Singly heavy baryons in nuclear matter from an SU(3) chiral soliton model

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I. Introduction

I. Introduction

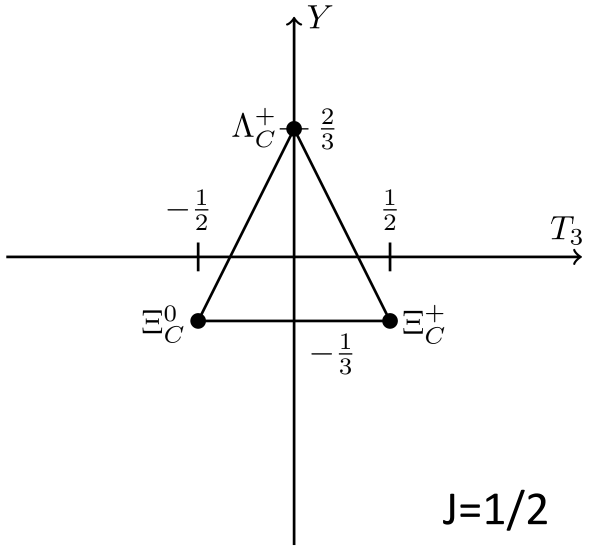
- Since the charmonium J/ψ and Σ_c were found [5-7], works on charmed nuclei have been performed [1-4], while medium modifications of heavy hadrons in nuclear matter have been much less studied than those of light ones.

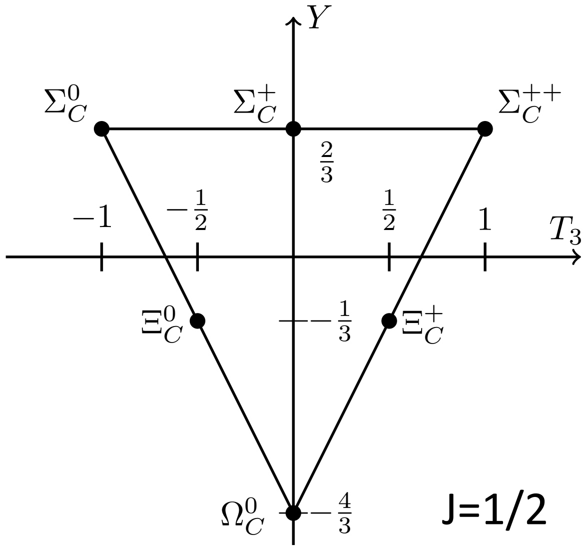
- We apply the medium modification [8] to the heavy meson bounded system and study how the in-medium modification of the heavy meson influences the mass spectrum of the singly heavy baryons in nuclear matter.

II. Formalism

SU(3) representation for heavy baryons

- In the infinitely heavy quark mass limit, a heavy quark spin is preserved.
- In this limit, a heavy quark can be considered as a color static source.
- Dynamics is governed by light quarks. ($3 \otimes 3 = \bar{3} \oplus 6$)





Topological soliton model

Nonlinear chiral effective meson Lagrangian [9]

$$\mathcal{L} = \frac{F_\pi^2}{16}\mathrm{Tr}\left[\partial_\mu U \partial^\mu U^\dagger\right] - \frac{1}{16e^2}\mathrm{Tr}\left[U^\dagger \partial_\mu U, U^\dagger \partial_\nu U\right]^2$$

