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Review of spectroscopy and strong decays of heavy baryons

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Abstract

Models which are used to examine both masses and decays of the baryons are considered. One major question of interest is the exact nature of the inter quark potential. Since baryon spectroscopy samples a different region of this potential then meson spectroscopy, it is of some interest to compare fits to both sets of data. Of even more interest would be an experiment starting with quarks placed fairly far apart and than moving them closer together. In the absence of such an experiment, the distance is varied by changing the quark flavour. Thus, changing from light u, d and s quarks to the c and b quarks yields a wealth of information about the inter quark potential.

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1. INTRODUCTION

Models are developed within the framework originally introduced by De Rújula, Georgi and Glashow [1]. At small distances QCD suggests a Coulomb-type potential $-a_s/r$, where a_s is the quark-gluon fine-structure constant. At large distances one expects a confining potential. Lattice gauge theory [2] and string models [3] lead one to expect a linear confining potential. Such a combination of a linear confining potential plus Coulombic-type short distance potential plus one-gluon-exchange forces provide a good fit to meson mass spectra [4]. For baryons the situation is much less clear. it has been suggested that the potential might not be in the form of a direct quark-quark interaction, but instead in the form of a branched string emanating from some central point in between the three quarks. It is probably not necessary to give special consideration to such models since it has been shown in an appropriate treatment of lattice gauge theory [5] that a sum of linear two-body forces has the same effect as such a three-body force.

Gromes and Stamatescu [6] studied the three-body potential in the baryons using Gaussian wave functions since the harmonic-oscillator potential is the only potential that can be solved exactly for any number of particles. [7] Indeed this procedure is the basis of the standard method in chemistry used to calculate molecular energies. [8,9,10] Precisely, Gromes and Stamatescu suggested setting

$$V'(r_{ij}) = \frac{1}{2}\mu\omega^2 r_{ij} + [V(r_{ij}) - \frac{1}{2}\mu\omega^2 b r_{ij}]$$
$$= V_0(r_{ij}) + U(r_{ij}) \qquad (1)$$
$$V(r_{ij}) = -C_F\alpha_s / r_{ij} + a r_{ij} + C$$

where m is the reduced mass, r_{ij} is the separation between quark i and quark j, C_F is the colour factor of baryons taken to be 2/3 as suggested by QCD, a is a constant describing the string strength and C is an overall constant. (In Gromes and Stamatescu b=1). $U(r_{ij})$ is treated perturbatively.

In this paper $V(r_{ij})$ will be taken to be a combination of a Coulomb and a linear potential. Since the potential is in principal unknown, Isgur and Karl, [11] rather than specifying an exact form, applied a parametrization of $U(r_{ij})$ involving three parameters to a highly successful calculation of the excited positive-parity baryons. The problem with this approach as utilized by Isgur and Karl is that different sets of parameters are needed to analyze the ground-state and negative-parity baryons. Kalman and Hall [12] and Kalman [13] by using a technique introduced by Kalman, Hall and Misra [14] were able to apply a single parameter set to all low-lying baryon states. In these two papers, mixing between the ground-state and first excited positive-parity states due to the hyperfine interaction was included by use of the composition and masses of the excited positive-parity baryons by Isgur and Karl [11]. The resulting parameter set was then successfully used to

make a full calculation of the masses of all the negative-parity baryons. Since the purpose of the work [12,13] was to use a single parameter set for all the baryon states, Kalman [15] performed a new calculation of the masses of all of the ground-state and first-excited positive-parity baryons containing u,d,s,c and b quarks treating all states on an equal footing. In addition to the interband mixing due to the hyperfine interaction, following the lead of the successful meson calculations of Kalman and Mukherji [16], the calculation also included interband mixing due to the potential itself. Complementing the work of Kalman and Pfeffer [17] covering all the ground-state and negative-parity baryons containing u,d,s,c and b quarks this work of Kalman [15] was the first paper to contain calculations of the masses of excited positive-parity baryons containing b quarks.

