Heavy Barions and new Interacting Boson Fermion Fermion Model results

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Single heavy Baryons

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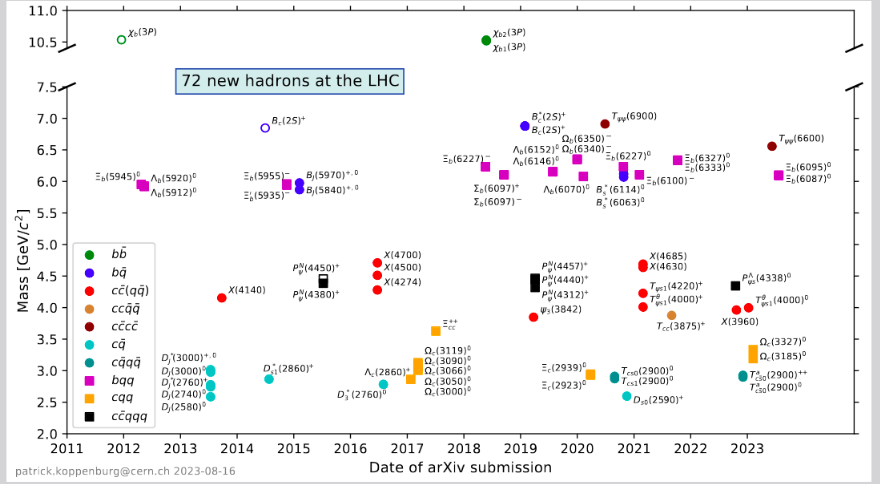
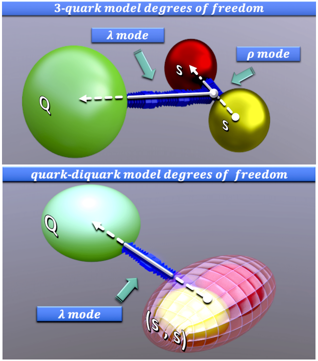
New hadrons discovered at LHC

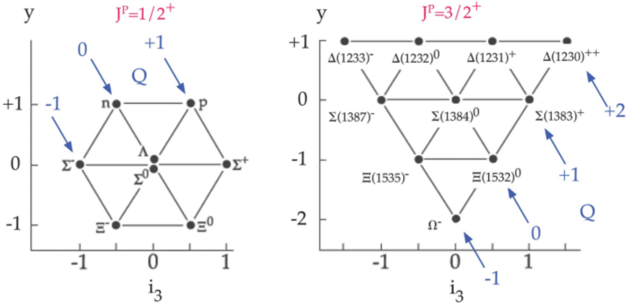


Motivation

- **Physics motivation:**
  - The internal configuration of baryons is still unknown.
  - Number of states depend on the model, i.e. the combination of the quantum numbers.
  - The three-quark model and the effective degrees of freedom
  - The quark-diquark model

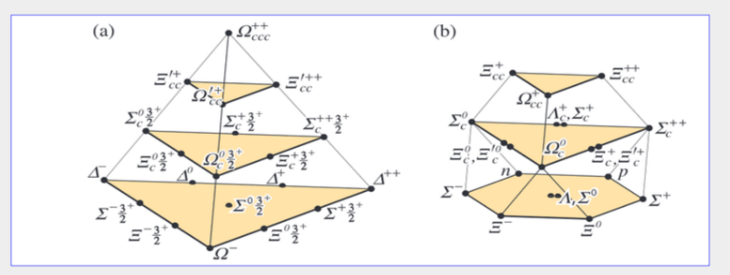


Light baryons in the $SU(3)$ flavor symmetry



"Baryons can be constructed from quarks by using the combination of (qqq), $(qqqq\bar{q})$ ...", M. Gell-Mann, "A schematic model of baryons and mesons", Phys. Lett. 8 (1964) 214

Heavy baryon with charm quarks

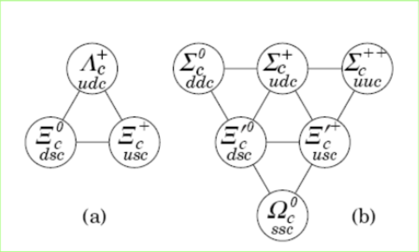


Wave function $\Psi = \sum \omega\psi\phi\chi$

Three particles of spin 1/2

$1/2 \times 1/2 \times 1/2 = 1/2 + 1/2 + 3/2$

Heavy baryon with a single charm quark

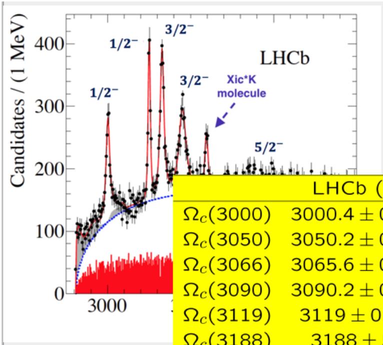


$$\Xi_c^0 := \frac{1}{\sqrt{2}}(|dsc\rangle - |sdc\rangle)$$
$$\Xi_c^+ := \frac{1}{\sqrt{2}}(|usc\rangle - |suc\rangle)$$
$$\Lambda_c^+ := \frac{1}{\sqrt{2}}(|udc\rangle - |duc\rangle)$$

$$\Omega_c := |ssc\rangle$$
$$\Xi_c'^0 := \frac{1}{\sqrt{2}}(|dsc\rangle + |sdc\rangle)$$
$$\Xi_c'^+ := \frac{1}{\sqrt{2}}(|usc\rangle + |suc\rangle)$$
$$\Sigma_c^{++} := |uuc\rangle$$
$$\Sigma_c^0 := |ddc\rangle$$
$$\Sigma_c^+ := \frac{1}{\sqrt{2}}(|udc\rangle + |duc\rangle)$$

