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The Meson Spectrum and the Glueball Spectrum

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Abstract: The paper discusses the experimental results for hadron spectroscopy with special emphasis on the search for glueballs and hybrids. At present, the strongest evidence for these states comes from antinucleon-nucleon annihilations. The results and their interpretation will be presented, followed by perspectives for the future at a newly built antiproton facility.

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1. Introduction

Hadron spectroscopy is the basis that inspired the SU(3) quark model and the QCD theory of strong interactions. Since QCD is a non-Abelian gauge theory, the gauge bosons—the gluons—can interact with each other. Thus one of the striking predictions of QCD in the non-perturbative regime is the existence of bound states of gluons, called glueballs (gg, ggg). Other types of hadronic matter in which gluons contribute to the overall quantum numbers, called hybrids ($q\bar{q}g$), could also exist.

The gluonic excitation in a hybrid leads to new $J^{\rm PC}$ quantum numbers for those states, where J denotes the total angular momentum of the resonance. Some $J^{\rm PC}$ combinations cannot be formed by the fermion-antifermion system $q\bar{q}$, so their observation would be the cleanest experimental evidence for a non-$q\bar{q}$ state. In any case, the precise measurement of the properties of several glueball or hybrid states and the comparison to $q\bar{q}$ mesons would help us understand QCD in the low-energy regime. More complicated color-neutral states like four-, five- and six-quark states are also predicted to exist.

The most prominent reactions to study gluonic degrees of freedom are radiative J/ψ decays, central productions processes, and antiproton-proton annihilation. Because of the existence of LEAR at CERN, antinucleon-nucleon ($\bar{N}N$) annihilation data now dominate. However, for the interpretation of the results it is worthwhile to compare all production processes. This will be done in the next sections.

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[*] Speaker.

Just at the time when these proceedings were due for submission, a positive decision to fund a major upgrade of the GSI accelerator center in Darmstadt was taken by the German government. This upgrade includes a dedicated antiproton facility for hadron physics that will allow detailed studies of gluonic excitations that were previously impossible. The second part of this paper will therefore illuminate briefly the physics perspectives for the future.

2. Antinucleon-Nucleon Annihilation

The study of $\bar{\mathrm{p}}\mathrm{p}$ annihilation has been underway for the past thirty years. Several bubble chamber experiments at CERN and BNL first investigated this area. In 1983, with the low-energy antiproton ring (LEAR) at CERN, a unique facility for antiproton physics came into operation. Until its closure at the end of 1996, LEAR provided pure and high-intensity antiproton beams (up to 2×10^6 $\bar{\mathrm{p}}$/s) in the momentum range between 60 and 1940 MeV/c with a small momentum spread of $\Delta p/p \sim 10^{-3}$. The first generation of LEAR experiments produced interesting new results. Nevertheless, neither these experiments nor the bubble chamber experiments were able to investigate the 60% of annihilation channels that contain more than one neutral particle in the final state. This led to the formation of several collaborations aiming at meson spectroscopy.

Since I am the spokesman of the Crystal Barrel collaboration I will mainly focus on the results from Crystal Barrel as far antinucleon-nucleon data are concerned. These results have been confirmed by other LEAR experiments like OBELIX. The Crystal Barrel collaboration, composed of over 70 scientists from 13 different institutions, constructed a detector that covers almost the entire 4π solid angle and detects neutral particles as effectively as charged particles. A more detailed description of the Crystal Barrel detector can be found in [1].

3. Theoretical Predictions

For a fermion-antifermion system like $\mathrm{q}\bar{\mathrm{q}}$, the P and C parities depend on the total spin S of the quarks and their relative angular momentum L:

$$P(\mathrm{q}\bar{\mathrm{q}}) = (-1)^{L+1} \tag{3.1}$$

$$C(\mathrm{q}\bar{\mathrm{q}}) = (-1)^{L+S} \tag{3.2}$$

In contrast, the parity and C-parity of a bosonic system like glueballs is given by:

$$P = (-1)^{L} \tag{3.3}$$

$$C = (-1)^{L+S} \tag{3.4}$$

Many QCD-inspired models—like the bag model [2, 3], potential models [4], QCD sum rules [5] and the flux-tube model [6, 7]—aim to understand the normal $\mathrm{q}\bar{\mathrm{q}}$ meson spectrum and provide guidelines for the masses and quantum numbers of non-$\mathrm{q}\bar{\mathrm{q}}$ states. The flux-tube models in particular predict the masses [8] and the decays [9] of mesons

