**Multi-GeV Gluonic Mesons**

Philip R. Page
*Theoretical Division, MS-B283, Los Alamos National Laboratory*
*Los Alamos, NM 87545*

**Abstract**

Lattice QCD gives reliable predictions for hybrid charmonium and multi-GeV glueball masses. Proton-antiproton annihilation may offer an excellent opportunity for the first observation of these states. There are two distinct possible programs: The search for $J^{PC}$-exotic *and* non-$J^{PC}$-exotic states. The latter program represents substantially higher cross sections and does not absolutely require partial wave analysis, two very attractive features. The program can be performed with a varying $\bar{p}$ energy $< 10$ GeV and a fixed target.

## 1 Introduction

From the theoretical side, the most interesting problem in medium energy physics is the mechanisms of strong QCD. Particularly, explicit glue tests QCD's strong gluonic interactions. The spectroscopy of the new states of matter with explicit glue, called *gluonic hadrons*, is essentially unknown. Within the taxa of possible gluonic hadrons, charmonium hybrids are under better theoretical control, due to heavy quarks, and experimentally cleaner, due to smaller widths, than light flavour hybrids. Glueball masses are well known theoretically, and there is the possibility that glueballs may be narrow in experiment.

The kinematics of a $\bar{p}$ with energy $E$ colliding with a $p$ at rest are expressed by

$$W^2 = 2m_p\,(m_p + \sqrt{m_p^2 + E^2}) \tag{1}$$

with $W$ the centre-of-mass energy and $m_p$ the mass of the proton. An immediate application of this formula is that for $E < 10$ GeV, $W < 4500$ MeV. As we shall see, this is perfectly sufficient for the study of hybrid charmonia and multi-GeV glueballs. The main qualitatively-new physics of interest above this $W$ region are the lowest-mass experimentally-undiscovered baryons with new flavours: double-charmed baryons. These will have $W \gtrsim 2 \times 3650$ MeV, so that $E \gtrsim 27$ GeV. Also of interest are the lowest-mass new-flavoured mesons: bottom-charm mesons. Here $W \geq 2 \times (6.40 \pm 0.39 \pm 0.13)$ GeV [1] and $E \gtrsim 86$ GeV. It is clear that there are vast energy deserts between $E$ of 10 GeV, 27 GeV and 86 GeV.

The competition for the physics program outlined here comes from the proposed Glue/Charm Factory at GSI Darmstadt, where $E < 15$ GeV [2].

## 2 Gluonic Mesons

### 2.1 Hybrid charmonia

These are charm-anticharm-glue composites. Many quenched lattice-QCD mass predictions for unmixed hybrid charmonium are available. Hence masses are under theoretical control. The quantum numbers of the eight low-lying hybrids are $J^{PC} = 1^{--}$, $(0,1,2)^{-+}$, $1^{++}$, and $(0,1,2)^{+-}$.

Decays are under less control, although there is a fairly general selection rule stating that the low-lying hybrid charmonia do not decay to $D\bar{D}$, $D^*\bar{D}^*$, $D_s\bar{D}_s$, $D_s^*\bar{D}_s^*$ and have only small decays to $D\bar{D}^*$, $D_s\bar{D}_s^*$. These final states are called *open charm.* The selection rule holds for OZI-allowed decay with nonrelativistic quarks. The $q\bar{q}$ pair is assumed to be created with nonrelativistic spin 1 [3]. The phenomenology of meson decay strongly supports spin 1 pair creation. The specific case of the $J^{PC} = 0^{+-}$ hybrid is particularly interesting. Its decays to $D\bar{D}$, $D^*\bar{D}^*$, $D^*\bar{D}$, $D_s\bar{D}_s$, $D_s\bar{D}_s^*$, $D_s^*\bar{D}_s^*$ are forbidden by general principles due to quantum numbers. The threshold for one orbitally-excited and one ground-state charmed meson, the $D^{**}D$ threshold, is at 4290 MeV. Below this threshold hybrid charmonium is narrow. Total widths for the $0^{+-}$ and $1^{-+}$ states have, for example, been estimated as respectively $\mathcal{O}$ (5, 20) MeV below the threshold [4, 5]. The main conclusion to draw is that there is a strong possibility that hybrid charmonia are narrower than the $\sim 50$ MeV/$c^2$ widths of conventional charmonia in the same mass region [1].

