PHYSICS OF EXOTIC AND NON-EXOTIC MESONS AT HESR

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Abstract
Medium energy physicist in the forthcoming years are confronted with the problems of phasetransition from pertubative to non-pertubative QCD and the source of CP-violation. It is possible to address many of the questions in these fields with a multipurpose detector and a fixed target pp environment. As there is emerging evidence for the existence for gluonic degrees of freedom in hadronic reactions it is mandatory to extend the energy range to the charmonium region where ambiguities are easier to resolve.

1 Introduction
Quantum Chromodynamics (QCD) has been a very successful theory and describes quantitatively the phenomena of strong interaction over several order of magnitudes [1]. Especially at high energies corresponding to small distances (much smaller than 0.3 fm) it has a very high predictive power. Nevertheless in the domain of distances of the order of the size of the nucleon (≈1 fm) the coupling constant $\alpha_S$ approaches unity and the pertubative expansion is no longer the appropriate description for the processes involved. The domain of long distance QCD is governed by effects which are strongly non-pertubative like coninfe and chiral symmetry breaking. While the physics of short distances is well treated (e.g. one-gluon-exchange), the phenomena of long-distances and soft energies are still not fully understood. To understand and to prove the validity of QCD at the non-pertubative end of the energy scale it is necessary to exploit many features of QCD which have been investigated theoretically in various models and theories but have not yet been tested with experiments. The proposed GSI upgrade including a High Energy Storage Ring (HESR) [2] for antiprotons would give the opportunity to investigate a variety of questions of low energy QCD including in-medium-effects of strongly bound systems, the existence of exotic matter (with gluonic degrees of freedom), the quark-quark and quark-antiquark-Potential, CP-Violation and many more.
In this report I will concentrate on formation and production of exotic and non-exotic meson. Exotic mesons are characterized by their internal non-qq̅-structure. It was Fritzsch and Gell-Mann who firstly proposed the possible existence of a system containing only gluons – the binding force of the strong field – which we nowadays know as glueballs. But also other systems without open color could be formed like multiquarks (and/or molecules) with a van-der-Waals-like interaction between conventional mesons. Another interesting possibility is the excitation of the gluonic field inside a meson, leading to a state which can be described in terms of non-singlet qq̅ and valence gluons, called a hybrid. The goal is to identify non-exotic mesons and their spectrum and decay characteristics to exploit hidden features in the non-pertubative limit.

The main problem in this respect is, that a conventional meson is not just a qq̅-pair. If one probes the meson at low momentum transfer, this object yields a much more complex structure. It can be represented as a Fock-expansion being composed of everything which contributes to the wave-function in the mass regime of the meson with the same quantum numbers (see fig. 1). Therefore

\[
    q\bar{q} = \begin{array}{c}
    \includegraphics[width=0.3\textwidth]{example}
    \end{array}
\]

Figure 1: The internal structure of a physical mass-eigenstate of light quark pairs is very complicated and might hide exotic states (Fock expansion). Suppressing the dominant qq̅ part may yield clean exotic resonances. This can be achieved by selection of exotic quantum numbers.

finding an exotic meson which has quantum numbers accessible by a qq̅-pair is not a very favorable exercise, because it might be hidden by the leading order qq̅-content. This picture is supported by the fact, that in addition to the well known spectrum of light "conventional" mesons, there are only a few exotic candidates, most of them with exotic quantum numbers. If they wouldn't mix with the Fock ground state, there would be many more mesons in this mass regime. This leads to two obvious scenarios for the experimental approach. On one hand one may reduce the contribution of higher Fock states by moving from low energies towards more massive particles. In addition one may look for resonances with exotic quantum numbers, which forbid a qq̅-contamination.

