Hadron Physics: Some Perspectives

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Abstract. Hadron phenomenology is a long standing research field in Mexico. In this article I present a short overview of the phenomena and their relevance. Special attention is paid to topics in which I have being involved. The perspective is intended to show to the freshman the still open possibilities to explore, rather than a historical one.

1. Introduction
What is hadron phenomenology? It would be the first question to ask, and the corresponding answer is so broad that it will be glimpsed along this article. I will begin with a description of some aspects of hadrons that are under study in Mexico as well as open possibilities of research. Then I will concentrate on more specific problems in which I have being involved, pointing out how interdisciplinary hadron physics can be. Let’s start by stating what a hadron is. The most fundamental particles we know of are the quarks and leptons. While leptons are interesting on their own and can be individually tested, quarks are not found individually but in collective groups. Such groups, are able to ensemble thanks to the strong interaction, which is carried by the gluons. Restrictions to the groups formation are summarized in the requirement of both color neutrality and integer global electric charge, irrespective of the numbers of members in such collective. Those are the hadrons. Groups of two quarks are called mesons and groups of three are baryons. Less common are the tetra-quark and penta-quark hadrons.

The variety of phenomena that hadrons can undergo is huge, just let us mention for example the following:

• Hadrons are relevant at the core of the stars. There, it is possible that they form condensates of pions, kaons (mesons) and even a superfluidity phase of quarks. For such processes it is important to understand the medium effects, namely density, magnetic fields and temperature.

• Hadrons appear in most of the colliders as the primary particles, which are accelerated and then collided producing new hadrons or new states, as expected to be the case at LHC (Large Hadron Collider) and RHIC (Relativistic Heavy Ion Collider). Using the flavor name of their constituents they take different names, for example, we have charm physics and B physics, and basically the main objective is to explain their behavior and properties.

• Kaons (mesons with at least a strange quark inside) were the hadrons who first revealed the violation of the CP symmetry in nature and its observation in the B system (mesons with at least a bottom quark inside) would sign the new directions of the SM.
• Observations of scalar mesons (states with quantum numbers $J^P = 0^+$) which do not naturally fit within the quark model require a new understanding of the role of the strong interaction to ensemble quarks in clusters of 4 quarks. Evidence has also been found of groups of 5 quarks, the so called pentaquarks states, although it remains controversial.

• The question of how the quarks are distributed inside the hadron is basically approached by the experimental extraction of the so called parton distribution function, while the theoretical counterpart offers a poorly answer so far.

• Hadrons are ultimately the ones who will tell us the relation between the quarks weak eigenstates and the physical ones. This is represented by the so called CKM matrix and it is far from being completely studied.

• Phenomena where the flavor of a hadron is changed through a neutral current (Flavor changing neutral currents, FCNC) is absent experimentally and it puts strong restrictions to possible extensions of the standard model.

• Vector mesons (hadrons with quantum numbers $J^P = 1^-$) and in general hadronic resonances are the kind of states that still offer challenges in particle physics. Although their quark composite nature in general fits within the quark model of the strong interaction, experimental difficulties are faced when their properties are tried to be measured. In particular, electromagnetic multipoles such as the Magnetic dipole moment (MDM) and the electric quadrupole moment have not been determined [1]. The lack of a reliable tool to handle QCD in the non-perturbative regime makes the predictions of their properties to rely phenomenological models, and then many models [2] are waiting to be tested.

The hadron community is at the interplay of nuclear theory and high energy physics phenomenology. Thus it is common to see articles published, for example, in journals like Physical Review C, Physical Review D or Journal of Physics G: Nuclear and Particle Physics. One source of information is provided by Los Alamos data base under the fields nucl-th and hep-ph (http://arxiv.org).

In the following I will focus on specific research on hadron properties, on which I have being particularly involved.

