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EXACT BOUNDS AND ESTIMATES ON THE MASSES OF "BEAUTIFUL" HADRONS

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A B S T R A C T

Using the QCD inspired postulate that forces between quarks are flavour-independent together with general concavity properties of the eigenvalues of a Hamiltonian as a function of a parameter, we derive upper bounds on the masses of B , B^* ($b\bar{u}$, $b\bar{d}$) Σ_b and Λ_b from the experimental information on strange and charmed hadrons. The bound on $M_B + M_{B^*}$ is so close to the experimental lower limit that we investigate the question whether our bounds are not in fact relatively accurate estimates and conclude affirmatively. We discuss the crucial experimental problem of the $B^* - B$ and $\Sigma_b - \Lambda_b$ mass differences and conclude in particular that the decay $\Sigma_b \rightarrow \Lambda_b + \pi$ is certainly allowed. We find $5208 \lesssim M_B < 5288$ MeV, $5285 \lesssim M_{B^*} < 5365$ MeV, $5574 \lesssim M_{\Lambda_b} < 5654$ MeV, $5771 \lesssim M_{\Sigma_b} < 5851$ MeV, $52 \lesssim M_{B^*} - M_B \lesssim 57$ MeV, $187 \lesssim M_{\Sigma_b} - M_{\Lambda_b} \lesssim 207$ MeV.

Dedicated to Andrei Sakharov on the occasion of his 60th birthday

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1. - INTRODUCTION

The qualitative and quantitative successes of the quark model of hadrons are extremely impressive ¹⁾. One particular success is the fit of the masses of the mesons consisting of heavy quark-antiquark pairs interacting by a flavour-independent potential ²⁾. The fits are almost too good since one expects non-negligible relativistic effects ³⁾ as well as deviations from flavour-independence, even though the basic QCD Lagrangian is flavour-independent ⁴⁾. How heavy should the quarks be to get quantitative agreement? It turns out that even strange quarks can be considered as heavy for this purpose ^{5),6)}. In fact, it has been known for some time that many semi-quantitative features of hadrons containing ordinary quarks can be described by a non-relativistic flavour-independent Hamiltonian ⁷⁾, provided the light quarks are given a large effective mass between 250 and 330 MeV ¹⁾.

The discovery of the upsilon states ⁸⁾ has shown the existence of the b (beautiful) quark, and after the observation of hidden beauty in three narrow states ⁹⁾ a fourth broad state has been seen to decay into pairs of mesons with naked beauty ¹⁰⁾. Naturally one would like to make predictions on hadrons with naked beauty, baryons as well as mesons. There exist already calculations with an explicit choice of interactions which lead to definite results ¹¹⁾, but we would like to make predictions which depend as little as possible on details of the model, such as the choice of the central force, the nature of the spin dependent interaction, the non-relativistic kinematics, etc. To be able to achieve this, one has to feed in the maximum possible amount of experimental information which will be the masses of hadrons containing one strange or one charmed quark. We shall also need the masses of the b , c , s quarks as determined from the fit of the $b\bar{b}$, $c\bar{c}$, $s\bar{s}$ pairs by a potential model ⁵⁾. Fortunately it has been shown ¹²⁾ that the mass differences between the heavy quarks are insensitive to the chosen particular model, and this is the quantity which is most important for us.

The basic remark will be that the only way the nature of the third quark (in baryons) or second quark (in mesons) appears in the Hamiltonian is through its mass. There is a general theorem which says that if you have a Hamiltonian

$$H = A + \lambda B \quad (1)$$

the ground state energy $E(\lambda)$ is a concave function of λ , i.e.,

$$\frac{d^2 E}{d\lambda^2} \leq 0 \quad (2)$$

The importance of this result has been stressed by Thirring¹³⁾. The proof comes from a variational argument : assume $\lambda = 0$, ψ_0 wave function at $\lambda = 0$. We have

$$E(\lambda) \leq E(0) + \lambda \langle \psi_0 | B | \psi_0 \rangle, \quad (3)$$

from which (2) follows.

A generalization is that if H , as an operator, is concave in λ , i.e.,

$$\langle x | \frac{\partial^2 H}{\partial \lambda^2} | x \rangle \leq 0, \quad \forall |x\rangle, \quad (4)$$

the ground state energy is again concave in λ .

2. - UPPER BOUNDS ON THE MASSES OF BEAUTIFUL HADRONS

We consider Qqq and $Q\bar{q}$ states where q is an ordinary (up-down) quark and Q a heavy quark.

