Baryon states with open beauty in the extended local hidden gauge approach

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Based on: **WHL, C.W. Xiao, E. Oset, Phys. Rev. D 89 (2014) 054023.**

Outline

1. Introduction
2. The local hidden gauge formalism
3. Preliminary results with J=1/2, 3/2 degeneracy
4. Breaking J=1/2, 3/2 degeneracy and the results
5. Summary

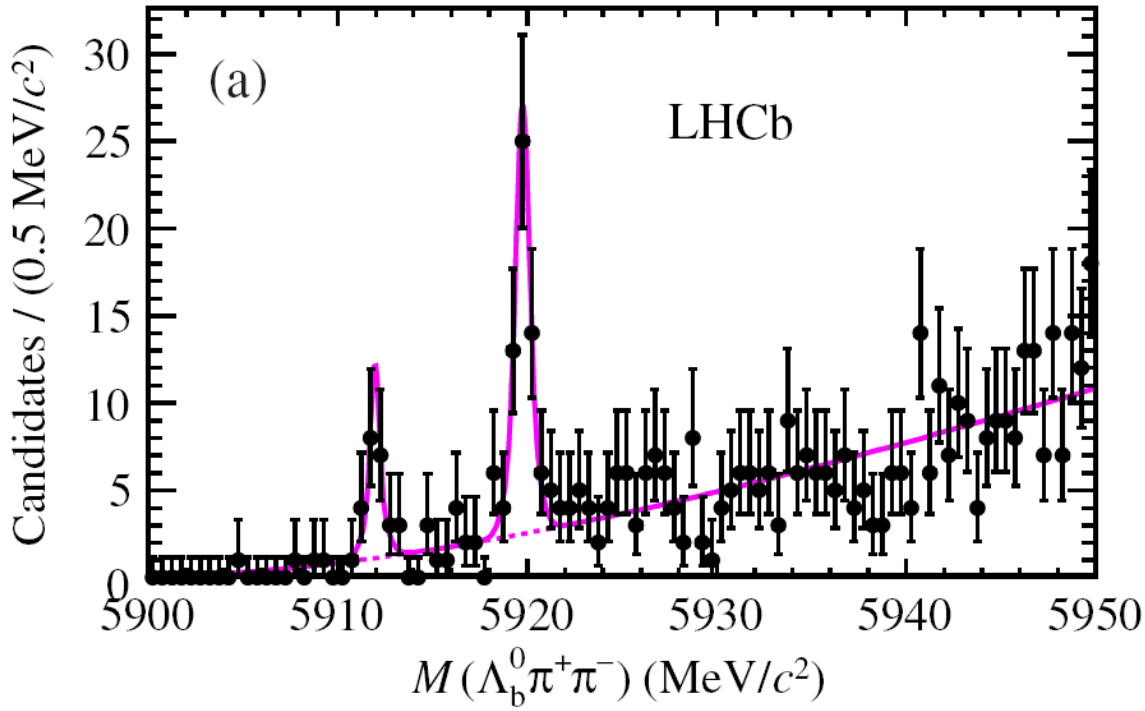
1. Introduction

- **Baryon states involving heavy quarks (charm or beauty) attracted much attention in the decade.**

$$\Lambda_c(2595),\ \Lambda_c(2625),\ \Lambda_b(5912),\ \Lambda_b(5920),\ P_c,\ \Omega_c^* \cdots$$

Multiqark states, hybrids, or hadronic molecules have been suggested in lots of work.

- **The experiments on Λ_b excited states**



[LHCb, PRL109(2012)172003]

[CDF, PRD88(2013)071101]

$$M_{\Lambda_b^{*0}(5912)} = 5911.97 \pm 0.12 \text{ MeV}/c^2 \qquad \Gamma_{\Lambda_b^{*0}(5912)} < 0.66 \text{ MeV}$$

$$M_{\Lambda_b^{*0}(5920)} = 5919.77 \pm 0.08 \text{ MeV}/c^2 \qquad \Gamma_{\Lambda_b^{*0}(5920)} < 0.63 \text{ MeV}$$

The states are interpreted as orbitally excited states of $\Lambda_b(5619)$, $J^P = 1/2^-,\ 3/2^-$.

