Challenges and Opportunities in Antiproton Physics in the Charmonium Region

Kamal K. Seth
Northwestern University
Evanston IL 60208

Abstract

The wide range of physics which can be addressed with antiprotons extends from atomic, to nuclear, to particle physics: Antihydrogen physics (at 10^{-8} GeV), nucleon-antinucleon physics ($\sqrt{s} \leq 3$ GeV), light quark spectroscopy ($\sqrt{s} \leq 3$ GeV), heavy quark spectroscopy ($\sqrt{s} \geq 3$ GeV), and open charm physics ($\sqrt{s} \geq 3.7$ GeV). In this review, I will confine myself primarily to the physics of charmonium, bound, unbound, and in and out of the nucleus.

1 Introduction

To begin with, let me answer the question, "Why?" Why does one study the spectroscopy of charmonium? At the most fundamental level, while the electroweak sector of the Standard Model of particle physics is extremely well established, its strong interaction sector – the quantum chromodynamics (QCD) part – is not so well established, especially in its large-distance, or confinement region. Many have called it the most important, unsolved part of QCD, and even of the Standard Model [1]. In order to study the interactions of QCD in the confinement region, one has to do precision spectroscopy of hadrons whose size is > 0.5 fm, but whose masses are large enough so that they do not present relativistic problems. Charmonium states are ideally suited for this purpose. Their spectrum is simple (Fig. 1), their radii range from 0.5 to 1.0 fm, and their $< v^2/c^2 > \approx 0.24$.

For ten years following the discovery of J/ψ in 1974, all charmonium physics was done at e^+e^- colliders at SLAC, DESY, ORSAY, ... A large amount of discovery physics was done, and a number of theoretical models (prominent among them – potential models and sum-rule models) were developed to explain the observations. However, the e^+e^- formation experiments had one inherent weakness – they could directly form only vector states: $e^+e^- \to \gamma_v \to |c\bar{c}{>}1^{--}$. That meant that all other states of charmonium had to be studied only via the decay (usually radiative) of the 1^{--} vector states ($J/\psi, \psi'$). This severely limited the precision achievable in these measurements, and in many cases, *e.g.* singlet states, made it nearly impossible even to find the states.

The limitations of the e^+e^- experiments can be overcome by forming charmonium states by antiproton-proton annihilation. Since $p\bar{p}$ annihilation must proceed via two or three gluons, it can directly produce states of any J^{PC}. The price that one has to pay for this great advantage is that the probability for two or three coherent quarks in the proton to find the corresponding antiquarks in the antiproton with which to annihilate is necessarily considerably smaller (by factors $> 10^2$) than for beams of e^+ and e^- to produce annihilations.

