Light-Quark Meson Spectroscopy with Crystal Barrel

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Light-quark meson spectroscopy provides a powerful tool to study QCD in the non-perturbative sector. Crystal Barrel has developed a lively experimental activity over the last decade and different high-statistics results have been published which have led to stimulating theoretical interpretations. A selection of results concerning the quest of constituent gluons in hadrons will be discussed.

1. Introduction

This contribution reports on experimental evidence for constituent gluons as observed in the Crystal Barrel experiment at the **L**ow **E**nergy **A**ntiproton **R**ing at CERN. After a brief introduction into the motivation and realization of Crystal Barrel some results on exotic hadronic states such as glueballs and hybrids will be discussed. In particular, the experimental evidence for a state with explicit exotic quantum numbers is an unambiguous signature for an exotic hadronic structure.

It is impossible in this brief introduction to justify the full range and depth of the scientific program of Crystal Barrel. The central issue is to study strong interaction phenomena in an energy regime of non-perturbative QCD. We know that at small distances QCD is a weakly coupled quark gluon theory amenable to a perturbative expansion in α_s. However, at large distances α_s becomes large and perturbation methods are no more applicable. All calculations depend on models such as bag models, QCD sum rules, color flux tube models or lattice gauge theory. The latter is considered to provide reasonable precise predictions. All those models agree on the existence of non-standard hadrons [1] such as *glueballs*, bound states of constituent gluons $\{\mathrm{gg}\}$,$\{\mathrm{ggg}\}$, *hybrids*, consisting of a $\bar{\mathrm{q}}\mathrm{q}$ pair and a constituent gluon $\{\bar{\mathrm{q}}\mathrm{qg}\}$, and *multi-quark states*, having a complex quark content such as $\{\bar{\mathrm{q}}\mathrm{q} - \bar{\mathrm{q}}\mathrm{q}\}$, $\{q^2 - \bar{\mathrm{q}}^2\}$ or $\{q^3 - \bar{\mathrm{q}}^3\}$. The search for those states is one of the basic objectives of Crystal Barrel. In this sense one can describe a key goal of Crystal Barrel to accomplish the understanding of the internal structure of hadronic matter.

The search for exotic states makes use of their predicted characteristics. The most promising conditions to find them are given in gluon-rich processes such as radiative J/Ψ-decay, central production or $\bar{\mathrm{p}}\mathrm{p}$ annihilation.

The glueball spectrum is expected to start below 2 GeV according to lattice QCD with a groundstate 0^{++} at a mass around 1550 MeV/c^2 followed by a 2^{++} state around 2300 MeV/c^2 [2]. A more recent calculation [3] predicts the mass of the 0^{++} glueball around 1750 MeV/c^2. As gluons couple equally to all kind of quark flavors glueballs are supposed to decay flavor-blind. Also the lowest mass hybrid states are expected below 2 GeV with quantum numbers of 0^{-+}, 1^{-+}or 1^{--} [4]. In particular the occurrence of the 1^{-+}, not accessible for standard $\bar{\mathrm{q}}\mathrm{q}$ systems, means an immediate proof for the existence of exotic matter. Also the third kind of exotic matter, multi-quark states, may have open exotic quantum numbers which are essential to identify unambiguously a new form of hadronic matter.

Establishing the existence and measuring the properties of the non-$\{\bar{\mathrm{q}}\mathrm{q}\}$ mesons is by no means a trivial undertaking as the mass scale of the exotic states overlaps completely with the stan-

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dard meson spectrum. This means one has to search for a missing state in a large background from states. Even worse, in spite of an almost 40 years of study the meson spectrum is not well understood. Recent experimental reviews can be found in [5], [6], and [7]. Moreover, potential dynamical effects introducing distortions makes light quark spectroscopy much more complicated than the spectroscopy of heavy quark systems; Törnqvist [8] emphasizes that final state interactions may lead to appreciable distortions of the conventional nonet mass and mixing pattern. Also opening inelastic channels provide a source of non-resonant background and can cause some confusion in assigning the observed states.

Under these circumstances only high statistics experiments of exclusive reactions can help to disentangle all contributing states by means of partial wave analysis. A powerful discovery strategy is to observe the same meson in a variety of reactions. The different production fractions or, even more, the observation of different decay modes of hadrons will help in assigning the observed states to their SU(3) nonets or to identify them as exotic states.