Kinetic term — Stabilizing term

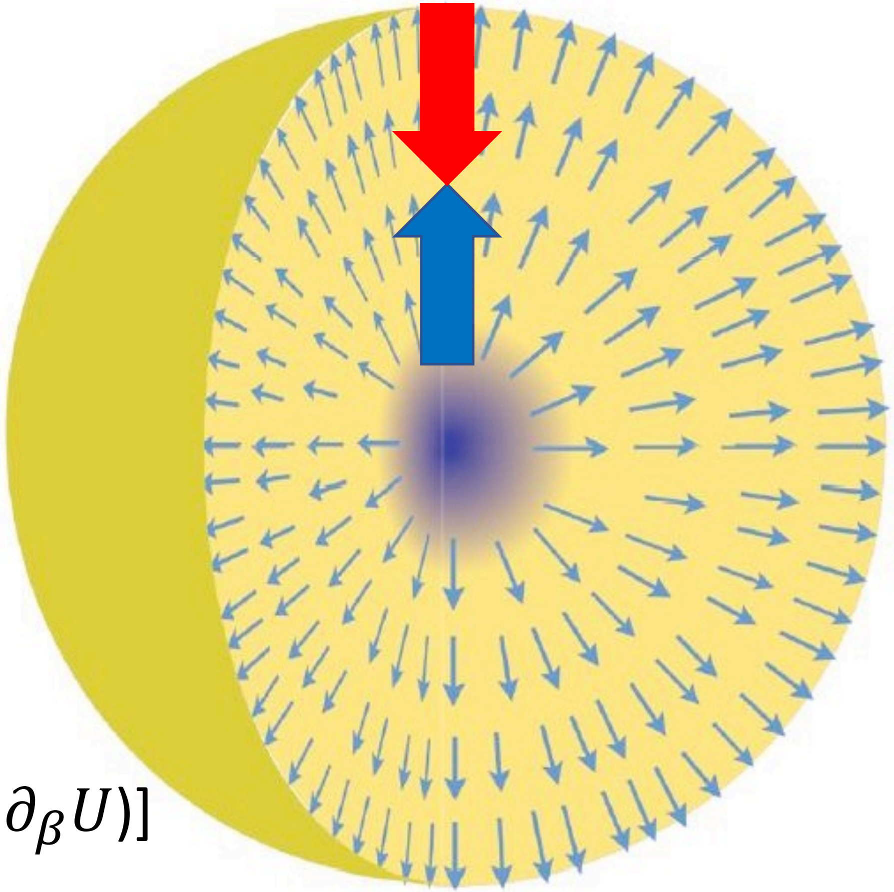
Hedgehog solution (nontrivial mapping)

$$U = \exp[i\boldsymbol{\tau}\cdot\hat{\boldsymbol{n}}F(r)]$$

Baryon number (topological number)

$$B = \int d^3r\, \mathcal{B}^0$$

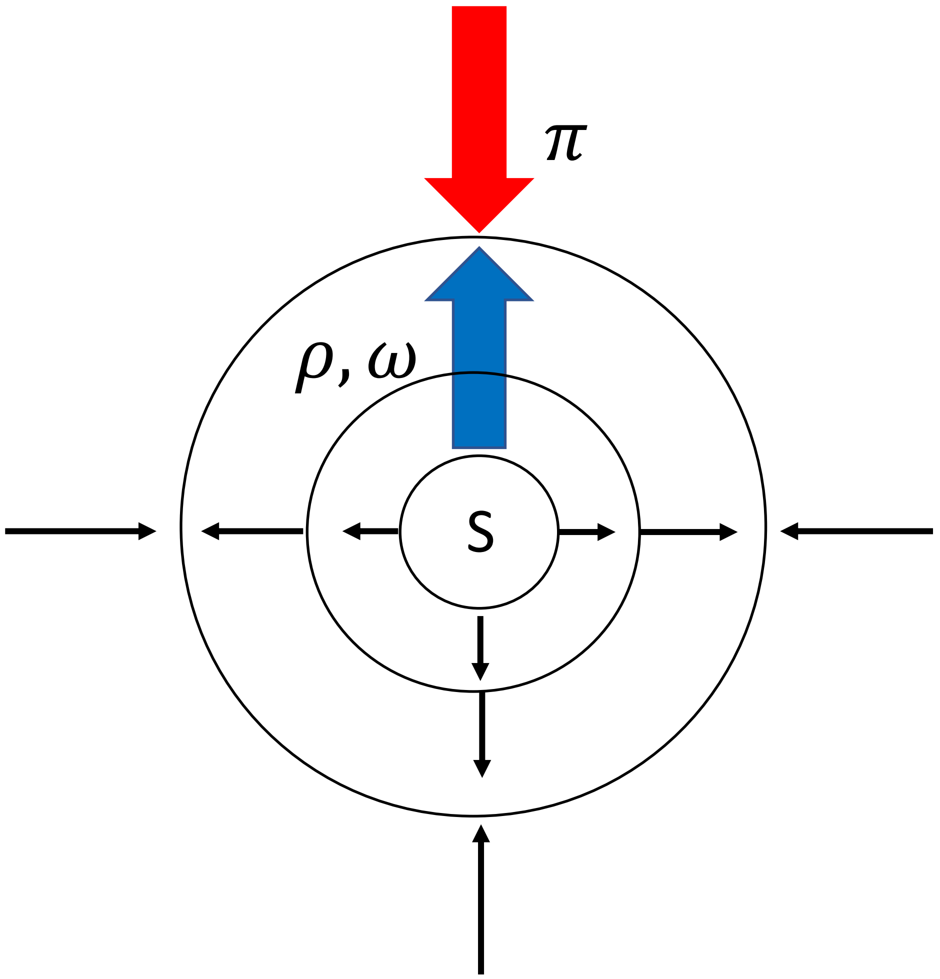
$$\mathcal{B}^\mu = \frac{\epsilon^{\mu\nu\alpha\beta}}{24\pi^2}\mathrm{Tr}[(U^\dagger\partial_\nu U)\,(U^\dagger\partial_\alpha U)\,(U^\dagger\partial_\beta U)]$$