In this work:

$$\Lambda_b(5912): \quad C = S = 0, \; B = -1, \; I = 0, J^P = 1/2^-.$$

$$\Lambda_b(5920): \quad C = S = 0, \; B = -1, \; I = 0, J^P = 3/2^-.$$

With the dynamics of the extended local hidden gauge approach, we examine the interaction of $\bar{B}N$, $\bar{B}^*N$ states, together with their coupled channels, look for states dynamically generated from the interaction.

Two Λ_b excited states are generated with masses close to the exp. ones. Predictions for other isospin and spin sectors are made.

2. The Local Hidden Gauge Formalism

Consider $PB \to PB$ and $VB \to VB$ scatterings with $C = S = 0$, $B = -1$ in 7 sectors with different I, J.

$P \equiv$ pseudoscalar, $V \equiv$ vector, $B \equiv$ baryon.

Sector A: PB channels with $I = 0, J^P = \frac{1}{2}^-$ $(\pi\Sigma_b,\ \eta\Lambda_b,\ \bar{B}N)$

$\Lambda_b(5912)$?

(J=1/2, 3/2 degeneracy)

Sector B: VB channels with $I = 0, J^P = \frac{1}{2}^-, \frac{3}{2}^-$ $(\bar{B}^*N,\ \omega\Lambda_b,\ \rho\Sigma_b,\ \phi\Lambda_b)$

$\Lambda_b(5912)$? $\Lambda_b(5920)$?

$$\text{Sector C}: \ PB \text{ channels with } I=0, J^P=\frac{3}{2}^- \quad (\pi\Sigma_b^*)$$

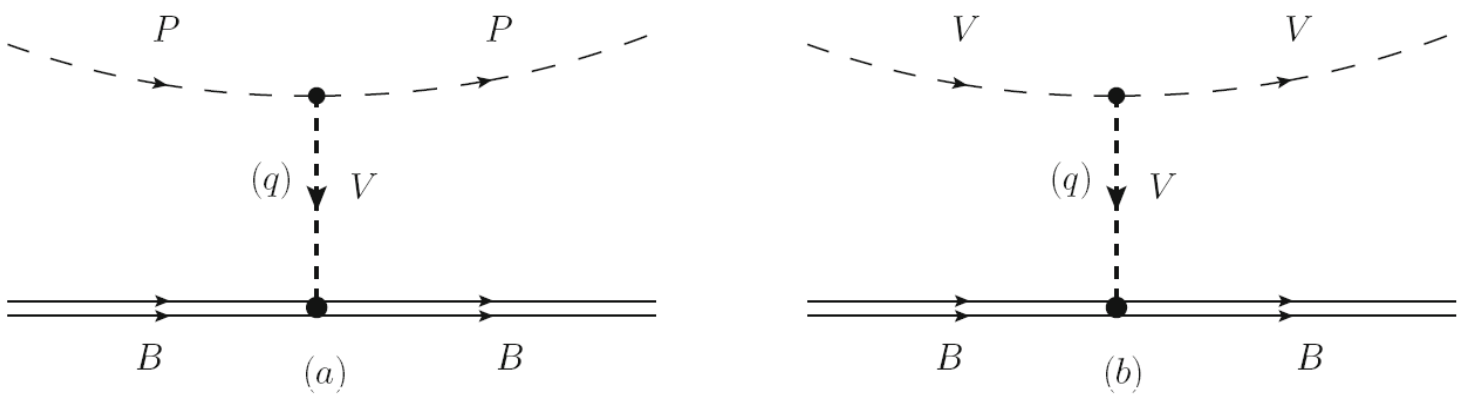
$$\textbf{Sector D}: \ \boldsymbol{PB} \textbf{ channels with } \boldsymbol{I=1, J^P=\frac{1}{2}^-} \quad (\bar{B}N, \pi\Sigma_b, \pi\Lambda_b, \eta\Sigma_b)$$

