Charmed nuclei within a microscopic many-body approach

Isaac Vidaña, INFN Catania

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Charmed Nuclei

The possible existence of charmed nuclei (in analogy with hypernuclei) was proposed soon after the discovery of charmed hadrons

- This possibility motivated several author to study the properties of these systems within different theoretical approaches, predicting a rich spectrum & a wide range of atomic numbers

- Production mechanism of charmed nuclei by means of *charm exchange* or *associate charm production* reactions were proposed in analogy to hypernuclei production

- However, experimental production of charmed nuclei is difficult (charmed particles formed with large momentum, short lifetimes of D-meson beams) & only 3 ambiguous candidates have been reported by an *emulsion experiment* carried out in Dubna in the mid 1970s

- Hopefully such difficulties will be overcome in the future GSI-FAIR and JPARC facilities where the production of charge particles will be sufficiently large to make the study of charmed nuclei possible

- In the last few years, different theoretical estimations (RMF, effective largrangians, quark cluster model, …) of charmed baryon properties in nuclear matter & finite nuclei has bee done

The talk in few words

- ✧ Study of the structure of charmed nuclei. To such end:
  - A Y_cN ineraction based on a SU(4) extension of the meson-exchange YN Ã potential of the Juelich group is used. Three models are considered
  - A perturbative many-body approach is employed to obtain the Λ_c self-energy in finite nuclei from which the Λ_c s.p. bound states can be obtained
- ✧ Scattering observables are computed & compared with those predicted by an Y_cN derived by Haidenbauer & Krein from the extrapolation to the pion physical mass of recent results of the HAL QCD Collaboration
- ✧ A small spin-orbit splitting is found as in the case of hypernuclei
- ✧ The role of the Coulomb interaction & the Λ_cN-Σ_cN coupling is analyzed

In collaboration with: Àngels Ramos & Estela Jiménez-Tejero (Barcelona)

For details see:

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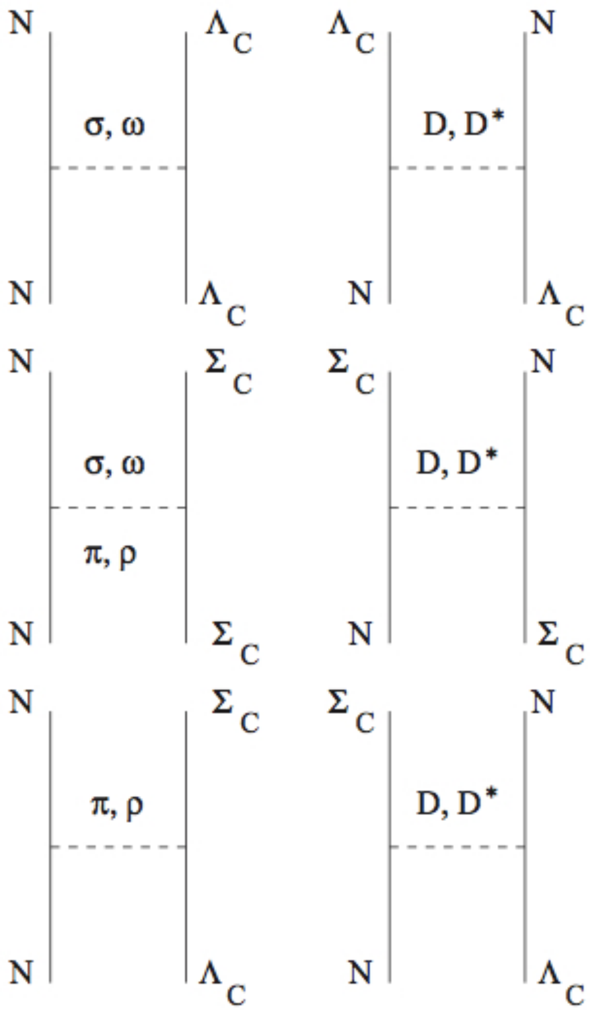
The Y_cN interaction model



Y_cN interaction based on a SU(4) extension of YN potential Ã of the Juelich group

Consist on single scalar (σ), pseudoscalar (π,D) & vector (ω,ρ,D^*) meson exchange potetials. Contribution of η & η' mesons neglected

✧ BBP vertices

$$\mathcal{L}_{\rm BBP} = g_{NN\pi}(N^\dagger\vec{\tau}N)\cdot\vec{\pi} + g_{\Lambda_c\Sigma_c\pi}[\vec{\Sigma}_c^\dagger\cdot\vec{\pi}\Lambda_c + \Lambda_c^\dagger\vec{\Sigma}_c\cdot\vec{\pi}] - ig_{\Sigma_c\Sigma_c\pi}(\vec{\Sigma}_c^\dagger\times\vec{\Sigma}_c)\cdot\vec{\pi} + g_{N\Lambda_c D}[(N^\dagger D)\Lambda_c + \Lambda_c^\dagger(D^\dagger N)] + g_{N\Sigma_c D}[(N^\dagger\vec{\tau}D)\cdot\vec{\Sigma}_c + \vec{\Sigma}_c^\dagger(D^\dagger\vec{\tau}N)]$$

✧ BBV vertices

$$\mathcal{L}_{\rm BBV} = g_{NN\rho}(N^\dagger\vec{\tau}N)\cdot\vec{\rho} + g_{\Lambda_c\Sigma_c\rho}[\vec{\Sigma}_c^\dagger\cdot\vec{\rho}\Lambda_c + \Lambda_c^\dagger\vec{\Sigma}_c\cdot\vec{\rho}] - ig_{\Sigma_c\Sigma_c\rho}(\vec{\Sigma}_c^\dagger\times\vec{\Sigma}_c)\cdot\vec{\rho} + g_{N\Lambda_c D^*}[(N^\dagger D^*)\Lambda_c + \Lambda_c^\dagger(D^{*\dagger}N)] + g_{N\Sigma_c D^*}[(N^\dagger\vec{\tau}D^*)\cdot\vec{\Sigma}_c + \vec{\Sigma}_c^\dagger(D^{*\dagger}\vec{\tau}N)] + g_{NN\omega}N^\dagger N\omega + g_{\Lambda_c\Lambda_c\omega}\Lambda_c^\dagger\Lambda_c\omega + g_{\Sigma_c\Sigma_c\omega}\vec{\Sigma}_c^\dagger\cdot\vec{\Sigma}_c\omega.$$