2. THE MASS CALCULATION

The model for this calculation by Kalman and Tran [18], based on non-relativistic-quantum-mechanics, uses fewer parameters than any other model; five parameters comprising the masses of the five u,d,s,c and b quarks and three parameters corresponding to the inter quark potential. Here rather than use an undetermined potential, the potential $V(r_{ij})$ of eq. 1 is taken to be a combination of a Coulomb and a linear potential, which in turn is modified according to eq. (1) by a harmonic-oscillator potential. As seen in fig. 1 this combination at short and medium range is

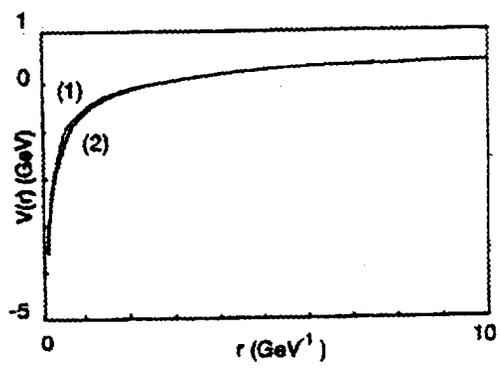

Fig. 1. The graphs of the potentials:
1) $V(r)=-0{,}667/r+0.08r-0.004r^2$ and
2) $V(r)=-0{,}667/r+0.191 \ln r$

similar to the combination of a Coulomb and a logarithmic potential used by Gromes and Stamatescu. [6] It should be noted that as Gromes and Stamatescu pointed out the logarithmic potential only describes the interaction at medium energy and the potential may have a different form at long range. Furthermore the energy of the states (mass of the baryons) corresponds only to the short- and medium-range behaviour of the chosen potential. Thus any modifications of the potential at long-range needed to produce complete confinement of the quarks is inconsequential to the mass calculation.

In this work a single set of parameters is used for all baryon states. The mixing between the ground-state and first-excited positive parity baryons as well as the mixing between the first-excited and second-excited -negative parity baryons are taken into account. The importance of this interband mixing was shown by Isgur and Karl. [19]

The full Hamiltonian employed by Kalman and Tran has the form;

$$H = \sum_i m_i + H_0 + \sum_{i<j} U(r_{ij}) + H^{ij}_{hyp},$$

where m_i are the quark masses and

$$H^{ij}_{hyp} = \frac{2\alpha_s}{3m_i m_j}\{\frac{8\pi}{3}\boldsymbol{S}_i \cdot \boldsymbol{S}_j \delta^3(\boldsymbol{r}_{ij}) \tag{2}$$

$$+\frac{1}{r_{ij}}[\frac{3(\boldsymbol{S}_i \cdot \boldsymbol{r}_{ij})(\boldsymbol{S}_j \cdot \boldsymbol{r}_{ij})}{r^2_{ij}} - \boldsymbol{S}_i \cdot \boldsymbol{S}_j]\},$$

H_0 is the harmonic-oscillator potential and $U(r_{ij})$ is found in eq. (1). As with the U term, the hyperfine interaction is treated perturbatively. In accordance with the previous remark, the mixings by the U term and the hyperfine interaction within each band and between different bands are also taken into account.

In terms of the Jacobi relative coordinates (see fig. 2)

$$\rho = \frac{1}{\sqrt{2}}(r_1 - r_2) \tag{3a}$$

$$\lambda = \frac{1}{\sqrt{6}}(r_1 + r_2 - 2r_3) \tag{3b}$$

the harmonic oscillator Hamiltonian decomposes into a description of two independent oscillators with the same spring

constant k. Hence;

$$H_o = \frac{P_\rho^2}{2m_\rho} + \frac{P_\lambda^2}{2m_\lambda} + \frac{3}{2}k(\rho^2 + \lambda^2) \qquad (4)$$

