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MESONIC CORRECTIONS TO THE BARYON MASS SPECTRUM

W.N. Cottingham and K. Tsu
Physics Department, University of Bristol

and

J. M. Richard
CERN - Geneva

A B S T R A C T

We here investigate possible pi mesonic contributions to the masses of the light baryons. The description of the spectrum is improved in particular for the Σ -A splitting. However, the meson and gluon exchange contributions are difficult to distinguish one from the other. The role of the pion field in the spectrum of P wave baryons and for the charge radius of the neutron is also briefly discussed.

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Much information on nucleons comes from nuclear physics. Nuclei are understood as bound states of nucleons with an average internucleon distance of about $1.7 F$. Also, the internucleon potential at distances greater than about $0.8 F$ is rather well described by conventional mesonic exchanges. In summary, nuclear physics supports a picture of a nucleon which has a small core region (which may well be described by quarks), surrounded by a mesonic cloud. On the other hand, many quark models of the nucleon have no mesonic cloud (or quark-antiquark pairs) and the three quarks occupy a rather large volume. For example, the harmonic oscillator model is typically ^{1),2)} taken to have a r.m.s. diameter of about $1.4 F$ and in the MIT bag model, the diameter is about $2.0 F$ ³⁾.

A tentative synthesis of the quark model and nuclear physics viewpoints has been made recently by Brown and Rho ⁴⁾. In their model, the constituent quarks are located within a region of about $0.6 F$ diameter only. This "little bag" is supplemented with a phenomenological pion field outside. The pion field pressure compresses the quark inside the bag which they estimate to attain the small equilibrium radius. In this model the increase in quark confinement energy is compensated for by the negative net energy of the pion field and its surface coupling, so that the total nucleon energy still equals its rest energy.

This little bag model suggests an attractive picture of the mechanism for the nucleon-nucleon force. At large internucleon distances the bags are distinct and the force is communicated by the well-understood meson fields ^{5),6)}; at smaller internucleon separation the bags begin to merge and explicit quark-quark forces come into play. In the little bag model this distance is about $0.6 F$ and corresponds quite closely with the size of the nucleon-nucleon core ⁷⁾. There is no convincing theory of the core as yet, but quarks could play a more explicit role here ⁸⁾.

The little bag, however, has a problem. It is well known that the three-quark model of baryons is very successful in describing the mass spectrum [Refs. 2),3),9),10)] and their electromagnetic transitions ^{11),12)} without any contribution from the meson field. In the little bag the meson field is not a small perturbation but completely distorts the simple model. For example, the three quarks in the nucleon of the little bag have a large probability of having net spin $\frac{3}{2}$, and, according to our estimations, this immediately spoils the successful neutron-to-proton magnetic moment ratio of the simple model ¹³⁾.

Here we take the view that the simple three-quark model is basically a good model of a baryon and consider the pion field effects to be small corrections. In perturbation theory, we examine the role played by the meson field

in the mass spectrum of strange and non-strange baryons. We find some evidence for contributions from the meson field, although they are difficult to distinguish accurately from gluon field effects. On the whole, the mesonic contributions to masses seem to be not greater than 10% of the total, an order of magnitude less than in the little bag model ⁴⁾.

To be specific, we consider the model of Brown and Rho in which the pion field outside the bag couples to the quarks inside the bag through the radial component of the axial vector current at the surface. We consider the quarks inside the bag to be in the ground orbital S states and in the usual SU(6) symmetric states of spin and flavour. The meson field is then an operator on the quark spin and flavour indices. Being isospin one, the pion field couples only to the up and down quark isodoublet. The contributions of the kaon field are neglected since the large kaon mass strongly suppresses the field outside the bag. The pion field operator is then

$$\phi_i(r) = \frac{Q}{4\pi} \tau_i \cdot \vec{\nabla} \cdot \vec{V} \left(\frac{e^{-\mu r}}{r} \right) \quad (1)$$

The normalization constant can be fixed either to the axial current or to the known pion field at large distances from a nucleon; in either case this gives

$$\frac{Q^2}{4\pi} = \frac{g}{25} \frac{1}{4M^2} \frac{g^2}{4\pi} = 0.05 \text{ (Fermi)}^2$$