We want to argue that if we identify $1/m_Q$ with λ in the Hamiltonian we can apply the concavity theorem of the previous section. For definiteness take the non-relativistic Hamiltonian. The kinetic energy of the quark Q is linear in $1/m_Q$. The spin dependent terms as given, for instance, in Ref. 8) behave like $1/m_Q$. Only the spin orbit terms contain $1/m_Q^2$ terms but these can be disregarded in the ground state of the system. Specifically we have

$$H = \frac{p_Q^2}{2m_Q} + \frac{1}{m_Q} H_{spin} + H' \quad (5)$$

H_{spin} contains the interaction of the spin of Q with the other spins. H' contains the central part of the Qq_1, Qq_2, q_1q_2 potentials, the energies and the spin-spin interactions of the two light quarks with all possible relativistic effects one likes. One can even give a relativistic kinetic energy to the Q quark. Indeed

$$\sqrt{p_Q^2 + m_Q^2} - m_Q$$

is an operator diagonal in p_Q and, as a function, it is a concave function of $1/m_Q$. Hence it is also concave as an operator in $1/m_Q$.

The theorem therefore applies, with, however, one precaution : hidden in H_{spin} there is a term $(\vec{\sigma}_Q \cdot \vec{\sigma}_q) \delta(\vec{r}_Q - \vec{r}_q)$. Strictly speaking such a Hamiltonian is not lower bounded. It must be understood that all delta functions must be smeared, all too singular interactions - like the tensor force - must be cut off before one applies the theorem.

With this precaution the theorem holds and we get, specifying, as we are allowed to do, quantum numbers like the total angular momentum or the isospin :

$$\left. \begin{array}{l} M(Q\bar{q}, J=0) - m_Q, M(Q\bar{q}, J=1) - m_Q \\ M_{\Lambda_Q} - m_Q, M_{\Sigma_Q} - m_Q \end{array} \right\} \quad (6)$$

are concave functions of $1/m_Q$

Remarks

- i) To apply the theorem we have not eliminated the centre-of-mass motion. It is our right, since we look only at the ground state.
- ii) Precisely, the theorem does not apply to radially excited states. Even if we could eliminate the centre-of-mass motion it would still not apply to individual levels but only to the sum of the energies of the first n levels including the ground state.
- iii) Flavour-dependent effects, in m_Q^{-1} , do not affect the validity of the theorem.

To apply these results, we need to know the effective masses of the b , c , s quarks. These can be taken from a fit of the $b\bar{b}$, $c\bar{c}$, $s\bar{s}$ spectra. The masses will be somewhat dependent of the potential chosen but as we said already the differences between the quark masses have been shown to be remarkably stable ¹²⁾. Here we use mainly the quark masses that we have proposed in Ref. 5) :

$$m_s = 0.518 \text{ GeV}, m_c = 1.8 \text{ GeV}, m_b = 5.174 \text{ GeV} \quad (7)$$

but we shall also use for comparison the masses proposed by Bertlmann and Ono ¹⁴⁾ who also propose a mass for the up-down quark :

$$m_u = m_d = 0.31 \text{ GeV}, m_s = 0.62 \text{ GeV}, m_c = 1.91 \text{ GeV}, m_b = 5.27 \text{ GeV}. \quad (8)$$

Both sets are based on the assumption that the absolute mass of the T is 9.46 GeV as indicated by the DESY experiments ¹⁵⁾.

Let us show how we use concavity in $(m_Q)^{-1}$ to obtain bounds on the B meson mass. We take $M_K = 496$ MeV and $M_D = 1866$ MeV. With the choice of masses (7), the expression

$$101.52 - \frac{64000}{m_Q} \text{ MeV}$$

reproduces exactly $M_K - m_s$ and $M_D - m_c$ and gives an upper bound on $M_{(Q\bar{q} J=0)} - m_Q$ for $m_Q > m_c$. Applied to M_B it gives

$$M_B \leq 5263 \text{ MeV} \quad (9)$$

while the other choice of masses given by (8) leads to

$$M_B \leq 5251 \text{ MeV} \quad (10)$$

Similarly, from $M_{K^*} = 892$ MeV and $M_{D^*} = 2009$ MeV, we get

$$M_{B^*} \leq 5340 \text{ MeV}, \quad \text{from (7)} \quad (11)$$

and

$$M_{B^*} \leq 5315 \text{ MeV}, \quad \text{from (8)} \quad (12)$$

It is interesting to notice that the two sets of quark masses, which differ by about 100 MeV lead to bounds which differ at most by 25 MeV.