Wave function $\Psi = \sum \omega\psi\phi\chi$
Three particles of spin 1/2
$1/2 \times 1/2 \times 1/2 = 1/2 + 1/2 + 3/2$

The Ω_c states observed by LHCb, PRL 118 (2017) 18, 182001



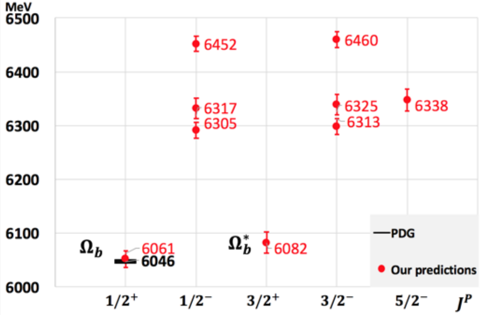
LHCb: proton-proton

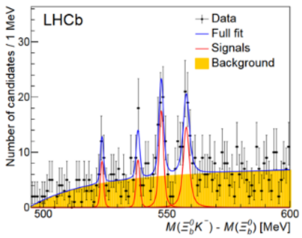
BELLE: electron-positron

	LHCb (2017)	BELLE (2018)
$\Omega_c(3000)$	$3000.4 \pm 0.2 \pm 0.1$	$3000.7 \pm 1.0 \pm 0.2$
$\Omega_c(3050)$	$3050.2 \pm 0.1 \pm 0.1$	$3050.2 \pm 0.4 \pm 0.2$
$\Omega_c(3066)$	$3065.6 \pm 0.1 \pm 0.3$	$3064.9 \pm 0.6 \pm 0.2$
$\Omega_c(3090)$	$3090.2 \pm 0.3 \pm 0.5$	$3089.3 \pm 1.2 \pm 0.2$
$\Omega_c(3119)$	$3119 \pm 0.3 \pm 0.9$	not seen
$\Omega_c(3188)$	$3188 \pm 5 \pm 13$	$3199 \pm 9 \pm 4$

Predictions of Ω_b excited states

First Observation of Excited Ωb States by LHCb collaboration, PRL 124, 082002 (2020)
In agreement with our predictions
Eur.Phys.J. C79 (2019) no.12, 1012





Mass	Width (MeV)	
6316	< 2.8 (4.2)	0.50
6330	< 3.1 (4.7)	2.79
6340	< 1.5 (1.8)	1.14
6350	< 2.8 (3.2)	0.62

Phenomenological model I

- The masses of the heavy single baryon states are calculated as the eigenvalues of the Hamiltonian , E. Santopinto, A. Giachino, J. Ferretti, H. Garcia-Tecocoatzi, M.A. Bedolla, R. Bijker, E. Ortiz-Pacheco, EPJC 79(12), 1012 (2019), which is modeled as:

$$H = H_{\mathrm{h.o.}} + P_s\, \mathbf{S}^2 + P_{sl}\, \mathbf{S}\cdot\mathbf{L} + P_I\, \boldsymbol{I}^2 + P_f\, \mathbf{C_2}(\mathrm{SU(3)_f}), \qquad (1)$$

  $\mathbf{S}, \mathbf{L}, \boldsymbol{I}$ and $\mathbf{C_2}(\mathrm{SU(3)_f})$ are the spin, orbital momentum, isospin and Casimir operators, respectively.

- We describe the observed excited states of Ω_c, Σ_c, Λ_c, Ξ_c, and Ξ'_c at the same time, PRD107 034031 (2023)
- We recently study the Ω_b, Σ_b, Λ_b, Ξ_b, and Ξ'_b states
- We work within the quark-model framework H. Garcia-Tecocoatzi, A. Giachino, A. Ramirez-Morales, A. Rivero-Acosta, E. Santopinto, and C. Vaquera e-Print: 2307.00505 [hep-ph] (2023)

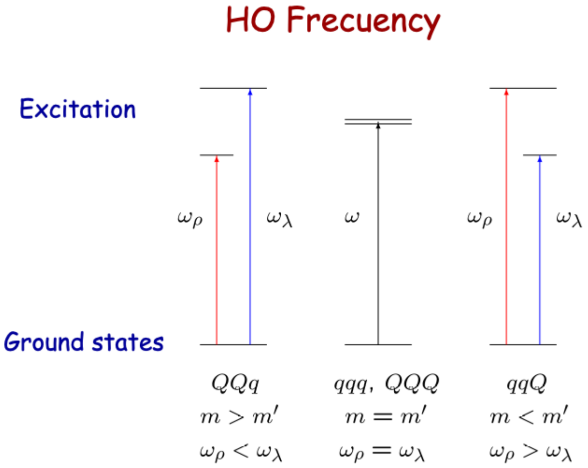
The Hamiltonian of three quark model

- The Hamiltonian of the harmonic oscillator is given:

$$H_{\mathrm{h.o.}} = \sum_{i=1}^{3} m_i + \frac{\mathbf{p}_\rho^2}{2m_\rho} + \frac{\mathbf{p}_\lambda^2}{2m_\lambda} + \frac{1}{2} m_\rho \omega_\rho^2 \boldsymbol{\rho}^2 + \frac{1}{2} m_\lambda \omega_\lambda^2 \boldsymbol{\lambda}^2 \tag{2}$$

- It is written in terms of Jacobi coordinates, $\boldsymbol{\rho}$ and $\boldsymbol{\lambda}$, and their conjugated momenta, $\mathbf{p}_\rho$ and $\mathbf{p}_\lambda$, whose eigenvalues are $\sum_{i=1}^{3} m_i + \omega_\rho\, n_\rho + \omega_\lambda n_\lambda$,
- Will we observe all the predicted states?