2. The Crystal Barrel Detector

The Crystal Barrel detector [9] was set-up at LEAR. This unique accelerator provided until late 1996 high-brilliant antiproton beams with no contaminating particles both in pulsed and slow extraction. Antiprotons of 200 MeV/c were stopped in a hydrogen target in the center of the magnetic Crystal Barrel spectrometer providing a 1.5 T field along the beam axis. Tracking of charged particles was done by a set of two cylindrical proportional wire chambers, replaced in a later phase by a silicon vertex detector, and a jet drift chamber with 23 sensitive layers azimuthally divided into 30 sectors. The detection of photons took place in a modular barrel-shaped calorimeter consisting of 1380 CsI(Tl) crystals with photodiode read-out. The detector covers about 95% of the 4π solid angle. The distinct features are high energy and momentum resolution both for charged particles and photons. This can be recognized e.g. by the achieved mass resolution $\sigma(\pi^0\to\gamma\gamma)=$ 8 MeV/c^2, $\sigma(\eta\to\gamma\gamma)=$ 15 MeV/c^2, and $\sigma(\omega\to\pi^0\pi^+\pi^-)=$ 16.3 MeV/c^2.

3. Status of the scalar meson nonet

Several arguments have been given in the introduction to investigate the field of scalar mesons, in particular, the search for the predicted glueball groundstate is of tremendous importance. A promising field to explore scalar mesons is the three pseudoscalar final state in $\bar{\mathrm{p}}\mathrm{p}$ annihilation at rest. It is assumed that the reaction proceeds in a sequence of two-body reactions forming in the intermediate state the scalar meson which decays into two pseudoscalars. As only angular momenta L=0 are involved no hindering centrifugal barrier effects occur.

From 16.8 million events taken with an *all-neutral* trigger accepting only events with no charged tracks events with exactly six electromagnetic showers have been selected. This data can be separated into several three pseudoscalar final states such as $\pi^0\pi^0\pi^0$ (712 k reconstructed events), $\pi^0\eta\eta$ (198 k events), and $\pi^0\eta\eta'$ (980 events). These channels can be consistently described in a partial wave analysis [10]. Several contributing I=0 scalar mesons have been observed; among those as common result is the occurrence of a isoscalar scalar resonance, $f_0(1500)$, with (m,Γ) = (1505$\pm$ 5, 110$\pm$12) MeV/c^2 and couplings to $\pi\pi$, $\eta\eta$, and $\eta\eta'$. But also the occurrence of the state $f_0(1380)$ with (m,Γ) = (1360$\pm$ 25, 350$\pm$40) MeV/c^2 is of interest as it nicely matches into the scalar meson nonet. Figure 1 and 2 show as examples for the high quality data of Crystal Barrel the Dalitz plots of the final states $\pi^0\pi^0\pi^0$ and $\pi^0\eta\eta$ clearly indicating the resonances of interest.

The six γ sample contains also the final states $\pi^0\pi^0\eta$ [11] and $2\pi^0\eta'$ [12]. Also here the partial wave analysis reveals the contribution of a new scalar resonance, the $a_0(1450)$, with I=1 and (m,Γ) = (1470$\pm$ 25, 265$\pm$30) MeV/c^2. This resonance is as well seen in the final state