We remark that (9) and (11) lead to

$$M_B + M_{B^*} \leq 10603 \text{ MeV} \quad (13)$$

and (10) and (12) to

$$M_B + M_{B^*} \leq 10566 \text{ MeV} \quad (14)$$

Experiment ¹⁶⁾ shows that the mass of the T''' , 10580 MeV, is less than $M_B + M_{B^*}$ since the reaction

$$M_{B^*} \rightarrow M_B + \gamma \quad (15)$$

is not observed in the decay products of T''' . This means that the bound (13) is very tight and that the bound (14) is slightly violated, but not in a very significant way.

In the baryon case the experimental input is

$$\begin{aligned} M_{\Lambda} = M_{\Lambda_s} &= 1115.6 \text{ MeV} & M_{\Sigma^0} &= 1192 \text{ MeV} \\ M_{\Lambda_c^+} &= 2285 \text{ MeV}^{17)} & M_{\Sigma_c^+} &= 2457 \text{ MeV}^{18)} \end{aligned} \quad (16)$$

and we get, from (7)

$$M_{\Lambda_b} \leq 5629 \text{ MeV} \quad M_{\Sigma_b} \leq 5826 \text{ MeV}, \quad (17)$$

from (8)

$$M_{\Lambda_b} \leq 5608 \text{ MeV} \quad M_{\Sigma_b} \leq 5810 \text{ MeV}. \quad (18)$$

Again, comparing (17) and (18) we get a shift of about 25 MeV. We propose to conclude that the upper bounds (9), (11) and (17) are accurate up to ± 25 MeV.

3. - ARE THE UPPER BOUNDS ESTIMATES ?

We have seen that the upper bound that we have obtained on $M_B + M_{B^*}$ is only 20 MeV above the experimental lower limit for this quantity. This seems to indicate that the upper bounds that we have obtained are in fact estimates. In the case of the B this is not a surprise since a formula with the correct structure proposed by Quigg and Rosner ¹⁹⁾ was known to reproduce correctly M_B , M_D and M_K ⁵⁾.

To check that we are getting estimates as well as upper bounds the only simple thing we can do is to look at non-relativistic models. In the two-body case the binding energy is a function of the reduced mass alone, i.e., $(1/m_q + 1/m_Q)^{-1}$ where m_q is the mass of a light quark. We can compare $M(Q\bar{q}) - M_Q - m_q$ with a formula $A + B(m_Q)^{-1}$, adjusted to reproduce the binding energy of $s\bar{q}$ and $c\bar{q}$, choosing for instance as quark masses :

$$m_q = 0.3 \text{ GeV} \quad m_s = 0.5 \text{ GeV} \quad m_c = 1.8 \text{ GeV}$$

We take as a measure of the accuracy the quantity δ , the error made for $m_Q = \infty$ divided by the $L = 0$ level spacing for $m_Q = \infty$. This procedure avoids difficulties in comparing confining and non-confining potentials. We get the following results :

$V = \text{Square Well}$	$\delta \equiv 0$	}
$V = r^2$	$\delta = +0.7\%$	
$V = r$	$\delta = +1\%$	
$V = \log r$	$\delta = +2\%$	
$V = -1/r$	$\delta = +7\%$	

(19)

taking as a typical level spacing 600 MeV, and knowing that the potential is not far from logarithmic, we get an estimate of the error, for a purely central interaction of 15 MeV.

Let us now discuss the spin effects in the meson case. Here the difficulty is that we know only a crude form of the interaction. We shall restrict ourselves to the spin-spin interaction :

$$C \frac{\langle \vec{\sigma}_q \cdot \vec{\sigma}_Q \rangle}{m_q m_Q} |\psi(0)|^2 . \quad (20)$$

To be meaningful $|\psi(0)|^2$ which arises from a δ function interaction should be replaced by an integral over $|\psi(r)|^2$. It will become obvious that this is really necessary because of the magnitude of the spin separation. If we take for simplicity a power potential

$$V = V_0 r^\alpha \quad (21)$$

Equation (20) becomes

$$C' \frac{\langle \vec{\sigma}_q \cdot \vec{\sigma}_Q \rangle}{m_q m_Q} \left[\frac{1}{m_q} + \frac{1}{m_Q} \right]^{-\frac{3}{2+\alpha}} \quad (22)$$