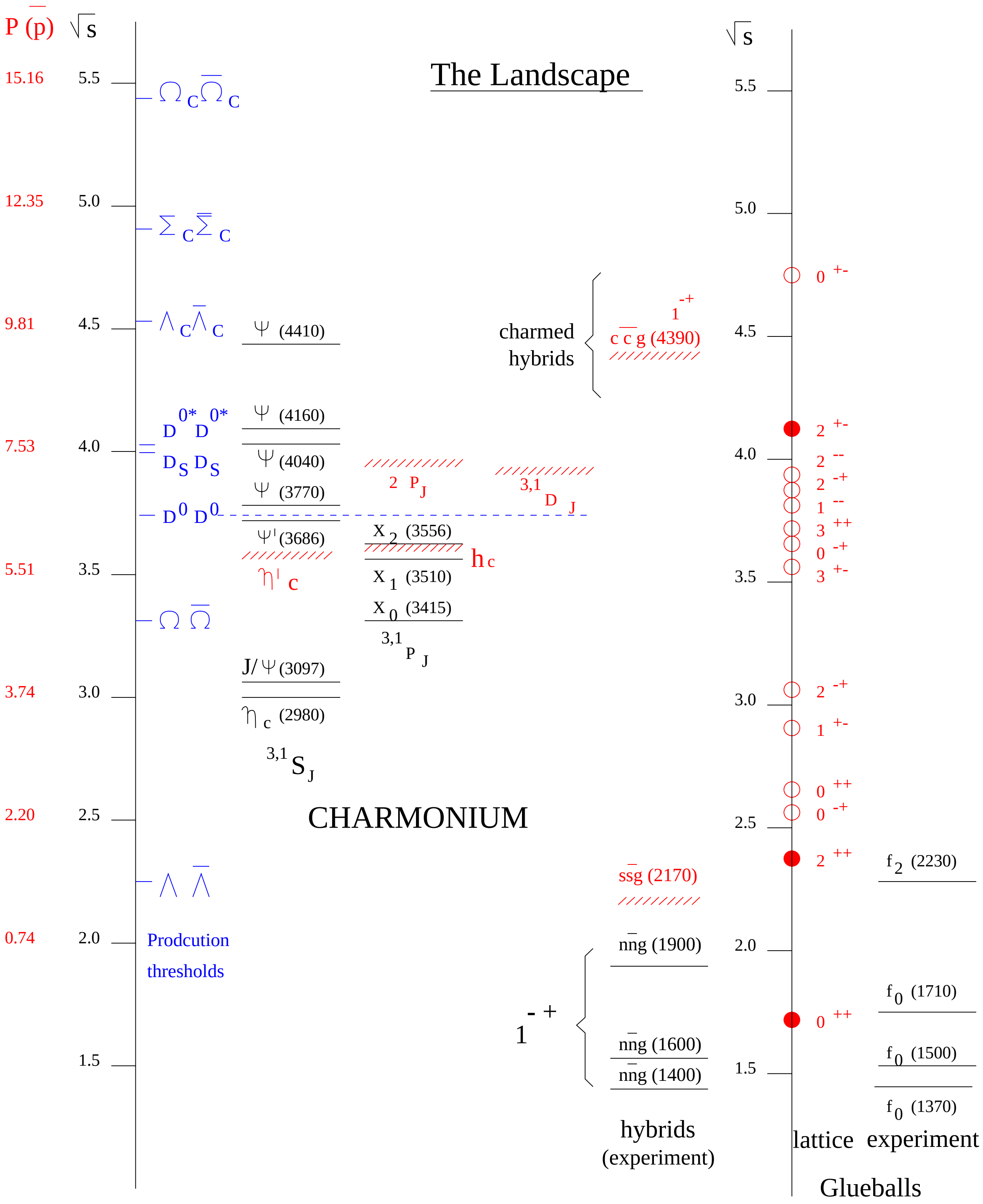

Figure 1: Landscape for hadron spectroscopy; theoretical predictions are indicated by hashed regions.

However, there is one great advantage with $p\bar{p}$ annihilation. Antiproton beams can be produced with extremely good energy resolution ($\Delta p/p \approx 10^{-4}$–$10^{-5}$) by stochastic or electron cooling, making it possible to determine masses and widths with unparalleled precision. The "proof of principle" experiment for $p\bar{p}$ to produce charmonium states was done by experiment R704 at the ISR at CERN [2]. However, serious exploitation of the technique became possible only at Fermilab, where experiments E760 cite3, E835 [4], and E835′ made great gains in precision spectroscopy of charmonium in the limited running time made available to them, when the antiproton source was not being used to service the Tevatron Collider. I will describe the major achievements of these experiments, but emphasize the great amount of work that remains to be done at a future dedicated antiproton facility, be it at Fermilab, or GSI, or elsewhere.