Couplings constants: pseudoscalar & vector mesons

SU(4) symmetry is used to derive the relations between different coupling constants. However, SU(4) is strongly broken due to the use of physical masses. Therefore, SU(4) is rather used as a mathematical tool

✧ We deal with $J^p=1/2^+$ baryons & $J^p=0^-$ & 1^- mesons belonging to 20'- & 15-plet irrep of SU(4)

- Baryon current: $\mathbf{20'} \otimes \overline{\mathbf{20'}} = \mathbf{1} \oplus \underbrace{\mathbf{15_1} \oplus \mathbf{15_2}} \oplus \mathbf{20''} \oplus \mathbf{45} \oplus \overline{\mathbf{45}} \oplus \mathbf{84} \oplus \mathbf{175}$

  Two ways to obtain an SU(4) scalar for the coupling $\mathbf{20'} \otimes \overline{\mathbf{20'}} \otimes \mathbf{15}$

- The two couplings can be related to the g_D & g_F usual symmetric (D) & antisymmetric (F) octet representations of the baryon current in SU(3)

$$g_{15_1} = \frac{1}{4}\left(7g_D + \sqrt{5}g_F\right) = \sqrt{\frac{10}{3}}g_8\left(7-4\alpha\right), \qquad g_{15_2} = \sqrt{\frac{3}{20}}\left(\sqrt{5}g_D - 5g_F\right) = \sqrt{40}g_8\left(1-4\alpha\right)$$

g_8: SU(3) octet strength coupling; α: F/(F+D) ratio

Couplings constants: pseudoscalar & vector mesons

✧ Baryon-Baryon-Pseudoscalar meson couplings

BBP couplings can easily be obtained by using SU(4) Clebsh-Gordan coefficients & the previous relations

$$g_{\Lambda_c \Sigma_c \pi} = \frac{2}{\sqrt{3}} g_{NN\pi} (1 - \alpha_p)$$

$$g_{\Sigma_c \Sigma_c \pi} = 2 g_{NN\pi} \alpha_p$$

$$g_{N \Lambda_c D} = -\frac{1}{\sqrt{3}} g_{NN\pi} (1 + 2\alpha_p)$$

$$g_{N \Sigma_c D} = g_{NN\pi} (1 - 2\alpha_p)$$

✧ Baryon-Baryon-Vector meson couplings

BBV couplings are obtained similarly

$$g_{\Lambda_c \Sigma_c \rho} = \frac{2}{\sqrt{3}} g_{NN\rho} (1 - \alpha_v)$$

$$g_{\Sigma_c \Sigma_c \rho} = 2 g_{NN\rho} \alpha_v$$

$$g_{N \Lambda_c D^*} = -\frac{1}{\sqrt{3}} g_{NN\rho} (1 + 2\alpha_v)$$

$$g_{N \Sigma_c D^*} = g_{NN\rho} (1 - 2\alpha_v)$$

$$g_{NN\omega} = g_{NN\rho} (4\alpha_v - 1)$$

$$g_{\Lambda_c \Lambda_c \omega} = \frac{g_{NN\rho}}{9} (6 + 3)$$

$$g_{\Sigma_c \Sigma_c \omega} = g_{NN\rho} (2\alpha_v - 1)$$

The physical ω meson results from the ideal mixing of the mathematical members ω_8 & ω_1 of the 15-plet

Tensor couplings f_{BBM} are obtained applying SU(4) relations to the "magnetic" coupling $G_{BBM} = g_{BBM} + f_{BBM}$

Couplings constants: scalar σ meson

The σ meson is not a member of any SU(4) muliplet. Therefore, is not possible to invoke this symmetry to obtain the BBσ couplings.

To explore the sensitivity of our results to these couplings we consider three different sets of values that together with the BBP & BBV coupling define three models for the $Y_c N$ interaction

- Model A: couplings $N\Lambda_c\sigma$ & $N\Sigma_c\sigma$ are assumed to be equal, respectively, to $N\Lambda\sigma$ and $N\Sigma\sigma$ of the YN Ã Juelich potential

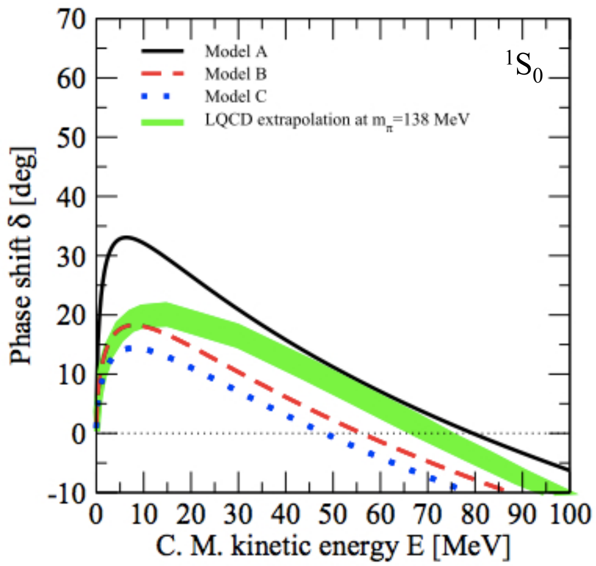
- Models B & C: couplings $N\Lambda_c\sigma$ & $N\Sigma_c\sigma$ are reduced 15% (B) and 20% (C) with respect to the $N\Lambda\sigma$ and $N\Sigma\sigma$ of the YN Ã Juelich potential