Replaced by vector mesons

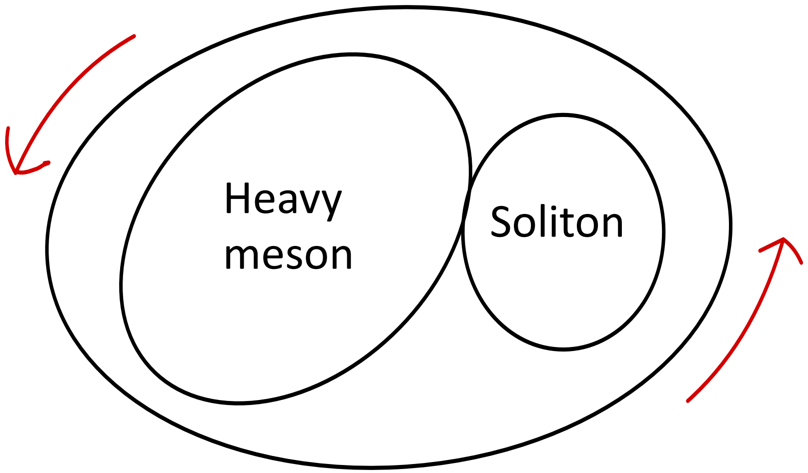
$$\mathrm{Tr}\left[U^\dagger\partial_\mu U, U^\dagger\partial_\nu U\right]^2$$
$$\to -\frac{1}{4}\mathrm{Tr}\left[F_{\mu\nu}, F_{\mu\nu}\right] - \frac{m_v^2}{2g^2}\mathrm{Tr}\left[\left(g\rho_\mu - v_\mu\right)^2\right]$$

Vector mesons make the soliton stable.



Heavy meson bound state system

Bound state approach



Heavy meson effective Lagrangian [10]

$$\mathcal{L}_{\text{heavy}} = iMV_\mu \mathrm{Tr}\left[H\left(\partial_\mu - i\alpha g\rho_\mu - i(1-\alpha)v_\mu\right)\bar{H}\right] + idM\mathrm{Tr}\left[H\gamma_\mu\gamma_5 p_\mu \bar{H}\right] + \frac{ic}{m_v}M\mathrm{Tr}[H\gamma_\mu\gamma_\nu F_{\mu\nu}\bar{H}]$$

Change of the baryon constraint

$$Y_R = 1 \;\rightarrow\; Y_R = \frac{2}{3}$$

Collective Hamiltonian

$$H_{coll} = M_{cl} + (W_4 + M\ ) + \frac{1}{2}\left(\frac{1}{\alpha^2} - \frac{1}{\beta^2}\right) J_s(J_s + 1) + \frac{1}{2\beta^2} C_2[\mathrm{SU}(3)] - \frac{1}{6\beta^2}$$

M_{cl} : classical soliton mass
W_4 : classical binding energy
M : heavy meson mass
α^2, β^2: moments of inertia
J_s : soliton spin
C_2 : SU(3) Casimir operator

\+ SU(3) flavour symmetry breaking

$$H_{SB}^{*} \sim \tau D_{88}(A), \quad \tau = \tau_{\mathrm{light}} + \tau_{\mathrm{heavy}}$$

Medium modification

The possible happenings in the nuclear medium:

- Deformation (swelling or shrinking, multipole deformations) of nucleons
- Characteristic changes: effective mass, charge distributions and all possible form factors
- Etc.