2 Fermilab E760/E835

Fig. 2 illustrates schematically the setup of the Fermilab experiment in the accumulator ring of the Antiproton Source. Up to 8×10^{11} antiprotons can be accumulated in the ring at 8.9 GeV/c. These circulate at $\sim$ 0.62 MHz, and intersect a hydrogen gas jet target whose density can be adjusted in the range $(1–32)\times 10^{13}$ atoms/cm^3. Thus the maximum possible luminosity is $\sim 16 \times 10^{31}$ cm^{-2}s^{-1}. In actual practice, usable luminosities are (2–5) $\times 10^{31}$ cm^{-2}s^{-1}. Mass resolution is $\sim 10^{-4}$ (300–600 keV), and energy precision is $\sim$ 1 part in 10^5 (30 keV at J/ψ). The detector system is optimized for detection and identification of electromagnetic reaction products (e^+, e^-, γ), and cross sections for final states containing e^+e^- pairs have been successfully measured down to 1 picobarn in the presence of a total $p\bar{p}$ cross section of $\sim$ 70 mb. The stored antiprotons can be decelerated to any energy, down to $\sim$ 3.5 GeV/c, without much loss of beam.

A typical charmonium resonance is studied by scanning across it by decelerating the circulating antiproton beam. The inset in Fig. 2 shows results of a scan of the χ_{c2} resonance with a beam whose FWHM was $\sim$ 600 keV (dashed peak). The width $\Gamma(\chi_{c2}) = 1.98 \pm 0.18$ MeV is determined. The corresponding result from Crystal Ball at SLAC was $\Gamma(\chi_{c2}) = 2.8^{+2.1}_{-2.0}$ MeV [5].

The E760/E835 experiments have made precision measurements of the masses and total widths of J/ψ and ψ' [6], χ_1 and χ_2 [5], and χ_0 [7] states of charmonium. They have made the best measurements of the branching ratios for $p\bar{p}$ decays of these states, and the two photon decay width of χ_2 [8]. The experiments have made the highest precision measurements of $p\bar{p}$ forward elastic scattering parameters[9], and timelike form factor of the proton up to $q^2 = 14$ (GeV/c)^2 [10]. They have shown evidence for enhanced excitation of mesons with masses of $\sim$ 1500, 1700, and 2100, which are among the most popular candidates for scalar glueballs [11].

The purpose of the present review is not to describe the successes of the Fermilab experiments E760/E835, but rather to point out what important investigations have so far been unsuccessful or incomplete, and thereby to highlight what needs to be done at a dedicated antiproton facility of the future.

