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COMMENTS ON BEAUTIFUL BARYONS AND ON QUARKONIUM

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A B S T R A C T

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COMMENTS ON BEAUTIFUL BARYONS AND ON QUARKONIUM

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First we re-examine the mass estimates of beautiful baryons and show that, with the exception of one lattice QCD calculation, there is a consensus from general arguments and explicit models for a mass of the Λ_b near 5.6 GeV. Second we make comments on quarkonium spectroscopy, stress the importance of observing the missing levels of the J/ψ and ψ , discuss the implications of a recent theorem on level spacing, and make some remarks on toponium physics and the dramatic consequences of a very large mass of the top quark.

1. BEAUTIFUL BARYONS

Some time ago, we obtained upper bounds on the masses of beautiful baryons¹ from a general concavity argument which is valid in a non-relativistic treatment of the baryons as three-quark states and also if relativistic kinetic energy is given to the quarks. Hopefully, this argument might have a more general validity. The property we use is the following.

The Hamiltonian of a (Qqq') system, where Q is a heavy quark and qq' light quarks is a concave function of $1/M_Q$, where M_Q is the mass of the quark. Then the binding energy of the ground state is a concave function of $1/M_Q$ if the forces between quarks are flavour independent. In this way, knowing the masses of strange and charmed baryons (and mesons) one can get upper bounds on the masses of beautiful baryons (and mesons). One may wonder if it is "legal" to consider the strange quark as "heavy". This is justified to some extent by the success of a global fit of $s\bar{s}$, $c\bar{s}$, $c\bar{c}$ and $b\bar{b}$ states treating the strange quark as heavy². The predictions of Ref. 1 were the following:

$$\begin{array}{ll} 1) & \begin{array}{l} M_{\Lambda_b} < 5.629 \text{ GeV} \\ M_{\Sigma_b} < 5.826 \text{ GeV} \end{array} & (1) \\ 2) & \begin{array}{l} M_B < 5.263 \text{ GeV} \\ M_{B^*} < 5.340 \text{ GeV} \end{array} & (2) \end{array}$$

In fact, since then, the masses of beautiful mesons have been measured and they are

$$\begin{array}{ll} & \begin{array}{l} M_B = 5.274 \text{ GeV}^3 \\ M_{B^*} = 5.325 \text{ GeV}^4 \end{array} & (3) \end{array}$$

Therefore the bound (2) for M_B is violated by 10 MeV. We rather consider this as a success than as a failure. As we shall see the uncertainty on the constituent quark masses, which is the weakest point of the approach, can very well account for this.

On the other hand, a recent "scalar" lattice QCD calculation⁵ (scalar means that the spins of the quarks are disregarded), predicts

$$M_{\Lambda_b} = 5900 \pm 35 \text{ MeV} \quad (4)$$

The authors point out that with this small theoretical uncertainty their prediction excludes the possibility that the object observed some years ago by the CERN-Bologna collaboration⁶ could be a Λ_b . At this conference, we shall hear a report on new experimental results on this question by Dr. Cifarelli.

This is what stimulated J.M. Richard and myself to re-examine the whole problem and obtain, as we shall see, a few additional predictions on other particles⁷. We have re-examined the question of upper bounds, derived as well lower bounds, and reviewed calculations using explicit models, including a generalization of the Richard-Taxil model to the b sector.

1.1 Upper bounds

The weak point of the upper bounds is the question of quark masses. The $M_b - M_c$ mass difference is now known more precisely from the $c\bar{c}$ and $b\bar{b}$ spectra. From there, one gets

$$\begin{aligned} M_B &< 5.292 & M_{B^*} &< 5.370 \\ M_{\Lambda_b} &< 5.659 & M_{\Sigma_b} &< 5.856 \end{aligned} \quad (5)$$

The bounds are slightly less constraining but still completely incompatible with Ref. 5, while the compatibility with experiments^{3,4} in the meson sector is restored.