Mass splitting due to ρ and λ excitations



Diquark description

- When $\mathbf{p}_\rho = 0$, the three-quark Hamiltonian becomes

$$H_{\mathrm{h.o.}} \quad = \quad m_D + m_Q + \frac{\mathbf{p}_\lambda^2}{2m_\lambda} + \frac{1}{2} m_\lambda \omega_\lambda^2 \boldsymbol{\lambda}^2. \tag{3}$$

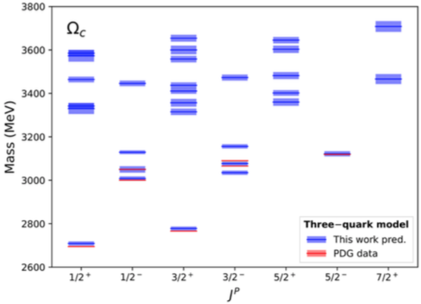
- The quark-diquark Hamiltonian depends on the relative coordinate $\boldsymbol{r}$ and the momentum $\mathbf{p}_r$ and is

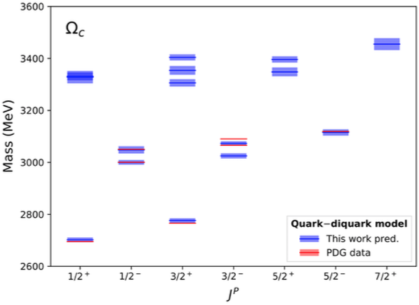
$$H_D = m_D + m_Q + \frac{p_r^2}{2\mu} + \frac{1}{2}\mu\omega_\lambda^2 \mathbf{r}^2, \tag{4}$$

- We can find a match as follows: $\frac{p_\lambda^2}{2m_\lambda} \to \frac{p_r^2}{2\mu}$ and $\frac{1}{2} m_\lambda \omega_\lambda^2 \boldsymbol{\lambda}^2 \to \frac{1}{2}\mu\omega_\lambda^2 \mathbf{r}^2$, where $\mu = \frac{m_D m_Q}{m_D + m_Q}$ is the reduced mass, $\mathbf{p}_r = \frac{m_Q \mathbf{p}_D - m_D \mathbf{p}_Q}{m_D + m_Q}$

Results for Ω_c,PRD107 034031 (2023)

Three-quark model vs quark-diquark model

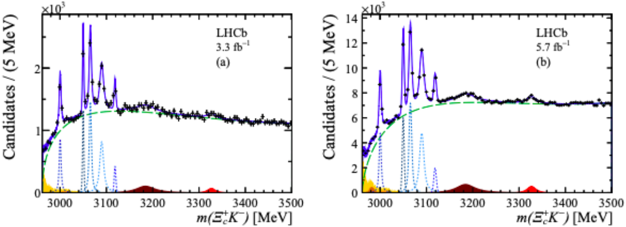




H. Garcia-Tecocoatzi, A. Giachino, J. Li, A. Ramirez-Morales, and E. Santopinto, PRD107 034031 (2023)

New Ω_c states observed by LHCb, PRL131 131902(2023)

New state $\Omega_c(3327)$ with mass$=3327.1 \pm 1.2$ MeV and $\Gamma = 20 \pm 5$ MeV



$\vert l_\lambda = 2, l_\rho = 0, k_\lambda = 0, k_\rho = 0\rangle$	$^2D_{3/2}$	3315^{+15}_{-14}	3306^{+14}_{-14}	†	11^{+5}_{-5}
$\vert l_\lambda = 2, l_\rho = 0, k_\lambda = 0, k_\rho = 0\rangle$	$^2D_{5/2}$	3360^{+17}_{-16}	3348^{+17}_{-17}	†	24^{+12}_{-12}
$\vert l_\lambda = 2, l_\rho = 0, k_\lambda = 0, k_\rho = 0\rangle$	$^4D_{1/2}$	3330^{+25}_{-25}	3328^{+24}_{-23}	†	16^{+8}_{-8}
$\vert l_\lambda = 2, l_\rho = 0, k_\lambda = 0, k_\rho = 0\rangle$	$^4D_{3/2}$	3357^{+18}_{-19}	3354^{+17}_{-17}	†	30^{+15}_{-15}
$\vert l_\lambda = 2, l_\rho = 0, k_\lambda = 0, k_\rho = 0\rangle$	$^4D_{5/2}$	3402^{+13}_{-13}	3396^{+12}_{-12}	†	62^{+31}_{-31}

H. Garcia-Tecocoatzi, A. Giachino, J. Li, A. Ramirez-Morales, and E. Santopinto, PRD107 034031 (2023)

Results for Ξ_c' and Ξ_c, PRD107 034031 (2023)

