Recent Ω_c states

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Meson baryon interaction. SU(3) chiral Lagrangians
Local hidden gauge approach
Extension to the charm sector
Ω_c states

Molecular Ω_c states generated from coupled meson-baryon channels

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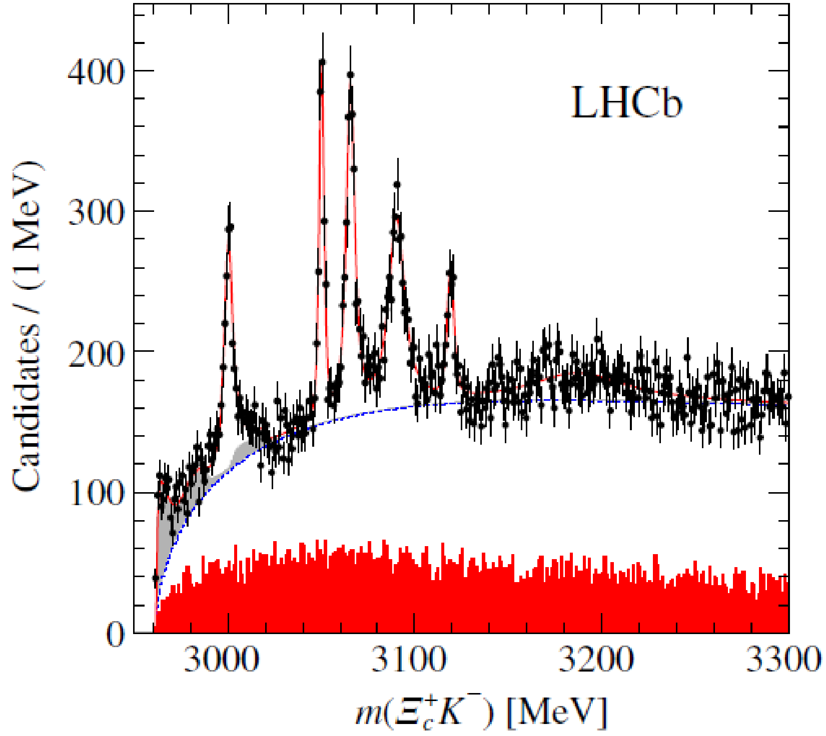
PRD (2018)



The Ξ_c K^- mass spectrum is studied with a sample of pp collision data by LHCb , PRL 017

Five clean narrow peaks are obtained

$$\Omega_c(3000)^0,\ \Omega_c(3050)^0,\ \Omega_c(3066)^0,$$
$$\Omega_c(3090)^0,\ \text{and}\ \Omega_c(3119)^0$$

Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
		<1.2 MeV, 95% C.L.
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$
		<2.6 MeV, 95% C.L.

Meson baryon interaction:

SU(3) Chiral Lagrangian

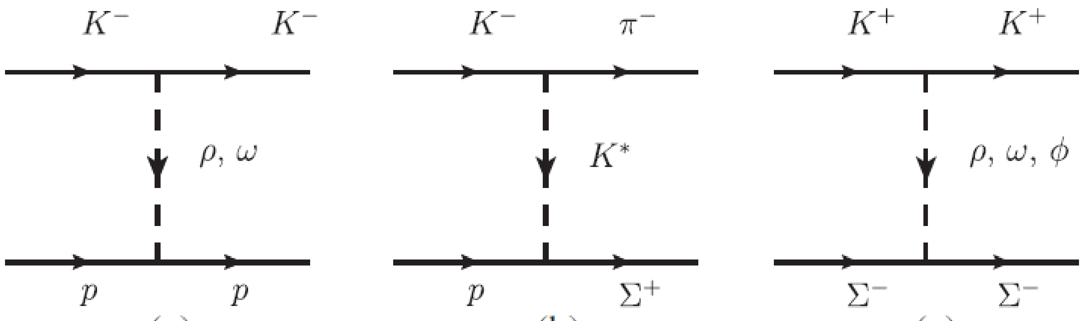
$$\mathcal{L}^B = \frac{1}{4f_\pi^2}\langle \bar{B} i\gamma^\mu [(\Phi\partial_\mu\Phi - \partial_\mu\Phi\Phi)B - B(\Phi\partial_\mu\Phi - \partial_\mu\Phi\Phi)]\rangle$$