1.2 Lower bounds

There exists an inequality linking baryons and mesons which is

$$M_{Q_1 Q_2 Q_3} > \frac{1}{2} (M_{Q_1 \bar{Q}_2} + M_{Q_2 \bar{Q}_3} + M_{Q_3 \bar{Q}_1}) \quad (6)$$

This inequality has been derived from QCD by Nussinov in the case $Q_1 = Q_2 = Q_3$. It can be obtained from a non-relativistic treatment⁸ if one assumes that the two-body potentials inside a baryon are such that

$$V_{Q_1 Q_2} = \frac{1}{2} V_{Q_1 \bar{Q}_2} . \quad (7)$$

This "prescription" is, in many respects, the most natural one and has led to a very successful prediction of the mass of the Ω^- particle⁹. Initially the inequality was derived neglecting spins. Spins are now included and we get the following:

Spin $3/2$ states

$$\begin{aligned} \Omega^- &= 1.672 > \frac{3}{2} \phi = 1.530 \\ \Delta &= 1.232 > \frac{3}{2} \rho = 1.155 \\ \Sigma^* &= 1.385 > K^* + \frac{1}{2} \rho = 1.275 \\ \Xi^* &= 1.532 > \rho + \frac{1}{2} \phi = 1.280 \\ \Sigma_b^* &> B^* + \frac{1}{2} \rho = 5.710 . \end{aligned} \quad (8)$$

Spin $\frac{1}{2}$, Σ -like states

$$\begin{aligned} N &= 0.938 > \frac{3}{4} \rho + \frac{3}{4} \pi = 0.681 \\ \Sigma &= 1.190 > \frac{1}{2} \rho + \frac{3}{4} K + \frac{1}{4} K^* = 0.979 \\ \Xi &= 1.319 > \frac{1}{2} \phi + \frac{3}{4} K + \frac{1}{4} K^* = 1.104 \\ \Sigma_c &= 2.450 > \frac{1}{2} \rho + \frac{3}{4} D + \frac{1}{4} D^* = 2.288 \quad (9) \\ \Sigma_b &> \frac{1}{2} \rho + \frac{3}{4} B + \frac{1}{4} B^* = 5.670 . \end{aligned}$$

Spin $\frac{1}{2}$, Λ -like states

$$\begin{aligned} \Lambda &= 1.116 > \frac{1}{2} \pi + \frac{3}{4} K^* + \frac{1}{4} K = 0.863 \\ \Lambda_c &= 2.286 > \frac{1}{2} \pi + \frac{3}{4} D^* + \frac{1}{4} D = 2.042 \\ \Lambda_b &> \frac{1}{2} \pi + \frac{3}{4} B^* + \frac{1}{4} B = 5.379 \end{aligned} \quad (10)$$

We see that, wherever the experimental numbers are known, the difference between the left-hand side and the right-hand side varies between 100 and 250 MeV. In the Λ family, the difference, for the Λ and Λ_c is of the order of 250 MeV, which, if this continues for the Λ_b , would give a mass of 5.63 GeV. In any case, a mass of 5.9 GeV would produce a striking anomaly in this table.

1.3 Models

A lot of model calculations exist in the literature, some of them pretty old, some of them purely non-relativistic, others with relativistic kinematics. For completeness we have added the generalization of the Richard-Taxil model to the b sector. We see that the consistency between the calculations is remarkable and that they are also consistent with the upper and lower bounds:

Λ_b	Σ_b	Σ_b^*	Authors	Ref.
5.596	5.859	5.877	Stanley and Robson	10
5.585	5.795	5.805	Maltman and Isgur	11
5.547	5.714	5.766	Basdevant and Boukraa	12
5.580	5.800	5.841	Richard-Taxil extended	13
5.64	5.78	5.82	Izatt et al.	14
5.66	5.86	5.91	Upper bound	
5.38	5.67	5.71	Lower bound	

Before changing subject, I would like to make one remark. To be sure to have seen the Λ_b it is necessary but not sufficient to find a state with the right mass. One important characteristic of the Λ_b is that it is expected to have a lifetime of the same order of magnitude as the B, i.e., about 10^{-12} seconds. If the Λ_b was produced in a fixed target experiment this could be seen as has happened once for the B mesons¹⁵. That would be an unmistakable signature.

2. QUARKONIUM: $b\bar{b}$ AND $c\bar{c}$

Crudely speaking everything is fine in $b\bar{b}$ and $c\bar{c}$ physics. Many levels are known and they can be fitted by a flavour-independent potential which is either QCD-inspired, like the one of Buchmüller and collaborators¹⁶, or calculated from lattice QCD¹⁷ (here quark loops are, as yet, neglected and must be put by hand to get the correct short-distance behaviour), or purely phenomenological², like my naive fit

$$V = A + B r^{0.1} \quad (11)$$

The naïve fit is almost as good as the others but it predicts the P states of the upsilon system 40 MeV too low. This is a fact interesting in itself since it shows that a singularity of the potential at the origin is needed.