$\Xi_c'(snc)$ $\mathcal{F} = \mathbf{6}_f$	$^{2S+1}L_J$	Three-quark predicted mass (MeV)	Quark-diquark predicted mass (MeV)	Experimental mass (MeV)	Predicted Γ_{tot} (MeV)	Experimental Γ (MeV)
$N=0$						
$\lvert l_\lambda=0, l_\rho=0, k_\lambda=0, k_\rho=0\rangle$	$^2S_{1/2}$	2571^{+8}_{-8}	2577^{+10}_{-10}	2578.0 ± 0.9 (*)	0	†
$\lvert l_\lambda=0, l_\rho=0, k_\lambda=0, k_\rho=0\rangle$	$^4S_{3/2}$	2640^{+7}_{-7}	2650^{+9}_{-9}	2645.9 ± 0.71 (*)	$0.4^{+0.2}_{-0.2}$	2.25 ± 0.41 (*)
$N=1$						
$\lvert l_\lambda=1, l_\rho=0, k_\lambda=0, k_\rho=0\rangle$	$^2P_{1/2}$	2893^{+9}_{-9}	2893^{+11}_{-11}	†	7^{+4}_{-3}	†
$\lvert l_\lambda=1, l_\rho=0, k_\lambda=0, k_\rho=0\rangle$	$^4P_{1/2}$	2935^{+14}_{-15}	2941^{+14}_{-14}	2923.0 ± 0.35	5^{+2}_{-3}	7.1 ± 2.0
$\lvert l_\lambda=1, l_\rho=0, k_\lambda=0, k_\rho=0\rangle$	$^2P_{3/2}$	2920^{+9}_{-9}	2919^{+13}_{-13}	2938.5 ± 0.3	28^{+14}_{-14}	15 ± 9
$\lvert l_\lambda=1, l_\rho=0, k_\lambda=0, k_\rho=0\rangle$	$^4P_{3/2}$	2962^{+9}_{-9}	2966^{+10}_{-10}	2964.9 ± 0.33 (*)	19^{+9}_{-9}	14.1 ± 1.6 (*)
$\lvert l_\lambda=1, l_\rho=0, k_\lambda=0, k_\rho=0\rangle$	$^4P_{5/2}$	3007^{+12}_{-12}	3009^{+14}_{-14}	†	43^{+21}_{-21}	†
$\lvert l_\lambda=0, l_\rho=1, k_\lambda=0, k_\rho=0\rangle$	$^2P_{1/2}$	3040^{+10}_{-9}	††	3055.9 ± 0.4 (*)	157^{+80}_{-80}	7.8 ± 1.9 (*)
$\lvert l_\lambda=0, l_\rho=1, k_\lambda=0, k_\rho=0\rangle$	$^2P_{3/2}$	3067^{+10}_{-10}	††	3078.6 ± 2.8 (*)	100^{+47}_{-48}	4.6 ± 3.3 (*)

$\Xi_c(snc)$ $\bar{\mathbf{3}}_f$	$^{2S+1}L_J$	Three-quark predicted mass (MeV)	Quark-diquark predicted mass (MeV)	Experimental mass (MeV)	Predicted Γ_{tot} (MeV)	Experimental Γ (MeV)
$N=0$						
$\lvert l_\lambda=0, l_\rho=0, k_\lambda=0, k_\rho=0\rangle$	$^2S_{1/2}$	2466^{+10}_{-10}	2473^{+10}_{-10}	2469.42 ± 1.77 (*)	0	≈0
$N=1$						
$\lvert l_\lambda=1, l_\rho=0, k_\lambda=0, k_\rho=0\rangle$	$^2P_{1/2}$	2788^{+10}_{-10}	2789^{+9}_{-9}	2793.3 ± 0.28 (*)	3^{+2}_{-2}	9.5 ± 2.0 (*)
$\lvert l_\lambda=1, l_\rho=0, k_\lambda=0, k_\rho=0\rangle$	$^2P_{3/2}$	2815^{+10}_{-10}	2814^{+9}_{-9}	2818.49 ± 2.07 (*)	5^{+2}_{-2}	2.48 ± 0.5 (*)
$\lvert l_\lambda=0, l_\rho=1, k_\lambda=0, k_\rho=0\rangle$	$^2P_{1/2}$	2935^{+12}_{-12}	††	†	17^{+9}_{-8}	†
$\lvert l_\lambda=0, l_\rho=1, k_\lambda=0, k_\rho=0\rangle$	$^4P_{1/2}$	2977^{+20}_{-20}	††	2968.6 ± 3.3	13^{+6}_{-6}	20 ± 3.5
$\lvert l_\lambda=0, l_\rho=1, k_\lambda=0, k_\rho=0\rangle$	$^2P_{3/2}$	2962^{+12}_{-12}	††	†	89^{+45}_{-45}	†
$\lvert l_\lambda=0, l_\rho=1, k_\lambda=0, k_\rho=0\rangle$	$^4P_{3/2}$	3004^{+17}_{-17}	††	†	56^{+29}_{-31}	†
$\lvert l_\lambda=0, l_\rho=1, k_\lambda=0, k_\rho=0\rangle$	$^4P_{5/2}$	3049^{+18}_{-19}	††	†	122^{+59}_{-60}	†
$N=2$						
$\lvert l_\lambda=2, l_\rho=0, k_\lambda=0, k_\rho=0\rangle$	$^2D_{3/2}$	3118^{+14}_{-14}	3113^{+14}_{-14}	3122.9 ± 1.23	50^{+24}_{-25}	4 ± 4

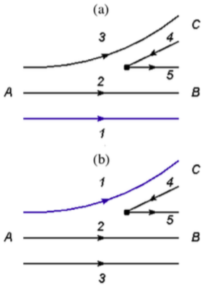
Strong decay widths

We can use the decay properties to identify new baryons

- The study of the decay channels can help experimentalist to look for them.
- At the moment, there is no decay model from first principles, i.e., a QCD decay model.
- There are many models inspired by QCD, such as the flux tube, the elementary emission model, effective Lagrangians, or $^3P_0$.

