Light-Quark Spectroscopy with Antiproton-Proton Annihilation

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Introduction

Hadron spectroscopy is the basis that inspired the SU(3) quark model and the QCD theory of strong interactions. QCD is a non-Abelian gauge theory, and as a consequence the gauge bosons, the gluons, can interact with each other. One of the striking predictions of QCD in the non-perturbative regime is thus 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^{PC} quantum numbers for those states, where J denotes the total angular momentum of the resonance. Some J^{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 compared 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 production processes, and antiproton-proton annihilation. Because of the existence of LEAR at CERN, antinucleon-nucleon ($\bar{N}N$) annihilation data now dominate.

The Crystal Barrel Experiment at LEAR

The study of $\bar{p}p$ annihilation has been underway for the past thirty years. Several bubble chamber experiments at CERN and BNL first investigated this topic. 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 $\bar{p}$/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 which 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 this experiment in my talk. The Crystal Barrel collaboration, composed of over 70 scientists from 13 different institutions, aimed to construct a detector that covers almost the entire 4π solid angle and detects neutral particles as effectively as charged particles. Figure 1 shows an overview of the detector setup. The detector is located inside a magnet that produces a field of 1.5 T. Antiprotons enter the detector from the left side and annihilate in a liquid hydrogen target. The silicon vertex detector (SVX) around the target provides fast information on the charged multiplicity of the annihilation event. It also gives additional information on the r/ϕ coordinates for charged particles close to the annihilation point in the target. The SVX is located inside the main detector for charged-particle tracking, a jet drift chamber (JDC) which measures tracks with a resolution of 125 μm. While the JDC determines the momentum of charged particles, the electromagnetic calorimeter can also detect neutral particles with the use of its

1380 individual crystals. Crystal Barrel used thallium-doped CsI crystals to cover an azimuthal angle of almost 4π and polar angles from 12° to 168°. The whole arrangement is designed to provide high-efficiency photon detection with good energy and spatial resolution in the energy range between 10 MeV and 2000 MeV. A more detailed description of the detector can be found in [1].

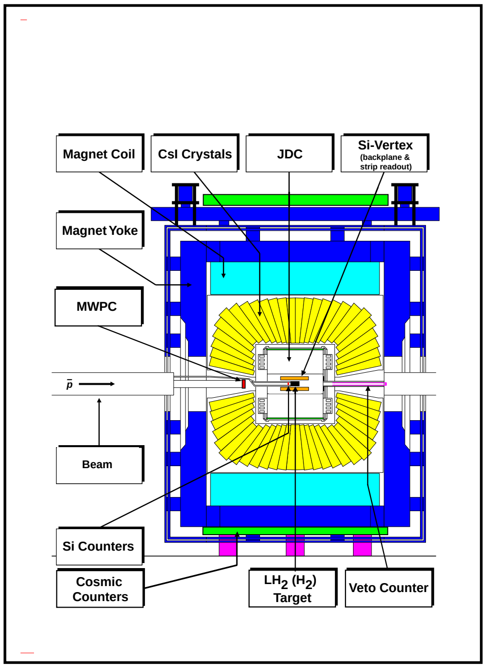


Figure 1: The Crystal Barrel detector

Theoretical Predictions

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

$$P(\overline{q}q) = (-1)^{L}$$
$$C(\overline{q}q) = (-1)^{L+S}$$

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

$$P(\overline{q}q) = (-1)^{L+1}$$
$$C(\overline{q}q) = (-1)^{L+S}$$

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 $q\overline{q}$ meson spectrum and can be taken as guidelines for the masses and quantum numbers of non-$q\overline{q}$ states. The flux-tube models in particular predict the masses [8] and the decays [9] of mesons with surprising accuracy. With the increase in available computing power, lattice QCD calculations have also improved significantly in recent years. In the meantime, a whole spectrum of glueballs with different quantum numbers has been predicted (Fig. 2) [10]. Because of the LEAR energy limitations, the only glueballs that seem accessible to the Crystal Barrel experiment are the scalar glueball ($J^{PC}=0^{++}$) with a mass of ~1.6 GeV, and the tensor (2^{++}) and pseudoscalar (0^{-+}) glueballs with masses of ~2.2 GeV.

