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СИБИРСКОЕ ОТДЕЛЕНИЕ АН СССР
ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ

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THE STRUCTURE OF HADRONS CONTAINING A HEAVY QUARK

ПРЕПРИНТ 80-64

Новосибирск

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Abstract

For large heavy quark mass m_h there exist some limit for $M-m_h$, where M is the mass of a hadron containing such quark. These limits, as well as $O(m_h^{-1})$ corrections are found for 0^-, 1^- mesons, Σ and Λ-type barions in the MIT bag model. Unlike the earlier works which ignored the problem of c.m. motion in the bag model, we find qualitatively different predictions which are in much better correspondence with data. We also discuss spin and electromagnetic splittings of these hadrons.

Submitted to Physics Letters B.

The masses of light (u,d,s) quarks are rather different, but still there exist approximate SU(3) and more accurate isotopic SU(2) symmetries for their substitution. The reason for this is that these masses are all too small to be important. Something similar takes place for heavy quarks (c, b, ...) for their masses are too large in the hadronic scale. So, some symmetry for their substitution should exist in the families of 0^-, 1^- mesons, Σ and Λ type barions etc. For each family some limit for $M-m_h$ exists , where M are their masses and m_h is the heavy quark mass which goes to infinity. Such limit also exists for other quantities like formfactors, radii, electromagnetic splittings etc.

For the estimates of these limits we use the MIT bag model [1,2] , which was rather successful for ordinary hadrons. Also important, that its main ingredient, the volume energy term, has recently been explained in the QCD framework as being due to partial suppression of instanton-induced effects inside hadrons, see [3,4] .

Another motivation for the present work was the very strong disagreement between the earlier straightforward applications of this model [5] and data for charmed hadrons and, most important, for B meson. So, one may susspect that something important is missing. And indeed, in the present work I propose very simple explanation for it, being essentially pure kinematical one. The main observation is that although the so called problem of c.m. motion is important for ordinary hadrons, it does not exists for those containing heavy quarks and one should account for this.

The Hamiltonian of the bag model as it was used in [5] is

$$H = E_{light} + m_h + E_h + E_{bag} + E_o + E_{G.E.} + E_{G.M.}$$

where $E_{light} = 2.04 \cdot N_{light}/R$, where N_{light} is the number of light quarks and R is the radiys of the bag. $E_h = \pi^2/2 \cdot m_h \cdot R^2$ is the kinetic energy of heavy quark, $E_{bag} = \frac{4}{3}\pi \cdot B \cdot R^3$ where $B^{1/4} = 145$ Mev. $E_o = -1.86/R$ and the last two terms are the gluoelectric and gluomagnetic interactions between quarks.

We are going to discuss critically this expression term-by-term and to propose its significant modifications for the case considered. These modifications do not concerns the numerical values of the parameters, which we by perpose use as they were determined in [2] in the fit to masses of ordinary hadrons.

Let us start with the problem of center of mass motion. It is known to appear each time if, instead of fixing the total momentum of some system, we put it in some collective potential well. The arising fluctuations of the total momentum are completely fictitious[1] and the corresponding energy should be subtracted. There is no strict way of doing this in the relativistic case, but still we may estimate this energy $E_{c.m.}$ by simple projection of the bag wave functions to that with zero momentum. Doing this we may conclude, that for usual hadrons $E_{c.m.} = (1 \div 1.5)/R$. So, the subtraction of this term explains the essential part of E_o given above. Originally [2] this term was ascribed to the so called Kasimir effect, or the modification of zero-point oscillations by the bag. This

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[1] After quantization they also produce fictitious excited states.

interpretation of E_o term, actually found from the fit to hadronic masses, is similar to the recent explanation [3,4] of the bag itself with larger and new zero-point oscillations, the instantons. At the same time, we are not yet able to calculate the dependence on the bag size, so the status of the rest of $E_o + E_{c.m.}$ is very uncertain. Still we include it in what follows.

Now we come to hadrons containing very heavy quark. The problem of c.m. motion becomes trivial for fixing the center of mass is just fixing the heavy quark. This was not done in [5] where the heavy quark moves freely in the fixed bag. Therefore, in this problem there is no fictitious c.m.motion to be subtracted and the corresponding part of E_o is not needed. This observation is most important numerically.