The main remaining questions is where to look and what one should expect. The p̅p-annihilation has been proven to be rich in terms of exotic meson production. All candidates for exotic mesons have been found in p̅p-annihilation...
with the Crystal Barrel experiment. Fig. 2 shows the evidence for the production of $f_0(1500)\pi$ and $\pi_1(1400)\pi$ and $\pi_1(1600)\pi$ in $\bar{p}N$-annihilations at rest (see Ref. [15, 14] for more information on the properties and the different decay modes). The hybrid candidates have been found also in $\pi N$-scattering experiments like E852 at BNL or VES [13, 12] but with a very weak coupling. The production rates in $p\bar{p}$-annihilations are usually comparable to the ones for conventional mesons – making this a unique source for exotic matter. Since $p\bar{p}$-annihilation involves a lot of intermediate glue this is not surprising and one would expect to find all the other exotics as well in comparable reactions.

![Figure 2](image.png)

**Figure 2:** $p\bar{p}$ annihilation has been proven to be an excellent source of exotic matter. This has been shown by huge production rates for the glueball (a/b), hybrid (c) and 4quark candidates (d).

The theoretical approaches are dominated by LatticeQCD calculations, where quite precise results emerged in recent runs. In the case of glueball calculations, with anisotropic lattices a major step was made towards reasonable errors for mass and widths in the quenched approximation [3] (see fig. 3). In the case of hybrids the process is more complicated since quarks are involved.
Figure 3: (a) The difference between quenched and unquenched LQCD in the $b\bar{b}$ system is negligible [4]. (b) the glueball spectrum from quenched anisotropic LQCD [3].

Figure 4: Mass range for exotic particles. Only particles without open flavor can be produced in formation, all others have to be produced in pairs.
But the results are very promising. The lightest hybrids (having light quark pairs) are expected in the region between 1.8 and 2.1 GeV/c² [5], thus verifying much older fluxtube results [7]. Unfortunately they might mix with conventional mesons and/or have decay channels which are rather complicated to extract from the data. In the sector of charmed hybrids the situation looks much more promising in respect of mixing and also the predictions for hybrids from the LatticeQCD are much more mature because of the slow charm quark within the hadron. The main uncertainty nowadays is the influence of the quenched approximation which has been investigated only for the $b\bar{b}$-potential so far (see fig. 3). The analysis shows only marginal differences and the assumption is that this holds also for $c\bar{c}$-systems [4]. The expected mass range for exotic mesons including the whole charm-sector is displayed in fig. 4. One sees that all hidden flavor states like the charmonium (hybrid) systems as well as the $D_{(s)}^{(s)}\bar{D}_{(s)}^{(s)}$ can be produced with an antiproton beam momentum up to 15 GeV/c.

2 Charmonium

For a very long time the charmonium system is believed to be the perfect example for a one-gluon exchange potential, thus showing the same gross properties as the textbook example of positronium which is also dominated by a one-boson exchange mediated by the photon. Nevertheless the simple QCD-potential with one-gluon-exchange creates as many problems as it may solve. Many attempts have been made to calculate the spectrum of $c\bar{c}$-systems and most of them lead to a pattern as shown in fig. 5. The main problem with the spectrum is that even if they are calculated accurately many of the states have not been discovered so far. The $\eta_c^*$ was only seen once after a magic background subtraction in Crystal Ball, the $D$-States are missing completely and the measurement on the $^1P_1$-state $h_{1c}$ is also doubtful. Since it should show up at the c.o.g. of the $P$-states – thus proving the wave function at the origin – it is an important piece in this puzzle of "QCD-atoms". On the other hand, a detailed understanding of the underlying meson spectrum is needed when a survey of additional resonances in the charmonium sector is be pursued. $p\bar{p}$-annihilation is also superior to other production techniques in this respect. It has been shown by E760/E835 at FNAL [11] that even narrow $c\bar{c}$-states are produced and detected easily in $p\bar{p}$-formation being accessed with a very cool antiproton beam. In contrast to the classical method in $e^+e^-$-machines (like BES) one is able to access all states with the same beam without recoil particles which leads to an ultimate resolution for the mass and the natural width
of these states (see fig. 6).

![Diagram](image)

Figure 5: The $c\bar{c}$ levels line up like the $e^+e^-$ levels, thus indicating a good correspondence between single photon and single gluon exchange. Nevertheless a careful study reveals severe problems which have to be explored.