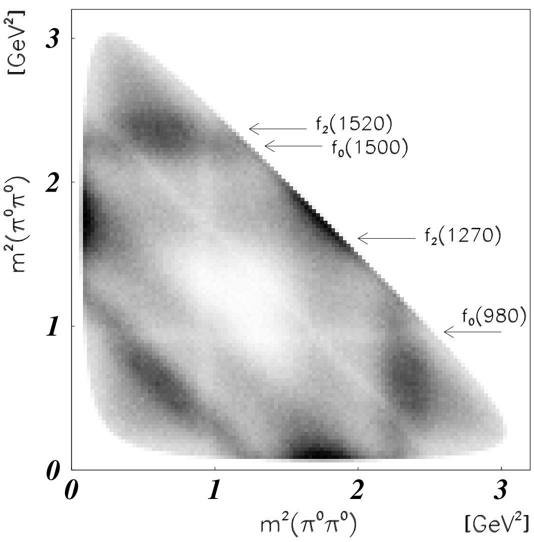

Figure 1. *Dalitz plot for* $\bar{p}p \to \pi^0\pi^0\pi^0$

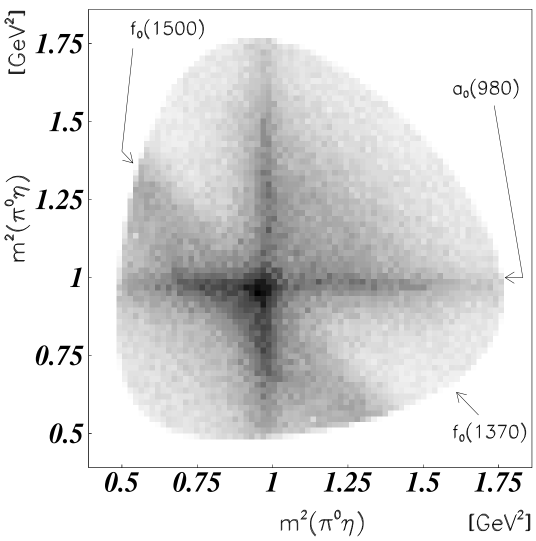

Figure 2. Dalitz plot for $\bar{\mathrm{p}}\mathrm{p} \to \pi^0\eta\eta$

$\mathrm{K}^{\pm}\pi^{\mp}\mathrm{K}^0_{\mathrm{L}}$ [13]. Anticipating the decay rate into $\bar{\mathrm{K}}\mathrm{K}$ one finds that this meson matches nicely the scalar nonet (table 1).

Table 1
Decay rates of $a_0(1450)$

decay	$\pi\eta$	$\bar{\mathrm{K}}\mathrm{K}$	$\pi\eta'$
SU(3)	1.	0.69±0.03	0.39±0.04
exp.	1.	0.88±0.23	0.35±0.16

The $f_0(1500)$ is as well seen in the $5\pi^0$ final state where its decay into 4π has been determined [14]. The 4π invariant mass shows a strong deviation from phase space distribution which is due to the decay of $f_0(1500)$ into $\sigma\sigma$ and $\pi(1300)\pi$. σ describes the low-energy part of the $\pi\pi$ S-wave. The decay rate is found to be

$$B(\bar{\mathrm{p}}\mathrm{p} \to f_0(1500)\pi^0 \to 5\pi^0) = (9.0 \pm 1.4) \cdot 10^{-4}. (1)$$

For a definite assignment of the $f_0(1500)$ knowledge of its decay ratio into $\bar{\mathrm{K}}\mathrm{K}$ is essential. Crystal Barrel has reconstructed the $\mathrm{K}^0_{\mathrm{L}}\mathrm{K}^0_{\mathrm{L}}\pi^0$ final state using the two photons from the π^0-decay and the direction of flight of one interacting $\mathrm{K}^0_{\mathrm{L}}$ [15]. The interaction probability of the $\mathrm{K}^0_{\mathrm{L}}$ is about 54 % . The Dalitz plot fig. 4 shows clear resonance features from $\mathrm{K}^*(892)$ interfering with resonances in the $\bar{\mathrm{K}}\mathrm{K}$ subsystem where both I=1 and I=0 are accessible. Due to this fact the partial wave analysis cannot disentangle the isospin contributions around 1400 MeV/c^2. Thus one may force an $a_0(1450)$ contribution up to 15 % with only minor effects in the quality of the fit but reducing the contribution of the $f_0(1500)$. In order to resolve this isospin ambiguity the reaction $\bar{\mathrm{p}}\mathrm{p} \to \mathrm{K}^{\pm}\pi^{\mp}\mathrm{K}^0_{\mathrm{L}}$ has been investigated. The event topology is two oppositly charged particles and a missing $\mathrm{K}^0_{\mathrm{L}}$. K and π are separated by the dE/dx information of the JDC. The data, displayed in fig. 5, again show strong K^* contribution but as the $\bar{\mathrm{K}}\mathrm{K}$ system can only couple to I=1 only $a_0(980)$, $a_0(1450)$ and $a_2(1320)$ are observed. The partial wave analysis determines the decay rate of the $a_0(1450)$ into $\bar{\mathrm{K}}\mathrm{K}$ to be $(8.9 \pm 1.7) \cdot 10^{-4}$. Using isospin symmetry one can dis-