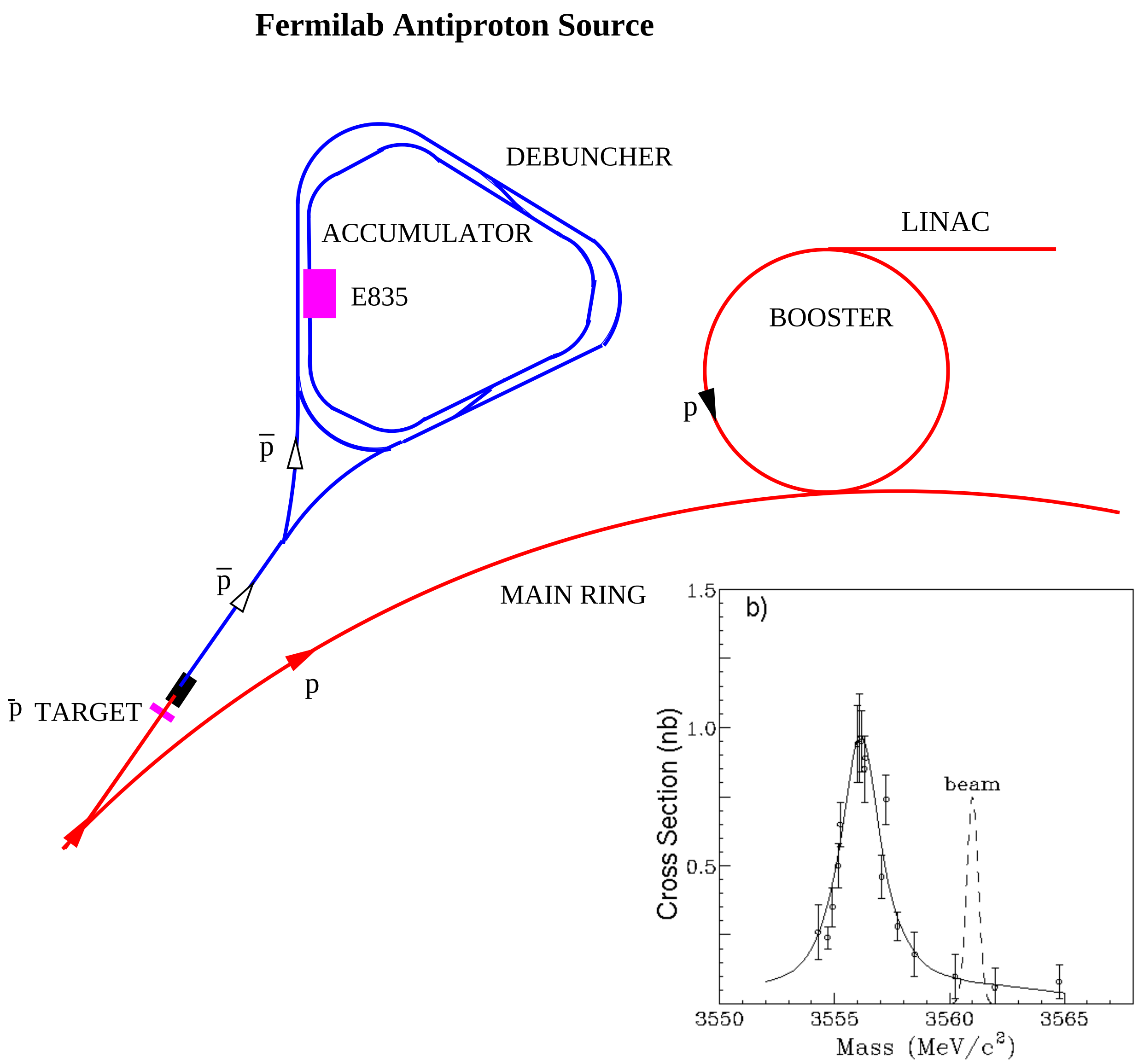

Figure 2: Fermilab Antiproton Source and the location of experiment E760/E835. Inset: χ_{2c} scan from E760.

3 Some Outstanding Problems Below the $D\overline{D}$ Threshold

Below the $D^0\overline{D}^0$ threshold at $\sqrt{s} = 3.73$ GeV, the spin-triplet states have been relatively extensively studied, whereas the spin-singlet states are still in bad shape.

3.1 $J/\psi(1^3S_1), \psi'(2^3S_1)$

Direct width measurements of J/ψ and ψ' by E760 showed that both widths were seriously underestimated (by as much as 35%) in e^+e^- annihilation experiments. As reliable as we believe the E760 measurements are, it is necessary to have an independent measurement of these widths, which form the cornerstone of pQCD application to charmonium. It is believed that a modern antiproton facility can cool the beam down to yield a mass resolution of the order of $\sim$ 100 keV, *i.e.* nearly a factor of five better than that achieved in E760, and thereby measure these widths with much greater precision.

An important outstanding problem about J/ψ and ψ' is the so-called "$\rho - \pi$ problem." It has been highlighted by recent measurements at BEPC [12]. It is found that contrary to the expectations of pQCD the ratios of corresponding hadronic widths of ψ' and ψ are not constant at 14%, but actually become as small as $< 0.2\%$ in certain decays. To understand this phenomenon it is essential to measure many more two body decays of ψ' for which at present only upper limits exist.

3.2 $\chi_c(1^3P_J)$

Less than 15% of the hadronic width of these states is accounted for, and even the few branching ratios which have been measured have errors larger than 30%. The simple prediction of pQCD, $BR(\chi_0 \to h)/BR(\chi_2 \to h) = 15/4$, seems not to hold. Many more hadronic decay channels need to be measured with precision in order to shed light on what is going on.

3.3 The problem of the spin-singlet states

The spin-singlet states are the *bête noir* of heavy quark spectroscopy. None has ever been identified in the bottomonium ($b\bar{b}$) system, and the situation in charmonium is not much better. The reason is that in e^+e^- annihilation experiments these states can be excited only by the extremely weak M1 transitions from J/ψ or ψ' ($\to \eta_c$ and η_c'), or the radiative transition ($\to h_c$) which is C-forbidden.