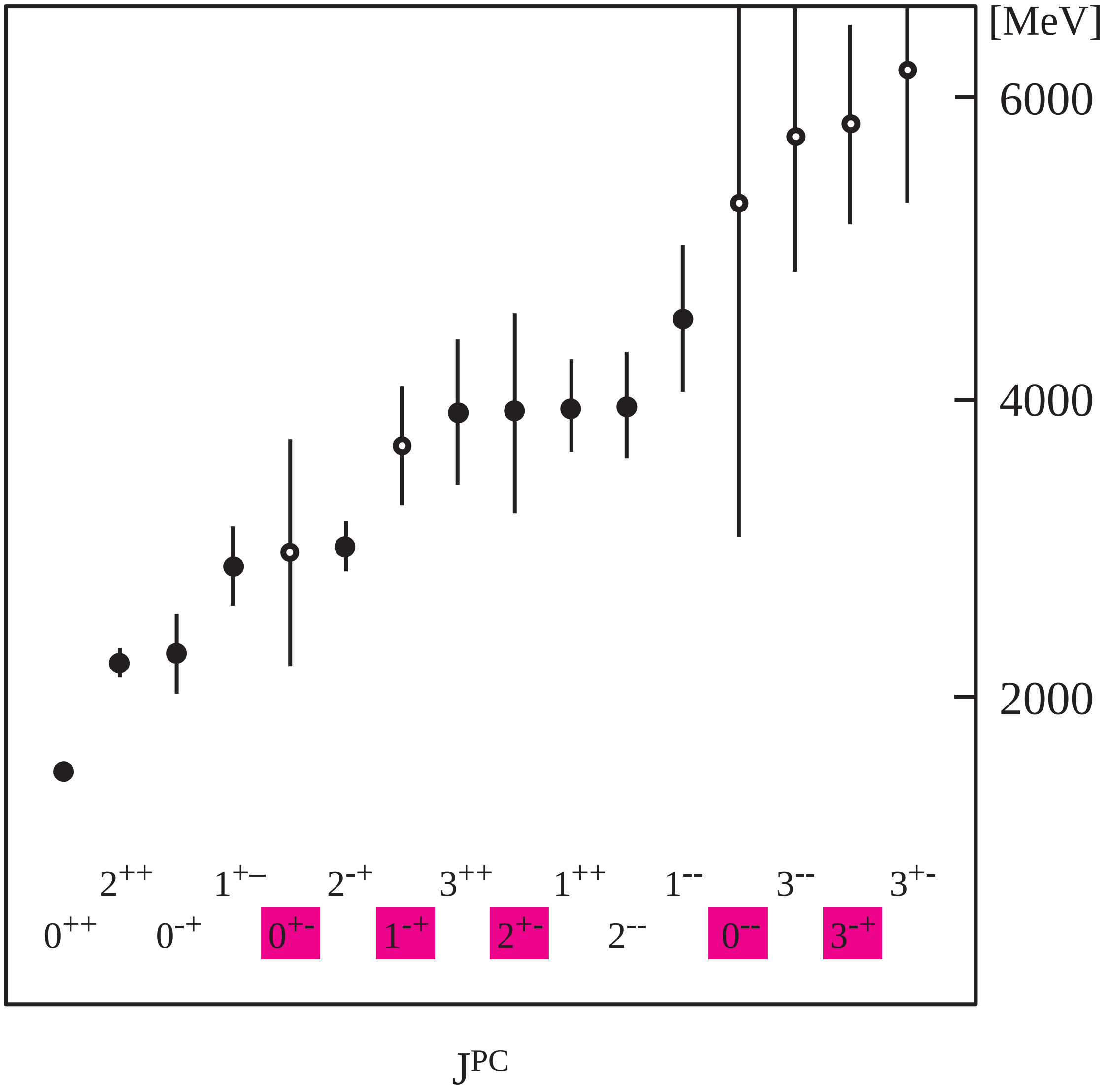

Figure 1: The glueball spectrum predicted by lattice calculations [10]. Exotic quantum numbers are marked as boxes.

with surprising accuracy. With the increase in available computing power, lattice QCD calculations have also improved significantly in recent years, yielding predictions [10] for a whole spectrum of glueballs with different quantum numbers (Fig. 1). Because of the LEAR energy limitations, the only glueballs that seem to be within the range of LEAR experiments are the scalar glueball ($J^{\mathrm{PC}} = 0^{++}$) with a mass of ~ 1.6 GeV, and the tensor (2^{++}) and pseudoscalar (0^{-+}) glueballs with masses of ~ 2.2 GeV.