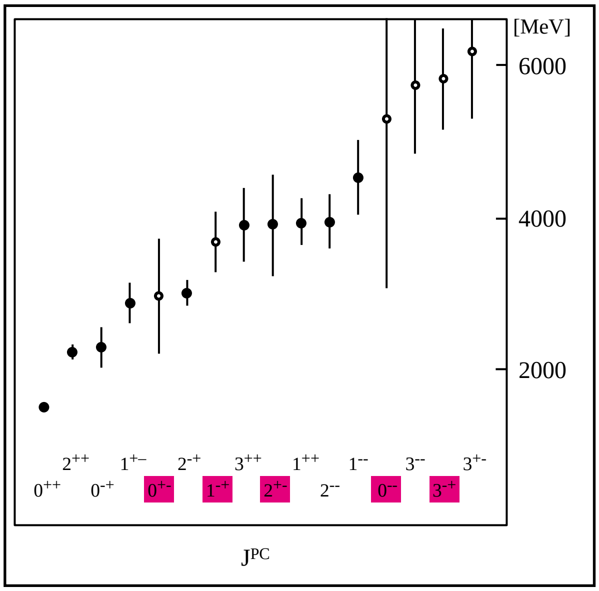


Figure 2: The glueball spectrum predicted by lattice calculations [10]. Exotic quantum numbers are marked as boxes.

Results

The simplest process in which to look for scalar resonances ($J^{PC}=0^{++}$) is antiproton-proton annihilation at rest into 3 pseudoscalars. In such a process, the scalar resonance $0^{+} \rightarrow 0^{-}0^{-}$ decays into 2 pseudoscalars and 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 ρ(770), which complicates the analysis of the underlying scalar resonances.

Before the Crystal Barrel experiment came into operation, the channel $\bar{p}p \rightarrow 3\pi^\circ$ had a data sample containing only 2100 events from optical spark chambers [11]. Crystal Barrel, on the other hand, obtained extremely high statistics of ~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. 3 shows two new resonances:

$f_0(1370)$: $m = 1330 \pm 50$ MeV $\Gamma = 300 \pm 80$ MeV
$f_0(1500)$: $m = 1500 \pm 15$ MeV $\Gamma = 120 \pm 25$ MeV.

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

$f_0(1370)$: $m = 1360 \pm 23$ MeV $\Gamma = 351 \pm 41$ MeV
$f_0(1500)$: $m = 1505 \pm 9$ MeV $\Gamma = 111 \pm 12$ MeV.

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 $\bar{p}p \rightarrow \eta\pi^\circ\pi^\circ$:

$a_0(1450)$: $m = 1474 \pm 19$ MeV $\Gamma = 265 \pm 13$ 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 $f_0(1370)$