Only η_c was painfully, but successfully, identified in the e^+e^- experiments, but its few decay channels which could be studied suffer from large errors (mostly statistical). The attempts of Fermilab E760/E835 to study η_c have been seriously compromised by the fact that with no magnetic analysis available, final states with charged hadrons could not be studied and one had to struggle with the very weak two-photon decay channel. Further, the non-hermeticity of the E760/E835 detector led to a large two-photon background. The net result is that the spectroscopy of η_c, the ground state of the charmonium family, is in poor shape. Even the mass and the total width are in controversy. Only a state-of-the-art modern detector can improve on this situation.

Quantum mechanics tells us that the first radial excitation of η_c, the $\eta_c'(2^1S_0)$ exists, that it is bound, and that it lies somewhere between χ_{c2} (3556 MeV/c^2) and ψ' (3686 MeV/c^2), and theoretical calculations tell us that its hadronic width, as well as its two photon width should be $\sim$ 50% to 75% of that of η_c. However, nobody has succeeded in finding it. E760 and E835 have failed to find it even at a level $\sim$ 16% of η_c [4]. DELPHI has established the two photon width ratio at the same level [13]. It is imperative that the mystery of the missing η_c' be solved; the implications of its weakness can be quite serious.

The third singlet state which is bound is $h_c(^1P_1)$. It was not found in e^+e^- annihilation experiments, and despite the early claim [14], it may not have been found even in $p\bar{p}$ annihilation experiments at Fermilab. It is essential to identify this state because its mass has important bearing on the spin dependence of the confinement part of the $q\bar{q}$ potential, for which we have essentially no other direct information.

3.4 Strong coupling constant

Wilczek has emphasized [15] that "a quantitative measure (of how good pQCD is) is how tightly is the strong coupling constant α_s constrained." He goes on to point out that "large Q^2 measurements are limited in their power to resolve possible values of α_s quantitatively", and recommends that "if you are interested in quantitative results for α_s, there is a large premium for working at small Q^2." The best estimate of $\alpha_s(\pm 10\%)$ from heavy quarkonium decay is from the decays of upsilon $(b\bar{b})$; at $m_b = 4.7$ GeV/c^2, $\alpha_s(m_b) = 0.163 \pm 0.002 \pm 0.014$. The only determination at smaller mass is from the semi-leptonic decay of the τ lepton ($m_\tau = 1.78$ GeV/c^2), $\alpha_s(m_\tau) = 0.35 \pm 0.03$. This large variation is of crucial importance in the "running" of α_s. Charmonium spectroscopy offers the only opportunity to provide an independent measurement of α_s at $m_c \approx 1.5$ GeV/c^2. Two-photon decays of η_c and χ_{c2} by E835 give $\alpha_s(m_c) = 0.34 \pm 0.02$ (see Fig. 3). Undoubtedly future better measurements will yield a more precise definition of α_s and its "running."

4 Some Outstanding Problems Above the $D^0\overline{D}^0$ Threshold (3.73 GeV)

Above the $D^0\bar{D}^0$ threshold essentially nothing is known. This is the region in which the radial excitations of $J/\psi(^3S_1, ^3D_1)$ and the $\chi_J(^{3,1}D_J)$ states exist, as do the $^{1,3}D_2$ states which must be narrow because they cannot decay to $D^0\overline{D}^0$. Claims for the higher vectors $\psi^{(2)}, \psi^{(3)}$, and $\psi^{(4)}$ exist, but the evidence is rather tentative, and neither the P-wave radials nor the D-wave states have ever been found. These are, of course, of crucial importance in understanding $c\bar{c}$ interaction in the confinement region.

An additional interest in the study of this region is that it is the ideal region for the production of prolific numbers of D-mesons, pairs of $D^0\overline{D}^0, D_s\overline{D}_s, D^*\overline{D}^*, \ldots,$ *i.e.* it is the home of what has been called "the D-factory", which is needed if experiments in $D^0\overline{D}^0$ mixing, CP violation in D-mesons, and precision measurements of CKM matrix elements (V_{cd}/V_{cs}) are ever to be realized.