The most obvious search channel is the decay of hybrid charmonium to conventional charmonium and light hadrons. This final state signals the $c\bar{c}$ nature of initial state. The most easily detected conventional charmonium is the $\psi$ with a substantial branching ratio into dileptons [1].

In $p\bar{p}$ annihilation at LEAR there are indications that the light-flavour hybrid-meson candidates $\hat{\rho}(1405)$ and $\rho(1450)$ are produced with substantial cross sections [6], comparable to or slightly less than conventional mesons. This is the main production process studied to date where hybrid mesons are significantly produced, underscoring the utility of $p\bar{p}$ annihilation as a choice for hybrid production.

### 2.2 Glueballs

These are gluonic composites without quark content. Good quenched lattice-QCD mass predictions are available for unmixed glueballs, providing theoretical control.

Unmixed glueballs are believed to be narrow because the process whereby $q\bar{q}$ pairs are created to enable decay into mesons is forbidden by the OZI rule. I shall outline three further reasons to believe that multi-GeV glueballs are narrow. Firstly, the flattening of the linear confining potential between quarks due to pair creation at large $q\bar{q}$ separations implies that there are no light-flavour conventional mesons $\gtrsim 3100 \pm 110$ MeV/$c^2$ in mass [7]. Secondly, the mixing of glueballs with charmonium is likely to be small due to the penalty incurred by the creation of a $c\bar{c}$ pair. These arguments suggest that the glueball will not mix substantially with light-flavour conventional mesons or charmonia. Thirdly, as will be demonstrated below, most multi-GeV glueballs in the mass region of interest do not decay to two other glueballs because of quantum numbers. The above strongly argue that multi-GeV glueballs are narrow. The main fly in the ointment is the possibility of mixing with light-flavour hybrid mesons.

The production of the glueball candidate $f_0(1500)$ in $p\bar{p}$ annihilation at LEAR is substantial, comparable to other mesons, but weaker than, for example, the $f_2$ [8]. Hence $p\bar{p}$ annihilation is well suited for glueball production. In fact, it is commonly thought to be a "glue-rich" process.

The main focus of this paper will be on hybrid charmonium. The discussions of hybrid charmonium and the glueball are somewhat different because hybrid charmonium's telltale decay to $\psi$ and light hadrons is so different from the purely light-hadron decays expected for the glueball. As we shall see, there is also a large difference in production cross sections.

## 3 $J^{PC}$ Exotics

When a list of the possible $J^{PC}$ of conventional mesons is made, there are certain $J^{PC}$'s which are not possible. These "exotic" $J^{PC} = 0^{--},\ 0^{+-},\ 1^{-+},\ 2^{+-},\ldots$ immediately indicate that the state is not a conventional meson. In the mass region of interest, it is most likely to be hybrid charmonium or a glueball, or possibly a four-quark state ($q\bar{q}q\bar{q}$). The detection of a $J^{PC}$ exotic state must hence be assigned the highest priority in the search for gluonic mesons. The advantage is that they cannot mix with conventional mesons. The flip side of the coin is that the $J^{PC}$ must be established experimentally, *i.e.* one needs detailed angular distributions and preferably a full partial-wave analysis (PWA).

### 3.1 Hybrid $c\bar{c}$: Mass

Quenched lattice-QCD mass predictions for hybrid charmonia are given in Table 1.

| $1^{-+}$ | $0^{+-}$ | Ref. |
|---|---|---|
| $4410^{+60}_{-150} \pm \text{sys}$ | $4560^{+110}_{-100} \pm \text{sys}$ | [9] |
| $4290^{+110}_{-190} \pm \text{sys}$ | $4560^{+80}_{-110} \pm \text{sys}$ | [9] |
| $4390 \pm 80 \pm 200$ | $4610 \pm 110 \pm 200$ | [10] |