One should also modify the E_h term, which is $O(m_h^{-1})$ correction. Using again the projection idea we may say, that light quarks move freely in a bag, and the recoil momentum is on the heavy quark. This gives $E_h = (2.04/R)^2/2.m_h$ for any light quark. Also in our "hydrogen-like" picture the interaction terms $E_{G.E.}$ and $E_{G.M.}$ are modified. The gluomagnetic interaction for fixed quark is due to its gluomagnetic moment, and can be written as

$$E_{G.M.} = \frac{g\,(\sigma^m \cdot \lambda_a)}{4\,m_h} B_m^a(0) \simeq \frac{0.3\,\alpha_s}{m_h \cdot R^2} (\sigma^m \lambda_a)(\sigma^m \lambda_a)$$

The second part of this formula is the estimate of the gluomagnetic field at the origin $B_m^a(0)$ with the bag model wave functions. Note, that this interaction is more short-range than that for light quarks, so the corresponding α_s value should be smaller. From $M(D^*)-M(D)=140$Mev one finds $\alpha_s=0.4$ to be compared with effective $\alpha_s=2.2$ for light quarks [2]. So, the perturbative aprroach is more justified. We find with our formulae $M(\Sigma_c)-M(\Lambda_c)=165$ Mev with very nice agreement with data 166 ± 16 Mev, but the existing evidences for Σ_c are so far rather weak.

The term $E_{G.E.}$ can be estemated as $-\frac{4 \cdot \alpha_s}{3} \cdot \langle \frac{1}{r} \rangle$. However, we know from charmonium theory that the Coulomb-like potential exists, if any, for $r < 0.3$ fermi, and then it is rather small. Moreover, we do not agree with the account for $E_{G.E.}$ in [2] and believe that it is included in E_0 term. So, we do not include this term at all.

Now we come to our results shown at Fig.1. Let us repeat that we made no fitting of the parameters, for in any case the accuracy is not better than 100 Mev. What we want to show is the qualitative difference between our results and [5] with the same set of parameters. This difference is dramatic for D,B mesons, for which there is strong compensation between E_{light} and E_0 in [5]. It makes these particles unusually "soft", so the vacuum pressure easily compresses them. Note, that their value of the bag radius, R=0.5 fermi, nearly twice smaller than ours 0.8, which is more common.

The question may be asked, how one may really check this difference. Let us note here the role of electromagnetic interaction, much better known than QCD one. Making use of the symmetry between different states with different heavy quarks, one is able to separate various terms from data on, say D and B mesons. For example, the magnetic interaction can be found from the following mass combination

$$E_M = M(D^+)-M(D^o)-M(D^{*+})+M(D^{*o})$$

in which we get rid of u-d quark mass difference and their QED self energies [6]. Its estimate from comparison with the gluomagnetic effect gives $E_M = \frac{\alpha}{2\alpha_s}[M(D^*)-M(D)] \simeq 1.2$ Mev. The available data are not accurate enoughto check this.

Another interesting quantity is the Coulomb interaction, available from the relation

$$E_E=M(D^+)-M(D^o)+M(B^-)-M(B^o)-3 \cdot E_M/4$$

Our estimates in the bag model are 3 Mev, while parameters of [5] give twice larger value and are in contradiction with the observed $M(D^+)-M(D^o)=5 \pm .8$ Mev, if one takes conventional $m_d-m_u = 3 \div 4$ Mev.

One short comment concerning Ξ-type particles with two heavy quarks. They make a kind of a nucleus in the center with quantum numbers of antiquark, so for the light quark this does not differ much from the case of the meson.

In conclusion, we propose significant modification of the bag model as applied to hadrons containing heavy quarks. The main point is simple kinematics: this quark stands in the center of the bag. The agreement with data is essentially improved.

These observations I made during the work on my lectures for a group of experimentalists, so I am indepted to their organizer, Prof. A.N.Skrinsky.

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Figure caption

The difference M-m_h versus m_h in Gev. The values from Υ, ψ theory are used, namely m_c=1300 Mev, m_b=4700 Mev. Solid lines are our calculations, the dashed ones are those of [2,5]. The latter give rather good fit to strange hadrons, but are wrong for larger quark masses.