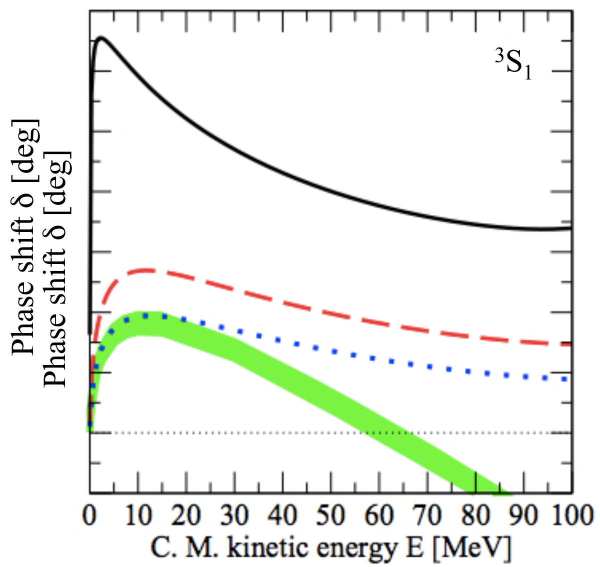
- NNσ coupling is taken for the three models equal to that used in the YN Ã Juelich potential

Couplings constants: Summary

Model	Vertex	$g_{BBM}/\sqrt{4\pi}$	$f_{BBM}/\sqrt{4\pi}$	Λ_{BBM} (GeV)
A, B, C	$NN\pi$	3.795	–	1.3
A, B, C	$\Lambda_c\Sigma_c\pi$	3.067	–	1.4
A, B, C	$\Sigma_c\Sigma_c\pi$	2.277	–	1.2
A, B, C	$N\Lambda_c D$	−3.506	–	2.5
A, B, C	$N\Sigma_c D$	1.518	–	2.5
A, B, C	$NN\rho$	0.917	5.591	1.4
A, B, C	$\Lambda_c\Sigma_c\rho$	0.000	4.509	1.16
A, B, C	$\Sigma_c\Sigma_c\rho$	1.834	3.372	1.41
A, B, C	$NN\omega$	4.472	0.000	1.5
A, B, C	$\Lambda_c\Lambda_c\omega$	1.490	2.758	2.0
A, B, C	$\Sigma_c\Sigma_c\omega$	1.490	−2.907	2.0
A, B, C	$N\Lambda_c D^*$	−1.588	−5.175	2.5
A, B, C	$N\Sigma_c D^*$	−0.917	2.219	2.5
A, B,C	$NN\sigma$	2.385	–	1.7
A	$\Lambda_c\Lambda_c\sigma$	2.138	–	1.0
A	$\Sigma_c\Sigma_c\sigma$ $(I = 1/2)$	3.061	–	1.0
A	$\Sigma_c\Sigma_c\sigma$ $(I = 3/2)$	3.102	–	1.12
B	$\Lambda_c\Lambda_c\sigma$	1.817	–	1.0
B	$\Sigma_c\Sigma_c\sigma$ $(I = 1/2)$	2.601	–	1.0
B	$\Sigma_c\Sigma_c\sigma$ $(I = 3/2)$	2.636	–	1.12
C	$\Lambda_c\Lambda_c\sigma$	1.710	–	1.0
C	$\Sigma_c\Sigma_c\sigma$ $(I = 1/2)$	2.448	–	1.0
C	$\Sigma_c\Sigma_c\sigma$ $(I = 3/2)$	2.481	–	1.12

Scattering Observables





- Model A predicts a more attractive $\Lambda_c N$ interaction in the $^1S_0$ & $^3S_1$ p.w. than the one derived by Haidenbauer & Krein (HK) from the extrapolation to the physical pion mass of recent results of the HAL QCD Collaboration

- Reduction of BBσ coupling in Models B & C leads to a better agreement with the interaction derived by HK

- HK predict a similar phase shift for both p.w. This is not the case for Models A, B & C which predict more overall attraction in the $^3S_1$ p.w.

	Model A	Model B	Model C	HK
a_s	−2.60	−1.11	−0.84	−0.85 . . . − 1.00
r_s	2.86	4.40	5.38	2.88 . . . 2.61
a_t	−15.87	−1.52	−0.99	−0.81 . . . − 0.98
r_t	1.64	2.79	3.63	3.50 . . . 3.15

Singlet & Triplet $\Lambda_c N$ scattering length & effective ranges

Scheme of the Calculation

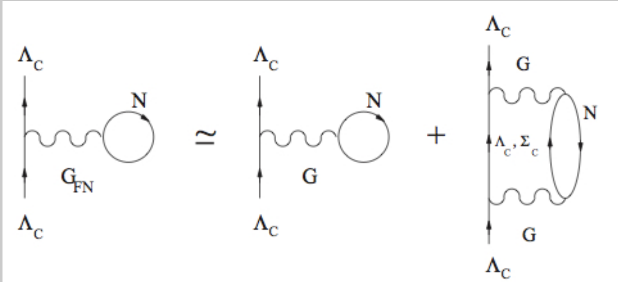
$$G_{NM} = V + V\left(\frac{Q}{E}\right)_{NM} G_{NM}$$

Nuclear matter G-matrix

$$G_{FN} = G_{NM} + G_{NM}\left[\left(\frac{Q}{E}\right)_{FN} - \left(\frac{Q}{E}\right)_{NM}\right]G_{FN}$$

Finite nuclei G-matrix

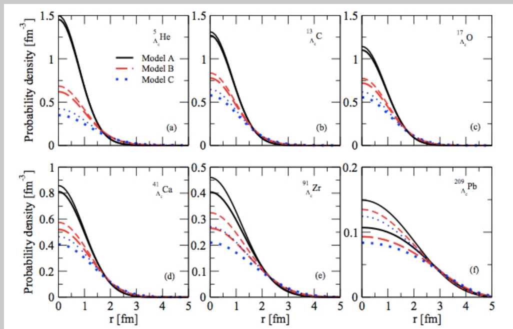
Λ_c irreducible self-energy in finite nuclei