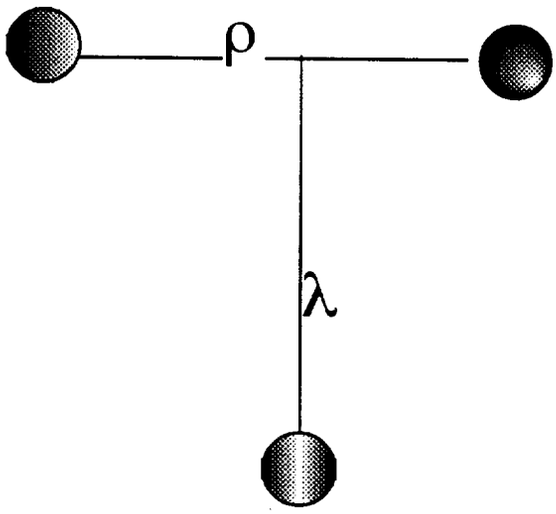

Fig. 2 The ρ and λ harmonic-oscillators

This particular decomposition is valid provided that at least two of the quark masses are equal. Baryons containing three different quark masses can still be included but require a different decomposition than that provided by the Jacobi coordinates introduced in eq. 3. In this paper, the convention will be used that in all cases the two quarks comprising the ρ oscillator are the ones with the same masses. Hence the reduced masses of m_ρ and m_λ of the ρ and λ oscillators, respectively have the form

$$m_\rho = m_1$$

$$m_\lambda = \frac{3m_1m_3}{2m_1 + m_3} \qquad (5)$$

Now set

$$\alpha_j^4 = 3km_j, \quad j = \rho, \lambda \qquad (6)$$

For the moment turn off the hyperfine interactions. The variational process is applied separately to the ρ and λ oscillators to determine α_ρ and α_λ. Note that for b > 1.0 as in our case, the potential will become unconfining at some point. At first this seems to be an unphysical potential. However as mentioned earlier, the energy of the states corresponds to the short- and medium- range of the potential and the potential used in the calculation is only valid in these ranges. We take view of Gromes and Stamatescu. [6] that the potential may be different than that used in this paper (Kalman and Tran [18) at long-range. Examining fig. 1, it is clear that in the regions of interest to this paper,(Kalman and Tran [18]) the potential is confining.

Turning the hyperfine interactions back on, the fit to the baryon spectra yields a= 0.08 GeV^2, b = 1.68, C=-0.6 GeV, α_s = 1.0, $m_u = m_d$=0.23 GeV, $x_1 = mu/m_s$ = 0.38, $x_2 = m_u/m_c$ =0.1237, $x_3 = m_u/m_b$ = 0.0455.

It is well established [20] that non-relativistic-quantum-mechanics gives a good account of spectroscopy. Extra relativistic energies simply accumulate in the mass of the *constituent* quarks which are situated at fixed distances from each other. Indeed until now no true relativistic potential model exists. The approach taken by many model builders is to adopt relativistic kinematics. [21,22] A study of the unequal-mass quarkonium spectra by Kalman and D'Souza [23] using only a few undetermined parameters and a nonrelativistic approach yields results which are extremely close to experimental data and which are similar to those obtained by Godfrey and Isgur [24] in a model based on relativistic kinematics. A better attempt to incorporate relativity to calculate the spectra of baryons containing u,d or s quarks is by Dong et al. [25] Their potential is derived from the exact three dimensional relativistic equation. In view of the earlier remarks found in this paper, it is interesting to note that Dong et al. end up incorporating a logarithmic term coming from the retardation expression. Dong et al. use their final section, discussions and conclusions to compare their results to the mass calculation of Kalman and Tran. [18] They point out that they have a somewhat better agreement with experiment than Kalman and Tran. Such a comparison is however difficult as Kalman and Tran use only 7 parameters to cover the part of the spectra of baryons containing u, d or s quarks compared to the 12 parameters used by Dong et al. Their slightly better agreement might be due to this feature alone.

3. THE QUARK PAIR CREATION MODEL OF LE YAOUANC et. al. [26]

The decay A->B+M, where A and B are baryons and M is a meson is shown in fig.3. During the process a quark-antiquark pair is created and combines with the original baryon B and the meson M. The initial quarks remain unaffected by the process.