$$\textbf{Sector E}: \ \boldsymbol{PB} \textbf{ channels with } \boldsymbol{I=1, J^P=\frac{3}{2}^-} \quad (\bar{B}\Delta, \pi\Sigma_b^*, \eta\Sigma_b^*)$$

$$\text{Sector F}: \ VB \text{ channels with } I=1, J^P=\frac{1}{2}^-, \frac{3}{2}^- \quad (\bar{B}^*N, \rho\Lambda_\mathrm{b}, \rho\Sigma_b, \omega\Sigma_b, \phi\Sigma_\mathrm{b})$$

$$\text{Sector G}: \ VB \text{ channels with } I=1, J^P=\frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^- \quad (\bar{B}^*\Delta, \rho\Sigma_b^*, \omega\Sigma_b^*, \phi\Sigma_b^*)$$

In the local hidden gauge appoach in SU(3), the meson-baryon interaction proceeds via the exchange of vector mesons.



(Weinberg-Tomozawa interaction)

The heavy quarks of the meson or the baryon act as spectators.

The interaction does not depend on their spin nor their flavor.

The lowest order Lagrangian:

$$\mathcal{L}_{VVV} = ig\langle V^\mu [V^\nu, \partial_\mu V_\nu]\rangle,$$
$$\mathcal{L}_{PPV} = -ig\langle V^\mu [P, \partial_\mu P]\rangle,$$
$$\mathcal{L}_{BBV} = g(\langle \bar{B}\gamma_\mu [V^\mu, B]\rangle + \langle \bar{B}\gamma_\mu B\rangle\langle V^\mu\rangle),$$

In coupled channels we will use the Bethe-Salpeter equation:

$$T = [1 - VG]^{-1} V,$$

with G the diagonal loop function for the propagating intermediate meson-baryon channels.

In the cutoff regularization,

$$G(s) = \int_0^{q_{\max}} \frac{d^3\vec{q}}{(2\pi)^3} \frac{\omega_P + \omega_B}{2\omega_P\omega_B} \frac{2M_B}{P^{02} - (\omega_P + \omega_B)^2 + i\varepsilon},$$

$q_{\max}$ — the cutoff of the three-momentum, the only free parameter.

V is the potential which is obtained from the lowest order chiral Lagrangian for meson-baryon interaction.

The transition potential from channel i to channel j is given by

$$V = -C_{ij}\frac{1}{4f^2}(2\sqrt{s} - M_{B_i} - M_{B_j})\sqrt{\frac{M_{B_i}+E_i}{2M_{B_i}}}\sqrt{\frac{M_{B_j}+E_j}{2M_{B_j}}},$$

with f the pion decay constant and M_{B_i} and E_i (M_{B_j} and E_j) the mass and energy, respectively, of the baryon of the i (j) channel. We take $f = f_\pi = 93$ MeV

The C_{ij} coefficients have been evaluated.

[Oset and Ramos, NPA635(1998)99]

[Sarkar, Oset and Vacas, NPA750(2005)294]

3. Preliminary results with J=1/2, 3/2 degeneracy

3.1 $PB \rightarrow PB$: $\pi\Sigma_b$[5951.8], $\eta\Lambda_b$[6167.3], $\bar{B}N$[6218.3] (Sector A)

$J^P = 1/2^-$

TABLE VIII. Energies for states in coupled channels $\bar{B}N$, $\pi\Sigma_b$, and $\eta\Lambda_b$ in $I = 0$ as a function of $q_{\max}$ (unit, MeV).

$q_{\max}$	700	750	800	850
V	5935.3	5897.3	5851.4	5802.0
	$6005.8 + i23.8$	$5988.9 + i26.4$	$5976.9 + i24.4$	$5968.0 + i20.5$

Neither of the states found can qualify as $\Lambda_b(5912)$ or $\Lambda_b(5920)$.