2. Radiative processes: soft photon theorems

Let us make some general remarks on radiative amplitudes. They turn out to be very useful when studying hadrons. Consider the radiative decay amplitude for $i \rightarrow f + \gamma$. It can be expressed as a power expansion in the photon energy $\omega$:

$$M = \frac{A}{\omega} + B\omega^0 + C\omega + \cdots$$

The photon knows about the electromagnetic structure of its source, then the multipole expansion must be reflected in the radiation amplitude, in fact, the electric charges contribute at $O(\omega^{-1})$ (first term) while the MDM enters at $O(\omega^0)$ (second term). Low’s Theorem [3] guarantees that the first two terms are model-independent in the sense that they only depend on the non-radiative decay amplitude and the multipoles involved. The terms of higher order in $\omega$ involve higher order electromagnetic multipoles and model-dependent contributions (typically reflected by different intermediate states). The squared amplitude, after summation over polarizations is:

$$\sum_{\text{pols } i,f} |M|^2 = \frac{\alpha_2}{\omega^2} + \alpha_0 \omega^0 + O(\omega) ,$$

The Burnett-Kroll’s theorem [4] states that the interference of the first and second terms in the amplitude expansion, in powers of the photon energy $\omega$, after sum over polarizations is null,
namely interferences of $O(\omega^{-1})$. Besides the electric charge form factor, which is fixed by electric charge conservation, no *ab initio* prescription exists for the electromagnetic form factors of non elementary particles like the hadrons.

3. Vector Mesons Magnetic Dipole Moment

How can we measure the MDM of vector mesons? We have pointed out to radiative decays as the most promising scenarios [5]. The main idea is that the photon emission off the vector mesons carries valuable information on its electromagnetic structure and then some observables could show important dependence on such parameter. At the amplitude level the leading contribution is the electric charge radiation and the MDM radiation contribution. It turns out that they contribute in different kinematical regions of the photon energy spectrum, opening a possibility to extract the MDM. However, it is required to have under control all the possible contributions coming from other sources, that we call model dependent. In the following we show that the interference of the electric charge radiation with any gauge invariant term of the transition amplitude exhibits a typical structure that allows us to suppress such model dependent contributions (which again can be considered as hadronic contributions). The other way around, we can enhance effects of intermediate states (model) to extract their relevant parameters.

3.1. Interference of gauge invariant amplitudes.

For a three body radiative decay $A^{-}(p) \rightarrow B^{-}(q)C^{0}(p')\gamma(\epsilon,k)$, the total amplitude can be written as a sum of two terms:

$$M = \epsilon^{\mu}(L_{\mu}M_{0} + M_{1,\mu})$$

where

$$L_{\mu} \equiv \left(\frac{p^{\mu}}{p \cdot k} - \frac{q^{\mu}}{q \cdot k}\right)$$

which satisfies that $L \cdot k = 0$ and therefore any term exhibiting a proportionality to $L_{\mu}$ is gauge invariant. The term, $M_{0}$, is the electric charge amplitude of order $\omega^{-1}$ and explicitly proportional to $L_{\mu}$, while $M_{1,\mu}$ is a gauge-invariant amplitude ($k \cdot M_{1} = 0$) starting at order $\omega^{0}$. The interference term between the electric charge and the remaining amplitude, after sum over polarizations, is given by:

$$I = 2Re \left[ (-g^{\mu\nu})L_{\mu}\sum_{pols=A,B,C} M_{0}^{\nu}M_{1,\nu}\right] \sim -aL^{2}.$$  

The factor within curly brackets in this equation can be parametrized in the most general form consistent with a Lorentz transformation. The gauge-invariance condition imposed on it requires to be also proportional to $L_{\mu}$ with a Lorentz invariant coefficient $a$. Therefore, all the contributions are proportional to $L^{2}$ [6]. Note that the kind of particles involved can be diverse and, therefore, the common structure has to have an origin not based on a particular field but the gauge invariance of any single amplitude interfering with the electric charge radiation.