The problems left in quarkonium physics are connected with the states which are not directly accessible by e^+e^- collisions. An improved knowledge of the η_c' reached from the ϕ' by photon emission is certainly highly desirable. The precise knowledge of the η_c' mass is needed to compare the $J/\psi-\eta_c$ and $\phi'-\eta_c'$ spacings which give precious indications on the range of the spin-spin forces and/or the effect of $D\bar{D}$ channels close by¹⁸.

Observing the η_b and η_b' is a must. There is a very large spread of theoretical predictions for the $T-\eta_b$ mass difference, from 35 to 120 MeV. QCD calculations favour 35 MeV¹⁹. Personally, I believe²⁰ that one has

$$(M_{\eta'})^2 - (M_{\eta_b})^2 > (M_{J/\psi})^2 - (M_{\eta_c})^2 \quad (12)$$

which leads to

$$M_{\gamma} - M_{\eta_b} \geq 40 \text{ MeV}.$$

This is because one observes that the difference of the masses squared of vector and pseudoscalar particles is constant for constant reduced mass as shown by K^*-K , D^*-D , B^*-B , and increases when the reduced mass increases as happens when one compares J/ψ and η_c .

Other states are extremely interesting notably those which cannot be reached even by radiative transitions and those which are predicted to be narrow even though they are heavier than the $D\bar{D}$ threshold because their decay is Zweig-forbidden by selection rules. This is the case for the 1D_2 and 3D_3 states of charmonium, which one might hope to produce in hadronic collisions. Perhaps the most exciting state both for the $c\bar{c}$ and $b\bar{b}$ systems is the 1P_1 state whose quantum numbers are $J^{PC} = 1^{+-}$. Producing this state has two interests. Firstly the knowledge of its mass gives precise indications on the range of the spin-spin forces. Indeed the weighted average of the triplet P states $1/9(5^2P_2 + 3^3P_1 + 3^3P_0)$ is insensitive, to lowest order in perturbations, to tensor and spin orbit forces. If the spin-spin forces have zero range, this weighted average will coincide with the 1P_1 mass because of the vanishing of the radial wave function at the origin. Secondly, testing the theoretical models for the production and decay of the 1P_1 state is very important, especially because these theoretical models are in conflict.

There are experimental indications for the existence of the 1P_1 state both for the $c\bar{c}$ and the $b\bar{b}$ systems. But in both cases the statistics is not sufficient to be completely convincing.

2.1 At the ISR (in fact the last experiment done at the ISR) the reaction $p\bar{p} \rightarrow Y$, $Y \rightarrow J/\psi + X$, with a p gas jet target, has been studied²¹. A peak has been found at a value of m_Y very close to the centre of gravity of the triplet P states and the interpretation proposed is

$$p\bar{p} \rightarrow ^1P_1(c\bar{c}) , \quad ^1P_1 \rightarrow J/\psi + \pi\pi .$$

However, a background effect cannot be excluded. Unfortunately, the experiment cannot be repeated at the ISR, but a similar experiment will be performed at Fermilab, using the antiprotons of the accumulator.

2.2 At CLEO²², the mass distribution of the 2π system, in the inclusive reaction

$$\gamma'' \rightarrow 2\pi + X$$

has been studied and again, a peak has been found a few MeV away from the centre of gravity of the P states. Again statistics are insufficient, but with

time and improvements of the detector, it will be possible to know if this is a real effect.

The theoretical situation was up to recently that, according to Tuan and Yan²³, the decay $T'' \rightarrow 2\pi + {}^1P_1$, calculated by using the multipole expansion of the gluon field, has a non-negligible branching ratio of a few per cent, while the isospin forbidden decay $T' \rightarrow {}^1P_1 + \pi$ had a much smaller rate. Similarly one expected a reasonable branching ratio for the process ${}^1P_1 \rightarrow 2\pi + J\psi$ though no explicit calculation was carried out.