3.2 $VB \to VB$: $\bar{B}^* N[6264.1]$, $\omega\Lambda_b[6402.1]$, $\rho\Sigma_b[6588.9]$, $\phi\Lambda_b[6638.9]$,

(Sector B)

$J^P = 1/2^-, 3/2^-$.

TABLE XIV. Energies for states in coupled channels $\bar{B}^* N, \rho\Sigma_b$, $\omega\Lambda_b$, and $\phi\Lambda_b$ in $I = 0$ as a function of $q_{\max}$ (unit, MeV).

$q_{\max}$	700	750	800	850
V	6019.2	5970.6	5919.8	5867.6
	$6364.6 + i0.8$	$6333.3 + i0.8$	$6303.0 + i0.6$	$6274.1 + i0.3$

TABLE XV. The coupling constants to various channels for certain poles in the $J = 1/2, 3/2$, $I = 0$ sector.

$5919.8 + i0$	$\bar{B}^* N$	$\rho\Sigma_b$	$\omega\Lambda_b$	$\phi\Lambda_b$
g_i	16.81	1.04	0.94	1.33
$g_i G_i^{II}$	−22.01	−5.46	−6.16	−5.67
$6303.0 + i0.6$	$\bar{B}^* N$	$\rho\Sigma_b$	$\omega\Lambda_b$	$\phi\Lambda_b$
g_i	$0.37 + i0.27$	$5.14 + i0.01$	$0.15 + i0.01$	$0.21 + i0.02$
$g_i G_i^{II}$	$-2.73 - i0.27$	$-46.81 - i0.13$	$-2.22 - i0.22$	$-1.50 - i0.15$

Within the local hidden gauge approach the interaction is spin independent.

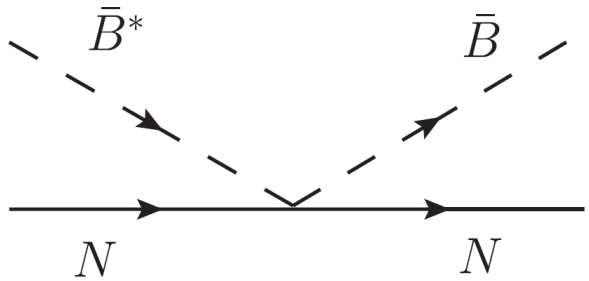
We get two degenerate states with $J^P = 1/2^-, 3/2^-$.

4. Breaking the J=1/2, 3/2 degeneracy and the results

Mix states of $\bar{B}N$ and $\bar{B}^*N$ in both Sector A and Sector B.

Consider $\bar{B}N \to \bar{B}^*N$ transition:

[Garzon, EPJA48(2012)5;
Oset, J.Mod. Phys. E21(2012)1230011;
Khemchandani, PRD84(2011)094018;
PRD83(2011)114041.]



Kroll-Ruderman term

+ pion exchang term

Fig. 6. Diagrams of the Kroll-Ruderman contact term for $\bar{B}N \to \bar{B}^*N$ transion.

