching ratios of the excited states of the 6 light baryon and 3 meson families, in particular of the $\Sigma^*$, $\Xi^*$ and $\Omega^*$ states below 4 GeV.

d) Broken symmetries play a major role in the theory of the strong interactions. We think here of chiral symmetry, flavor symmetry with its sub areas of isospin and SU(3) symmetry and the U(1) symmetry. There has been considerable speculation on the occurrence of chiral restoration at intermediate energy [13] and some on U(1) restoration. Do there exist other symmetries which play a role in the structure of the baryons at ordinary density due to a diquark substructure of the baryons [14]? Are there other clues besides the occurrence of parity doublets? The parity doublets are seen in the baryon spectra above a certain mass which is 1600 MeV for the $N^*$ family. By contrast they do not occur for the meson families. We recall the occurrence of the extraordinary S-wave $\eta$ decays of the low lying $J^P = \frac{1}{2}^-$ octet baryons, the $N(1535)$, $\Lambda(1670)$ and $\Sigma(1750)$. It is of interest to see if this special $\eta$-decay feature occurs in the $\Xi$ family as well. The above set of 3 states suggests the existence of a $\Xi$ state with $J^P = \frac{1}{2}^-$ and a mass of approximately 1875 MeV.

The first excited state in the $N^*$ family is the $N(1440)\frac{1}{2}^+$ and in the $\Lambda^*$ it is the $\Lambda(1600)\frac{1}{2}^+$. They have the same spin/parity as the family’s ground state and they are relatively broad. The same holds for the $\Delta(1600)\frac{3}{2}^+$, which is a decuplet state. We speculate that this phenomenon applies to the other baryon families as well and urge a search for a $\Sigma^*\frac{1}{2}^+$ octet state of mass $\sim 1680$ MeV as well as a $\Xi^*\frac{1}{2}^+$ octet state around 1800 MeV. Furthermore we anticipate a $\Sigma^*\frac{3}{2}^+$ decuplet state of mass $\sim 1770$ MeV, a $\Xi^*\frac{3}{2}^+$ decuplet state around $\sim 1900$ MeV and a $\Omega^*\frac{3}{2}^+$ at $\sim 2050$ MeV. All are expected to be relatively broad states.

e) Creation of matter out of energy is another important subject. The Einstein condition:

$$E^2 = p^2c^2 + m^2c^4$$

which is incorporated in QCD does not say anything about changing energy into $q\bar{q}$ pairs and gluons. It would be quite useful to understand how the features of mass creation such as the simple reaction $\pi^-p \rightarrow \pi^0\pi^0n$ come out of QCD. Chiral perturbation theory has been very successful in giving a detailed account of threshold $\pi^0$ photoproduction. The next step is the threshold production of the other two Goldstone bosons, the $K$ and $\eta$. The creation of new particles at low energy is related to a process called hadronization in high energy physics. This is the creation of hadrons by a high energy quark or gluon in jet-type events.

It is desirable to make a systematic study of meson and baryon-antibaryon production using beams of $\pi^\pm$, $K^\pm$, $p$, $\bar{p}$, $e^-$ and $\gamma$.

f) The development of effective models for the making of practical calculations of hadron-hadron scattering, resonance decay, and particle production is a mandatory aspect of our field. Which are the most suitable degrees of freedom to use? How complementary are the different models and how well does each model implement the symmetries of QCD? There is a large variety of strong interaction models to choose from: chiral perturbation theory, the $N^*_c^{-1}$ expansion, Skyrmions, meson exchange, nuclear potentials, vector meson dominance, bag models, and so forth.

4 Input parameters to QCD and to effective Lagrangians.

QCD needs 3 types of input:

1. $\Lambda_{QCD}$, the fundamental strength scale; one can also choose the running coupling constant $\alpha_s$.