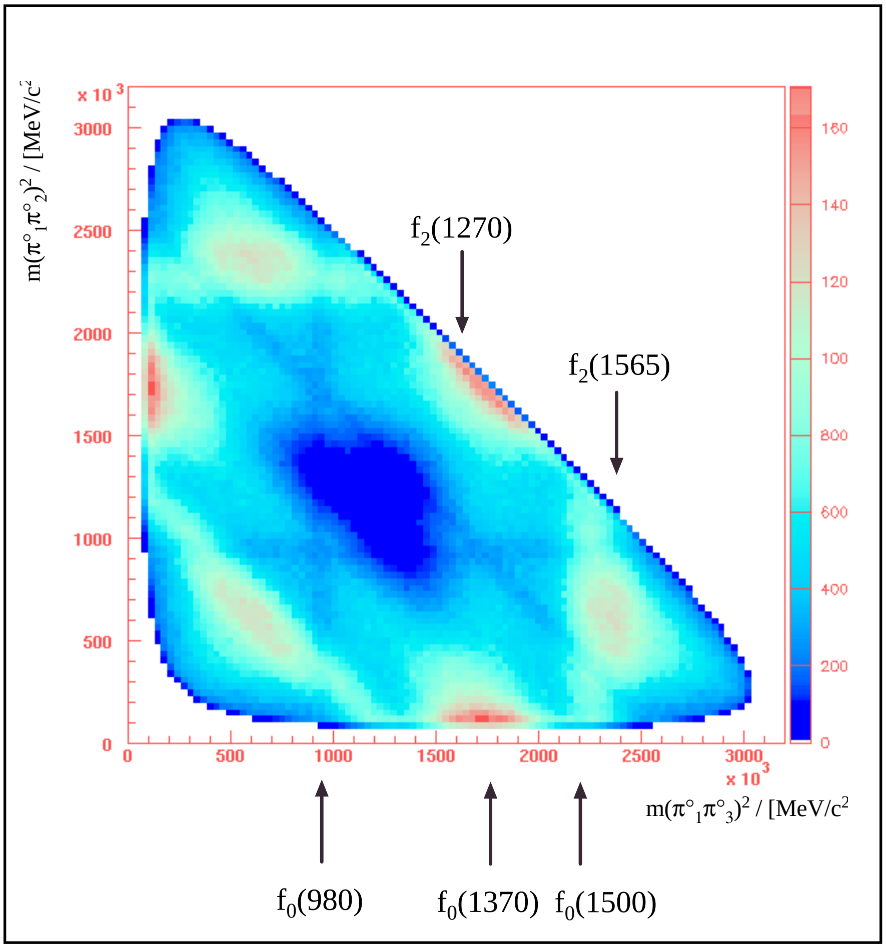


Figure 3: 3π° Dalitz plot. Each event appears six times for symmetry reasons.

and $f_0(1500)$ make it likely that at least one of these 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. It is observed in γγ collisions at LEP by the L3 collaboration in a K_SK_S decay mode [17], but not by the ALEPH collaboration in the ππ 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 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. Two different mixing schemes have been put forward, both of which assume two ordinary $q\bar{q}$ mesons and one 0^{++} glueball:

$$\begin{aligned}
f_0(1370) &= -0.43\,|G\rangle + 0.25\,|s\bar{s}\rangle + 0.87\,|1/\sqrt{2}\,(u\bar{u}+d\bar{d})\rangle \\
f_0(1500) &= -0.22\,|G\rangle + 0.91\,|s\bar{s}\rangle - 0.36\,|1/\sqrt{2}\,(u\bar{u}+d\bar{d})\rangle \\
f_0(1710) &= 0.88\,|G\rangle + 0.33\,|s\bar{s}\rangle + 0.34\,|1/\sqrt{2}\,(u\bar{u}+d\bar{d})\rangle
\end{aligned}$$

and

$$\begin{aligned}
f_0(1370) &= -0.50\,|G\rangle + 0.13\,|s\bar{s}\rangle + 0.86\,|1/\sqrt{2}\,(u\bar{u}+d\bar{d})\rangle \\
f_0(1500) &= 0.61\,|G\rangle - 0.61\,|s\bar{s}\rangle + 0.43\,|1/\sqrt{2}\,(u\bar{u}+d\bar{d})\rangle \\
f_0(1710) &= 0.60\,|G\rangle - 0.76\,|s\bar{s}\rangle + 0.22\,|1/\sqrt{2}\,(u\bar{u}+d\bar{d})\rangle
\end{aligned}$$

The first mixing scheme [19] sees the $f_0(1500)$ as the $s\bar{s}$ 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 $s\bar{s}$ nonet member.

The properties of the $f_0(1500)$ seem to favor the second mixing scheme. 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; one would have expected the $f_0(1500)$ 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, giving an upper limit of $\Gamma(\gamma\gamma \to f_0(1500) \bullet BR(f_0(1500) \to \pi^+\pi^-)$ < 0.31 keV [18]. This is significant because a $q\bar{q}$ meson would couple to $\gamma\gamma$, while a glueball does not. The latter argument clearly disfavors the $f_J(1700)$ as glueball candidate since 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 spin 0 state and its decay pattern. Crystal Barrel sees a state decaying into K_SK_S [22] similar like L3, but no decay of such a state into $\eta\eta$ [23]. Clearly this is an indication for a $s\bar{s}$ nature of that state, but not enough information to finally claim it.