$^3P_0$ decay model

- The $q\bar{q}$ pair is created with the vacuum quantum numbers: 0^{++}
- Due to parity conservation, the pair is created in P-wave
- The spin should be $S = 1$ to couple to $J = 0$
- It has only one coupling constant γ_0



Strong decay widths

- The two-body strong decay widths are calculated with the predicted masses and their predicted quantum numbers
- The $^3P_0$ model is used for calculating the strong-decay widths of a single heavy baryon A into a single heavy baryon B plus a meson C, or a single heavy baryon A into a light baryon B plus a heavy meson C, $A \to BC$

$$\Gamma = \frac{2\pi\gamma_0^2}{2J_A+1}\,\Phi_{A\to BC}(q_0)\sum_{M_{J_A},M_{J_B}}\left|\mathcal{M}^{M_{J_A},M_{J_B}}\right|^2 \tag{5}$$

Results, partial-decay widths PRD107 034031 (2023)

$\Omega_c(ssc)\ \mathcal{F} = \mathbf{6}_f$	$\Xi_c K$	$\Xi'_c K$	$\Xi^*_c K$	$\Xi_c K^*$	$\Xi'_c K^*$	$\Xi^*_c K^*$	$\Omega_c \eta$	$\Omega^*_c \eta$	$\Omega_c \phi$	$\Omega^*_c \phi$	$\Omega_c \eta'$	$\Omega^*_c \eta'$	$\Xi_8 D$	$\Xi_{10} D$	Predicted Γ_{tot}
$\Omega_c(2709)^2S_{1/2}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$\Omega_c(2778)^4S_{3/2}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$\Omega_c(3008)^2P_{1/2}$	4.1	0	0	0	0	0	0	0	0	0	0	0	0	0	4.1
$\Omega_c(3050)^4P_{1/2}$	7.5	0.1	0	0	0	0	0	0	0	0	0	0	0	0	7.6
$\Omega_c(3035)^2P_{3/2}$	26.3	0	0	0	0	0	0	0	0	0	0	0	0	0	26.3
$\Omega_c(3077)^4P_{3/2}$	6.3	0.4	0	0	0	0	0	0	0	0	0	0	0	0	6.7
$\Omega_c(3122)^4P_{5/2}$	40.9	8.9	0.3	0	0	0	0	0	0	0	0	0	0	0	50.1
$\Omega_c(3129)^2P_{1/2}$	—	8.9	5.5	0	0	0	0	0	0	0	0	0	0	0	14.4
$\Omega_c(3156)^2P_{3/2}$	—	61.1	10.5	0	0	0	0	0	0	0	0	0	0	0	71.6
$\Omega_c(3315)^2D_{3/2}$	1.9	1.8	2.3	0	0	0	0.3	—	0	0	0	0	4.3	0	10.6
$\Omega_c(3360)^2D_{5/2}$	5.4	5.1	0.5	0	0	0	1.2	—	0	0	0	0	12.2	0	24.4
$\Omega_c(3330)^4D_{1/2}$	0.2	0.2	3.3	0	0	0	0.1	0.1	0	0	0	0	12.3	0	16.2
$\Omega_c(3357)^4D_{3/2}$	2.0	0.5	5.2	0.2	0	0	0.2	0.6	0	0	0	0	21.7	0	30.4
$\Omega_c(3402)^4D_{5/2}$	5.0	1.2	5.0	1.6	0	0	0.3	1.2	0	0	0	0	46.9	1.1	62.3
$\Omega_c(3466)^4D_{7/2}$	7.8	2.0	5.0	2.6	0	0	0.8	0.9	0	0	0	0	83.2	20.9	123.2
$\Omega_c(3342)^2S_{1/2}$	0.2	0.3	0.1	0	0	0	0.1	—	0	0	0	0	0.5	0	1.2
$\Omega_c(3411)^4S_{3/2}$	0.2	0.1	0.4	0.2	0	0	—	0.1	0	0	0	0	2.1	0.2	3.3
$\Omega_c(3585)^2S_{1/2}$	0.3	1.0	0.7	3.0	11.6	0.1	1.1	0.5	0	0	0	0	—	—	18.3
$\Omega_c(3654)^4S_{3/2}$	0.1	0.1	1.2	2.8	1.0	17.2	0.2	1.4	0	0	—	0	—	—	24.0
$\Omega_c(3437)^2D_{3/2}$	—	6.5	107.0	53.5	0	0	4.0	27.0	0	0	0	0	—	—	198.0