However, in a recent ITEP preprint, Voloshin²⁴, using techniques connected with the QCD sum rules, claims that in fact the rate $T'' \rightarrow \pi\pi + {}^1P_1$ is very small, much smaller than the isospin forbidden decay $T' \rightarrow \pi + {}^1P_1$, and that therefore the peak seen in the two-pion mass distribution by the CLEO group can only be due to a statistical fluctuation. Voloshin also thinks that the ISR events are also due to statistical fluctuations²⁵. However, in another preprint, Kuang, Tuan and Yan²⁶ re-examine the Kuang-Yan work in the light of the criticism of Voloshin. Though they somewhat weaken their conclusions, they maintain that within one order of magnitude the predictions of Kuang and Yan were correct and they estimate the branching ratio for ${}^1P_1(c\bar{c}) \rightarrow \pi\pi + J\psi$ and find a number in agreement with the ISR experiment if the peak observed at the centre of gravity of the triplet P states is interpreted as 1P_1 . I personally find it very difficult to find out who is right. I think that a confirmation of the experimental indications for the 1P_1 state, both in $c\bar{c}$ and $b\bar{b}$ is essential.

I would like to finish these remarks on $b\bar{b}$ and $c\bar{c}$ spectroscopy with a presentation of some new theoretical results on the spacing of the levels in potential models²⁷ and a comparison with experiment. There are theoretical reasons to believe that the quark-antiquark potential obtained from lattice QCD is monotonous and concave²⁸, i.e.:

$$\frac{dV}{dr} > 0 \quad \text{and} \quad \frac{d^2V}{dr^2} < 0. \quad (13)$$

This implies also the weaker statement that $V(r)$ as a function of r^2 is also concave, i.e.:

$$\frac{d}{dr} \frac{1}{r} \frac{dV}{dr} < 0. \quad (14)$$

Crudely speaking this means that $V(r)$ increases less fast than a harmonic oscillator potential. Then if we designate the energies by $E(n, \ell)$, n number of nodes of the radial wave function, ℓ orbital angular momentum we have²⁹

$$E(0, l) > \frac{1}{2} [E(0, l+1) + E(0, l-1)] \quad (15)$$

$$E(n, l+1) > \frac{1}{2} [E(n+1, l) + E(n, l)] \quad (16)$$

(sure for $n = 0$, very likely for $n > 0$).

This implies the following inequalities for the masses

$$\begin{aligned} \chi_c &> \frac{1}{2} [\mathcal{J}/\psi + \psi'], \quad \chi_c > \frac{1}{2} [\psi'' + \mathcal{J}/\psi] \\ \chi_b &> \frac{1}{2} [\gamma + \gamma'] \\ \chi_{b'} &> \frac{1}{2} [\gamma' + \gamma'']. \end{aligned} \quad (17)$$

These inequalities are all satisfied, for instance the one before last is

$$9.90 \text{ GeV} > \frac{1}{2} [10.02 + 9.46] \text{ GeV}.$$

We have also obtained some results on the spacing of the $l = 0$ levels. The most striking and simple one is that if $V'' < 0$, which is the case in lattice QCD

$$E(n+1, 0) - E(n, 0) < E(n, 0) - E(n-1, 0). \quad (18)$$

So far this has only been proved in the WKB approximation, but though the rigorous proof may take some time (some years perhaps!) I believe (18) very strongly. It is gratifying that

$$M_{\gamma'} - M_{\gamma} > M_{\gamma'} - M_{\gamma''} > M_{\gamma'''} - M_{\gamma''}. \quad (19)$$

However, if we interpret the first peak in the cross-section above the T'' as an $l = 0$ state, we have

$$M_{\gamma^{\#}} - M_{\gamma'''} > M_{\gamma'''} - M_{\gamma''} \quad (20)$$

This indicates clearly the breakdown of a naïve one-channel potential model! There are many ways out, including some gluon admixture³⁰, but the most credible one is just the effect of the channels with beauty-antibeauty meson pairs, as suggested for instance by Törnqvist³¹.

3. TOPONIUM

Predictions on toponium physics depend critically on the mass of the top. It was believed³² that the mass of the top was between 30 and 50 GeV. Therefore most of the work on toponium was concentrated on this interval. Then, in the worst possible case the total width of toponium would be less than 0.1 MeV and therefore a certain number of $\ell = 0$ states are guaranteed to be narrow, say 10 to 11 for a mass of the top of 40 GeV. This number scales with the square root of the top mass.

The 2S-1S mass difference is sensitive to the short range of the potential. For instance, again with $M_t = 40$ GeV,

$$\begin{aligned} M_{2S} - M_{1S} &= 520 \text{ MeV for } V = A + Br^{0.1} \\ &= 625 \text{ MeV for the Buchmüller et al. potential, with } A = 0.2 \text{ GeV.} \end{aligned}$$

The spacing of the higher levels is insensitive to the particular potential chosen, provided this potential fits well the $b\bar{b}$ and $c\bar{c}$ spectra, and the observation of, say, the 3S-2S mass difference will constitute a test of flavour independence.