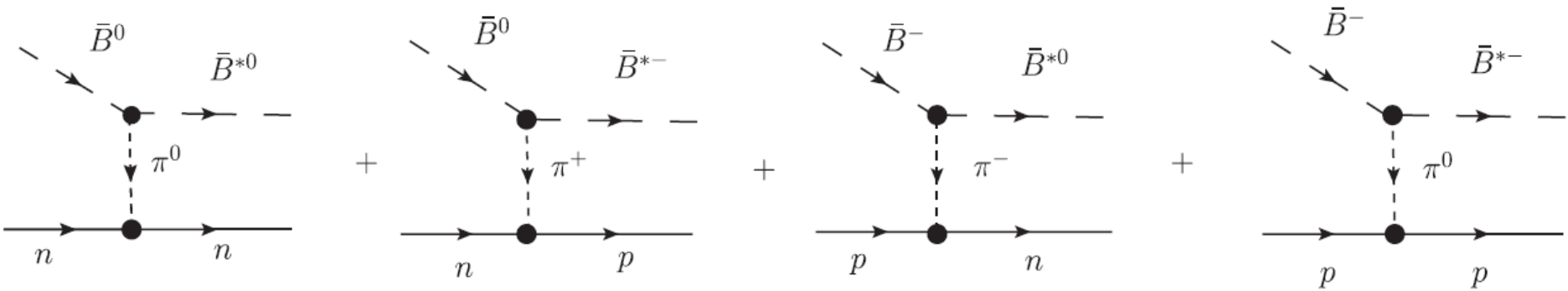


Fig. 4. Pion exchange diagrams for the transion $\bar{B}N \to \bar{B}^*N$ in $I=0$.

The $VP\pi$ vertex is given by the Lagrangian, $\mathcal{L}_{VPP} = -ig\langle [P, \partial_\mu P] V^\mu \rangle,$

• Contributi on from $\bar{B}N \to \bar{B}^* N \to \bar{B}N$ box diagrams :

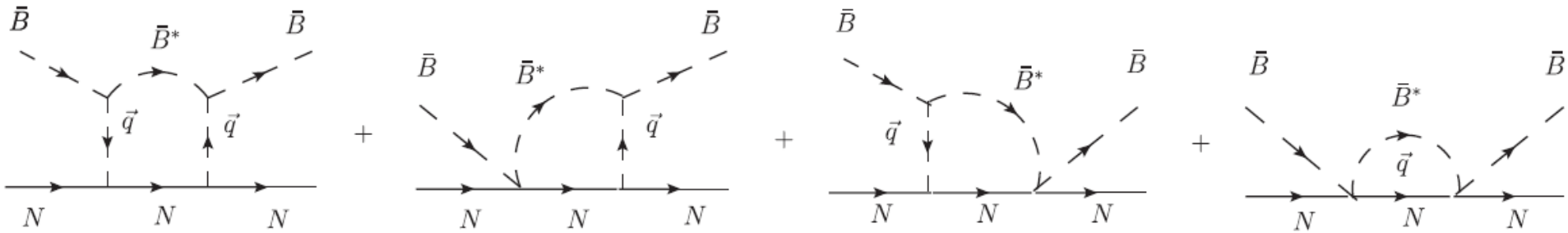


FIG. 7. All of the diagrams for the $\bar{B}^* N$ in the intermediate state.

$$J = 1/2:\ \delta V = FAC\left(\frac{\partial}{\partial m_\pi^2} I_1 + 2I_2 + I_3\right),$$

$$I_1 = \int \frac{d^3q}{(2\pi)^3} 4\vec{q}^{\,4} \frac{1}{2\omega_{B^*}(\vec{q})} \frac{M_N}{E_N(\vec{q})} \frac{Num}{Den},$$

$$I_2 = \int \frac{d^3q}{(2\pi)^3} 2\vec{q}^{\,2} \frac{1}{2\omega_{B^*}(\vec{q})} \frac{M_N}{E_N(\vec{q})} \frac{Num}{Den},$$

$$I_3 = \int \frac{d^3q}{(2\pi)^3} \frac{3}{2\omega_{B^*}(\vec{q})} \frac{M_N}{E_N(\vec{q})} \times \frac{1}{P^0_{\rm in} + K^0_{\rm in} - E_N(\vec{q}) - \omega_{B^*}(\vec{q}) + i\epsilon},$$

Add δV to the potential V in the BS Eq.

- **Contributi on from $\bar{B}^* N \to \bar{B} N \to \bar{B}^* N$ box diagrams :**

For J=3/2 case, the KR term does not contribute.