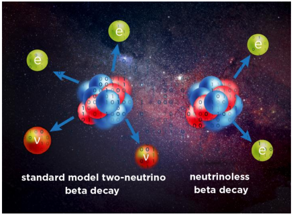
Summary

- I calculated the mass spectra of the single heavy baryons (ρ and λ mode excitations up to the D-wave.
- The identification of the baryons states is a complex task
- The strong decay calculations systematically consider the (anti-triplet/sextet) heavy baryon-(octet/singlet) vector/pseudoscalar meson and (octet/decuplet) baryon-(triplet) pseudoscalar/vector heavy meson as possible final states.
- The future experiments will help us to understand the structure of the hadrons
- Single bottom baryons H. Garcia-Tecocoatzi, A. Giachino, , A. Ramirez-Morales, A. Rivero-Acosta, E. Santopinto, and C. Vaquera e-Print: 2307.00505 [hep-ph] (2023)

Theoretical calculations for the NUMEN Experiment

- Motivation
- The NUMEN project
- **Theoretical results using IBM and its extensions**

Double Beta Decay of eve-even nuclei



- **Double Beta Decay with Neutrinos ($2\nu\beta\beta$)**
  - Experimentally observed
  - Transitions between ground states
  - Effective values of g_A

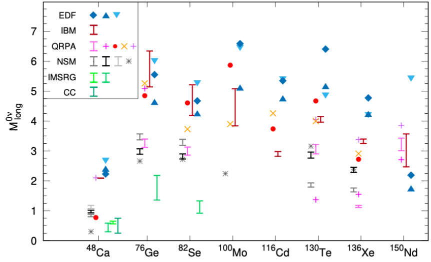
- **Neutrinoless Double Beta Decay ($0\nu\beta\beta$)**
  - Not observed experimentally
  - Its observation implies that the neutrino is its own antiparticle
  - Physics beyond the standard model

$0\nu\beta\beta$ and the open problem of NME

- **Half-life of Double Beta Decay without Neutrinos**

$$\tau_{0\nu}^{-1}(A \to B) = G_{0\nu} \left| M_{0\nu} \right|^2 \left| \frac{m_{\beta\beta}}{m_e} \right|^2 \qquad (6)$$

where $\left| M_{0\nu} \right|$ is the nuclear matrix element between nuclear states.



Agostini, et al., Rev. Mod. Phys. 95, 025002 (2023)

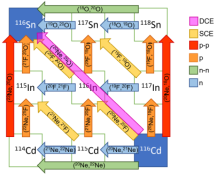
The NUMEN Project

- Study target candidates for neutrinoless double beta decay.
- **Double charge-exchange reactions induced by heavy ions**

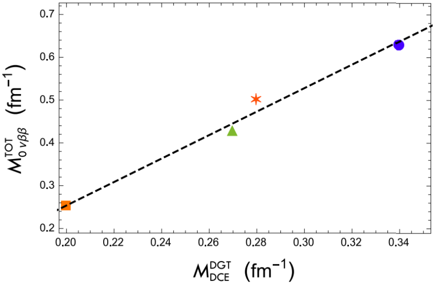
$$\begin{aligned} N_T(A,Z) + N_P(a,z) &\to N_T(A,Z+2) + N_P(a,z-2) \\ N_T(A,Z) + N_P(a,z) &\to N_T(A,Z-2) + N_P(a,z+2) \end{aligned} \tag{7}$$

- Use experimental information to constrain nuclear models (Shell Model, QRPA, IBM,...)

F. Cappuzzello, ..., H. Garcia-Tecocoatzi, et al., [NUMEN Collaboration] Prog.Part.Nucl.Phys. 128 (2023) 103999



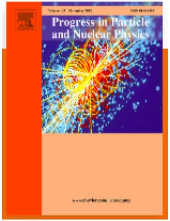
Double charge exchange reactions and its relation to Neutrinoless Double Beta Decay



E. Santopinto, H. Garcia-Tecocoatzi, R. I. Magana-Vsevolodovna, and J. Ferretti Phys. Rev. C 061601(R) (2018)

The possible competition of different reaction mechanisms

F. Cappuzzello, ..., H. Garcia-Tecocoatzi, et al., [NUMEN Collaboration]
Prog.Part.Nucl.Phys. 128 (2023) 103999



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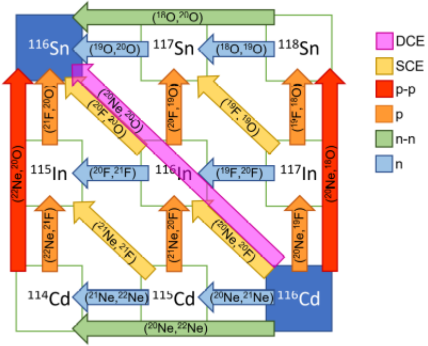


Interacting Boson Model (IBM)

The Interacting Boson Model

- This model was proposed by Akito Arima and Francesco Iachello in 1974, Physical Review Letters 35 (16): 1069–1072 (1975).
- The nucleons (protons or neutron) pair up, essentially acting as a single particle with boson properties, with integral spin of either 2 (D-boson) or 0 (S-boson).
- Describes the even-even nuclei