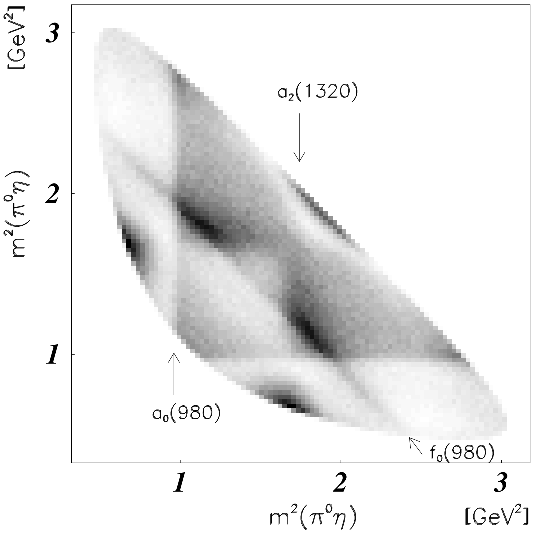

Figure 3. Dalitz plot for $\bar{\mathrm{p}}\mathrm{p}\to\pi^0\pi^0\eta$

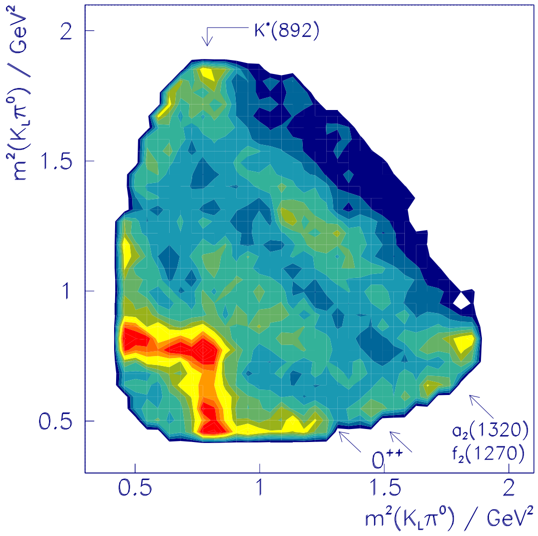

Figure 4. Dalitz plot for $\bar{\mathrm{p}}\mathrm{p}\to\mathrm{K}_\mathrm{L}^0\mathrm{K}_\mathrm{L}^0\pi^0$

entangle now I=0 and I=1 contributions in the $\mathrm{K}_\mathrm{L}^0\mathrm{K}_\mathrm{L}^0\pi^0$ final state and finds

$$B(\bar{\mathrm{p}}\mathrm{p}\to f_0(1500)\pi^0\to\bar{\mathrm{K}}\mathrm{K}\pi^0) = (4.5\pm0.4)\cdot10^{-4}. \quad (2)$$

From the observed scalar particles and in particular from the new states observed in $\bar{\mathrm{p}}\mathrm{p}$ annihilation a reasonable 0^{++} nonet can be constructed. Starting from the $\mathrm{K}_0^*(1430)$, the only established $I=\frac{1}{2}$ scalar object [16], as a fixpoint, one may assign the following states to the nonet:

$f_0(1370)$	is the mostly $\{\mathrm{u\bar{u}}+\mathrm{d\bar{d}}\}$ member
$f_0(1xxx)$	is the mostly $\{\mathrm{s\bar{s}}\}$ member
$a_0(1450)$	is the isovector member
$\mathrm{K}_0^*(1430)$	is the $\mathrm{I}=\frac{1}{2}$ strange member

These states match nicely to the quark model predictions [17] and form a 0^{++} nonet similar to the familiar 2^{++} one but at slightly higher mass. Also the decay widths of the states are of the expected order of magnitude. The weakest point of this assignment is the missing $\{\mathrm{s\bar{s}}\}$ isoscalar. The $f_0(1500)$ shows a by far too low decay rate into $\bar{\mathrm{K}}\mathrm{K}$ to be the $\mathrm{s\bar{s}}$ partner. Moreover, the mass of the $\mathrm{s\bar{s}}$ state is expected to be around 1700 MeV/c^2. Therefore, the $f_J(1700)$ appears to be more likely the missing $\mathrm{s\bar{s}}$ member in case its spin is confirmed to be J = 0.

With this assignment the states $a_0(980)$, $f_0(980)$ and $f_0(1500)$ are superfluous states with potential exotic internal structure. The $a_0(980)$, $f_0(980)$ are considered as candidates for $\bar{\mathrm{K}}\mathrm{K}$ molecules or four quark states due to their strong coupling to $\bar{\mathrm{K}}\mathrm{K}$. There are preliminary results on radiative Φ-decays from VEPP at Novosibirsk favoring the four-quark interpretation [20].