4. Results

The simplest process in which to look for scalar resonances ($J^{\mathrm{PC}} = 0^{++}$) is antiproton-proton annihilation at rest into 3 pseudoscalars. In such a process, the scalar resonance decays into 2 pseudoscalars ($0^+ \to 0^-0^-$) while the third recoiling pseudoscalar removes the excess energy. No angular momentum barrier is present. Such processes have been investigated in the past, mainly involving charged pions; but the annihilation process into charged pions is dominated by the production of the $\rho(770)$, which complicates the analysis of the underlying scalar resonances.

Before the Crystal Barrel experiment came into operation, the channel $\bar{p}p \to 3\pi^0$ had a data sample containing only 2100 events from optical spark chambers [11]. Crystal Barrel, on the other hand, obtained extremely high statistics of $\sim 700,000$ events for this reaction [12]. Besides the known resonances $f_0(980)$, $f_2(1270)$ and $f_2(1565)$, the Dalitz plot in Fig. 2 shows two new resonances:

$$\begin{array}{lll} f_0(1370): & m = 1330 \pm 50 \text{ MeV}, & \Gamma = 300 \pm 80 \text{ MeV} \\ f_0(1500): & m = 1500 \pm 15 \text{ MeV}, & \Gamma = 120 \pm 25 \text{ MeV} \end{array}$$

The $f_0(1500)$ has also been seen by Crystal Barrel in its decay modes into $4\pi^0$ ($\bar{p}p \to 5\pi^0$), $\eta\eta$ ($\bar{p}p \to \eta\eta\pi^0$), $\eta\eta'$ ($\bar{p}p \to \eta\eta'\pi^0$), and $K_L K_L$ ($\bar{p}p \to K_L K_L \pi^0$). An analysis of these channels, partly as a coupled-channel analysis using the K-matrix formalism [13, 14, 15], further constrains the masses and widths of these resonances:

$$\begin{array}{lll} f_0(1370): & m = 1360 \pm 23 \text{ MeV}, & \Gamma = 351 \pm 41 \text{ MeV} \\ f_0(1500): & m = 1505 \pm \ 9 \text{ MeV}, & \Gamma = 111 \pm 12 \text{ MeV} \end{array}$$

In addition to these new isoscalar states, Crystal Barrel has found a new isovector state [16] with the quantum numbers $J^{PC} = 0^{++}$ in the channel $\bar{p}p \to \eta\pi^0\pi^0$:

$$a_0(1450): \quad m = 1474 \pm 19 \text{ MeV} \quad \Gamma = 265 \pm 13 \text{ MeV}$$

The properties of the $a_0(1450)$ make it likely to be the $q\bar{q}$ isovector state of the scalar nonet that contains the well-established $K_0^*(1430)$. The $a_0(1450)$ would thus replace the $a_0(980)$, which is probably a $K\bar{K}$ molecule rather than a $q\bar{q}$ state. The closeness in mass of the $a_0(1450)$, $f_0(1370)$ and $f_0(1500)$ make it likely that at least one of the two latter states is the isoscalar state of the nonet, making the nonet close to ideally mixed. Finally, if the spin of the $f_J(1710)$ is indeed confirmed to be zero, it would be a candidate for the $s\bar{s}$ isoscalar state of the nonet. This is because it is observed in $\gamma\gamma$ collisions at LEP by the L3 collaboration in a $K_S K_S$ decay mode [17] but not by the ALEPH collaboration in the $\pi\pi$ decay mode [18]. However, the L3 spin assignment could be either 0 or 2.

The presence of three f_0 mesons with the same quantum numbers and similar masses would have at least two consequences:

1. since only two of them can be accommodated as ordinary $q\bar{q}$ nonet members within the quark model, one of them must be a QCD exotic; and
2. the three states mix with each other.