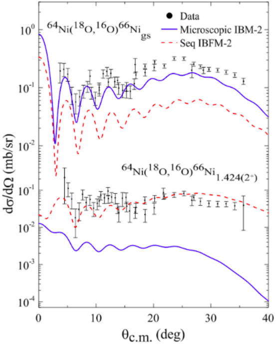
$$
\begin{aligned}
H^{\mathrm{B}} = {} & \epsilon_d \left(n_{d_\nu} + n_{d_\pi}\right) + \kappa \left(Q^{\mathrm{B}}_\nu \cdot Q^{\mathrm{B}}_\pi\right) + \frac{1}{2}\xi_2 \left((d^\dagger_\nu s^\dagger_\pi - d^\dagger_\pi s^\dagger_\nu) \cdot (\tilde{d}_\nu s_\pi - \tilde{d}_\pi s_\nu)\right) \\
& + \sum_{K=1,3} \xi_K \left([d^\dagger_\nu \times d^\dagger_\pi]^{(K)} \cdot [\tilde{d}_\pi \times \tilde{d}_\nu]^{(K)}\right) + \frac{1}{2} \sum_{K=0,2,4} c^{(K)}_\nu \left([d^\dagger_\nu \times d^\dagger_\nu]^{(K)} \cdot [\tilde{d}_\nu \times \tilde{d}_\nu]^{(K)}\right),
\end{aligned}
$$

Two neutron transfer reaction

- Study of the transition ^{64}Ni (^{18}O, ^{16}O) ^{66}Ni
- Direct process: Interacting Boson Model (IBM)
- Sequential process: Interacting Boson-Fermion Model (IBFM)

- IBM describes even-even nuclei
- IBFM describes even-odd nuclei considering an unpaired nucleon

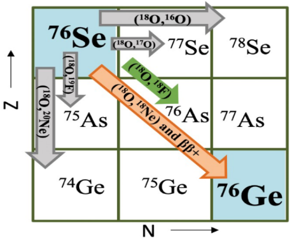
B. Paes, H. Garcia-Tecocoatzi,et al. PRC 96, 044612 (2017)



Proton Transfer in the ^{76}Se (^{18}O, ^{19}F) ^{75}As reaction

- Study the ^{76}Se (^{18}O, ^{19}F) ^{75}As reaction.
- Use experimental information to constrain nuclear models.

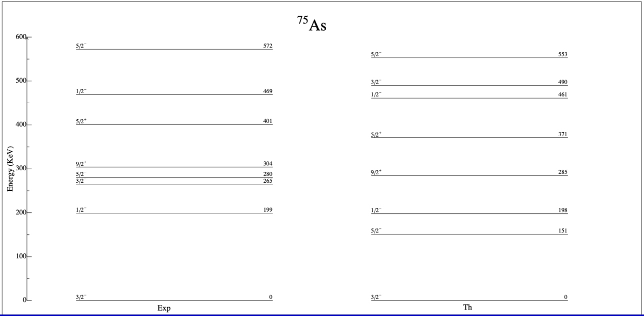
The ^{76}Se is described using IBM-2, with 34 protons and 42 neutrons:
$N_\pi = 3$ proton bosons
$N_\nu = 4$ neutron bosons (holes)
I. Ciraldo, H. Garcia-Tecocoatzi, et al., NUMEN Collaboration, submitted to PRC



Reaction ^{76}Se (^{18}O, ^{19}F) ^{75}As

- ^{75}As is described as ^{74}Ge+p, ^{74}Ge:
  $N_\pi = 2$ proton bosons
  $N_\nu = 4$ neutron bosons (holes)
  The IBFM-2 Hamiltonian is given by

$$H = H^{B} + H_{\rho}^{F} + V_{\rho}^{BF}. \quad (8)$$



Proton Transfer in the Reaction ^{76}Se (^{18}O, ^{19}F) ^{75}As

- Transition Operators

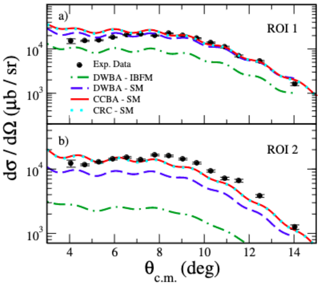
$$A_m^{\dagger(j)} = \zeta_j a_{jm}^\dagger + \sum_{j'} \zeta_{jj'} s^\dagger [\tilde{d} \times a_{j'}^\dagger]_m^{(j)}, \quad (11)$$

$$\tilde{B}_m^{(j)} = -\theta_j^* s a_{jm}^\dagger - \sum_{j'} \theta_{jj'}^* [\tilde{d} \times a_{j'}^\dagger]_m^{(j)}, \quad (12)$$

$$\tilde{A}_m^{(j)} = \zeta_j^* \tilde{a}_{jm} + \sum_{j'} \zeta_{jj'}^* s[d^\dagger \times \tilde{a}_{j'}]_m^{(j)}, \quad (13)$$

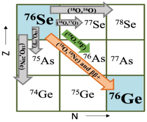
$$B_m^{\dagger(j)} = \theta_j s^\dagger \tilde{a}_{jm} + \sum_{j'} \theta_{jj'} [d^\dagger \times \tilde{a}_{j'}]_m^{(j)}, \quad (14)$$

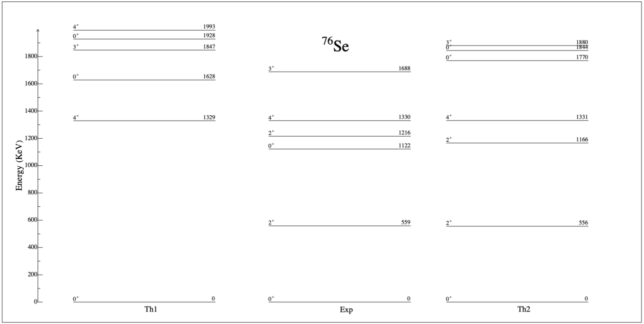
I. Ciraldo, H. Garcia-Tecocoatzi, et al., NUMEN Collaboration, submitted to PRC