3.2. $g = 2$ for vector mesons

We can naturally wonder if the polarized amplitudes show the vanishing feature of the Burnett-Kroll terms. We have shown under which conditions it happens, it turns out that it does vanish when $g = 2$ (here we will refer to the MDM by the gyromagnetic ratio $g$). Considering the soft photon approximation, i.e. the first two terms in Eq. (1), we can compute the polarized amplitudes. A look to the interferences of $O(\omega^{-1})$ (by just counting the powers on $k$) equivalent to the Burnett-Kroll ones for the non polarized case, reveals that all of them are not null, unless the magnetic dipole moment takes the canonical value $g = 2$ [7]. Thus this result offers a new
feature of the effect of the MDM in polarized radiative decays. It is worth mentioning that in the non-polarized case the same value can lead to a vanishing of the total amplitude in a particular kinematical region [8] and other interesting properties of radiative processes [9, 10, 11, 12]. An open task is to exploit the relative magnitudes when $g \neq 2$ which is expected to be the case due to structure effects of the vector mesons, as a possibility for an experimental determination of the MDM. It is clear that an experimental set up is far more difficult than the non-polarized case. Because the properties of the vector mesons are similar to those of the deuteron, except for the lifetime, it could also be used to get a more precise value of its MDM.

4. Finite width effects of hadrons.
A finite propagation length (or width $\Gamma$) separating production and decay vertices and its mass are two parameters which characterize a resonant state. In particular the mean life time ($\tau = \hbar/\Gamma$) and the mass parameter corresponds to the pole position in the S-matrix amplitude and has deserved an extensive treatment in the literature [13, 14]. The consistent description of resonances in quantum field theory is related to the electromagnetic (EM) gauge invariance property of a given process to ensure the good behavior at high energies of the scattering amplitude for example, otherwise it could become a disaster in terms of the predictability of a given theory.

4.1. The breaking of EM gauge invariance
Let us make clear the point related to the breaking of the EM gauge invariance when including the decay width of resonances. Consider the electromagnetic Ward identity (which is a manifestation of the gauge invariance of the theory) for the radiation off a massive spin-1 particle:

$$k_\mu \Gamma^{\mu\nu\lambda} = i D^{\nu\lambda}(q_1)^{-1} - i D^{\nu\lambda}(q_2)^{-1},$$

where $\Gamma^{\mu\nu\lambda}$ denotes the EM vertex for two particles with momentum $q_1$ and $q_2$ whose propagators are $D^{\nu\lambda}(q_i)$ and $k_\mu$ is the photon momentum. For the W gauge boson the tree level electromagnetic vertex $W(q_1, \nu) \rightarrow W(q_2, \lambda)\gamma(k, \mu)$ takes the form [15]:

$$\Gamma_0^{\mu\nu\lambda} = g^{\nu\lambda}(q_1 + q_2)^\mu - g^{\mu\nu}(q_1 + k)^\lambda - g^{\mu\lambda}(q_2 - k)^\nu \tag{6}$$

and the propagator, set in the unitary gauge, becomes:

$$D_0^{\nu\mu}(q) = -i(g^{\mu\nu} - q^{\mu}q^{\nu}/M^2)/(q^2 - M^2 + i\epsilon). \tag{7}$$

The inverse propagator can be found from the condition $D^{\mu\nu}(D_0^{\nu\mu})^{-1} = g^{\mu\nu}$. Then we can make the replacement $M^2 \rightarrow M^2 - iM\Gamma$ everywhere to include the width [16]. Upon these changes the Ward identity becomes:

$$k_\mu \Gamma_0^{\mu\nu\lambda} = i D_0^{\nu\lambda}(q_1)^{-1} - i D_0^{\nu\lambda}(q_2)^{-1} - iM\Gamma(-q_1^\nu q_1^\lambda + q_2^\nu q_2^\lambda)/q_1^2 M^2 + q_2^2 M^2 - M^2) \tag{8}$$

i.e. it is not fulfilled any longer. Then it is clear that some care has to be taken in order to introduce the finite width of the resonance without spoiling the EM gauge invariance.