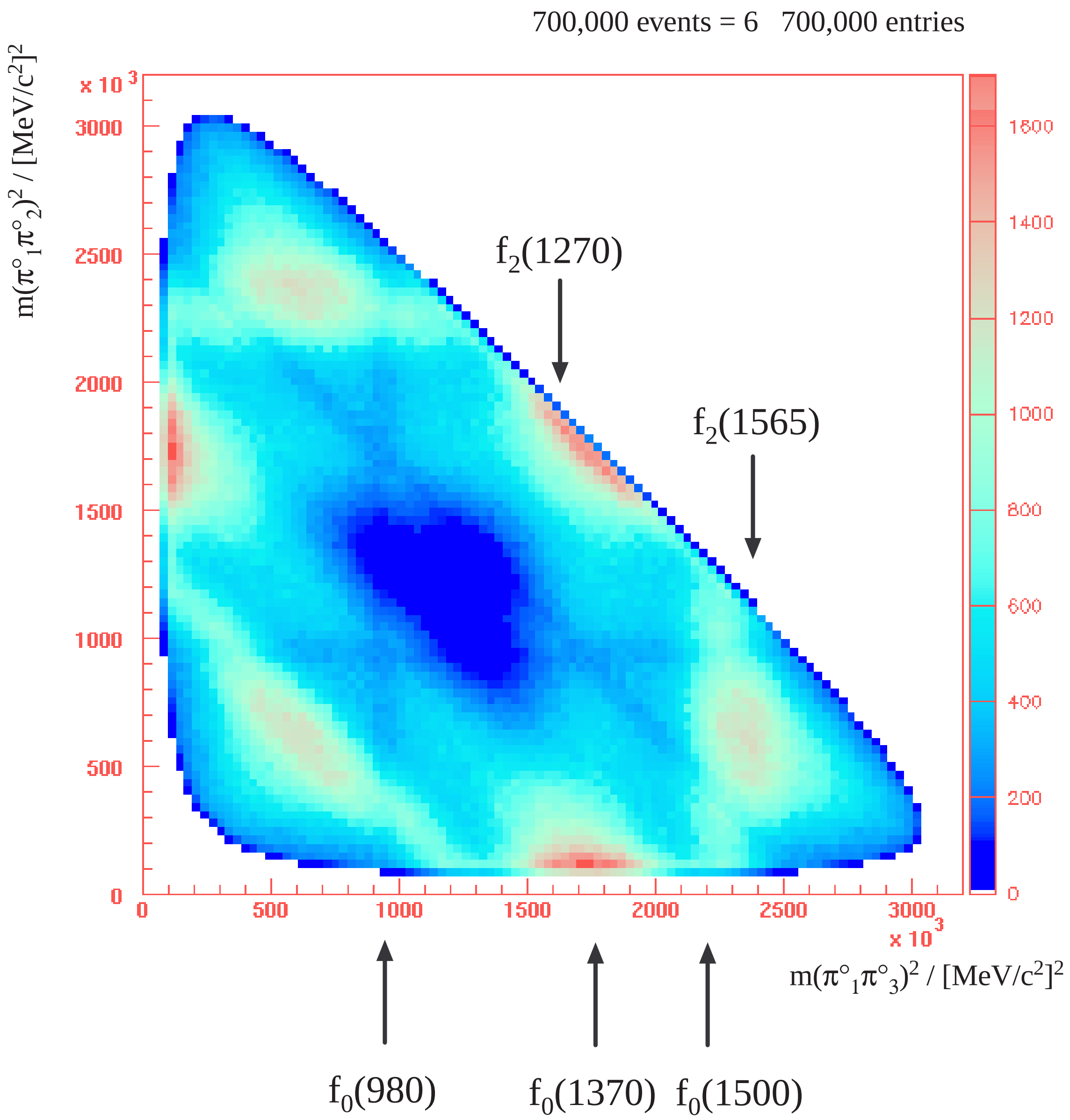

Figure 2: The $3\pi^0$ Dalitz plot. Each event appears six times for symmetry reasons.