Equivalent method:
Local hidden gauge
Approach. M. Bando

$$\mathcal{L}_{VPP} = -ig\langle[\Phi, \partial_\mu\Phi]V^\mu\rangle, \qquad \mathcal{L}_{BBV} = g\left(\langle\bar{B}\gamma_\mu[V^\mu, B]\rangle + \langle\bar{B}\gamma_\mu B\rangle\langle V^\mu\rangle\right)$$

$$\Phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix} \qquad B = \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & \Sigma^+ & p \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda \end{pmatrix}$$

$$V_\mu = \begin{pmatrix} \frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & \rho^+ & K^{*+} \\ \rho^- & -\frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}_\mu$$



(a) (b) (c)

Instead of using the Lagrangians, one can use the meson or baryon wave functions with the suitable operators

PPV vertex (Sakai, Roca, E. O, PRD 96 (2107))

$$g' \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}), \quad \text{for } \rho^0 \text{ exchange},$$

$$g' \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}), \quad \text{for } \omega \text{ exchange},$$

Operator for ρ_0 exchange

$$-g' \frac{1}{\sqrt{2}}((u\partial_\mu \bar{u} - \partial_\mu u\bar{u}) - (d\partial_\mu \bar{d} - \partial_\mu d\bar{d}))$$

Example: $D^+ = c\bar{d}$

$$-\langle c\bar{d}|g' \frac{1}{\sqrt{2}}((u\partial_\mu \bar{u} - \partial_\mu u\bar{u}) - (d\partial_\mu \bar{d} - \partial_\mu d\bar{d}))|c\bar{d}\rangle$$

$$= -g' \frac{1}{\sqrt{2}}(ip_\mu + ip'_\mu)$$

One does not need to use SU(4). Yet, it is practical to evaluate it using $\mathcal{L}_{VPP} = -ig\langle[\Phi, \partial_\mu \Phi]V^\mu\rangle$, and the SU(4) matrices

$$P = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{3}}\eta + \frac{1}{\sqrt{6}}\eta' & \pi^+ & K^+ & \bar{D}^0 \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{3}}\eta + \frac{1}{\sqrt{6}}\eta' & K^0 & D^- \\ K^- & \bar{K}^0 & -\frac{1}{\sqrt{3}}\eta + \sqrt{\frac{2}{3}}\eta' & D_s^- \\ D^0 & D^+ & D_s^+ & \eta_c \end{pmatrix}$$

$$V = \begin{pmatrix} \frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & \rho^+ & K^{*+} & \bar{D}^{*0} \\ \rho^- & -\frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & K^{*0} & \bar{D}^{*-} \\ K^{*-} & \bar{K}^{*0} & \phi & D_s^{*-} \\ D^{*0} & D^{*+} & D_s^{*+} & J/\psi \end{pmatrix}$$

Lower vertex
BBV

$$\rho^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}),$$
$$\omega = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}),$$
$$\phi = s\bar{s}.$$

approximation of taking $\gamma^\mu \to \gamma^0$

In SU(3)

$$\langle p|g\rho^0|p\rangle \equiv \frac{1}{\sqrt{2}}\frac{1}{\sqrt{2}}\langle \phi_{\mathrm{MS}}\chi_{\mathrm{MS}} + \phi_{\mathrm{MA}}\chi_{\mathrm{MA}}|g\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})| \times \phi_{\mathrm{MS}}\chi_{\mathrm{MS}} + \phi_{\mathrm{MA}}\chi_{\mathrm{MA}}\rangle, \quad (10)$$

TABLE I. $J = 1/2$ states chosen and threshold mass in MeV.

States	$\Xi_c \bar{K}$	$\Xi'_c \bar{K}$	ΞD	$\Omega_c \eta$	ΞD^*	$\Xi_c \bar{K}^*$	$\Xi'_c \bar{K}^*$
Threshold	2965	3074	3185	3243	3327	3363	3472

TABLE II. $J = 3/2$ states chosen and threshold mass in MeV.

States	$\Xi^*_c \bar{K}$	$\Omega^*_c \eta$	ΞD^*	$\Xi_c \bar{K}^*$	$\Xi^* D$	$\Xi'_c \bar{K}^*$
Threshold	3142	3314	3327	3363	3401	3472

Note that we do not use SU(4) baryon wave functions, the heavy quark is singled out and flavor-spin symmetry is demanded for the light quarks.

Back to Ω_c states

BARYON WAVE FUNCTIONS

Ξ_c^+: $\frac{1}{\sqrt{2}} c(us - su)$, and the spin wave function is the mixed antisymmetric, $\chi_{\rm MA}$, for the two light quarks.

Ξ_c^0: the same as Ξ_c^+, changing $(us - su) \to (ds - sd)$.

$\Xi_c'^+$: $\frac{1}{\sqrt{2}} c(us + su)$, and now the spin wave function for the three quarks is the mixed symmetric, $\chi_{\rm MS}$, in the last two quarks,

$\Xi_c'^0$: the same as Ξ'_c, changing $(us + su) \to (ds + sd)$.