Improving the description of the ^{76}Se (^{18}O, ^{19}F) ^{75}As reaction

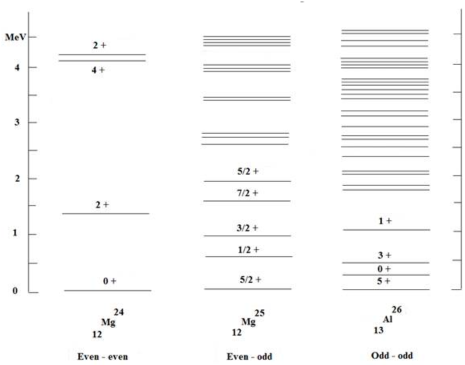
- Improve the description of even-even and even-odd nuclei.





Odd-Odd Nuclei

- The complexity of odd-odd nuclei.



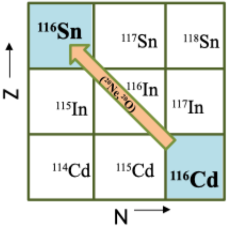
Odd-Odd Nuclei in IBFFM

- IBFFM Hamiltonian

$$H = H^{\mathrm{B}} + H_{\pi}^{\mathrm{F}} + V_{\pi}^{\mathrm{BF}} + H_{\nu}^{\mathrm{F}} + V_{\nu}^{\mathrm{BF}} + V_{\mathrm{RES}}. \quad (15)$$

where

$$\begin{aligned} V_{\mathrm{RES}} = & \; 4\pi \, V_{\delta} \, \delta(\boldsymbol{r}_{\pi} - \boldsymbol{r}_{\nu}) \, \delta(r_{\pi} - R_0) \, \delta(r_{\nu} - R_0) \\ & - \tfrac{1}{\sqrt{3}} \, V_{\sigma\sigma} \, (\boldsymbol{\sigma}_{\pi} \cdot \boldsymbol{\sigma}_{\nu}) \\ & + 4\pi \, V_{\sigma\sigma\delta} \, (\boldsymbol{\sigma}_{\pi} \cdot \boldsymbol{\sigma}_{\nu}) \delta(\boldsymbol{r}_{\pi} - \boldsymbol{r}_{\nu}) \, \delta(r_{\pi} - R_0) \, \delta(r_{\nu} - R_0) \\ & + V_T \left(3 \, \frac{(\boldsymbol{\sigma}_{\pi} \cdot \boldsymbol{r}_{\pi\nu})(\boldsymbol{\sigma}_{\nu} \cdot \boldsymbol{r}_{\pi\nu})}{r_{\pi\nu}^2} - (\boldsymbol{\sigma}_{\pi} \cdot \boldsymbol{\sigma}_{\nu}) \right). \end{aligned} \quad (16)$$



New ODDODD code July 2023!!!!

Transfer reactions between even-even and odd-odd nuclei

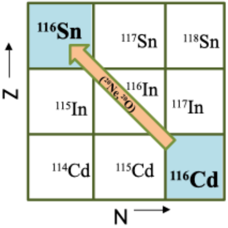
- Transition Operators

$$T^{(\lambda)}_{j_\nu j_\pi} = \left[A^{\dagger(j_\nu)}_m \times \tilde{B}^{(j_\pi)}_m\right]^{(\lambda)} \quad (17)$$

$$T^{(\lambda)}_{j_\nu j_\pi} = \left[B^{\dagger(j_\nu)}_m \times \tilde{A}^{(j_\pi)}_m\right]^{(\lambda)} \quad (18)$$

$$A^{\dagger(j)}_m = \zeta_j a^\dagger_{jm} + \sum_{j'} \zeta_{jj'} s^\dagger [\tilde{d} \times a^\dagger_{j'}]^{(j)}_m,$$

$$\tilde{B}^{(j)}_m = -\theta^*_j s a^\dagger_{jm} - \sum_{j'} \theta^*_{jj'} [\tilde{d} \times a^\dagger_{j'}]^{(j)}_m,$$



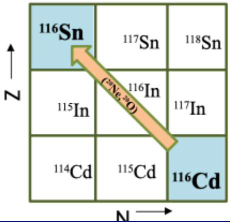
Spectroscopic amplitudes between even-even and odd-odd nuclei

- Spectroscopic amplitudes

$$\langle {}^{116}\mathrm{In}| \left[A_m^{\dagger(j_\nu)} \times \tilde{B}_m^{(j_\pi)} \right]^{(\lambda)} |{}^{116}\mathrm{Cd}\rangle \tag{19}$$

$$\langle {}^{116}\mathrm{Sn}| \left[B_m^{\dagger(j_\nu)} \times \tilde{A}_m^{(j_\pi)} \right]^{(\lambda)} |{}^{116}\mathrm{In}\rangle \tag{20}$$

- Two-step double charge exchange reaction
- $0\nu\beta\beta$ NME without the closure



Conclusions

- Now we have the formalism and operators to calculate the spectroscopic amplitudes in the IBFFM scheme, from even-even to odd-odd nuclei.
- The new odd-odd code can generate positive and negative parity states (odd-odd nuclei).
- The spectroscopic amplitudes will be used in a reaction code, for both single and double charge exchange reactions.
- We are using experimental data for improving the description of even-even nuclei

Thanks for listening!