The second order perturbation contribution to the SU(6) ground state baryon mass operator is then

$$\Delta M = -m \sum_{i,j} \vec{\nabla}_i \cdot \vec{\nabla}_j \vec{\tau}_i \cdot \vec{\tau}_j \quad (2)$$

where

$$m = \frac{Q^2}{4\pi} \frac{1}{6} \frac{e^{-2\mu R}}{R^3} (1 + \mu R) (2 + 2\mu R + \mu^2 R^2) \quad (3)$$

and R is the bag radius, taken to be the same for the whole supermultiplet.

The sums in Eq. (2) are only over the up and down quark isodoublet and

$$\sum_{i,j} \vec{\nabla}_i \cdot \vec{\nabla}_j \vec{\tau}_i \cdot \vec{\tau}_j = C_2 - 4S(S+1) - 4I(I+1) \quad (4)$$

where C_2 is the quadratic, spin isospin SU(4) Casimir operator and S and I are the net spin and isospin of the up and down quarks in the baryon. These numbers for the ground state supermultiplet are given in Table I. Also

shown are the actual masses of those baryons. In order to keep the quark content of the states as similar as possible, the spin $\frac{1}{2}$ states have been chosen with zero charge (they all contain an up and two charge $-1/3$ quarks), except for the Δ , the spin $\frac{3}{2}$ states contain three charge $-1/3$ quarks. No data on the mass of the Δ^- exist and we take the nominal P.D.G. value ¹⁴⁾.

It is interesting to note that the meson field gives positive contributions to the Σ - Λ and Λ - N mass differences, but gives zero mass difference to the Ξ^* - Ξ and Σ^* - Σ baryons. This latter circumstance immediately shows the need for a more conventional QCD quark spin-spin force. We therefore regard the "meson exchange" contribution to the baryon masses to be in addition to the more usual chromomagnetic splittings.

Such a quark spin-spin interaction, with its proper flavour dependence, is included for instance in the MIT bag ³⁾. This model is very attractive but it does have some difficulties, e.g., in its treatment of the quark centre-of-mass motion and of the already mentioned chiral invariance and long-distance nuclear interaction. In spectroscopy, this model is not perfect. A reasonable fit of the masses was obtained by the authors of Ref. 3). However, they cannot account for the Σ - Λ splitting, in spite of the choice of a rather large value of α_s

$$\alpha_s^0 = 4 \alpha_c = 2.2$$

For example, in a spherical cavity of radius $R=1$ F, the r.m.s. quark momentum is 0.41 GeV. Using Eq. (22) of Ref. 9) to extrapolate the running coupling constant to $q=0.41$ GeV, we find $\alpha_s \sim 1.1$.

Our strategy is to regard α_s as a free parameter and to add the mesonic contributions to the gluonic hyperfine splittings estimated by the MIT group. For instance

$$\delta = M_{\Sigma^0} - M_{\Lambda} = 16 m + \delta^0 \frac{\alpha_s}{\alpha_s^0}$$

where δ^0 is the result of Ref. 3), in which $m=0$, $\alpha_s = \alpha_s^0$ [we disregard the fact that in Ref. 3) the magnetic interaction is not treated perturbatively but included in the minimization scheme for each baryon]. The mesonic term m provides an additional parameter which we use to reproduce the correct Σ - Λ splitting. Results are given in Table II and compared with those of Ref. 3). It is interesting to note that introducing pionic corrections allows us simultaneously

- i) to reduce the value of α_s ;
- ii) to fit both Δ -N and Σ - Λ mass differences;
- iii) to improve the agreement for the Σ^* - Σ and Ξ^* - Ξ splittings.

Also, the value of m in Table II is consistent with the initial choice of a large bag, namely the MIT one, with only small pionic corrections treated perturbatively. Indeed, Eq. (3) gives $R \sim 1F$ for $m \sim 2.6$ MeV.

Our hybrid model, where hyperfine structure has gluonic and pionic origins, appears rather successful. We are, however, aware that there are many open problems.