Two different mixing schemes have been put forward, both of which assume two ordinary $q\bar{q}$ mesons and one 0^{++} glueball:

$$\begin{aligned}
f_0(1370) &= -0.43\,|G\rangle + 0.25\,|s\bar{s}\rangle + 0.87\,|(u\bar{u}+d\bar{d})/\sqrt{2}\rangle \\
f_0(1500) &= -0.22\,|G\rangle + 0.91\,|s\bar{s}\rangle - 0.36\,|(u\bar{u}+d\bar{d})/\sqrt{2}\rangle \\
f_0(1710) &= 0.88\,|G\rangle + 0.33\,|s\bar{s}\rangle + 0.34\,|(u\bar{u}+d\bar{d})/\sqrt{2}\rangle
\end{aligned}$$

and

$$\begin{aligned}
f_0(1370) &= -0.50\,|G\rangle + 0.13\,|s\bar{s}\rangle + 0.86\,|(u\bar{u}+d\bar{d})/\sqrt{2}\rangle \\
f_0(1500) &= 0.61\,|G\rangle - 0.61\,|s\bar{s}\rangle + 0.43\,|(u\bar{u}+d\bar{d})/\sqrt{2}\rangle \\
f_0(1710) &= 0.60\,|G\rangle - 0.76\,|s\bar{s}\rangle + 0.22\,|(u\bar{u}+d\bar{d})/\sqrt{2}\rangle
\end{aligned}$$

The first mixing scheme [19] sees the $f_0(1500)$ as the s$\bar{\text{s}}$ nonet member and identifies the $f_0(1710)$ with the glueball. The second mixing scheme [20, 21] has the $f_0(1500)$ as the glueball and most likely the $f_0(1710)$ as the s$\bar{\text{s}}$ nonet member.

The properties of the $f_0(1500)$ seem to favor the second mixing scheme and its interpretation of the $f_0(1500)$ as the glueball ground state. First, its width of about 100 MeV is much narrower than those of the $a_0(1450)$, $f_0(1370)$ and $K_0^*(1430)$, all of which are typically around ∼300 MeV; if the $f_0(1500)$ were a normal q$\bar{\text{q}}$ nonet member, one would expect it to have a width of at least 250 MeV. Second, an analysis by the ALEPH collaboration shows that the $f_0(1500)$ is not produced in $\gamma\gamma$ collisions, with an upper limit of $\Gamma\left(\gamma\gamma \to f_0(1500)\right) \cdot \mathrm{BR}\left(f_0(1500) \to \pi^+\pi^-\right) < 0.31$ keV [18]. This is significant because a q$\bar{\text{q}}$ meson would couple to $\gamma\gamma$, while a glueball does not. The latter argument clearly disfavors the $f_J(1700)$ as a glueball candidate because it is seen by L3 in $\gamma\gamma$ collisions.

The missing element in the interpretation of the $f_0(1500)$ is the unambiguous identification of the $f_J(1700)$ as a spin-zero state and determination of its decay pattern. Like L3, Crystal Barrel sees a state decaying into $K_\mathrm{S}K_\mathrm{S}$ [22]; but it sees no decay of such a state into $\eta\eta$ [23]. Clearly this is an indication for the s$\bar{\text{s}}$ nature of that state, though not enough information to finally claim it. The BABAR collaboration at SLAC sees a signal in $K_\mathrm{S}K_\mathrm{S}$ at a mass of around 1700 MeV/c^2 in D_S decays, which hints at a s$\bar{\text{s}}$ state. The data and the partial-wave analysis are awaiting publication.

Crystal Barrel has also searched for a narrow tensor glueball candidate $\xi(2230)$, which had been reported by the BES collaboration in radiative J/ψ decays [24, 25]. In a $\bar{\text{p}}$p formation experiment, the $\pi^0\pi^0$ and $\eta\eta$ decay channels were measured in a scan of the mass region between 2220 and 2240 MeV/c^2. No evidence for the existence of $\xi(2230)$ was found with a 95% confidence upper limit [26].