Binding energies & wave functions of s.p. bound states

	${}^{5}_{\Lambda_c}$He Model A	${}^{5}_{\Lambda_c}$He Model B	${}^{5}_{\Lambda_c}$He Model C	${}^{5}_{\Lambda}$He JĀ	${}^{13}_{\Lambda_c}$C Model A	${}^{13}_{\Lambda_c}$C Model B	${}^{13}_{\Lambda_c}$C Model C	${}^{13}_{\Lambda}$C JĀ	${}^{17}_{\Lambda_c}$O Model A	${}^{17}_{\Lambda_c}$O Model B	${}^{17}_{\Lambda_c}$O Model C	${}^{17}_{\Lambda}$O JĀ
$1s_{1/2}$	−13.58	−3.24	−1.05	−1.49	−27.26	−10.20	−5.47	−7.84	−31.76	−12.47	−6.96	−10.04
$1p_{3/2}$	−1.74	–	–	–	−14.91	−2.13	–	–	−19.99	−4.32	−0.51	−0.33
$1p_{1/2}$	−0.39	–	–	–	−13.42	−1.03	–	–	−18.79	−3.22	–	−0.35
$1d_{5/2}$	–	–	–	–	−4.10	–	–	–	−9.02	–	–	–
$1d_{3/2}$	–	–	–	–	−2.13	–	–	–	−6.96	–	–	–
$2s_{1/2}$	–	–	–	–	−3.59	–	–	–	−7.13	–	–	–

	${}^{41}_{\Lambda_c}$Ca Model A	${}^{41}_{\Lambda_c}$Ca Model B	${}^{41}_{\Lambda_c}$Ca Model C	${}^{41}_{\Lambda}$Ca JĀ	${}^{91}_{\Lambda_c}$Zr Model A	${}^{91}_{\Lambda_c}$Zr Model B	${}^{91}_{\Lambda_c}$Zr Model C	${}^{91}_{\Lambda}$Zr JĀ	${}^{209}_{\Lambda_c}$Pb Model A	${}^{209}_{\Lambda_c}$Pb Model B	${}^{209}_{\Lambda_c}$Pb Model C	${}^{209}_{\Lambda}$Pb JĀ
$1s_{1/2}$	−41.09	−16.89	−9.60	−17.33	−44.76	−18.46	−10.51	−24.61	−52.52	−20.33	−10.32	−31.41
$1p_{3/2}$	−32.39	−10.41	−4.13	−7.67	−39.60	−14.27	−6.75	−17.66	−49.06	−18.28	−8.82	−27.59
$1p_{1/2}$	−31.60	−9.67	−3.42	−7.78	−39.24	−14.00	−6.49	−17.58	−48.84	−18.10	−8.64	−27.58
$1d_{5/2}$	−23.10	−3.91	–	–	−33.74	−9.63	−2.57	−9.12	−42.37	−12.94	−4.25	−19.24
$1d_{3/2}$	−21.84	−2.74	–	–	−33.17	−9.01	−1.95	−8.91	−41.97	−12.58	−3.88	−19.20
$1f_{7/2}$	−13.54	–	–	–	−27.06	−4.65	–	−1.35	−37.47	−9.11	−0.59	−10.51
$1f_{5/2}$	−11.82	–	–	–	−26.29	−3.80	–	−1.13	−37.07	−8.65	−0.10	−10.41
$2s_{1/2}$	−20.47	−2.74	–	–	−31.13	−8.05	−1.29	−6.60	−40.53	−10.20	−1.13	−17.43
$2p_{3/2}$	−10.20	–	–	–	−22.81	−2.23	–	−0.39	−39.21	−9.28	−0.03	−7.68
$2p_{1/2}$	−9.24	–	–	–	−22.24	−1.45	–	−0.38	−38.95	−9.06	–	−7.60
$2d_{5/2}$	−2.04	–	–	–	−14.62	–	–	–	−30.28	−5.36	–	−4.85
$2d_{3/2}$	−0.95	–	–	–	−14.03	–	–	–	−29.83	−4.75	–	−4.79
$2f_{7/2}$	–	–	–	–	−7.90	–	–	–	−22.57	–	–	–
$2f_{5/2}$	–	–	–	–	−6.81	–	–	–	−22.10	–	–	–
$3s_{1/2}$	−1.15	–	–	–	−13.41	–	–	–	−23.80	−1.51	–	−3.59
$3p_{3/2}$	–	–	–	–	−5.65	–	–	–	−22.32	–	–	–
$3p_{1/2}$	–	–	–	–	−5.61	–	–	–	−21.95	–	–	–
$3d_{5/2}$	–	–	–	–	–	–	–	–	−19.05	–	–	–
$3d_{3/2}$	–	–	–	–	–	–	–	–	−18.33	–	–	–
$3f_{7/2}$	–	–	–	–	–	–	–	–	−5.58	–	–	–
$3f_{5/2}$	–	–	–	–	–	–	–	–	−5.02	–	–	–
$4s_{1/2}$	–	–	–	–	–	–	–	–	−14.31	–	–	–
$4p_{3/2}$	–	–	–	–	–	–	–	–	−1.19	–	–	–
$4p_{1/2}$	–	–	–	–	–	–	–	–	−0.78	–	–	–
$4d_{5/2}$	–	–	–	–	–	–	–	–	−0.68	–	–	–
$5s_{1/2}$	–	–	–	–	–	–	–	–	−0.52	–	–	–



Finite nuclei hyperon-nucleon G-matrix

- Finite nuclei G-matrix

$$G_{FN} = V + V\left(\frac{Q}{E}\right)_{FN} G_{FN}$$

- Nuclear matter G-matrix

$$G_{NM} = V + V\left(\frac{Q}{E}\right)_{NM} G_{NM}$$

Eliminating V:

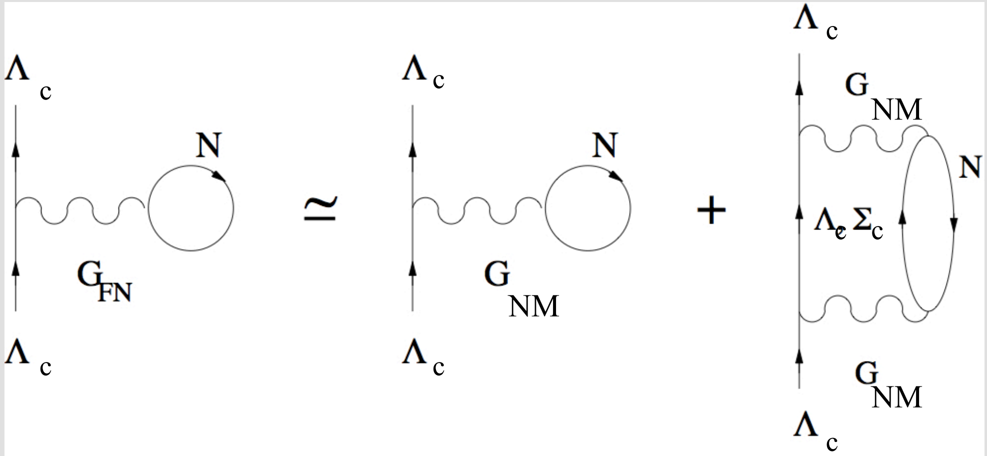
$$G_{FN} = G_{NM} + G_{NM}\left[\left(\frac{Q}{E}\right)_{FN} - \left(\frac{Q}{E}\right)_{NM}\right]G_{FN}$$