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 also cannot be confused with a glueball, which must be an isoscalar state. The quantum numbers 1^{-+} cannot be produced by a normal $q\bar{q}$ pair. A state with exactly these exotic quantum numbers was reported before Crystal Barrel by the GAMS collaboration at CERN [24] in the reaction $\pi^-p \to \pi^\circ\eta n$; but a reanalysis of the data gave ambiguous solutions. More recently, in the reaction $\pi^-p \to \pi^-\eta p$ in an 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 [25].

Crystal Barrel studied the reaction $\bar{p}p \to \pi^-\pi^\circ\eta p_{spectator}$ [26], which corresponds to the annihilation on a neutron. The advantage of this reaction is that no isoscalar resonances can contribute to this final state. The Dalitz plot (Fig. 4) 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 that 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

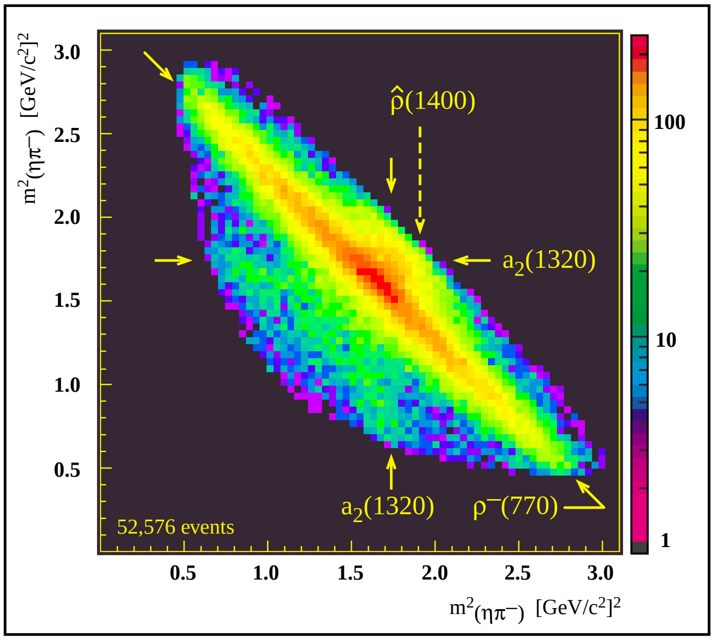


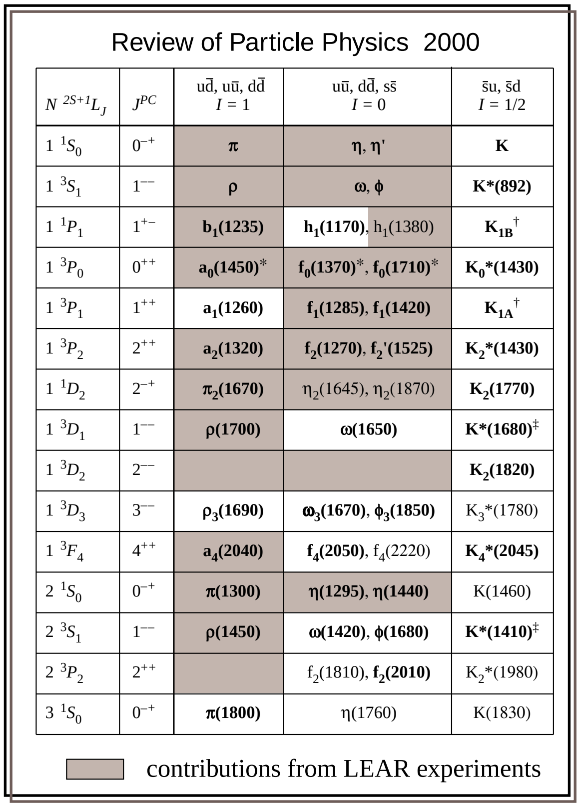
Figure 4: Dalitz plot of the reaction $\bar{p}p \to \pi^-\pi^\circ\eta p_{spectator}$ (52576 events).

with relative P-wave between the two mesons. The mass and width of this 1^{-+} resonance are:

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

The resonance draws 11% of the total intensity of the Dalitz plot, so its production rate in $\bar{p}p$ annihilation is comparable with those of normal mesons like the $a_2(1320)$ (15%). The quantum numbers of this state are exotic and it could be a hybrid state or a four-quark resonance.