Table 1: Quenched lattice-QCD mass predictions for hybrid charmonia in MeV/$c^2$.

| $J^{PC}$ | Open charm | Hidden charm | Light hadrons |
|---|---|---|---|
| $0^{+-}$ | Forbidden for all cominations of $D^{(*)}D^{(*)}$ | $J/\psi\{f_{\{0,1,2\}},(\pi\pi)_S\}$<br>$h_c\eta;\ \eta_c h_1$<br>$\chi_{c0}\omega$<br>$\chi_{c\{1,2\}}\{\omega,h_1,\gamma\}$ | $a_{\{0,1,2\}}\rho;\ a_{\{1,2\}}\{b_1,\gamma\}$<br>$b_1\pi;\ h_1\eta^{(')}$<br>$\{(\pi\pi)_S,f_0\}\{\omega,\phi\}$<br>$f_{\{1,2\}}\{\omega,h_1,\phi,\gamma\}$ |
| $0^{--}$ | $D^*D$ | $h_c(\pi\pi)_S$<br>$J/\psi\{f_{\{1,2\}},\eta^{(')}\}$<br>$\chi_{c0}h_1;\ \eta_c\{\omega,\phi\}$<br>$\chi_{c\{1,2\}}\{\omega,h_1,\gamma\}$ | $a_{\{0,1,2\}}b_1;\ a_{\{1,2\}}\{\rho,\gamma\}$<br>$\rho\pi$<br>$f_0h_1;\ \eta^{(')}\{\omega,\phi\}$<br>$f_{\{1,2\}}\{\omega,h_1,\phi,\gamma\}$ |
| $1^{-+}$ | $D^*D,\ D^*D^*$ | $\chi_{c\{0,1,2\}}(\pi\pi)_S$<br>$\eta_c\{f_{\{1,2\}},\eta^{(')}\}$<br>$\chi_{c\{1,2\}}\eta$<br>$\{h_c,J/\psi\}\{\omega,h_1,\phi,\gamma\}$ | $a_{\{0,1,2\}}a_{\{0,1,2\}};\ a_{\{1,2\}}\pi$<br>$f_{\{0,1,2\}}f_{\{0,1,2\}};\ f_{\{1,2\}}\eta^{(')}$<br>$\{\rho,\gamma\}\{\rho,b_1\};\ b_1b_1$<br>$\{\omega,h_1,\phi,\gamma\}\{\omega,h_1,\phi,\gamma\}$ |
| $2^{+-}$ | $D^*D,\ D^*D^*$ | $\{h_c,J/\psi\}\{f_{\{0,1,2\}},(\pi\pi)_S\}$<br>$\{h_c,J/\psi\}\eta^{(')}$<br>$\{\eta_c,\chi_{c\{0,1,2\}}\}\{\omega,h_1,\phi,\gamma\}$ | $a_{\{0,1,2\}}\{\rho,b_1,\gamma\}$<br>$\{\rho,\gamma,b_1\}\pi$<br>$\{\eta^{(')},f_{\{0,1,2\}}\}\{\omega,h_1,\phi,\gamma\}$ |

Table 2: Some possible experimentally-accessible final states of $J^{PC}$-exotic hybrid charmonia and glueballs below $D^{**}D$ threshold [4]. Decays to $p\bar{p}\{\pi,\eta^{(')},\omega,\rho,\phi\}$ are allowed for all states listed.

As indicated in subsection 2.1, below the $D^{**}D$ threshold the $1^{-+}$ and $0^{+-}$ hybrid charmonia are expected to be narrow. It is clear that mass predictions for the $1^{-+}$ straddle the $D^{**}D$ threshold, while the $0^{+-}$ is most likely above the threshold. The $2^{+-}$ and $0^{--}$ exotics are probably above the threshold too, if lattice calculations for light-quark hybrids serve as a guide. Hence one concludes that there is likely to be no more than one narrow exotic hybrid charmonium!