Truncating the expansion up <u>second order</u>:

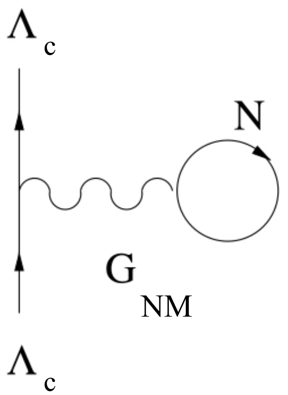
$$G_{FN} \approx G_{NM} + G_{NM}\left[\left(\frac{Q}{E}\right)_{FN} - \left(\frac{Q}{E}\right)_{NM}\right]G_{NM}$$

Finite nucleus Λ_c self-energy in the BHF approximation

Using G_{FN} as an effective YN interaction, the finite nucleus Λ_c self-energy is given as sum of a 1st order term & a 2p1h correction



✧ 1st order term

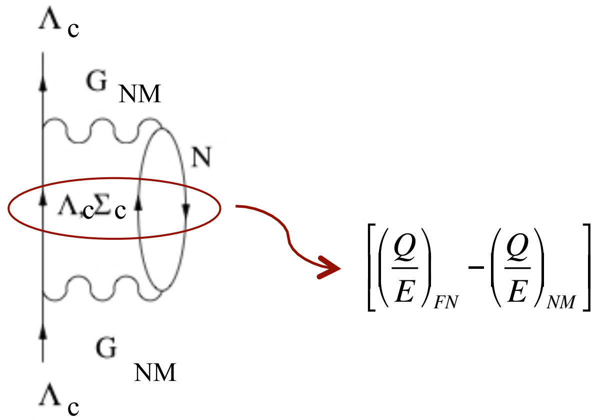


$$\mathcal{V}_1(k_{\Lambda_c}, k'_{\Lambda_c}, l_{\Lambda_c}, j_{\Lambda_c}) = \frac{1}{2j_{\Lambda_c}+1}\sum_{\mathcal{J}}\sum_{n_h l_h j_h t_{z_h}} (2\mathcal{J}+1) \times \langle (k'_{\Lambda_c} l_{\Lambda_c} j_{\Lambda_c})(n_h l_h j_h t_{z_h})\mathcal{J}|G|(k_{\Lambda_c} l_{\Lambda_c} j_{\Lambda_c})(n_h l_h j_h t_{z_h})\mathcal{J}\rangle$$

This contribution is real & energy-independent

N.B. most of the effort is on the basis transformation $\left|(k_{\Lambda_c} l_{\Lambda_c} j_{\Lambda_c})(n_h l_h j_h t_{z_h})J\right\rangle \rightarrow \left|KLqLSJTM_T\right\rangle$

✧ 2p1h correction



This contribution is the sum of two terms:

- The first, due to the piece $G_{NM}(Q/E)_{FN}G_{NM}$, gives rise to an imaginary energy-dependent part in the Λ_c self-energy

$$\mathcal{W}_{2p1h}(k_{\Lambda_c}, k'_{\Lambda_c}, l_{\Lambda_c}, j_{\Lambda_c}, \omega) = -\frac{\pi}{2j_{\Lambda_c}+1} \sum_{n_h l_h j_h t_{z_h}} \sum_{\mathcal{L}LSJ\mathcal{J}} \sum_{Y'=\Lambda_c\Sigma_c} \int dq q^2 \int dK K^2 (2\mathcal{J}+1)$$
$$\times \langle (k'_{\Lambda_c} l_{\Lambda_c} j_{\Lambda_c})(n_h l_h j_h t_{z_h})\mathcal{J}|G|K\mathcal{L}qLSJ\mathcal{J}TM_T\rangle$$
$$\times \langle K\mathcal{L}qLSJ\mathcal{J}TM_T|G|(k_{\Lambda_c} l_{\Lambda_c} j_{\Lambda_c})(n_h l_h j_h t_{z_h})\mathcal{J}\rangle$$
$$\times \delta\left(\omega + \varepsilon_h - \frac{\hbar^2 K^2}{2(m_N + m_{Y'_c})} - \frac{\hbar^2 q^2 (m_N + m_{Y'_c})}{2m_N m_{Y'_c}} - m_{Y'_c} + m_{\Lambda_c}\right)$$

From which can be obtained the contribution to the real part of the self-energy through a dispersion relation

$$\mathcal{V}^{(1)}_{2p1h}(k_{\Lambda_c}, k'_{\Lambda_c}, l_{\Lambda_c}, j_{\Lambda_c}, \omega) = \frac{1}{\pi}\mathcal{P}\int_{-\infty}^{\infty} d\omega' \frac{\mathcal{W}_{2p1h}(k_{\Lambda_c}, k'_{\Lambda_c}, l_{\Lambda_c}, j_{\Lambda_c}, \omega')}{\omega' - \omega}$$