On this expression, we can make the same numerical experiment as before : take an expression $A + B/m_Q$, adjust it to (22) for $m_Q = m_s$ and $m_Q = m_c$ and consider $\rho = A/[A+B/m_c]$ as a measure of the error committed for large m_Q . We find

$$\left. \begin{array}{ll} \text{for } V=r & \rho = 37\% \\ V=\log r & \rho = 41\% \\ V=-\frac{1}{r} & \rho = 85\% \end{array} \right\} \quad (23)$$

The least one can say is that the approximation is not very good ! Taking (22) for valid and using 143 MeV as D^*-D separations, we see that with the logarithmic potential and the $1/m_Q$ fit we make an error in the limit $m_Q \rightarrow \infty$ which is

$$+15 \text{ MeV} \quad \text{for } J=1 \text{ states} \quad (24)$$

$$-44 \text{ MeV} \quad \text{for } J=0 \text{ states} \quad (25)$$

This latter result indicates that our treatment is too rough. Indeed, adding up the positive shift due to recoil and the shift due to spin-spin interaction we should get an over-all positive shift, according to the general theorem. This is not the case for $J = 0$ states. This is evidence that the spin-spin interaction cannot be treated perturbatively at least in the $J = 0$ states and this naturally necessitates the replacement of the delta function by an extended function. This is not terribly astonishing when one sees that the K^*-K separation is of the same order of magnitude as the K mass itself. The only thing we can do is to disregard (25) as impossible and take the same error for the $J = 0$ and $J = 1$ states of

$$15 + 15 = 30 \text{ MeV} \quad (26).$$

We now turn to the three-body case, using for the time being spin independent forces. Here, unless we want to start extensive numerical calculations we have to consider only an exceptionnally simple case that of three bodies with harmonic oscillator forces and two equal masses. This had a well-known solution but we repeat it to be self-contained. We consider two cases.

i) no forces between light quarks

The wave function is

$$\exp - \alpha [r_{Qq_1}^2 + r_{Qq_2}^2] - \beta r_{q_1q_2}^2 \quad (27)$$

with

$$\begin{aligned} V &= 2\alpha^2 \left[\frac{2}{m_Q} + \frac{1}{m_q} \right] \\ \beta &= \frac{\alpha}{2} \left[-1 + \sqrt{1 + 2 \frac{m_q}{m_Q}} \right] \end{aligned} \quad (28)$$

and the energy

$$E = 6 \left[\frac{\alpha + \beta}{m_q} + \frac{\alpha}{m_Q} \right] \quad (29)$$

If we fit with a linear formula in $(m_Q)^{-1}$ for $m_Q - m_s$ and $m_Q = m_c$ we can measure again the error committed for $m_Q \rightarrow \infty$, dividing by the energy spacing. We find

$$\delta = +0.021\% \quad (30)$$

ii) equal strength between all quarks

Equation (28) is replaced by

$$\beta = \frac{\alpha}{2} \left[-1 + \sqrt{3 + 6m_q/m_Q} \right] \quad (31)$$

and again we get

$$\delta = 0.0217_0 \quad (32)$$

If we take the same basic spacing of 600 MeV and multiply by a 2.5 safety factor based on the comparison between the r^2 and $\log r$ potentials in the two-body case, we get an estimate of the error of

$$30 \text{ MeV} \quad (33)$$

Concerning the spin-dependent part in Qqq , let us first notice that in Λ_Q it will be (we restrict ourselves to Fermi interactions !) independent of m_Q in the case of equal strength r^2 forces. Indeed the couplings between Qu and Qd cancel each other and the probability for $r_{ud} = 0$ is independent of m_Q because the wave function can be factored as

$$f(\vec{r}_Q - \frac{1}{2}(\vec{r}_u + \vec{r}_d)) g(\vec{r}_u - \vec{r}_d)$$

The extrapolation is therefore trivial.