$$J = 1/2: \ \delta V = FAC\left(\frac{\partial}{\partial m_\pi^2} I_1' + 2I_2' + I_3'\right),$$

$$J = 3/2: \ \delta V = FAC\left(\frac{\partial}{\partial m_\pi^2} I_1'\right),$$

$$I_1' = \int \frac{d^3q}{(2\pi)^3} \frac{4}{3} \vec{q}^{\,4} \frac{1}{2\omega_B(\vec{q})} \frac{M_N}{E_N(\vec{q})} \frac{Num}{Den},$$

$$I_2' = \int \frac{d^3q}{(2\pi)^3} 2\vec{q}^{\,2} \frac{1}{2\omega_B(\vec{q})} \frac{M_N}{E_N(\vec{q})} \frac{Num}{Den},$$

$$I_3' = \int \frac{d^3q}{(2\pi)^3} \frac{3}{2\omega_B(\vec{q})} \frac{M_N}{E_N(\vec{q})} \frac{1}{P_{in}^0 + K_{in}^0 - E_N(\vec{q}) - \omega_B(\vec{q}) + i\epsilon},$$

TABLE XVI. Poles with a box diagram in coupled channels $\bar{B}^*N$, $\rho\Sigma_b$, $\omega\Lambda_b$, and $\phi\Lambda_b$ in $I = 0$ as a function of V and $q_{\max}$ (unit, MeV).

$q_{\max}$	700	750	776	800
$J = 1/2$	$5991.9 + i0$ $6364.2 + i1.4$	$5939.2 + i0$ $6332.6 + i1.4$	$5910.7 + i0$ $6316.6 + i1.4$	$5884.0 + i0$ $6301.1 + i1.4$
$J = 3/2$	$5998.8 + i0$ $6363.5 + i2.1$	$5948.0 + i0$ $6331.7 + i2.0$	$5920.7 + i0$ $6315.7 + i1.9$	$5895.1 + i0$ $6301.2 + i1.7$

The splitting of energies between the J=1/2, 3/2 levels is about 10 MeV, rather independent of the cutoff used.

TABLE XVII. Poles with a box diagram in coupled channels $\bar{B}N$, $\pi\Sigma_b$, and $\eta\Lambda_b$ in $I = 0$ as a function of V and $q_{\max}$ (unit, MeV).

$q_{\max}$	700	750	776	800
$J = 1/2$	$5902.6 + i0$ $5985.6 + i29.1$	$5850.1 + i0$ $5974.1 + i26.8$	$5820.9 + i0$ $5969.5 + i24.6$	$5793.3 + i0$ $5965.8 + i22.3$

Summary of the results

$q_{max} = 776\,\mathrm{MeV}$

TABLE XXIV. Energies and widths of the states obtained and the channels to which the states couple most strongly.

Main channel	J	I	(E, Γ) [MeV]	Exp.
$\bar{B}N$	1/2	0	5820.9, 0	
$\pi\Sigma_b$	1/2	0	5969.5, 49.2	
$\bar{B}^*N$	1/2	0	5910.7, 0	$\Lambda_b(5912)$
$\bar{B}^*N$	3/2	0	5920.7, 0	$\Lambda_b(5920)$
$\rho\Sigma_b$	1/2	0	6316.6, 2.8	
$\rho\Sigma_b$	3/2	0	6315.7, 3.8	
$\bar{B}N$, $\pi\Sigma_b$	1/2	1	6179.4, 122.8	
$\pi\Sigma_b$	1/2	1	6002.8, 132.4	
$\bar{B}^*N$	1/2, 3/2	1	6202.2, 0	
$\rho\Sigma_b$	1/2, 3/2	1	6477.2, 10.0	

5. Summary

We study the interaction of $\bar{B}N$ and $\bar{B}^{*}N$ states with its coupled channels using dynamics in the local hidden gauge approach, extrapolated from the light quark sector to the heavy one.

The mixing of the *PB* and *VB* states is done through pion exchange (box diagram).

We search for poles of the scattering matrix in different states of spin and isospin.

The couplings of the states to the different channels are evaluated, together with their wave function at the rigin.

$\Lambda_b(5912)$ and $\Lambda_b(5920)$ are dynamically generated from the interaction of VB + PB.

The splitting of energies between the J=1/2, 3/2 levels is about 10 MeV, rather independent of the cutoff used.

Some Λ_b and Σ_b states are predicted.

Thanks for your attention!