The $f_0(1500)$ is a strong candidate to be the groundstate glueball. It is seen in gluon-rich processes such as $\bar{\mathrm{p}}\mathrm{p}$ annihilation and radiative J/Ψ-decay as a recent reanalysis of Mark III data shows [18]. $f_0(1500)$ shows only a weak coupling to 2γ processes as found by the ALEPH collaboration [19] indicating a strongly restricted $\mathrm{\bar{q}q}$ admixture. The parameters (m,Γ) compare well with lattice QCD calculation. However, the decay pattern (table 2) indicates clearly that it cannot be a pure glueball with flavor-blind decay.

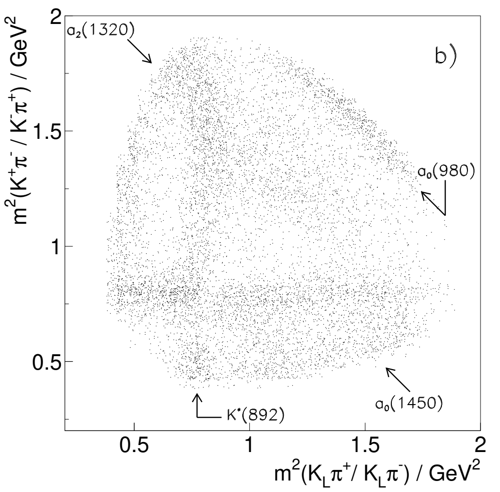

Figure 5. Dalitz plot for $\bar{\mathrm{p}}\mathrm{p}\to\mathrm{K}^{\pm}\pi^{\mp}\mathrm{K}^0_{\mathrm{L}}$

Table 2
Decay rates of $f_0(1500)$ compared to a pure glueball

decay	$\pi\pi$	$\eta\eta$	$\eta\eta'$	$\bar{\mathrm{K}}\mathrm{K}$
glueball	3.	1.	0.	4.
exp.	4.4±0.2	1.	1.4±1.0	1.1±0.4

The observation of the $\eta\eta'$ decay and the smallness of the $\bar{\mathrm{K}}\mathrm{K}$ coupling proves that $f_0(1500)$ has to be mixed with $\bar{\mathrm{q}}\mathrm{q}$ states. A good description of the decay pattern is given by Amsler and Close assuming that $f_0(1500)$ is mixed with the nearby I=0 scalar mesons [21].

4. The 1^{-+}story

The discussion on the $f_0(1500)$ clearly demonstrates the difficulty to distinguish non-standard $\bar{\mathrm{q}}\mathrm{q}$ states from the many conventional ones. Therefore, much attention is focused to the search for states with explicit exotic quantum numbers. The $\pi^0\eta$ system provides a simple channel in which the exotic quantum number combinations $J^{PC}= 1^{-+}$ can occur. Indeed, the GAMS collaboration has observed in the charge exchange reaction $\pi^-\mathrm{p} \to \pi^0\eta\mathrm{n}$ at 100 GeV/c a strong forward-backward asymmetry in the Gottfried-Jackson frame of the $\pi^0\eta$ system due the interference of the $a_2(1320)$ and a resonant P-wave with the parameters:(m,Γ) = (1406 ± 20, 180 ± 30) MeV/c^2 [22]. While the asymmetry was observed earlier in the same reaction at 40 GeV/c [23], no resonance behaviour was found in that analysis. Later experiments searching for the charged partner of the $\widehat{\rho}$ in the reaction $\pi^-\mathrm{N} \to \pi^-\eta\mathrm{N}$ are also somewhat contradictory. The KEK experiment [24] observes an enhancement in the exotic P-wave and a large forward-backward asymmetry and also the VES experiment in Serpukhov [25] sees a broader $\widehat{\rho}$-like resonance in the P-wave. This state is also seen in the final state $\pi^-\eta'\mathrm{N}$ indicating in addition the existence of a second $J^{PC}= 1^{-+}$ at a mass around 1600 MeV/c^2. These results are confirmed in a recent high statistics study at Brookhaven [26]. The parameters of the exotic $\pi\eta$ resonance were found to be (m,Γ)=(1370±16, 385±40) MeV/c^2.