- The second, due to the piece $G_{NM}(Q/E)_{NM}G_{NM}$, gives also a real & energy-independent contribution to the Λ self-energy and avoids double counting of Y'N states

$$
\mathcal{V}^{(2)}_{2p1h}(k_{\Lambda_c}, k'_{\Lambda_c}, l_{\Lambda_c}, j_{\Lambda_c}) = \frac{1}{2j_{\Lambda_c}+1} \sum_{n_h l_h j_h t_{z_h}} \sum_{\mathcal{L} L S J \mathcal{J}} \sum_{Y'=\Lambda_c \Sigma_c} \int dq q^2 \int dK K^2 (2\mathcal{J}+1) \times \langle (k'_{\Lambda_c} l_{\Lambda_c} j_{\Lambda_c})(n_h l_h j_h t_{z_h})\mathcal{J} | G | K \mathcal{L} q L S J \mathcal{J} T M_T \rangle \times \langle K \mathcal{L} q L S J \mathcal{J} T M_T | G | (k_{\Lambda_c} l_{\Lambda_c} j_{\Lambda_c})(n_h l_h j_h t_{z_h})\mathcal{J} \rangle \times Q_{Y'N} \left(\Omega - \frac{\hbar^2 K^2}{2(m_N + m_{Y'_c})} - \frac{\hbar^2 q^2 (m_N + m_{Y'_c})}{2 m_N m_{Y'_c}} - m_{Y'_c} + m_{\Lambda_c} \right)^{-1}
$$

Summarizing, in the BHF approximation the finite nucleus Λ self-energy is given by:

$$
\Sigma_{l_{\Lambda_c} j_{\Lambda_c}}(k_{\Lambda_c}, k'_{\Lambda_c}, \omega) = \mathcal{V}_{l_{\Lambda_c} j_{\Lambda_c}}(k_{\Lambda_c}, k'_{\Lambda_c}, \omega) + i\mathcal{W}_{l_{\Lambda_c} j_{\Lambda_c}}(k_{\Lambda_c}, k'_{\Lambda_c}, \omega)
$$

with

$$
\mathcal{V}_{l_{\Lambda_c} j_{\Lambda_c}}(k_{\Lambda_c}, k'_{\Lambda_c}, \omega) = \mathcal{V}_1(k_{\Lambda_c}, k'_{\Lambda_c}, l_{\Lambda_c}, j_{\Lambda_c}) + \mathcal{V}^{(1)}_{2p1h}(k_{\Lambda_c}, k'_{\Lambda_c}, l_{\Lambda_c}, j_{\Lambda_c}, \omega) - \mathcal{V}^{(2)}_{2p1h}(k_{\Lambda_c}, k'_{\Lambda_c}, l_{\Lambda_c}, j_{\Lambda_c})
$$

$$
\mathcal{W}_{l_{\Lambda_c} j_{\Lambda_c}}(k_{\Lambda_c}, k'_{\Lambda_c}, \omega) = \mathcal{W}_{2p1h}(k_{\Lambda_c}, k'_{\Lambda_c}, l_{\Lambda_c}, j_{\Lambda_c}, \omega)
$$

Λ_c single-particle bound states

Λ s.p. bound states can be obtained using the real part of the Λ_c self-energy as an effective Y_c-nucleus potential in the Schroedinger equation

$$\sum_{p=1}^{N_{max}} \langle k_n | \frac{\hbar^2 k_n^2}{2M_{\Lambda_c}} \delta_{np} + \Sigma_{BHF}(\omega = e_\gamma) + V_C | k_p \rangle \langle k_p | \gamma \rangle \quad = e_\gamma \langle k_n | \gamma \rangle$$

solved by diagonalizing the Hamiltonian in a complete & orthonormal set of regular basis functions within a spherical box of radius R_{box}

$$\Phi_{nl_{\Lambda_c} j_{\Lambda_c} m_{j_{\Lambda_c}}}(\vec{r}) = \langle \vec{r} | k_n l_{\Lambda_c} j_{\Lambda_c} m_{j_{\Lambda_c}} \rangle = N_{nl_{\Lambda_c}} j_{l_{\Lambda_c}}(k_n r) \psi_{l_{\Lambda_c} j_{\Lambda_c} m_{j_{\Lambda_c}}}(\theta, \phi)$$

- $N_{nl\Lambda_c}$ ⟶ normalization constant
- N_{max} ⟶ maximum number of basis states in the box
- $j_{j\Lambda_c}(k_n r)$ ⟶ Bessel functions for discrete momenta ($j_{j\Lambda_c}(k_n R_{box})=0$)
- $\psi_{l\Lambda_c j\Lambda_c mj\Lambda_c}(\theta,\phi)$ ⟶ spherical harmonics the including spin d.o.f.
- $\Psi_{nl\Lambda_c j\Lambda_c mj\Lambda_c} = \langle k_n l_{\Lambda_c} j_{\Lambda_c} m_{j\Lambda_c} | \Psi \rangle$ ⟶ projection of the state $|\Psi\rangle$ on the basis $|k_n l_{\Lambda_c} j_{\Lambda_c} m_{j\Lambda_c}\rangle$

N.B. a self-consistent procedure is required for each eigenvalue

Λ_c single-particle bound states: Energy

	$^{5}_{\Lambda_c}$He			$^{5}_{\Lambda}$He	$^{13}_{\Lambda_c}$C			$^{13}_{\Lambda}$C	$^{17}_{\Lambda_c}$O			$^{17}_{\Lambda}$O
	Model A	Model B	Model C	JĀ	Model A	Model B	Model C	JĀ	Model A	Model B	Model C	JĀ
$1s_{1/2}$	−13.58	−3.24	−1.05	−1.49	−27.26	−10.20	−5.47	−7.84	−31.76	−12.47	−6.96	−10.04
$1p_{3/2}$	−1.74	–	–	–	−14.91	−2.13	–	–	−19.99	−4.32	−0.51	−0.33
$1p_{1/2}$	−0.39	–	–	–	−13.42	−1.03	–	–	−18.79	−3.22	–	−0.35
$1d_{5/2}$	–	–	–	–	−4.10	–	–	–	−9.02	–	–	–
$1d_{3/2}$	–	–	–	–	−2.13	–	–	–	−6.96	–	–	–
$2s_{1/2}$	–	–	–	–	−3.59	–	–	–	−7.13	–	–	–