Beside the spectroscopy of states containing gluonic degrees of freedom, all LEAR experiments have contributed to many aspects of meson spectroscopy. If we do not consider open strangeness mesons, for almost every meson below 2 GeV there is an entry from antiproton experiments in the newest edition of the Particle Data Book [27] as shown in Fig. 5 .



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$N\ ^{2S+1}L_J$	J^{PC}	$u\bar{d}$, $u\bar{u}$, $d\bar{d}$ $I = 1$	$u\bar{u}$, $d\bar{d}$, $s\bar{s}$ $I = 0$	$\bar{s}u$, $\bar{s}d$ $I = 1/2$
$1\ ^1S_0$	0^{-+}	▨ **π**	▨ **η, η'**	**K**
$1\ ^3S_1$	1^{--}	▨ **ρ**	▨ **ω, ϕ**	**K*(892)**
$1\ ^1P_1$	1^{+-}	▨ **$b_1(1235)$**	**$h_1(1170)$**, ▨ $h_1(1380)$	**K_{1B}**†
$1\ ^3P_0$	0^{++}	▨ **$a_0(1450)$***	▨ **$f_0(1370)$***, **$f_0(1710)$***	**$K_0^*(1430)$**
$1\ ^3P_1$	1^{++}	**$a_1(1260)$**	▨ **$f_1(1285)$, $f_1(1420)$**	**K_{1A}**†
$1\ ^3P_2$	2^{++}	▨ **$a_2(1320)$**	▨ **$f_2(1270)$, $f_2'(1525)$**	**$K_2^*(1430)$**
$1\ ^1D_2$	2^{-+}	▨ **$\pi_2(1670)$**	▨ $\eta_2(1645)$, $\eta_2(1870)$	**$K_2(1770)$**
$1\ ^3D_1$	1^{--}	▨ **$\rho(1700)$**	**$\omega(1650)$**	**$K^*(1680)$**‡
$1\ ^3D_2$	2^{--}	▨	▨	**$K_2(1820)$**
$1\ ^3D_3$	3^{--}	**$\rho_3(1690)$**	**$\omega_3(1670)$, $\phi_3(1850)$**	$K_3^*(1780)$
$1\ ^3F_4$	4^{++}	▨ **$a_4(2040)$**	**$f_4(2050)$**, $f_4(2220)$	**$K_4^*(2045)$**
$2\ ^1S_0$	0^{-+}	▨ **$\pi(1300)$**	▨ **$\eta(1295)$, $\eta(1440)$**	$K(1460)$
$2\ ^3S_1$	1^{--}	▨ **$\rho(1450)$**	**$\omega(1420)$, $\phi(1680)$**	**$K^*(1410)$**‡
$2\ ^3P_2$	2^{++}	▨	$f_2(1810)$, **$f_2(2010)$**	$K_2^*(1980)$
$3\ ^1S_0$	0^{-+}	**$\pi(1800)$**	$\eta(1760)$	$K(1830)$

▨ contributions from LEAR experiments

Figure 5: Contributions of LEAR experiments to the RPP2000.

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 $J^{PC} = 1^{-+}$which cannot be a normal $q\bar{q}$ meson.

Clearly therefore a new type of spectroscopy seems to evolve, the spectroscopy of QCD exotics. It might be exactly this spectroscopy that will enlarge our knowledge about the “constituent gluon,” at least to me no other way is known. Since the gluons are associated with confinement, QCD-exotic spectroscopy could play a key role for solving this important question of nature.

Previous antiproton experiments have proved that the annihilation process is an extremely rich source of gluons, and gluonic states like glueballs and hybrids are formed in similar numbers as regular mesons. Unfortunately the LEAR accelerator was limited in energy and most of the QCD-exotic states are considered to have a mass beyond this limit (Fig. 2). Therefore, to continue the very successful work in terms of spectroscopy, a new high quality antiproton accelerator, that has not the energy limitations of LEAR, should be built. Together with a modern experimental setup it will provide essential information on the strong interaction and help to understand confinement.

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