Ω_c^0: css, and the spin wave function $\chi_{\rm MS}$ in the last two quarks, like that for Ξ'_c.

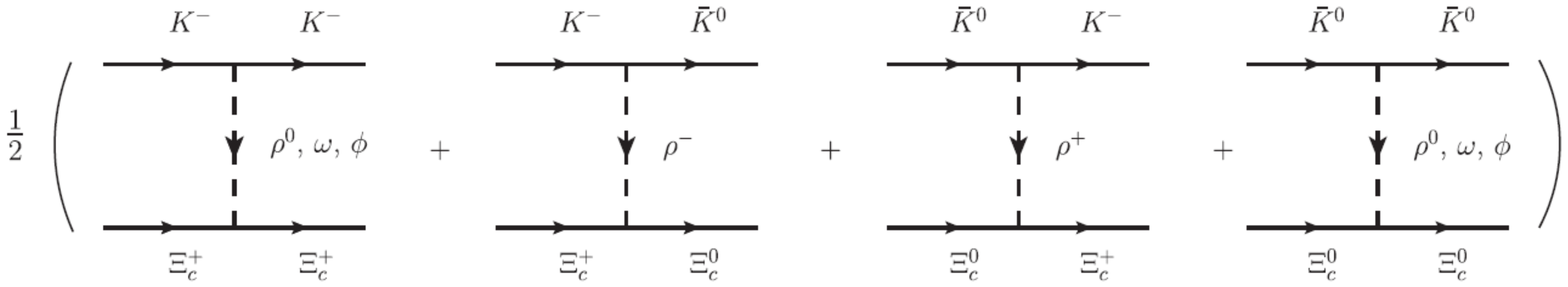


FIG. 3. Diagrams in the $\bar{K}\Xi_c \to \bar{K}\Xi_c$ transition.

Upper vertex

$$\mathcal{L}_{\rm VPP} = -ig\langle[\Phi, \partial_\mu\Phi]V^\mu\rangle$$

$$-it_{K^-\to K^-}\begin{pmatrix}\rho^0\\ \omega\\ \phi\end{pmatrix} = gV_\mu(-ip^\mu - ip'^\mu)\begin{pmatrix}1/\sqrt{2}\\ 1/\sqrt{2}\\ -1\end{pmatrix},$$

$$-it_{K^-\to\bar{K}^0\rho^-} = g\rho^{+\mu}(-ip^\mu - ip'^\mu),$$

g=m_V/2 f,
f=93 MeV

Lower vertex

$$\frac{1}{\sqrt{2}}\langle(us - su)|\begin{pmatrix} g\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})\\ g\frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\\ gs\bar{s}\end{pmatrix}|\frac{1}{\sqrt{2}}(us - su)\rangle$$

$$= \begin{pmatrix}\frac{1}{\sqrt{2}}g\\ \frac{1}{\sqrt{2}}g\\ g\end{pmatrix}.$$

No need to invoke SU(4)

With light vector exchange the heavy quarks are spectators. Nothing depends upon them. Heavy quark symmetry is automatically implemented

$$V_{ij} = D_{ij} \frac{1}{4f_\pi^2}(p^0 + p'^0)$$

The exchange of heavy vectors is penalized

$$\frac{1}{(q^0)^2 - |\mathbf{q}|^2 - m_{D_s^*}^2} \approx \frac{1}{(m_D - m_K)^2 - m_{D_s^*}^2},$$

$$\lambda \equiv \frac{-m_V^2}{(m_D - m_K)^2 - m_{D_s^*}^2} \approx 0.25$$

TABLE III. D_{ij} coefficients of Eq. (23) for the meson-baryon states coupling to $J^P = 1/2^-$ in s-wave.

$J = 1/2$	$\Xi_c \bar{K}$	$\Xi'_c \bar{K}$	ΞD	$\Omega_c \eta$	ΞD^*	$\Xi_c \bar{K}^*$	$\Xi'_c \bar{K}^*$
$\Xi_c \bar{K}$	-1	0	$-\frac{1}{\sqrt{2}}\lambda$	0	0	0	0
$\Xi'_c \bar{K}$		-1	$\frac{1}{\sqrt{6}}\lambda$	$-\frac{4}{\sqrt{3}}$	0	0	0
ΞD			-2	$\frac{\sqrt{2}}{3}\lambda$	0	0	0
$\Omega_c \eta$				0	0	0	0
ΞD^*					-2	$-\frac{1}{\sqrt{2}}\lambda$	$\frac{1}{\sqrt{6}}\lambda$
$\Xi_c \bar{K}^*$						-1	0
$\Xi'_c \bar{K}^*$							-1

$$T = [1 - VG]^{-1} V, \qquad G_l^{II} = G_l^I + i\frac{2M_l q}{4\pi\sqrt{s}}, \qquad T_{ij} = \frac{g_i g_j}{\sqrt{s} - z_R}$$

Exp (MeV)
M Γ

TABLE VI. The coupling constants to various channels for the poles in the $J^P = 1/2^-$ sector, with $q_{\max} = 650$ MeV, and $g_i G_i^{II}$ in MeV.