The experimental determination of this input is done using high energy experiments that operate in the perturbative regime of QCD. The present precision achieved is several percent. To go much beyond that one must first learn how to make the hadronic corrections which belong in the domain of non-perturbative QCD. The hadronic corrections are made using a suitable effective Lagrangian.
Efforts are underway to use large computers and many new algorithms for lattice-gauge calculations; they still have a long way to go before becoming practical.

2. The masses of the six quarks. Since there are no free quarks the mass determinations are a joint endeavor of theory and experiment. What we know best is the ratio of quark mass differences.

3. The $\theta$ parameter of QCD. The upper limit on the electric dipole moment of the neutron provides an upper bound $\theta \leq 2 \times 10^{-10}$. It does not play a significant role in QCD at present.

The effective models needed for calculating strong interaction results in the non-perturbative regime of QCD require a large set of inputs. Many of these are discussed in detail at our MENU symposium and related workshops and conferences such as MESON 2001, Baryon 2001, NSTAR 2001 and PANIC. We mention a few inputs of the many needed:

- a) The meson decay constants: $F_\pi, F_\eta, F_K$, etc.
- b) The meson-nucleon coupling constants: $G_{\pi NN}, G_{\eta NN}$, etc.
- c) The meson-meson scattering lengths: $a_{\pi\pi}, a_{\eta\pi}$, etc.
- d) Various mixing angles such as the SU(3) singlet-octet mixing angles for the pseudoscalar and vector mesons etc.
- e) Hadron form factors for the proton, neutron and the light mesons.

5 Goals of Hadron Physics.

The meeting entitled “Key Issues in Hadronic Physics held in Duck, NC on Nov. 6–9 2001 provided the following useful formulation of the overall objectives of our field [1].

The primary goals of hadronic physics are to determine the relevant degrees of freedom that govern hadronic phenomena at all scales, to establish the connection of these degrees of freedom to the parameters and fundamental fields of QCD, and to use our understanding of QCD to quantitatively describe a wide array of hadronic phenomena, ranging from terrestrial nuclear physics to the behavior of matter in the early universe. We list below some very specific goals for the near future in our area.

1. The determination of the ratio of the difference and sum of the up and down current-quark masses,

$$R = \frac{m_d - m_u}{m_d + m_u}.$$ 

The ratio eliminates many of the conceptual problems arising from the fact that free quarks have never been observed, despite much searching, and are not expected to be seen as free particles. Experimentally, a nice, clean way to investigate the up-down quark mass difference is by a measurement of the absolute decay rate for the decay $\eta \to 3\pi$. Another good way is by an accurate measurement of the ratio

$$\Gamma(\eta \to \pi^+\pi^-\pi^0)/\Gamma(\eta \to 3\pi^0).$$

Other ways include 2 special ratios of meson decay modes,

$$\Gamma(\eta' \to \eta 2\pi^0)/\Gamma(\eta' \to 3\pi^0),$$

and

$$\Gamma(\psi' \to \eta\psi)/\Gamma(\psi' \to \pi^0\psi).$$
2. The determination of the ratio of quark-masses

\[ \frac{m_s - m_u}{m_d + m_u} \]

This requires careful measurements of SU(3) flavor breaking such as probed in the Gell-Mann-Okubo octet and Gell-Mann decuplet mass relations. This should be done for different spin/parity baryons.

3. It would be nice to have a full QCD calculation of the neutron-proton mass difference which is known experimentally to an accuracy of a few parts in \(10^7\).

4. It is time that we measured the magnetic dipole moment of other particles than the ground state octet and decuplet baryons.

5. The determination of \(\pi^0 - \eta\) mixing in different nuclear environments.

6. Accurate measurements of the inputs to the various effective theories such as the meson-nucleon coupling constants, the meson-meson scattering lengths, the decay constants, and so forth.