### 3.2 Hybrid $c\bar{c}$: Production

The first production process, $p\bar{p}\to$ exotic, is called *formation*. This process can not produce $J^{PC}$-exotic states, though. This follows because the $p\bar{p}$ system, just like the $q\bar{q}$ system, cannot be $J^{PC}$ exotic. For $\bar{p}$ in flight a large tower of $J^{PC}$ is accessed by the $p\bar{p}$ system, but none of these is exotic.

The second process, $p\bar{p}\to$ exotic $+(\pi^0,\ \pi\pi,\ \pi\pi\pi,\ \eta,\ldots)$, can produce $J^{PC}$-exotic states, and is called *production*. When the extra light hadron, *e.g.* the $\pi^0$, is accounted for, the condition $E<10$ GeV is equivalent to $m_{\text{exotic}}<4360$ MeV$/c^2$. This bound is above the $D^{**}D$ threshold, so that there is no need for a $\bar{p}$ energy above 10 GeV.

### 3.3 Hybrid $c\bar{c}$: decay

From the list of possible decay modes in Table 2 the easy ones involving $\psi$ are $1^{-+} \to \psi\ (\omega, \phi, \gamma) \to e^+e^-e^+e^-$ or $e^+e^-\gamma$. The radiative decay is likely to have a small branching ratio, since it is electromagnetic, and the $\omega$ and $\phi$ have small branching ratios to $e^+e^-$ [1]. Direct detection of all final-state particles may hence be problematic. In the decay $0^{+-} \to \psi\ (\pi\pi)_S\ [\psi\pi^0\pi^0] \to e^+e^-\gamma\gamma\gamma\gamma$ one looks at the $\pi^0\pi^0$ combination because that can only be in an even wave by Bose symmetry. Here identification of all final products is most likely to be hampered by the large $\pi\pi$ background in $p\bar{p}$ annihilation. Instead of detecting all final-state particles, the technique of missing mass may be more promising: detect only the $\pi^0$ and $\psi$ in $p\bar{p} \to$ exotic $\pi^0 \to \psi X \pi^0$.

### 3.4 Hybrid $c\bar{c}$: cross section

The cross section for production of the $\psi$ is $\sigma(p\bar{p} \to \psi\pi^0) = 130 \pm 25$ pb [11]. As pointed out in subsection 2.1, the $J^{PC}$-exotic light-flavour $\hat{\rho}(1405)$ discovered at LEAR was observed in production at a similar level to other light flavour mesons. Hence we shall take the production cross section of hybrid charmonium to be 130 pb. With a luminosity of $10^{33}$ cm$^{-2}$ s$^{-1}$ foreseen for the new Fermilab $\bar{p}$ facility, 50% efficiency, and a conservative branching ratio $BR(\text{exotic} \to \psi\omega) = 1\%$, we estimate 10 $1^{-+}$ hybrid charmonia to be detected via missing mass per day. This is not a promising rate, keeping in mind that $\gtrsim 5000$ events were collected in the first $1^{-+}$ light meson discovery experiments at Brookhaven E852, due to the constraints imposed by viable PWA.

### 3.5 Glueballs

The production of a glueball has a substantially larger cross section than hybrid charmonium. This is easy to see: The light quarks comprising the $p\bar{p}$ move into the outgoing light-flavour meson. Gluons are readily converted to glueballs. For hybrid charmonium to be formed one requires, in addition to the gluons, the costly creation of a $c\bar{c}$ pair.

A glueball, contrary to hybrid charmonium, is not expected to decay to charmonium and light hadrons. This is because a glueball would have to create a $c\bar{c}$ pair, while hybrid charmonium already has one present.

The glueball hence has the advantage over hybrid charmonium that its cross section is large, but has the disadvantage that it has numerous decay channels to light hadrons.

Quenched lattice QCD predicts an exotic $2^{+-}$ glueball at $4140 \pm 50 \pm 200$ MeV/$c^2$ [12]. This is in fact the lightest exotic glueball. An exotic $0^{+-}$ glueball is also predicted at $4740 \pm 70 \pm 230$ MeV/$c^2$ [12], but it is too heavy relative to the hybrid-charmonium masses of interest. Hence the search appears to be for just one glueball!