In Σ_Q the thing is slightly more complicated. Since the spin terms give a constant contribution to Λ_Q we can look at the $\Sigma_Q - \Lambda_Q$ mass difference only which, in the harmonic oscillator model, is given perturbatively by

$$M_{\Sigma_Q} - M_{\Lambda_Q} = C \left[\frac{1}{m_q} \left(\frac{\alpha}{2} + \beta \right)^{3/2} - \frac{1}{m_Q} \left(\frac{\alpha(\alpha + 2\beta)}{\alpha + \beta} \right)^{3/2} \right]. \quad (34)$$

For reasons already given, $\alpha/2 + \beta$ is independent of m_Q . We make again a linear fit in $1/m_Q$ of this formula and find a relative error of -10% of $M_{\Sigma_C} - M_{\Lambda_C}$ for all $m_Q > m_C$, i.e., an error of at most -17 MeV. At $m_Q = m_b$ the relative error is -6%. We remark that the shift has the same sign as in the pseudoscalar meson case but this time it is small enough compared to the shift due to recoil. The conclusion is that the estimate (33) is unaffected by spin interactions.

We end up with the following list of inequalities, taking into account the extrapolation errors and the uncertainty on the quark masses :

$$\left. \begin{array}{l} 5208 < M_B < 5288 \text{ MeV} \\ 5285 < M_{B^*} < 5365 \text{ MeV} \\ 5574 < M_{\Lambda_b} < 5654 \text{ MeV} \\ 5771 < M_{\Sigma_b} < 5851 \text{ MeV} \end{array} \right\} \quad (35)$$

The errors we are giving are probably too big. There are in fact strong correlations and the error on any difference between two of these masses is much smaller than what is given by (35). In the next section we discuss two of these differences.

4. - THE $B^* - B$ AND $\Sigma_b - \Lambda_b$ MASS DIFFERENCES

We have seen in the last section that for various reasons the $B^* - B$ mass difference does not fit very well with an expression $A + B m_Q^{-1}$. In fact, though we have good reasons to believe that lowest order perturbation theory is too naïve to reproduce the $K^* - K$ mass difference, we have every reason to believe that a formula of the kind (20) applies for $m_Q \rightarrow \infty$ as well as the Fermi hyperfine splitting formula applies in atoms. We propose to try another extrapolation formula which automatically incorporates the $(m_Q)^{-1}$ behaviour as $m_Q \rightarrow \infty$. We take

$$C(m_Q)^{-1} + D(m_Q)^{-2} \quad (36)$$

To test the flexibility of this formula we make the same kind of numerical experiments we did before with power potentials using (22), the perturbation expression for the splitting [we expect higher order effects to decrease like $(m_Q)^{-2}$ and to be accommodated by (36)]. Using as a basis the splitting for $m_Q = m_c$ we find that the maximum relative error made by using (36), fitted to $s\bar{q}$ and $c\bar{q}$, is :

$$\left. \begin{array}{ll} -1.3\% & \text{for } V = r \\ -2.3\% & \text{for } V = \log r \\ -6.5\% & \text{for } V = -1/r \end{array} \right\}$$

We can therefore apply (36), with an error of -3% of 143 MeV. In this way we get, using either masses (7) or masses (8) :

$$52 \text{ MeV} < M_{B^*} - M_B < 57 \text{ MeV}. \quad (38)$$

Concerning the $\Sigma_b - \Lambda_b$ mass difference we have already discussed the extrapolation procedure in the previous section. We have estimated the error using the standard extrapolation procedure to be $\pm 6\%$ of the $\Sigma_c - \Lambda_c$ mass difference. We get, in this way

$$M_{\Sigma_b} - M_{\Lambda_b} = 197 \pm 10 \text{ MeV} \quad (39)$$

This means that we predict that the decay $\Sigma_b \rightarrow \Lambda_b + \pi$ is ~~allowed~~. This agrees with some model calculations with a particular potential ¹¹⁾ but is in disagreement with other calculations based on SU(6) symmetry ²⁰⁾. We believe that in the presence of so large mass differences, the use of symmetries is very dangerous and we stick to our result. There is an extra indication in our favour. It is the fact that extrapolating to infinite Q mass we get

$$M_{\Sigma_\infty} - M_{\Lambda_\infty} = 211 \pm 20 \text{ MeV} \quad (40)$$

Here the mass difference is entirely due to the light quark pair. In the harmonic oscillator model the probability for the two light quarks to coincide is independent of the mass of the third quark and it is therefore the same as in the N - Δ system. The ratio $M_{\Sigma_\infty} - M_{\Lambda_\infty} / M_\Delta - M_N$ is therefore purely given by spin factors in the harmonic oscillator model. Numerically we get

$$\frac{211}{297} = 0.71 \text{ instead of } 2/3. \quad (41)$$

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