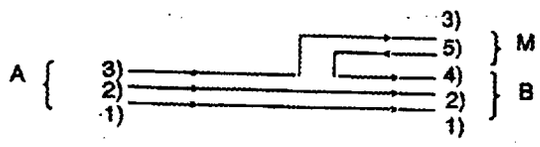

Fig. 2. - Diagram of the decay A-> B + M

The $q\bar{q}$ pair has the quantum numbers of the vacuum. It is a colour singlet and flavour singlet and has zero momentum and zero total angular momentum. The pair must also be of positive parity for parity conservation. Finally a fermion-antifermion pair has $P=(-1)^{l+1}$, $C=(-1)^{l+s}$, so the pair must be in a $^3P_0$ state. In the QPC model by Le Yaouanc et al. **[26]** the pair creation is the same for all processes. In Kalman and Tran [27], the creation strength γ is replaced by k_M^γ to include other effects as discussed in Kalman and Tran. To have the correct unit for the decay widths, it should be understood that there is a constant a = 1 GeV^{-1} attached to k_M. Since each state in the spectroscopy is the result of the mixing of several states, the decay amplitude from $|A\rangle$ to $|B\rangle$ is the sum of all individual amplitudes between the components of $|A\rangle$ and $|B\rangle$. The mixings of the states are given in Kalman and Tran [27] and the exact form of the bayonwave functions are found in Kalman and Tran. [18] Thewavefunction of the ground state meson is given by:

$$\psi_M = (\frac{1}{\pi\alpha_M^2})^{3/4} \exp[\frac{-1}{\pi\alpha_M^2}(\mathbf{k}_1 - \mathbf{k}_2)^2] \quad (7)$$

4. DISCUSSION OF RESULTS AND CONCLUSIONS.

Of the two major analyses, that of Koniuk and Isgur [28] does not cover the N = 3 band baryons and the one by Forsyth and Cutkosky [29]. does not cover the L and S sectors. The N = 3 band in the L and S sectors has not been considered before Kalman and Tran [20]. The results of Kalman and Tran [20] show a generally good agreement with the experimental data. A large number of resonances are essentially decoupled from the studied channels, a result first noted by Koniuk and Isgur [28]. Koniuk and Isgur have suppressed the dependence of the amplitudes on the structure of the wave functions, which has an important affect on the decay amplitudes, and replaced two constants in the forward and recoil terms by four independent constants. Similarly Forsyth and Cutkosky allow these two constants to be different in different spin and orbital states of the $q\bar{q}$ pair. In effect they used eight parameters in addition to the baryon and meson radii. In this work, beside the meson radius, g and a_M are the only parameters of the decay model. The main purpose of this work is to establish the baryon spectrum, namely identifying the resonances with the experimental data. We are confident that with the results obtained, this goal is indeed achieved despite the fact that only the nonrelativistic quark model and the simple QPC model are used. We believe this is the most consistent quark model to-date describing the baryon spectroscopy in the sense that a single set of parameters is used for the whole spectra and then subjecting all of their properties namely the masses, radii and their wavefunction structures to a strict test by a decay model which has only two parameters. Finally the point should be stressed that the model here uses far less parameters than used by any other model. Not counting the masses of the c and b quarks, the model here uses six parameters as compared to thirteen in the relativized quark model. Forsyth's model only considers the nonstrange section and employs nine parameters compared to five employed to calculate the nonstrange sector in this model. Finally note that this model uses only 7 parameters to cover this part of the spectra of baryons containing u,d or s quarks compared to the 12 parameters used by Dong et al. [25] Tables 1 and 2 contain a new version of a portion of the tables found in Kalman and Tran [18] for baryons containing a single b quark. This new version is based on taking the mass of the ground state of Λ_b

to be 5640 Mev based on the observed value of 5641 ± 50 MeV. We then note:

$M(\Sigma^*_b) - M(\Lambda_b)$
= 256 MeV This calculation
= 253± 20 MeV Experiment
= 230± 20 MeV Roncaglia et. al. [24]

$M(\Sigma^*_b) - M(\Lambda_b)$
= 250 MeV This calculation
= 200± 20 MeV Experiment
= 197± 20 MeV Roncaglia et. al. [24]

High-energy experiments reveal a richness in the spectrum of the strongly interacting particles. The vast amount of the experimental data in baryon spectrum and the complicated three-body problem would by itself justify the study of the spectroscopy. One major question of interest is the exact nature of the inter quark potential. Since baryon spectroscopy samples a different region of this potential then meson spectroscopy, it is of some interest to compare fits to both sets of data. Of even more interest would be an experiment starting with quarks placed fairly far apart and than moving them closer together. Although such an experiment is out of the question, we can achieve the desired result of varying the distance by changing the quark flavour. That is changing from light u, d and s quarks to the c and b quarks yields a wealth of information about the inter quark potential. To permit an accurate examination of the wealth of new data, Ian D'Souza and I are completing a new calculation of all the results of Kalman and Tran to correct for all the effects of the renormalization group on the parameters. This should be available early in 1997.

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