The $2^{+-}$ glueball can energetically decay to two of any of the $0^{++}$, $2^{++}$ and $0^{-+}$ glueballs. However, these energetically-uninhibited decays are $C$-parity forbidden, thus not allowing the glueball to become wide.

| $J^{PC}$ | Gluon exchange [15] | Confinement [16] |
|---|---|---|
| $0^{-+}$ | $-180$ | 8 |
| $1^{-+}$ | $-50$ | 4 |
| $1^{--}$ | 60 | 0 |
| $2^{-+}$ | 210 | $-4$ |

Table 3: The splittings between the four lowest-lying hybrid charmonia (in MeV).

## 4 $J^{PC}$ Unknown

Suppose the search for $J^{PC}$ exotics outlined in the previous section is abandoned, due to low cross sections, the paucity of states (one hybrid charmonium and one glueball), and the requirement of excellent angular coverage and understanding of the detector imposed by PWA. There are several advantages to abandoning the search for $J^{PC}$ exotics. Firstly, although PWA is always preferable, it is possible not to do it and to resort to bump hunting. The latter possibility will be our assumption for the remainder of this section. When PWA is not performed, conventional charmonia in the mass region of interest will also show up as bumps. Secondly, the narrowness or decay modes of hybrid charmonia and glueballs are likely to be distinctive from conventional charmonia, enabling discrimination. Lastly, small conventional charmonium mixing with hybrid charmonium or a glueball is expected. The latter is due to the penalty incurred by the creation of a $c\bar{c}$ pair, and the former is due to the heaviness of the charm quarks which enable a Born-Oppenheimer approximation, separating conventional and hybrid charmonia by virtue of their orthogonal gluonic wave functions. (The preceding argues that the mixing matrix elements are small. However, mixing can still be substantial in case of coincidental mass degeneracies before mixing. Such a coincidence might in fact occur for $1^{--}$ charmonia [13].)

### 4.1 Hybrid $c\bar{c}$: mass

As alluded to in subsection 2.1, there are eight low-lying hybrid charmonia. Three of these are exotic, which, as we shall see in the next subsection, will not be of further interest. Quenched lattice QCD indicates that the hybrid charmonia $1^{--}, (0,1,2)^{-+}$ are less massive than $1^{++}, (0,1,2)^{+-}$ [14].

The splittings between the four lowest lying hybrid charmonia are indicated in Table 3. The vector-gluon-exchange contribution was calculated in cavity QCD, *i.e.* the spherical bag model,[1] setting the size of splitting consistent with those observed between the $\psi(1S)$ and $\eta_c(1S)$ and the $\psi(2S)$ and $\eta_c(2S)$. The scalar confinement contribution was calculated from the Thomas precession in the flux-tube model, and is clearly subdominant. The splittings are consistent with quenched lattice QCD [17]. There are general arguments based on heavy-

[1] This calculation is an improvement of the calculation in Table 1 of ref. [19]. Here the Z-topology and Coulomb diagrams [15] were not included. Also, an *ad hoc* value for the size of splitting was used.

quark spin-orbit splitting and the masses of light-flavour exotic hybrids from quenched lattice QCD that suggest that $0^{-+} < 1^{-+} < 2^{-+}$ [5], consistent with the above. One also obtains the following new prediction for the mass ordering: $0^{-+} < 1^{-+} < 0^{+-} < 1^{+-} < 2^{+-}$ [5]. We shall take the $0^{-+}$ and $1^{--}$ hybrid charmonia as being most likely to be below the $D^{**}D$ threshold.

### 4.2 Hybrid $c\bar{c}$: formation

The formation $p\bar{p}\rightarrow$ non-exotic is allowed. Because exotic $J^{PC}$ cannot be formed, we shall only be interested in non-exotics in this section. As was derived in section 1, $W < 4500$ MeV. In order to access different $W$, the $\bar{p}$ energy must be varied.

