Photon-cloud effects on isomultiplet mass differences of charmed and uncharmed baryons

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(Received 20 April 1988)

Isomultiplet mass differences of $\frac{1}{2}^+$ and $\frac{3}{2}^+$ baryons are studied in the constituent-quark model. We find that the mass differences of octet and decuplet baryons can be explained well in the presence of photon-cloud contributions. In the charmed sector, only the $\Sigma_c^0-\Sigma_c^{++}$ mass difference has recently been measured. By including the photon-cloud effects, we obtain a negative sign of the $\Sigma_c^0-\Sigma_c^{++}$ mass difference.

It is well known that the isomultiplet mass differences of hadrons arise from the up-down quark mass difference and two-quark electromagnetic interactions. Quantum chromodynamics has provided significant insight into hadron masses. Particularly, the idea that hyperfine splitting arising due to the short-distance single-gluon exchange between quarks led to the realization that such a strong-interaction splitting would also contribute to isomultiplet mass differences.[1,2] Several attempts have henceforth been made to study these mass differences in a QCD-inspired quark model[1-11] but with only partial success.

In an earlier paper,[10] we pointed out that the electromagnetic mass differences of $\frac{1}{2}^+$ baryons can be interpreted better when photon-cloud contributions are included in the mass operator. In the present work, we extend that analysis to charmed baryons and to $J^P=\frac{3}{2}^+$ baryons. We estimate the photon-cloud contribution within the quark-model framework. The results obtained here again confirm the role played by the photon cloud. In the charmed-baryon sector, the mass difference[12] between Σ_c^0 and Σ_c^{++} has been measured recently.[13] The observed feature $\Sigma_c^{++}(cuu)>\Sigma_c^0(cdd)$ violates the empirical rule that the baryon states with more d quarks are more massive. In this paper, we demonstrate that the photon-cloud effects can make Σ_c^{++} heavier than Σ_c^0. Similar results are predicted for Σ_c^*, Ξ_{cc}, and Ξ_{cc}^* baryons.

In the constituent-quark model, the s-wave baryon mass formula can be written as a sum of the constituent-quark masses m_i and hyperfine splitting due to the spin-spin interaction, i.e.,

$$M=\sum_i m_i+\sum_{i>j}\frac{b}{m_i m_j}(\sigma_i\cdot\sigma_j)\ , \tag{1}$$

where

$$b=\frac{4\pi}{9}\alpha_s\langle\psi_0\,|\,\delta^3(r_{ij})\,|\,\psi_0\rangle\ . \tag{2}$$

Using the average u-d quark mass,[6]

$$m=\frac{2(\Lambda-N)(\Xi^*-\Xi)}{3(\Sigma-\Lambda)}=330\ \text{MeV}$$

and determining $\delta m=m_d-m_u$ from the $n-p$ mass difference, the isomultiplet mass differences can be obtained, as given in the second columns of Tables I and II. The disagreement with experiment for the charmed and uncharmed sectors is quite evident.

Since the hadrons emit and absorb photons in the presence of the electromagnetic (em) interaction, photon-

TABLE I. Isomultiplet mass differences of $J^P=\frac{1}{2}^+$ baryons.

Mass difference	Without photon cloud ($\delta m=1.8$ MeV)	Photon-cloud contribution (MeV)	With photon cloud ($\delta m=2.4$ MeV)	Expt. (Ref. 14) (MeV)
$n-p$	1.3[a]	−0.6	1.3[a]	1.2933
$\Sigma^--\Sigma^+$	3.7	2.2	7.0	7.97±0.07
$\Sigma^--\Sigma^0$	1.9	2.0	4.4	4.88±0.06
$\Sigma^++\Sigma^--2\Sigma^0$	0	1.8	1.8	1.79±0.14
$\Xi^--\Xi^0$	2.4	2.8	5.8	6.4 ±0.6
$\Sigma_c^+-\Sigma_c^{++}$	1.6	−3.4	−1.2	
$\Sigma_c^0-\Sigma_c^{++}$	3.3	−5.0	−0.5	−1.8±0.8±0.3
$\Sigma_c^{++}+\Sigma_c^0-2\Sigma_c^+$	0	1.8	1.8	
$\Xi_c^0-\Xi_c^+$	1.7	−1.5	0.9	
$\Xi_c'^0-\Xi_c'^+$	2.3	−1.6	1.2	
$\Xi_{cc}^+-\Xi_{cc}^{++}$	2.0	−5.6	−3.0	

[a]Input.

TABLE II. Isomultiplet mass differences of $J^P=\frac{3}{2}^+$ baryons.