5 Charmonium in Nuclei and the Quark-Gluon Plasma (QGP)

Charmonium attenuation in the presence of QGP is considered one of the best signatures of QGP formation in collisions of relativistic heavy ions. J/ψ attenuation has indeed been observed in p-A, as well as in A-A collisions, but it is not clear whether the attenuation

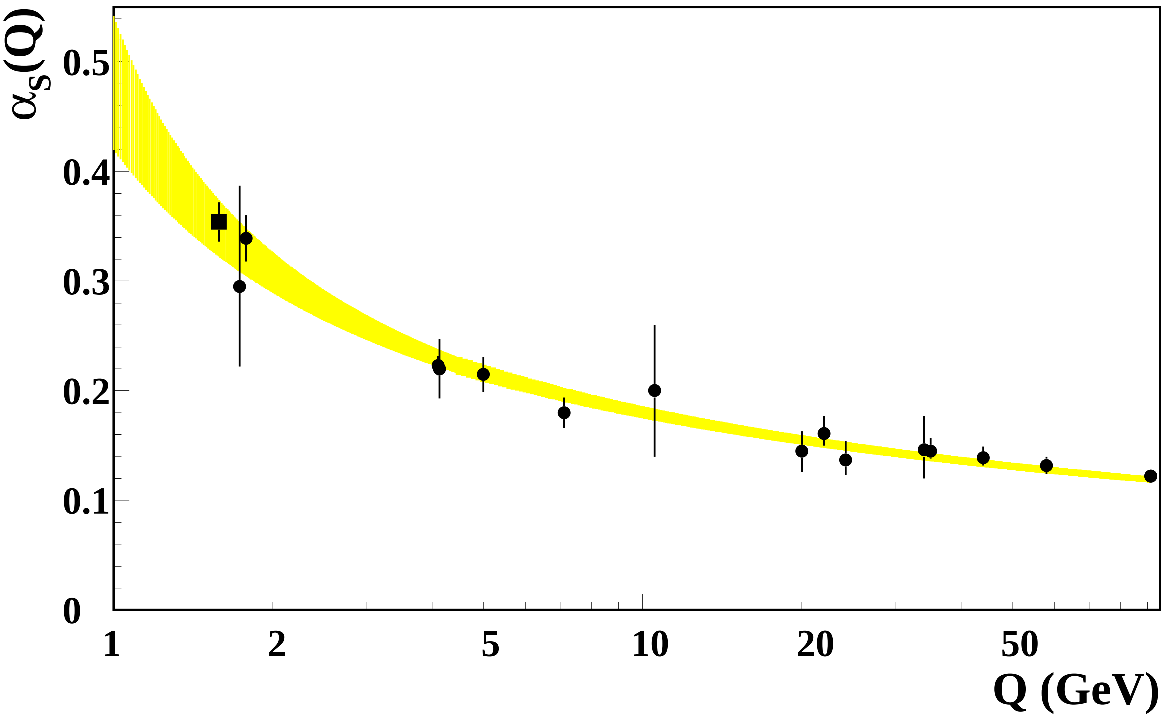

Figure 3: The strong coupling constant of QCD, α_s, as a function of momentum transfer. The leftmost point is from the E835 determination of α_s from two-photon decays of η_c and χ_2.

observed in A-A collisions (even the attenuation observed in Pb-Pb collisions recently at CERN) can be explained in the same terms as that in p-A collisions, or whether QGP-induced attenuation has to be invoked. The main problem lies in the fact that the J/ψ-nucleon cross section has never been measured at low enough energy where the $c\bar{c}$ pair, which is formed in the initial collision, has enough time to hadronize into J/ψ within the nuclear volume [6]. Recently, it has been proposed [6] that the most direct way to measure the $J/\psi - N$ cross section is to form J/ψ resonantly in the annihilation of antiprotons with protons in a nucleus. Such a measurement can be made very conveniently at the proposed GSI antiproton facility with the circulating $\bar{p}$ beam intersecting a nuclear-gas (methane, neon, argon, . . .) target. Attenuation of ψ', and χ_J states can also be measured. Such measurements are not possible with any other known technique.