### 4.3 Hybrid $c\bar{c}$: decay

In the formation $p\bar{p}\rightarrow$ non-exotic $\rightarrow \psi X$ the $\psi$ is detected, and $X$ is constructed from missing mass. Here $X = \eta,\ \eta',\ \omega,\ \phi,\ \pi\pi,\ K\bar{K},\ldots$. An interesting feature is that conventional charmonium is expected to be suppressed relative to hybrid charmonium in these final states, because conventional charmonium freely decay to open charm, meaning that their branching ratios to the listed final states are small.

Two of the simplest final states are $\psi\eta$ and $\psi\omega$. The former can arise from the non-exotic hybrid charmonia $1^{--}$, $1^{+-}$, and the latter from $0^{-+}$, $2^{-+}$, $1^{++}$.

Other possible final states are decays of non-exotic hybrid charmonium to $e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$, and $\gamma\gamma$. However, theoretically their widths are expected to be substantially smaller than for conventional charmonium [18].

### 4.4 Hybrid $c\bar{c}$: cross section

We assume a formation cross section $\sigma = 0.1\ \mu$b for hybrid charmonium [19, 20]. This is smaller than the measured formation cross section of the $\psi$. One should keep in mind that the cross section decreases strongly with increasing $W$ [21]. With a luminosity of $10^{33}$ cm$^{-2}$s$^{-1}$, a 50% efficiency, and $BR(\text{exotic} \rightarrow \psi\omega) = 1\%$, we obtain 5000 events/day. This is a very healthy rate.

Since no PWA is required, we can detect the decays, non-exotic $\rightarrow \psi X$, for all $X$. This could well have a branching ratio of 20%, yielding 100000 events per day. However, as we shall see below, this procedure has the disadvantage of the appearance of many overlapping states, making isolation of the gluonic mesons difficult.

### 4.5 Glueballs

As in subsection 3.5, glueball formation will be considerably enhanced above that of hybrid charmonium, and glueballs will have many decay channels to light hadrons. One expects the electromagnetic coupling of non-exotic glueballs to $e^+e^-$ $\mu^+\mu^-$, $\tau^+\tau^-$, and $\gamma\gamma$ to be small. The glueballs predicted in the relevant mass region are the $1^{--}$ at $3850 \pm 50 \pm 190$ MeV/$c^2$, $2^{-+}$ at $3890 \pm 40 \pm 190$ MeV/$c^2$, $2^{--}$ at $3930 \pm 40 \pm 190$ MeV/$c^2$, and the $3^{--}$ at $4130 \pm 90 \pm 200$ MeV/$c^2$ [12].

The $1^{--}$, $2^{--}$, and $3^{--}$ glueballs cannot decay to two glueballs for the same reason as in subsection 3.5. The $2^{-+}$ glueball will have P-wave decay to $0^{++}2^{++}$ glueballs and D-wave decay to $0^{++}0^{-+}$ glueballs, both near threshold. There is hence a distinct possibility that decay to two glueballs will not allow the $2^{-+}$ to become wide.

### 4.6 Bump hunting

There is little reason to expect hybrid charmonium below 4 GeV. In the mass region $4.0-4.3$ GeV/$c^2$, we expect 18 conventional charmonia: two 3S states at $\sim 4.0$ GeV/$c^2$, four 1F states at $\sim 4.1$ GeV/$c^2$, four 2D and four 1G states at $\sim 4.2$ GeV/$c^2$, and four 3P states at $\sim 4.3$ GeV/$c^2$ (the $D^{**}D$ threshold) [7, 22]. Assuming that the average resonance has a width of $\sim 50$ MeV/$c^2$ [1], we expect contiguous resonances in the mass region $4.0-4.3$ GeV/$c^2$ of interest. In addition, we expect $\gtrsim 4$ non-exotic glueballs, *i.e.* those documented in the previous subsection, noting that not all glueballs in the mass region of interest have probably been calculated by theory. There are also $\lesssim 5$ non-exotic hybrid charmonia, given that not all states documented in subsection 4.1 will necessarily lie in the mass region of interest.