In the search for hybrids, Crystal Barrel concentrated on $\eta\pi$ and $\eta'\pi$ final states. A 1^{-+} hybrid would decay to $\eta\pi$ and $\eta'\pi$ with a relative P-wave between the two pseudoscalar mesons. Because such a state would be an isovector it cannot be confused with a glueball, which must be an isoscalar state. The quantum numbers 1^{-+} cannot be produced by a normal q$\bar{\text{q}}$ pair. A state with exactly these exotic quantum numbers was reported before Crystal Barrel by the GAMS collaboration at CERN [27], in the reaction $\pi^- p \to \pi^0 \eta\, n$; but a reanalysis of the data gave ambiguous solutions. More recently, in the reaction $\pi^- p \to \pi^- \eta\, p$ in a 18 GeV pion beam at BNL, an asymmetry in the forward/backward $\pi\eta$ angular distribution was explained by the existence of a 1^{-+} state [28].

Crystal Barrel studied the reaction $\bar{\text{p}}\text{p} \to \pi^-\pi^0\eta\, p_\text{spectator}$ [29], which corresponds to annihilation on a neutron. The advantage of this reaction is that no isoscalar resonances can contribute to this final state. The Dalitz plot (Fig. 3) with 52,567 events contains the $\rho^-(770)$ and the $a_2(1320)$. The strong presence of events in the $\eta\pi$ mass region around 1300 MeV, which appears only above the ρ band, hints at interferences between the $a_2(1320)$ and some other amplitude. Indeed, the partial-wave analysis requires the inclusion of a resonant $\eta\pi$ amplitude with relative P-wave between the two mesons. The mass and width of this 1^{-+} resonance are:

$$\pi_1(1400): \quad m = 1400 \pm 30 \text{ MeV}, \quad \Gamma = 310 \pm 70 \text{ MeV}$$