Hybrids should also be produced in $\bar{\mathrm{p}}\mathrm{p}$ annihilations and, as matter of fact, the Crystal Barrel collaboration has investigated right from the beginning the final state $\pi^0\pi^0\eta$, as mentioned above, with the aim to confirm the existence of the $\widehat{\rho}$. A weak but significant contribution from $(\pi\eta)$-P-wave is seen. A clear preference for resonant behaviour could, however, only be demonstrated in a simultaneous analysis of data from annihilations in gaseous and liquid hydrogen. In a more recent analysis the reaction $\bar{\mathrm{p}}\mathrm{n}\to\pi^-\pi^0\eta$ where antiprotons annihilate in liquid deuterium has been investigated [27]. For data selection the spectator momentum has to be less than 100 MeV/c in order to guarantee an annihilation on a quasi-free neutron. In this reaction only I=1 is possible which reduces the amount of contributing resonances considerably. The Dalitz plot (fig. 6) is characterized by a simple resonance pattern formed by the dominating ρ^- and two weak bands from $a_2(1320)$. The initial state can be either $^3\mathrm{S}_1$ or $^1\mathrm{P}_1$. A good description of the Dalitz plot ask for a contribution of a L=1 $\pi\eta$ resonance system. The contribution of $\widehat{\rho}$ is 11 % in total, 8 % coming from ^{3}S$_1$ and 3 % from ^{1}P$_1$. The resonance parameters (m,Γ) = (1400 ± 20, 310 ± 50) MeV/c^2 compare well with those from the BNL experiment.

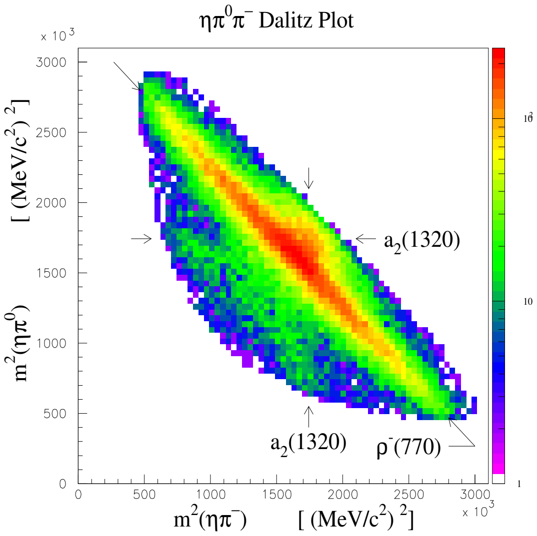

Figure 6. Dalitz plot for $\bar{\text{p}}\text{p}\rightarrow\pi^-\pi^0\eta$

5. Summary and outlook

After more than 30 years of experiments in the field of light quark spectroscopy many new features such as new states, unknown decay branching ratios or production mechanism are still revealed. These results are urgently needed to generate a basis for understanding QCD in the confinement region. So far, no QCD-based model is capable of describing the hadron spectrum in all details. The important question, existence of exotic forms of hadronic matter, is just starting to be answered. The discovery of the glueball ground state, the $f_0(1500)$, mixed with the nearby scalar mesons and the observation of a hybrid state with explicit exotic quantum numbers are a first step.

This success in hadron spectroscopy is based on the progress in experimental techniques. The availability of high-quality particle beams such as the $\bar{\text{p}}$ beams at LEAR/CERN and of large acceptance spectrometers with good energy and spatial resolution for both charged and neutral particles, good particle identification, and very selective trigger capabilities makes the online selection of appropriate exclusive processes possible. Thus high statistics data samples become available for detailed spin-parity analyses needed to disentangle all contributing partial waves.

For future work in meson spectroscopy it is necessary to make the glueball assignment absolutely definitive. Therefore, the extraction of the whole glueball spectrum is an important objective. For this it is essential also to investigate in detail the spectrum of ordinary mesons. In particular, masses and decay modes of radial excitations have to be established. It has to be emphasized that the study of $\{\bar{\text{q}}\text{q}\}$-mesons, glueballs, hybrids, and multi-quark states is indivisible as they are described by the same theory - QCD.

Particularly important experimental features in hadron spectroscopy to be investigated in the near future are:

- The observation of the complete glueball excitation spectrum as predicted by lattice QCD.
- The spin assignment of the $f_J(1710)$.
- The existence of further states with exotic quantum numbers such as the 1^{-+} at 1400 MeV/c^2.
- A search for the decay of a {ggg} glueball into {gg} + meson.

An answer to all those questions look technically straightforward in the huge amount of in flight data from Crystal Barrel.

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