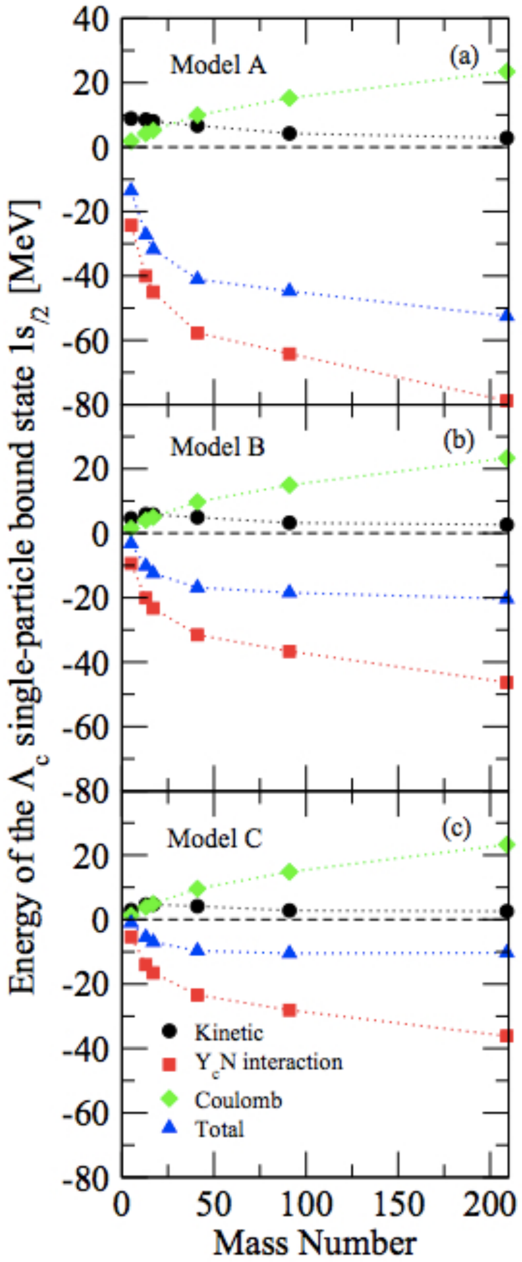
	$^{41}_{\Lambda_c}$Ca			$^{41}_{\Lambda}$Ca	$^{91}_{\Lambda_c}$Zr			$^{91}_{\Lambda}$Zr	$^{209}_{\Lambda_c}$Pb			$^{209}_{\Lambda}$Pb
	Model A	Model B	Model C	JĀ	Model A	Model B	Model C	JĀ	Model A	Model B	Model C	JĀ
$1s_{1/2}$	−41.09	−16.89	−9.60	−17.33	−44.76	−18.46	−10.51	−24.61	−52.52	−20.33	−10.32	−31.41
$1p_{3/2}$	−32.39	−10.41	−4.13	−7.67	−39.60	−14.27	−6.75	−17.66	−49.06	−18.28	−8.82	−27.59
$1p_{1/2}$	−31.60	−9.67	−3.42	−7.78	−39.24	−14.00	−6.49	−17.58	−48.84	−18.10	−8.64	−27.58
$1d_{5/2}$	−23.10	−3.91	–	–	−33.74	−9.63	−2.57	−9.12	−42.37	−12.94	−4.25	−19.24
$1d_{3/2}$	−21.84	−2.74	–	–	−33.17	−9.01	−1.95	−8.91	−41.97	−12.58	−3.88	−19.20
$1f_{7/2}$	−13.54	–	–	–	−27.06	−4.65	–	−1.35	−37.47	−9.11	−0.59	−10.51
$1f_{5/2}$	−11.82	–	–	–	−26.29	−3.80	–	−1.13	−37.07	−8.65	−0.10	−10.41
$2s_{1/2}$	−20.47	−2.74	–	–	−31.13	−8.05	−1.29	−6.60	−40.53	−10.20	−1.13	−17.43
$2p_{3/2}$	−10.20	–	–	–	−22.81	−2.23	–	−0.39	−39.21	−9.28	−0.03	−7.68
$2p_{1/2}$	−9.24	–	–	–	−22.24	−1.45	–	−0.38	−38.95	−9.06	–	−7.60
$2d_{5/2}$	−2.04	–	–	–	−14.62	–	–	–	−30.28	−5.36	–	−4.85
$2d_{3/2}$	−0.95	–	–	–	−14.03	–	–	–	−29.83	−4.75	–	−4.79
$2f_{7/2}$	–	–	–	–	−7.90	–	–	–	−22.57	–	–	–
$2f_{5/2}$	–	–	–	–	−6.81	–	–	–	−22.10	–	–	–
$3s_{1/2}$	−1.15	–	–	–	−13.41	–	–	–	−23.80	−1.51	–	−3.59
$3p_{3/2}$	–	–	–	–	−5.65	–	–	–	−22.32	–	–	–
$3p_{1/2}$	–	–	–	–	−5.61	–	–	–	−21.95	–	–	–
$3d_{5/2}$	–	–	–	–	–	–	–	–	−19.05	–	–	–
$3d_{3/2}$	–	–	–	–	–	–	–	–	−18.33	–	–	–
$3f_{7/2}$	–	–	–	–	–	–	–	–	−5.58	–	–	–
$3f_{5/2}$	–	–	–	–	–	–	–	–	−5.02	–	–	–
$4s_{1/2}$	–	–	–	–	–	–	–	–	−14.31	–	–	–
$4p_{3/2}$	–	–	–	–	–	–	–	–	−1.19	–	–	–
$4p_{1/2}$	–	–	–	–	–	–	–	–	−0.78	–	–	–
$4d_{5/2}$	–	–	–	–	–	–	–	–	−0.68	–	–	–
$5s_{1/2}$	–	–	–	–	–	–	–	–	−0.52	–	–	–

- Model A: more attractive $\Lambda_c N$ interaction ⟶ more bound s.p states & a larger number than B & C

But in the lack of exp. data we cannot say a priori which model is better

- Small spin-orbit splitting as in the case of Λ-hypernuclei

- Since $M_{\Lambda c} > M_{\Lambda}$ the level spacing of Λ_c s.p. energies is smaller that for the corresponding hypernuclei



Effect of the Coulomb interaction

- ✧ The Coulomb contribution increases because of the increase of the number of protons with Z
- ✧ The kinetic energy contribution decreases with A because the wave function becomes more & more spread due to the larger extension of the nuclear density over which the Λ_c wants to be distributed
- ✧ The increase of the nuclear density lead to a more attractive Λ_c self-energy that translates into a more negative contribution of the Y_cN interaction
- ✧ The total energy decreases by several MeV in the low-mass-number region and tends to saturate for heavier nuclei. This is due to a compensation between the attraction of the Y_cN interaction & the Coulomb repulsion
- ✧ Despite the Coulomb repulsion, even the less attractive of out Y_cN interaction models (C) is able to bind the Λ_c in all the nuclei considered