- a) As in Refs. 3) and 9), the colour magnetic interaction is treated in the one-gluon-exchange approximation, although α_s is still rather large. Also no modification due to confinement is accounted for in the gluon propagator.
- b) We still carry some difficulties of the MIT model. In particular, our bag is too large to satisfy nuclear physicists.
- c) The same model, if taken literally, would give the wrong ordering for the ω and ρ masses. In the mesonic sector, one has to account for the mixing of quark configurations and for other unitarity loop corrections like $V \rightarrow VV \rightarrow V$, as explained in detail in Ref. 15). Probably a complete treatment of the baryonic sector is also more complicated than suggested here.
- d) Bearing in mind these uncertainties, it is hard to separate accurately for S wave baryons the contributions from gluon exchange (inside the bag) from pion exchange (outside).

The above investigations of the S wave baryons can be repeated for the $L=1$ non-strange supermultiplet. It is known that a positive spin-spin potential acting on SU(6) wave functions immediately gives the result that the $S_{11}(1535)$ and $D_{13}(1520)$ should be degenerate and split downwards by half the Δ -N difference from the $D_{13}(1700)$, $S_{11}(1700)$, $D_{15}(1670)$, $S_{31}(1650)$ and $D_{33}(1670)$ which should also, in this approximation, be degenerate. Again this spin-spin force can be attributed to gluon-exchange¹⁰⁾, pionic effects as per Eq. (2) or, more likely, to a mixture of both. There are in fact two ways of distinguishing between meson and gluon contributions. One is that gluon exchange has a large spin orbit part, and pion exchange does not. Empirically, the spin orbit splittings seem to be small¹⁰⁾, which favours a model with small α_s and some pionic contribution. A second

difference can be seen in the small tensor contribution, which gives rise to a mixing of the S_{11} and to a lesser extent of the D_{13} states. The pionic and chromomagnetic tensor forces have opposite signs. Empirically, the observed mixing agrees with the gluon exchange sign and this suggests that gluon exchange is the most important mechanism.

We have also looked at the influence of mesons on the electromagnetic properties of baryons. The most obvious positive indication is the negative charge radius of the neutron (empirically $\sqrt{\langle r^2 \rangle} = 0.31$ F). The long-range meson field around a neutron is predominantly π^- rather than π^+ and so contributes a term to the charge radius of the correct sign, again though, so does gluon exchange ¹⁶⁾. Apart from the neutron and proton magnetic moments, the other dipole transition amplitudes are not well enough known to distinguish small deviations from the quark model ^{12), 17)}. The very successful quark model prediction of the neutron to proton magnetic moment ratio ¹³⁾ suggests that both gluon and pion corrections are not large.

The idea of restoring the role of the pion field around the nucleon is good, since it is required by chiral considerations and by nucleon-nucleon dynamics. The "little bag" seems, however, too extreme in detail since it destroys the good predictions of the quark model. Introducing the pion field as a small perturbation around the MIT bag ^{*)} leads to good spectroscopic predictions, although in our particular calculation the nucleons still have a very large diameter, a problem for nuclear physicists.

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*) At attempt was made previously by Gross in Ref. 18).

TABLE I : Baryon masses and coefficients entering into mesonic corrections.

Baryon	C_2	S	I
N (939.6)	63	$\frac{1}{2}$	$\frac{1}{2}$
Λ (1115.6)	36	0	0
Σ^0 (1192.5)	36	1	1
Ξ^0 (1314.9)	15	$\frac{1}{2}$	$\frac{1}{2}$
Δ (1232)	63	$\frac{3}{2}$	$\frac{3}{2}$
Σ^- (1387.5)	36	1	1
Ξ^- (1535.0)	15	$\frac{1}{2}$	$\frac{1}{2}$
Ω^- (1672.2)	0	0	0

TABLE II : Mass differences between S wave baryons.

Quantity	Ref.3)	Our fit	Exp
m	0	2.62	
α_s	2.2	1.75	
$m_\Delta - m_N$	295	298	298
$m_\Sigma - m_\Lambda$	39	73	73
$m_{\Sigma^*} - m_\Sigma$	241	192	193
$m_{\Xi^*} - m_\Xi$	240	191	212

R E F E R E N C E S

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