At present the situation has changed. There are indications from the UAL experiment³³ that the mass of the top might be larger than 40 or 50 GeV. Also, the discovery of $B_0 - \bar{B}_0$ mixing by Argus implies that the top mass is large, at least 50 GeV³⁴, but possibly even larger than 90 GeV³⁵. All these statements contain some uncontrollable theoretical uncertainty and should not discourage experimentalists from looking for a light top. However, one should re-think toponium physics with the assumption that the top is heavy³⁶.

We shall treat as an exercise the case where the mass of the top is close to the mass of the W, say 81 GeV. Then the total width is completely dominated by single quark decay and as we shall see below is about

$$\Gamma_{tot}(m_t = 81 \text{ GeV}) = 4 \text{ MeV}.$$

The levels of toponium are still narrow and their spacing is much more sensitive to the short-distance behaviour of the potential

with $V = A + Br^{0.1}$ we expect $M_{2S} - M_{1S} = 500$ MeV;

with V QCD inspired, we expect $M_{2S} - M_{1S} \sim 1$ to 2 GeV.

Here the next spacing is also sensitive to the potential!

It may seem that we are doing a purely academic exercise because even if toponium is conceptually well defined (if $m_t < 81$ GeV) we may be afraid that the

signal will be hidden in the background. However, experiments considered as impossible today may be possible tomorrow (look for instance at the history of neutrino physics!).

What is worse is that if m_t is slightly higher the very notion of toponium may disappear. As long as $m_t < m_W + m_b$ the total width of the t , decaying into lepton pairs or quark pairs plus b , via a virtual W , behaves like G_F^2 . If m_t is appreciably larger than $m_W + m_b$, the real decay $t \rightarrow W+b$ is possible and the total width behaves like G_F !

A formula covering the whole transition region from $m_t < m_W$ to $m_t > m_W$ has been recently derived³⁷. Reference 38 reproduces this formula with misprints corrected. The width, for the particular final state $e\nu$, after the decay of the W is given by:

$$\Gamma(t \rightarrow b + e^+ + \nu) = \frac{G_F^2 m_t^5}{192 \pi^3} |U_{tb}|^2 f\left(\left(\frac{m_t}{m_W}\right)^2, \left(\frac{m_b}{m_t}\right)^2, \left(\frac{\Gamma_W}{m_W}\right)^2\right)$$

with

$$f(\rho, \mu, \gamma) = 2 \int_0^{(1-\sqrt{\mu})^2} \frac{dx}{(1-x\rho)^2 + \gamma} \left[(1-\mu)^2 + (1+\mu)x - 2x^2 \right] \times \sqrt{1+\mu^2+x^2-2\mu-2\mu x-2x} \quad (21)$$

It should be multiplied by a factor of 2×9 to get the total width of toponium. For $\rho \ll 1$ it reduces to the formula given by Kühn³⁹ if one forgets γ . For $m_t \gg m_W + m_b$, the denominator in the integral behaves like a delta function and after multiplication by 9 one gets the total width for the decay $t \rightarrow W+b$. For very large m_t one gets³⁷

$$\Gamma_{t\bar{t}} \simeq 360 \text{ MeV} \times |U_{tb}|^2 \times \left(\frac{m_t}{m_W}\right)^3 \quad (22)$$

Typical values for the total width of toponium have been calculated by P. Chiappetta, including the effects of running α

$\Gamma_{t\bar{t}} = 4 \text{ MeV}$	for $m_t = m_W = 81 \text{ GeV}$
$\Gamma_{t\bar{t}} = 12 \text{ MeV}$	for $m_t = 86 \text{ GeV}$ (threshold)
$\Gamma_{t\bar{t}} = 39 \text{ MeV}$	for $m_t = 90 \text{ GeV}$
$\Gamma_{t\bar{t}} = 157 \text{ MeV}$	for $m_t = 100 \text{ GeV}$

We see that the change is drastic. Beyond $m_t = 130$ GeV, the very notion of toponium ceases to be meaningful since the width becomes comparable to the spacing between the levels. Below we give the curve for f , with the correct scale, again from Chiappetta's calculation.

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