4.2. Restoring the EM gauge invariance
Two key points which will prove to be very useful in restoring the invariance are the following:

(i) In Quantum Field Theory, widths arise naturally from the imaginary parts of higher order diagrams describing boson self-energies, resummed to all orders in a perturbative expansion.

(ii) The linearity of the Ward identity, which is fulfilled order by order in perturbation theory.
4.3. Fermion-loop scheme

One of the schemes that has been introduced is the so-called fermion-loop scheme \([17, 18, 19]\), to deal with \(W\)-resonance mediated processes. It requires to go beyond the tree level and to include consistently the resummation of the fermion loops in propagators AND the corrections in the electromagnetic vertices. The imaginary part of the fermion loops introduces the tree level width in the gauge boson propagator and the gauge invariance is not violated since the fermion loops obey the Ward identity order by order.

4.4. Boson-loop scheme

Hadronic resonances like the \(\rho\) vector meson, are typically identified as a two-pseudoscalar resonant state. Their couplings to the photon and propagator can be shown to have exactly the same form of the \(W\) gauge boson and the difference arises only at the level of their form factor, which should reflect their composite nature. The issue of gauge invariance in this case is relevant in processes like \(\tau \rightarrow \nu \pi \pi \gamma\), where the intermediate state is dominated by the resonant part of the two pions. In the same spirit of the fermion-loop scheme, we can consider the contribution due to these bosons in the loop of the \(\rho\) propagator and electromagnetic vertex \([20]\) of the vector meson. Vacuum polarization contributions in the propagator can be computed as shown in figure 1 and the corresponding modification in the vertex now include diagrams with the photon attached not only to the charged particles, but also the so-called contact term, figure 2.

$$\Gamma_{\mu\nu\lambda} = \Gamma_{\mu\nu\lambda}^0 (1 + i \frac{\Gamma}{M_\rho})$$

\(\Gamma\) is the decay width, and \(M_\rho\) is the mass of the \(\rho\) meson. The general expressions are quite large \([20]\). Just let us say that the EM vertex split in tree-level and 1-loop level contributions and the propagator resummed by the bosons loop, in the chiral limit, i.e. when pions in the loop are massless, take the form:
\[ D^{\mu\nu}(q) = -iC(g^{\mu\nu} - \frac{q^\mu q^\nu}{M_\rho^2 - iM_\rho \Gamma})/(q^2 - M_\rho^2 + iM_\rho \Gamma). \] (10)

which are similar to those found in the fermion loop scheme for the same limit, irrespective of the particles in the loop. To our knowledge the contributions arising from the fermions and the bosons when describing resonances are not restricted to be the same. Therefore we can conjecture that it is a general feature of any consistent description of resonances in quantum field theory, if we wish to keep the EM gauge invariance, to follow this prescription: The replacement of the mass term \( M_\rho^2 \rightarrow M_\rho^2 - iM_\rho \Gamma \) as prescribed in the complex mass scheme[16] and the modification of the vertex by a factor \((1 + i \Gamma_{\rho})\).

5. Hadrons and quark matter

Searches for a deconfined quark matter state are currently being conducted at terrestrial laboratories as well as at space-based observatories. Indeed, a substantial effort has been devoted on experimental searches at both CERN and Brookhaven National Laboratory (BNL) and more are proposed in the future for the relativistic heavy-ion collider (RHIC) and the large-hadron collider (LHC). These terrestrial experiments are being complemented by observational searches for quark stars.