The summary of the above discourse is that precision measurements in charmonium spectroscopy are of great importance to our understanding of QCD, and they call for the creation of a new dedicated facility for antiproton physics.

6 Symbiotic Measurements

Quite apart from the programmatic measurements described above, a class of important non-programmatic experiments can also be done with a new antiproton facility. I present three examples.

6.1 QCD exotics

Because $p\bar{p}$ annihilation proceeds through two or three gluons, it is ideally suited for forming hadrons with explicit gluon degrees of freedom: the $q\bar{q}g$ hybrids and the gg (or ggg) glueballs, in both formation and production modes. Lattice-gauge predictions for the masses of these states are indicated on the right-hand side of Fig. 2. Recently, candidates have emerged for the low-lying scalar (0^{++}) and tensor (2^{++}) glueballs, but most of the glueball (predicted) region remains unexplored.

The present controversies about the lowest 0^{++} and 2^{++} glueball experimental candidates result from the fact that they reside in a mass range in which scores of $q\bar{q}$ states with the same quantum numbers exist, and the glueballs mix with them [3]. As Fig. 1 illustrates, above 2.5 GeV/c^2 mass this problem is much reduced, because $q\bar{q}$ ($q = (u, d) \equiv n$) states have become so broad and overlapping that none have ever been isolated and identified. So, there is very good chance that at least in the 2.5–3.5 GeV/c^2 region relatively pure glueball states can be successfully identified. Of course, an exotic glueball with non-$q\bar{q}$ $J^{PC} = 2^{+-}$ is predicted by lattice calculations at 4.14 GeV/c^2. It will be certainly accessible at GSI, and it is guaranteed not to have any mixing problems!

The identification of hybrids ($q\bar{q}g$) is far less ambiguous because with the right choice of J^{PC} (0^{+-}, 1^{-+}, 2^{+-}, ...) one avoids all problems of mixing with $q\bar{q}$ states which can not have these quantum numbers. Recently, at least two (perhaps three) excellent $1^{-+}(n\bar{n}g)$ candidates have emerged with masses between 1400–1900 MeV/c^2 [4]. If one or more of these are indeed $|n\bar{n}g\rangle$ hybrids, the entire nonet lies nearby, undiscovered so far. Then there is the exotic $|s\bar{s}g\rangle 1^{-+}$ hybrid predicted at ≈ 2.2 GeV/c^2 and the exotic $|c\bar{c}g\rangle$ hybrid predicted at ≈ 4.4 GeV/c^2 waiting to be discovered. It is interesting to note that the latter can have a very unique decay signature: $|c\bar{c}g\rangle 1^{-+} \to \chi_{C1}(1^{++}) + \eta(0^{-+}) \to \gamma J/\psi + \eta \to \gamma(e^+e^-) + \eta$.

6.2 Proton form factor

The measurement of the timelike form factor of the proton via the reaction $p\bar{p} \to e^+e^-$ up to the highest momentum transfers offers another example. This would shed important light on how far the differences between form factors for timelike and spacelike momentum transfers, revealed in recent Fermilab experiments [10], persist, and whether the two ever become equal, as certain (naive?) predictions of pQCD require.

6.3 Masses of τ and ν_τ leptons

Another example is provided by the masses of τ and ν_τ leptons. If $\bar{p}$ beam momentum resolutions of the order ($\Delta p/p \approx 10^{-5}$) can be realized in a new $\bar{p}$ facility, it can be shown that $m(\tau)$ can be measured with an error less than $\pm$ 50 keV/c^2 (present best $\approx$ 350 keV/c^2), and $m(\nu_\tau)$ to $\leq$ 5 MeV/c^2 (present best is $\leq$ 18.2 MeV/c^2).

7 Epilogue

What a great challenge and opportunity for wonderful physics a dedicated antiproton facility will present!

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