### 3 Charmed Hybrids

Charmed hybrids are expected to appear in the vicinity of $4.3 \text{ GeV}/c^2$ [6] (from LatticeQCD). The fluxtube model – being investigated since nearly two decades – proposes that the decay into an $S$ and a $P$-wave meson to be dominant [7]. This approach was applied to light mesons but may also be valid for heavy hybrids. Such a channel would be $DD^{**}$. If the hybrid would be below the production threshold for those channels, it is assumed to be narrow. Several theoretical studies lead to width below $10 \text{ MeV}/c^2$ for these objects [8]. But not all of them could be formed in $p\bar{p}$-annihilation. The spin-exotics of those would have to be produced with a recoiling partner to conserve quantum numbers. The first weak evidence that resonances between $c\bar{c}$ and other light mesons might exist was reported recently by CLEO: A peaking $J/\psi \phi$ structure was discovered around $4.3$-$4.4 \text{ GeV}/c^2$ in a B-decay channel (see fig. 7) [9].

### 4 Experimental technique

The experimental technique used in $p\bar{p}$-annihilation is either formation of resonances be a fusion of the proton with the antiproton, leading to a new system after annihilation of some quark-antiquark-pairs and rearrangement of the others. How glueballs, light hybrids and charmonium with and without gluon component can be formed is exemplified in fig. 8. There are many more graphs which actually contribute to formation and production. The analysis technique is a full determination of all partial waves in a scan of $\vec{p}$-momenta.
Figure 6: Charmonium ($c\bar{c}$) formation in $p\bar{p}$-annihilation (upper plots from E835 and E760) is superior to $e^+e^-$-production experiments (like BES in the lower plots).

Figure 7: The Dalitz plot of the reaction $B \rightarrow J/\psi\phi K$ from CLEO demonstrates the importance for a high statistics measurement on heavy $c\bar{c}$ systems.
The feasibility of this technique has been shown by Crystal Barrel in an earlier p\(\bar{p}\)-experiment at LEAR [17].

![Diagram](image1)

Figure 8: Formation (a-c) and production (d-f) of resonances (exotic and non-exotic, G=glueball, H=hybrid (=q\(\bar{q}\)q)) in p\(\bar{p}\) annihilations.

In addition to the production of glueballs, light and heavy hybrids and charmonia another topic can be attacked. It has been shown [16], that a lepton-pair trigger could be used to tag the production of 4-quark systems, also an exotic kind of matter which has not been established so far (see fig. 9). The production rate os quite sizeable and a trigger on lepton pairs matches the design criteria for a charmonium experiment quite well.

![Diagram](image2)

Figure 9: Drell-Yan-production of 4quark-states in p\(\bar{p}\) annihilations in flight.

5 Experimental Layout - Design issues

The main goals driving the design of a detector capable of detecting with high accuracy the formation and production experiment on glueballs, light and heavy hybrids and charmonia as well as open charm physics and charmed baryon spectroscopy are an excellent neutral and charged particle detector accompanied by fast trigger capabilities including particle identification over a
broad momentum spectrum. This can be achieved with a DIRC-like Cherenkov device for the central part and an aerogel detector for the forward part. All this equipment has to operate in an environment of hadronic interactions with reaction rates in the order of a few 10⁷/s. Therefore a detector system with very fast electromagnetic calorimetry is envisaged, probably with PbWO₄ crystals surrounding the central detector within a solenoidal magnetic field. μ-chambers on the outside of the magnet are added to allow for a broad coverage of decay channels. Tracking could be done with straw chamber surrounding several layers of silicon vertex detector. The very forward region would be covered by a large dipole to enhance the detectable angular coverage of the decay products of the formed resonances. The forward region would also contain tracking and calorimetry devices. The detector would incorporate a gas-jet or pellet target within a circulating antiproton beam of some 10¹² p allowing for a luminosity of up to a few 10³² cm⁻² s⁻¹. A sketch of the detector is shown in fig. 10.

Figure 10: First sketch of a detector at the HESR. The layout is driven by the requirements for high speed charged and neutral particle detection as well as triggering purposes.

References
[4] G. Bali et al. (Sesam and TχL Coll.), hep-lat/0003012