The contiguity of resonances is, however, much more conducive to bump hunting when a specific decay channel is considered. For example, only 3 of the 18 conventional charmonia, 2 of the $\lesssim 5$ hybrid charmonia, and 2 of the $\gtrsim 4$ glueballs can decay in S- or P-wave to $\psi\eta$. More gluonic than conventional mesons actually appear! The seven resonances in the relevant mass region will clearly stand out as bumps. Assuming a good understanding of conventional states, the new states will be distinctive.

An energy scan in the $W = 4.0-4.3$ GeV region in 10 MeV bins corresponds (from Eq. 1) to a $\bar{p}$ beam tuned to 50 MeV with 30 steps. Similarly, an energy scan in 30 MeV bins corresponds to a $\bar{p}$ beam tuned to 150 MeV with 10 steps.

## 5 Conclusions

There are two distinct possible programs, the search for $J^{PC}$-exotic and non-$J^{PC}$-exotic states as elaborated in Table 4. A search for $J^{PC}$-exotic states would unambiguously isolate gluonic mesons. However, the second program represents substantially higher cross sections and does not absolutely require partial-wave analysis.

| $J^{PC}$ exotics | $J^{PC}$ unknown |
|---|---|
| Need PWA | Do not need PWA |
| Fixed $\bar{p}$ energy | Varying $\bar{p}$ energy |
| Low $\sigma$ | High $\sigma$ |

Table 4: Possible search programs for $J^{PC}$-exotic and non-$J^{PC}$-exotic states.

## References


[1] D. E. Groom *et al.*, Eur. Phys. J. **C15**, 1 (2000).

[2] Letter of Intent "Construction of a GLUE/CHARM-Factory at GSI," March 1999, unpublished.

[3] P. R. Page, Phys. Lett. **B402**, 183 (1997).

[4] F. E. Close *et al.*, Phys. Rev. D **57**, 5653 (1998).

[5] P. R. Page, Acta Phys. Polon. **B29**, 3387 (1998).

[6] U. Wiedner, these proceedings.

[7] M. M. Brisudová, L. Burakovsky and T. Goldman, Phys. Rev. D **61**, 054013 (2000).

[8] D. V. Bugg, private communication.

[9] C. Bernard *et al.*, Nucl. Phys. Proc. Suppl. **73**, 264 (1999).

[10] C. Bernard *et al.*, Phys. Rev. D **56**, 7039 (1997).

[11] R. Cester, Workshop on Phys. at SuperLEAR, Inst. of Physics Conf. Series No. 124, p. 91, Zurich, Switzerland, (Oct. 1991).

[12] C. J. Morningstar and M. Peardon, Phys. Rev. D **60**, 034509 (1999).

[13] S. B. Gerasimov, Proc. of $11^{th}$ Int. Conf. on Problems of Quantum Field Theory , Dubna, Russia, (July 1998), hep-ph/9812509; F. E. Close and P. R. Page, Phys. Lett. **B366**, 323 (1996).

[14] K. J. Juge, J. Kuti and C. J. Morningstar, Nucl. Phys. Proc. Suppl. **83**, 304 (2000); T. Manke *et al.*, Phys. Rev. **D57**, 3829 (1998).

[15] P. R. Page, D. Phil. Thesis, Univ. of Oxford (1995), unpublished.

[16] J. Merlin and J. Paton, Phys. Rev. D **35**, 1668 (1987).

[17] T. Manke *et al.*, Nucl. Phys. Proc. Suppl. **86**, 397 (2000); I. T. Drummond *et al.*, Phys. Lett. **B478**, 151 (2000).

[18] S. Ono *et al.*, Z. Phys. **C26**, 307 (1984); Phys. Rev. D **34**, 186 (1986); P. R. Page, Nucl. Phys. **B495**, 268 (1997).

[19] F. E. Close, SuperLEAR Workshop [11], p. 63.

[20] K. Königsmann, SuperLEAR Workshop [11], p. 71.

[21] G. Zioulas *et al.*, Proc. of $3^{rd}$ Biennial Conf. on Low Energy Antiproton Physics (LEAP 94), Bled, Slovenia (Sep. 1994), World Scientific, p. 65.

[22] K. Heikkilä, N. A. Törnqvist and S. Ono, Phys. Rev. D **29**, 110 (1984).