Exp (MeV) M, Γ	$3054.05 + i0.44$	$\Xi_c \bar{K}$	$\Xi'_c \bar{K}$	ΞD	$\Omega_c \eta$	ΞD^*	$\Xi_c \bar{K}^*$	$\Xi'_c \bar{K}^*$
3050, 0.8	g_i	$-0.06 + i0.14$	$1.94 + i0.01$	$-2.14 + i0.26$	$1.98 + i0.01$	0	0	0
	$g_i G_i^{II}$	$-1.40 - i3.85$	$-34.41 - i0.30$	$9.33 - i1.10$	$-16.81 - i0.11$	0	0	0
	$3091.28 + i5.12$	$\Xi_c \bar{K}$	$\Xi'_c \bar{K}$	ΞD	$\Omega_c \eta$	ΞD^*	$\Xi_c \bar{K}^*$	$\Xi'_c \bar{K}^*$
3090, 8.7	g_i	$0.18 - i0.37$	$0.31 + i0.25$	$5.83 - i0.20$	$0.38 + i0.23$	0	0	0
	$g_i G_i^{II}$	$5.05 + i10.19$	$-9.97 - i3.67$	$-29.82 + i0.31$	$-3.59 - i2.23$	0	0	0

TABLE VIII. The coupling constants to various channels for the poles in the $J^P = 3/2^-$ sector, with $q_{\max} = 650$ MeV, and $g_i G_i^{II}$ in MeV.

Exp (MeV) M, Γ	3124.84	$\Xi_c^* \bar{K}$	$\Omega_c^* \eta$	ΞD^*	$\Xi_c \bar{K}^*$	$\Xi^* D$	$\Xi'_c \bar{K}^*$
3119, 1.1	g_i	1.95	1.98	0	0	−0.65	0
	$g_i G_i^{II}$	−35.65	−16.83	0	0	1.93	0
	$3290.31 + i0.03$	$\Xi_c^* \bar{K}$	$\Omega_c^* \eta$	ΞD^*	$\Xi_c \bar{K}^*$	$\Xi^* D$	$\Xi'_c \bar{K}^*$
	g_i	$0.01 + i0.02$	$0.31 + i0.01$	0	0	$6.22 - i0.04$	0
	$g_i G_i^{II}$	$-0.62 - i0.18$	$-5.25 - i0.18$	0	0	$-31.08 + i0.20$	0

We get three states in very good agreement with experiment, both mass and width

Related work:

[15] J. Hofmann and M. F. M. Lutz, Nucl. Phys. **A763**, 90 (2005).

[16] C. E. Jimenez-Tejero, A. Ramos, and I. Vidana, Phys. Rev. C **80**, 055206 (2009).

[17] O. Romanets, L. Tolos, C. Garcia-Recio, J. Nieves, L. L. Salcedo, and R. G. E. Timmermans, Phys. Rev. D **85**, 114032 (2012).

Revisions made after experiment to fit some parameter

[41] G. Montaña, A. Feijoo, and A. Ramos, Eur. Phys. J. A **54**, 64 (2018).

Uses SU(4) : matrix elements exchanging light vectors are equal. Results similar to ours, but only two states, since they study $1/2^-$ states only

J.~Nieves, R.~Pavao and L.~Tolos, Omega _c excited states within a SU(6)}_ HQSS model, Eur. Phys. J. C 78 114 (2018)

Better results than in [17] but the widths and the positions not so good as in the works of Montaña and present work .

Conclusions

Extension of chiral unitary theory to the heavy sector, using the exchange of vectors in the hidden gauge approach, together with unitarity in coupled channels leads to neat predictions for molecular states

The important terms in the interaction come from light vector Exchange -> 1) heavy quaks are spectators and matrix elements do not depend upon them HEAVY QUARK SYMMETRY AUTOMATICALLY FULFILLED.
2) One does not have to invoke SU(4) to evaluate matrix elements.

Recent results for Ω_c states and the new pentaquarks states of hidden charm, are giving support to these molecular pictures.