Effect of the $\Lambda_c N$ - $\Sigma_c N$ coupling

$^{17}_{\Lambda c}O$

	Model A		Model B		Model C		JÃ	
$1s_{1/2}$	−31.54	(-31.76)	−12.57	(-12.47)	−7.11	(-6.96)	−8.78	(-10.04)
$1p_{3/2}$	−19.69	(-19.99)	−4.37	(-4.32)	−0.58	(-0.51)	–	(-0.33)
$1p_{1/2}$	−18.45	(-18.79)	−3.24	(-3.22)	–		–	(-0.35)
$1d_{5/2}$	−8.71	(-9.02)	–		–		–	
$1d_{3/2}$	−6.62	(-6.96)	–		–		–	
$2s_{1/2}$	−7.02	(-7.13)	–		–		–	

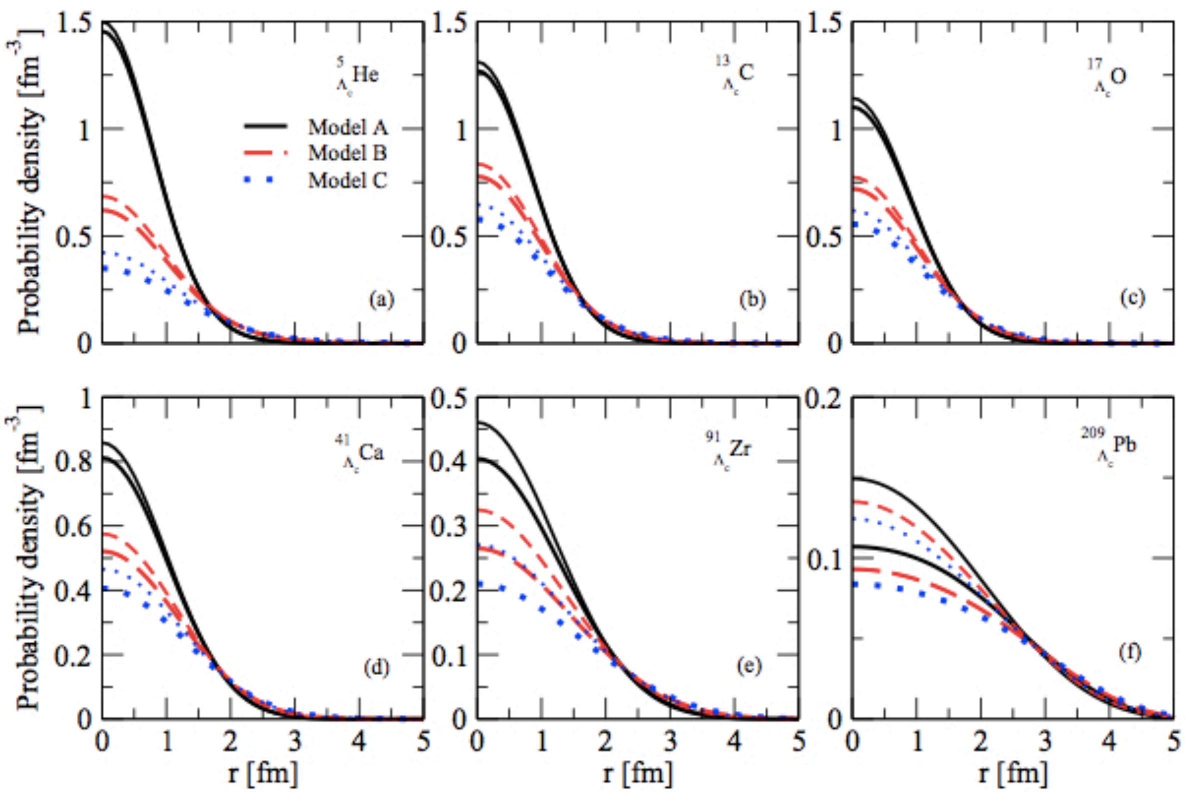
Channels located at:

- $\Lambda_c N$: 3224 MeV
- $\Sigma_c N$: 3394 MeV

✧ The effect the $\Lambda_c N$ - $\Sigma_c N$ is negligible as expected since the two channels are separated by ~ 170 MeV. Compared to the ~80 MeV separation of ΛN - ΣN

✧ The elimination of the coupling leads, in the case of models B & C to more attraction, contrary to what happens for model A and hypernuclei

Λ single-particle bound states: probability density distribution of the $1s_{1/2}$ state



- ✧ The probabitity density at the center decreases & becomes more distributed over the whole nucleus when moving from light to heavy nuclei due to the increase of the nuclear density.

- ✧ As expected Coulomb repulsion pushes the Λ_c away from the center of the nucleus. (Results when the Coulomb interaction is swifted off are shown by the thin solid, dashed and dotted lines)

- ✧ A similar discussion can be done for the other s.p states

The Message (again) of this Talk

- ✧ Study of the structure of charmed nuclei. To such end:
  - A Y_cN ineraction based on a SU(4) extension of the meson-exchange YN Ã potential of the Juelich group is used. Three models are considered
  - A perturbative many-body approach is employed to obtain the Λ_c self-energy in finite nuclei from which the Λ_c s.p. bound states can be obtained
- ✧ Scattering observables are computed & compared with those predicted by an Y_cN derived by Haidenbauer & Krein from the extrapolation to the pion physical mass of recent results of the HAL QCD Collaboration
- ✧ A small spin-orbit splitting is found as in the case of hypernuclei
- ✧ The role of the Coulomb interaction & the Λ_cN-Σ_cN coupling is analyzed
  - Despite the Coulomb repulsion it is found that even the less attractive of our Y_cN interaction models is able to bind the Λ_c in all the nuclei considered
  - The effect of the Λ_cN-ΣcN coupling is negligible due to the large mas difference between Λ_c & Σ_c

✧ You for your time & attention

✧ My collaborators: Àngels Ramos & Estela Jiménez-Tejero