Mass difference	Without photon cloud ($\delta m=1.8$ MeV)	Photon-cloud contribution (MeV)	With photon cloud ($\delta m=2.4$ MeV)	Expt. (Ref. 14) (MeV)
$\Delta^0-\Delta^{++}$	2.6	-3.0	0.8	2.4 ± 0.5
$\Delta^--\Delta^{++}$	3.9	-1.8	3.9	7.9 ± 6.8
$\Delta^0-\Delta^+$	1.3	-0.6	1.3	
$\Sigma^{*-}-\Sigma^{*+}$	2.8	0.9	4.8	5.1 ± 0.7
$\Sigma^{*-}-\Sigma^{*0}$	1.4	1.3	3.3	5.4 ± 2.6
$\Sigma^{*+}+\Sigma^{*-}-2\Sigma^{*0}$	0	1.8	1.8	
$\Xi^{*-}-\Xi^{*0}$	1.5	1.5	3.5	3.2 ± 0.6
$\Sigma_c^{*+}-\Sigma_c^{*++}$	1.5	-2.9	-0.9	
$\Sigma_c^{*0}-\Sigma_c^{*+}$	1.5	-1.2	0.9	
$\Sigma_c^{*++}+\Sigma_c^{*0}-2\Sigma_c^{*+}$	0	1.8	1.8	
$\Xi_c^{*0}-\Xi_c^{*+}$	1.6	-1.0	1.2	
$\Xi_{cc}^{*+}-\Xi_{cc}^{*++}$	1.7	-2.5	-1.2	

cloud energy can also contribute to the isomultiplet mass differences. To lowest order, the effective Lagrangian describing the contribution is[7]

$$\mathcal{L}_{\text{em}}=-\tfrac{1}{2}e^2\int d^4y\, D(x-y)TJ^{\mu}(x)J_{\mu}(y)\ , \tag{3}$$

where D is the photon propagator and $J_\mu(x)$ is the em current. In an earlier paper,[10] we have included such contributions as estimated through the electron scattering data.[7] However, these can also be calculated within the quark-model framework. The em current in the model is given by

$$J_\mu(x)=\sum_i Q_i\bar{q}_i(x)\gamma_\mu q_i(x)\ , \tag{4}$$

where Q_i is the charge (in units of e) of the ith quark and $q(x)$ is the field operator. This effectively leads to the following two types of contributions,[3] in which the virtual photon is (i) emitted and absorbed by the same quark and (ii) exchanged between two different quarks of the baryon. The first type of contribution, i.e., em self-energy of the quark, though difficult to determine, gets absorbed into the effective quark masses. The effects of the second type of electric and magnetic contributions[9] are calculated by taking expectation values of the perturbative Hamiltonian

$$H_{ij}=\alpha\left[\frac{Q_iQ_j}{r_{ij}}-\frac{8\pi}{3}\boldsymbol{\mu}_i\cdot\boldsymbol{\mu}_j\delta^3(\mathbf{r}_{ij})\right] \tag{5}$$

where $\boldsymbol{\mu}_i$ is the magnetic moment of the ith quark and $\mathbf{r}_{ij}$ is the distance between i and j quarks. We take the inverse of the average distance,

$$\left\langle\psi\left|\frac{1}{r_{ij}}\right|\psi\right\rangle=390\text{ MeV}\ ,$$

as determined by Itoh *et al.* in a harmonic-oscillator[4] model. A similar value has also been estimated[5] with a linear confining potential. We fix the expectation value of $\delta^3(r_{ij})$ from the hyperfine splitting with $\alpha_s\simeq0.5$ using Eq. (2). Including these photon-cloud contributions given in the third columns of Tables I and II and using the $n-p$ mass difference to refix $\delta m=2.4$ MeV, we give the calculated isomultiplet mass differences of $\frac{1}{2}^+$ and $\frac{3}{2}^+$ baryons in the fourth columns of Tables I and II.

We note that the isomultiplet mass differences have improved significantly in the presence of photon-cloud contributions. All the mass differences of uncharmed baryons match well with experimental values.[14] The prediction of a negative value of charmed-baryon mass difference $\Sigma_c^0-\Sigma_c^{++}$ is found to be consistent with the recently measured experimental value.[12,13] Recently, $\Sigma_c^{++}-\Sigma_c^0$ has also been calculated by other workers.[11] Mass difference obtained in the present paper is consistent with their values.

Notice that similarly charged-baryon mass difference $\Delta^0-\Delta^{++}$, though found to be smaller than experiment, remains positive in the present calculations. Other Δ-mass difference and the following experimentally observed combination[14]

$$(\Delta^--\Delta^{++})+\left[\frac{\Delta^0-\Delta^+}{3}\right]=4.3\text{ MeV}$$

$$(4.6\pm0.2\text{ MeV})\ \ \text{(experiment)}$$

are in better agreement with the experimental values. A more precise measurement for Δ masses is certainly desirable. Notice that similar to Σ_c states, Σ_c^* and $C=2$ baryons Ξ_{cc} and Ξ_{cc}^* also reverse the sign of their isomultiplet mass differences in the presence of the photon contributions. These present interesting tests for future experiments.

One of us (R.C.V.) thanks Professor J. Franklin for useful suggestions. S.S. gratefully acknowledges the financial assistance received from University Grants Commission, New Delhi.

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