6 **The importance of Hadron Physics in testing the Standard Model.**

The Standard Model (SM) of electroweak interactions has been subjected to many experimental tests and passed them all with flying colors. Yet, the SM is called a model and not a theory. It suffers from having 17 input parameters which must be extracted from many experiments and this does not include 3 or 6 possible neutrino masses and several mixing angles. The SM does not explain why there are three families of fundamental fermions; parity violation is inserted into the theory by choosing a left-handed doublet and a right-handed singlet of fermions in the input structure; the nature of the spontaneous symmetry breaking that generates the mass of the elementary fermions is unknown; these are just some of the shortcomings of the SM. New ideas, such as supersymmetry, are going beyond the classical SM. Experiments which explore the limits of the SM, euphemistically called “Searches for New Physics”, are limited by the insufficiently known hadronic corrections. Since there is no analytic solution to QCD in the vast non-perturbative domain, one is forced to rely on effective Lagrangians and on models. Below are a few examples of recent precision measurements in the frontier of the SM, they involve real as well as virtual hadrons. The usefulness of the experiments is limited mainly by the uncertainties in the hadronic corrections.

1. The latest measurement of \(g - 2\), the anomalous g-value of the muon magnetic moment, made at BNL, is of sufficient precision to be sensitive to “New Physics” [7]. \(g - 2\) calculations have 3 components: a. the pure QED part, which is known to 0.025 ppm; b. the electroweak part known to 0.03 ppm; c. the hadronic corrections, which have an uncertainty of 0.57 ppm, originate in the higher order electromagnetic interactions of leptons arising from virtual hadronic contributions to the photon propagator. An important contribution comes from light-light scattering where the error is due mainly to the poorly known form factors of the intermediate \(\pi, \eta\) and \(\eta'\). This can be improved if new measurements are made of single and particularly of double Dalitz decays such as \(\eta \to e^+e^-\mu^+\mu^-\).

2. An important investigation into the nature of \(CP\)-violation is the determination of the ratio of the direct to indirect \(CP\)- violation parameters, \(c \to c'\) [8,9]. This is done by measuring the ratio of \(K^0\) and \(K^0\) decay into \(\pi^+\pi^-\) and \(\pi^0\pi^0\) at the level \(10^{-3}\) to \(10^{-4}\). It is immediately clear that at this level the hadronic corrections originating in the \(s - d\) quark transition and the isospin breaking due to the \(u - d\) quark mass difference are major, they greatly cloud the interpretation of the precision measurements.

3. \(CP\) violation has finally been seen outside the \(K^0 - \bar{K}^0\) system namely in \(B\) decays at the \(B/\bar{B}\) and Belle storage [15,16] rings. The data are subject to similar type corrections as in \(K\)-decays.
4. The Standard Model requires that the Kobayashi-Maskawa-Cabbibo (CKM) matrix is a unitary matrix. This has not been verified to any desirable precision. The CKM matrix provides a test in which supersymmetry could show up before the LHC turns on. This test requires only accurate values for $V_{ud}$ and $V_{us}$; $V_{ub}$ is very small and is known well enough for the purpose. $V_{ud}$ is being measured in super-allowed beta decays, also in neutron decay. $V_{us}$ must be obtained from a precision measurement of the decay rate and spectrum of $K_{e3}$ decay, $K^+ \rightarrow \pi^0 e^+ v$. The limits are due to the uncertainties in the handling of SU(3) breaking and isospin violation, if the latter is a surprise it is due to $\pi^0 - \eta$ mixing in the final state.

5. Another area where the hadronic corrections limit the accuracy of the results is the determination of the input parameters to QCD and the SM. The success of perturbative QCD may be illustrated compactly by the internal agreement on the average value of the strong coupling parameter $\alpha_s$ obtained in 12 different ways [5]. The average value quoted [5] is $\alpha_s(M_Z) = 0.1181 \pm 0.002$. To do much better one needs to know the masses of the quarks for which one depends on non-perturbative QCD!

Our conclusion is that major advances in the frontier of particle and nuclear physics depend on the advances that are being made in the physics of the non-perturbative sector.

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