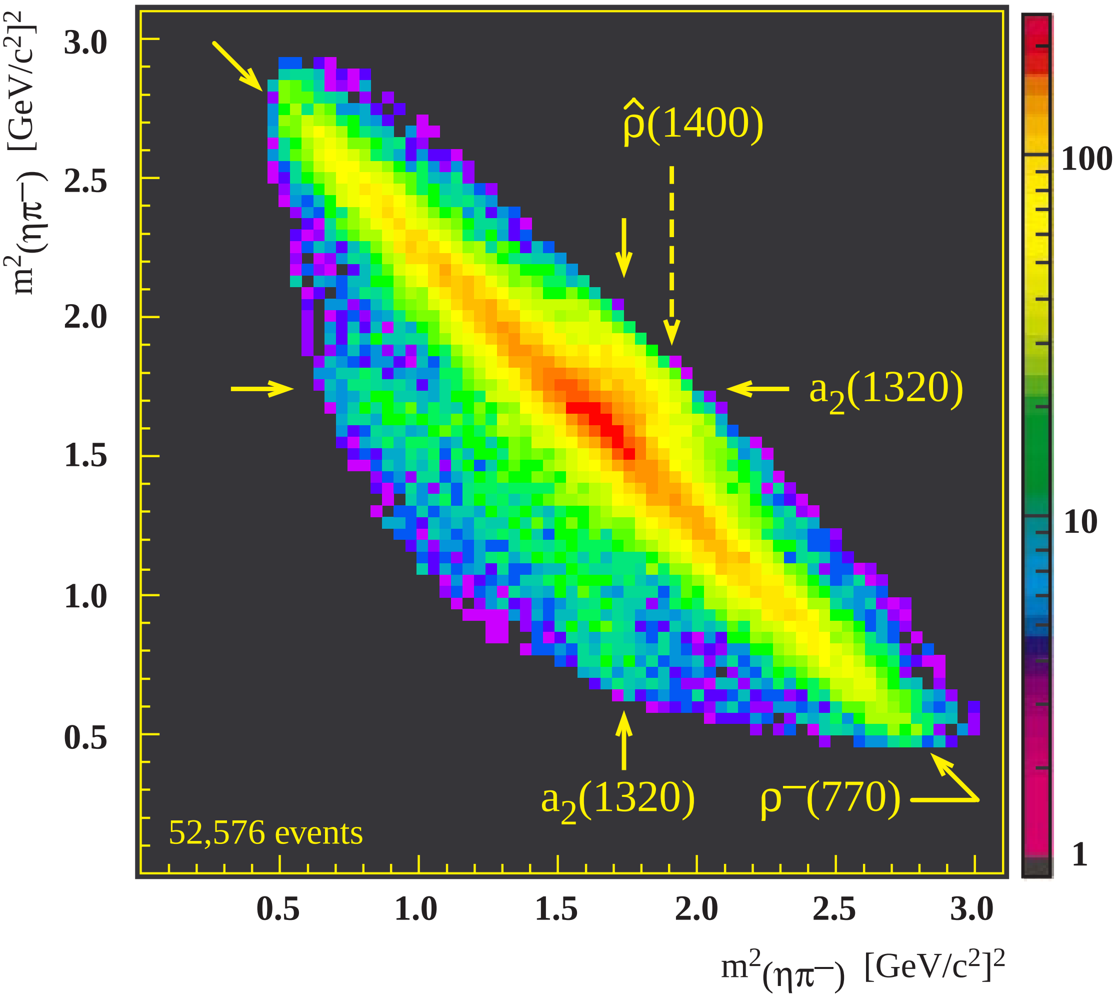

Figure 3: Dalitz plot of the reaction $\bar{p}p \to \pi^- \pi^0 \eta \, p_{\text{spectator}}$. The π_1 is shown with its old name $\hat{\rho}$.

The resonance draws 11% of the total intensity of the Dalitz plot, so its production rate in p̄p annihilation is comparable to those of normal mesons like the $a_2(1320)$ (15%). The quantum numbers of the $\pi_1(1400)$ are exotic and it could be a hybrid state or a four-quark resonance. However, if it were a four-quark state, one would have expected many of them to have been reported in other reactions (like $\gamma\gamma$ collisions).

5. Future searches for gluonic excitations

It is clear that precise measurements of the properties of several glueball or hybrid states and their comparison to qq̄ mesons would help us to understand QCD in the non-perturbative regime better.

But why is it so important to find the gluonic degrees of freedom? The elementary particles of the Standard Model gain their mass through the Higgs mechanism. However, only a few percent of the mass of the proton is due to the Higgs mechanism. The rest is created in an unknown way by the strong interaction. Glueballs would be massless without the strong interaction, and their predicted masses arise solely from the strong interaction. The possibility to study a whole spectrum of glueballs might therefore be the key to understanding the mass creation by the strong interaction.

From what we have seen so far, what is striking is the fact that glueballs and hybrids are produced in $\bar{\mathrm{p}}\mathrm{p}$ annihilations with the same strength as ordinary mesons. It therefore seems that the gluon richness of the annihilation process makes $\bar{\mathrm{p}}\mathrm{p}$ annihilations the prime search ground for gluonic excitations. Unfortunately, as mentioned earlier, the energy range of the LEAR machine was limited, and therefore higher-mass glueballs were out of reach. As shown in Fig. 1, the majority of them is predicted by lattice calculations to have a mass between 3 and 5 GeV/c^2. Because of this high mass, most of them are not accessible to radiative J/ψ decays and central production processes. A new antiproton machine seems to be the only chance to find them and study their properties. It is worth pointing out that in $\bar{\mathrm{p}}\mathrm{p}$ annihilations all glueballs, even those with exotic quantum numbers, can be produced directly.

Charmonium hybrids ($\mathrm{c\bar{c}g}$) are predicted above 4 GeV/c^2. The ground state has exotic quantum numbers ($J^{\mathrm{PC}} = 1^{-+}$) and is expected to be rather narrow. Lattice calculations predict its most-favored decay mode to be $\chi + (\pi^0\pi^0)_{\mathrm{S-wave}}$ [30, 31]. The appearance of the charmonium state in the decay channel facilitates the detection in the experiment.

The search for the gluonic degrees of freedom will be done in the future at the new proposed high-energy storage ring for antiprotons, HESR, at GSI in Darmstadt. At the HESR, the physics of strange and charm quarks will be accessible for hadron physics. This region is exactly the transition region between the perturbative QCD at short scales and strong QCD. The availability of cooled antiproton beams with momenta of up to 15 GeV/c at the HESR will provide a broad research program that includes, in addition to searches for gluonic degrees of freedom, many other interesting physics aspects such as:

- spectroscopy of charmonium states
- spectroscopy of hypernuclei and double hypernuclei
- in-medium modifications of charmed mesons
- search for CP violation in the charm sector.