5.1. Strange matter

A deconfined state of quark matter consisting of almost equal amounts of up, down, and strange quarks, has been speculated to be the absolute ground state of hadronic matter [21, 22], this is the so-called strange matter. If true, nucleons and nuclei — and thus most of the luminous matter in the universe — are in a long-lived metastable state. Undoubtedly, the confirmation of such hypothesis would have far reaching consequences on a variety of fields, ranging from astronomy and cosmology all the way to particle and nuclear physics. If a pulsar with a period falling below the limit of gravitationally bound stars were discovered, the conclusion that the confined hadronic phase of nucleons and nuclei is only metastable would be virtually inescapable [23].

The existence of a quark-matter phase at the core of neutron stars (NS) will lead to smaller limiting masses and different mass-radius relations. Thus a study of the strangeness content of hadronic matter, using a “QCD-inspired” model, is desirable. For static and spherically symmetric neutron stars obeying the Oppenheimer-Volkoff equations the only physical ingredient that remains to be specified is the equation of state. Yet an equation of state that is accurate over the whole range of densities present in a neutron star remains a formidable challenge. Traditional studies of strange matter have been conducted in two vastly different pictures [24, 25, 26]. One picture uses a hadronic model — similar to ordinary nuclei — where the fundamental degrees of freedom are mesons and baryons. The other picture uses a quark model consisting of massless, noninteracting quarks confined inside a bag. Yet this division seems ad-hoc and arbitrary; for example, at what density should one switch from a nuclear- to quark-based description? Perhaps the most serious difficulty encountered in modeling the density dependence of hadronic matter and the resulting EOS is how to model a system that has quarks confined inside color-neutral hadrons at low density but free quarks at high density [27].

That the emergence of strange quarks at high-baryon density is energetically favorable is easy to understand. As the density of the system increases, the Pauli exclusion principle forces the chemical potential to increase from the light-quark mass \( m \) to \( E_F = \sqrt{k_F^2 + m^2} \), where \( k_F \) is the Fermi momentum. When \( E_F \) is comparable to the strange quark mass, the appearance of the quark \( s \) helps to lower the system energy.
5.2. Color screening

Although the evidence in support of QCD as the correct theory of the strong interactions is overwhelming, at present no rigorous solution of QCD exists in the regime of high-baryon density. Thus, one must resort to QCD-inspired phenomenological models. Such models of hadronic matter using quarks as the underlying degrees of freedom have been developed to reproduce some properties of QCD [28, 29, 30, 31]. The main feature of these models — generically known as “string-flip” models [32] — is the existence of a many-body potential able to confine quarks within color-singlet clusters, the transition is dynamical without the need to rely on ad-hoc parameters. Hence, such models should shed light on the possibility of stable strange matter.

What is not easy to understand are the details of the transition from hadronic to quark matter. For example, do clustering correlations remain important at the transition density or has the system evaporated into the free quarks? Does the EOS predicted by the model yield self-bound and absolutely stable stars? These are the sort of questions that are still waiting for a definite answer. There exist suggestions [33] that the suppression on the formation of heavy quark bound states (like the J/ψ hadron) will be one of the signatures of the transition. Several studies show that the modification of its properties, due to the color screening of the medium, strongly correlates with the drop of the interaction confining quarks into hadrons [34].

6. Closing remarks

Hadrons are the objects which the experiments can directly see rather than the quarks. Particle physics is rooted in the hadron phenomenology and nowadays is a lively subject of research which will offer definite answers to the properties of quarks, the underlying symmetries in nature and the interactions. In this article we have focused on some open questions regarding the hadron properties themselves and exhibited general features useful in the analysis of their respective processes. The full understanding of hadrons will eventually permeate to other fields and its impact can be of unprecedented relevance. Research on this field is conducted in Mexico by several groups at UNAM (IFUNAM and ICN-UNAM), Cinvestav, U. de Guanajuato, Universidad de Michoacán (UMSNH) and U. de San Luis Potosí among others.

Acknowledgments

This work was partially supported by Conacyt, México under grants 41600-A1, 41048-A1 and 42026-F and by UNAM PAPIIT IN112902-3.
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