6. The Antiproton Accelerator Complex

The GSI upgrade foresees the installation of several new accelerator rings. The 30 GeV protons from the SIS100 can be used to produce antiprotons that are subsequently collected, stored and cooled in two smaller storage rings. Those pre-cooled antiprotons can then be transferred via the SIS100 into a dedicated antiproton storage ring called HESR, which will be equipped with one internal target station. The HESR will provide antiprotons with momenta between 1.5 and 15 GeV/c, giving a cm-energy of up to 5.5 GeV. The beam will be stochastically cooled over the whole momentum range giving a beam momentum spread of $\delta p/p = 10^{-4}$. For the high-precision charmonium spectroscopy, an additional high-energy electron cooling for momenta of up to 8 GeV/c is foreseen. This additional electron cooling is expected to bring the momentum spread down to $\delta p/p = 10^{-5}$.

The antiproton program is only part of the whole proposed GSI upgrade. However, to make best use of the facility, the accelerator complex is optimized for maximum parallel operation between the antiproton physics program and the other physics programs. A more detailed description can be found in the conceptual design report, which is available on the internet under http://www.gsi.de/GSI-Future/cdr/.

7. The PANDA Detector

Most of the experimental program will be done with a general-purpose detector. This detector is currently being designed by the PANDA group, which consists of 36 institutions worldwide.[1]

To achieve the physics aims, the detector needs to cover the full solid angle. Good particle identification and high energy and angular resolutions for charged particles and photons are mandatory. Therefore, the internal target, which could be a pellet target of frozen hydrogen droplets or a gas jet target, is surrounded by Si-pixel detectors in the vertex region. The main vertex tracking further out is done with straw chambers and mini drift chambers. Ring-imaging Cherenkov counters will provide the particle identification. The electromagnetic calorimeter proposed is an arrangement of $PbWO_4$ crystals, read out by avalanche photo diodes. A superconducting solenoid (2 T) and a dipole magnet in the forward direction provide the magnetic field for the tracking. Finally, muon counters are placed outside the iron yoke. The inner part of the detector can be modified to fulfill the needs for experiments with strange hypernuclei. More up-to-date information on PANDA is available at http://www.gsi.de/hesr/panda.

8. Conclusions

The LEAR experiments have collected orders of magnitude more antiproton-proton annihilation data than previous experiments. The high-statistics data samples allowed the discovery of several new resonances. One of them, the $f_0(1500)$, is a prime candidate for the long-awaited glueball ground state. In addition, Crystal Barrel has established a resonance with clearly exotic quantum numbers ($J^{\mathrm{PC}} = 1^{-+}$), which cannot be a normal $\mathrm{q\bar{q}}$ meson.

Clearly therefore a new type of spectroscopy seems to be evolving: the spectroscopy of QCD exotics. It may be precisely this spectroscopy that will enlarge our knowledge about gluonic excitations. Since gluons are associated with confinement, QCD-exotic spectroscopy could play a key role in solving this important question of nature and in unveiling the secrets of mass creation by the strong interaction.

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[1] Bochum, Bonn, Brescia, Catania, Cracow, Dresden, Dubna I & II, Erlangen, Ferrara, Frascati, Genova I & II, Giessen, Glasgow, KVI Groningen, FZ Jülich I & II, Los Alamos, Mainz, TU München, Münster, Northwestern, BINP Novosibirsk, Pavia I & II, Silesia, Torino, Dep. A. Avogadro Torino, Torino Politecnico,Trieste, TSL Uppsala, Tübingen, Uppsala, SINS Warsaw, AAS Wien.

Previous antiproton experiments have proven that the annihilation process is an extremely rich source of gluons and gluonic states; glueballs and hybrids are formed in numbers similar to those of regular mesons. Unfortunately, the LEAR accelerator was limited in energy and most of the QCD-exotic states are thought to have a mass beyond this limit (Fig. 1). Therefore, to continue the very successful work in spectroscopy, a new high-quality antiproton accelerator is needed that does not have the energy limitations of LEAR. As part of its upgrade, GSI proposed the contruction of a dedicated antiproton facility for cooled antiprotons with momenta of up to 15 GeV/c. The future antiproton storage ring HESR will be equipped with a universal detector named PANDA. Following the recent approval of this program by the German government, our knowledge of gluonic excitations like glueballs and hybrids, and together with it our knowledge of the strong interaction, will improve dramatically in the future.

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