Soliton structure in the nuclear medium (phenomenological way)

- Outer shell modifications: information from pionic atom
- Inner core modifications: change of the meson cloud

→ in our research, vector mesons' modifications

Modified parameters and medium functionals

Modified pion decay constant and vector meson coupling constant [10]

- Outer shall part: $F_\pi \to \sqrt{\alpha_p} F_\pi$
- Inner core part: $g \to \sqrt{\zeta} g$
- Pion mass: $m_\pi \to \sqrt{\frac{\alpha_m}{\alpha_p}} m_\pi$

$$\alpha_{p,s} = 1 + C_1 \lambda$$
$$\zeta_s = 1 + C_2 \lambda$$

Spatial part

$$\alpha_{p,t} = 1 + C_3 \lambda$$
$$\zeta_t = \alpha_{p,s} \zeta_s \alpha_{p,t}^{-1}$$

Temporal part

Fixing parameters – binding energy

The volume term in the binding energy per nucleon

$$\varepsilon_V(\lambda) = \frac{ZM_p^*(\lambda) + NM_n^*(\lambda)}{A} - \frac{ZM_p + NM_n}{A}$$
$$= M_N^*(\lambda) - M_N$$

$$\lambda = \frac{\rho}{\rho_0}, \quad \rho_0 = 0.16\,\mathrm{fm}^{-3}$$

Empirical information

$$\varepsilon_V(1) = 16\,\mathrm{MeV}$$

The volume energy value

$$\left.\frac{\partial \varepsilon_V(\lambda)}{\partial \lambda}\right|_{\lambda=1} = 0$$

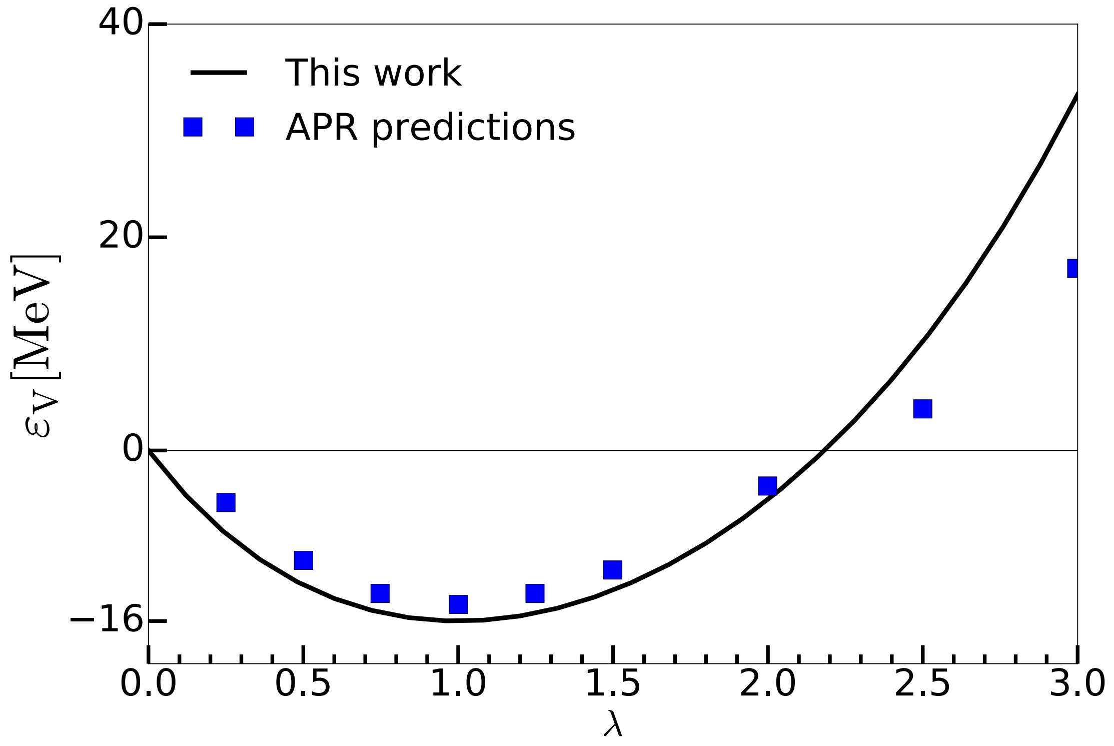
The stability condition

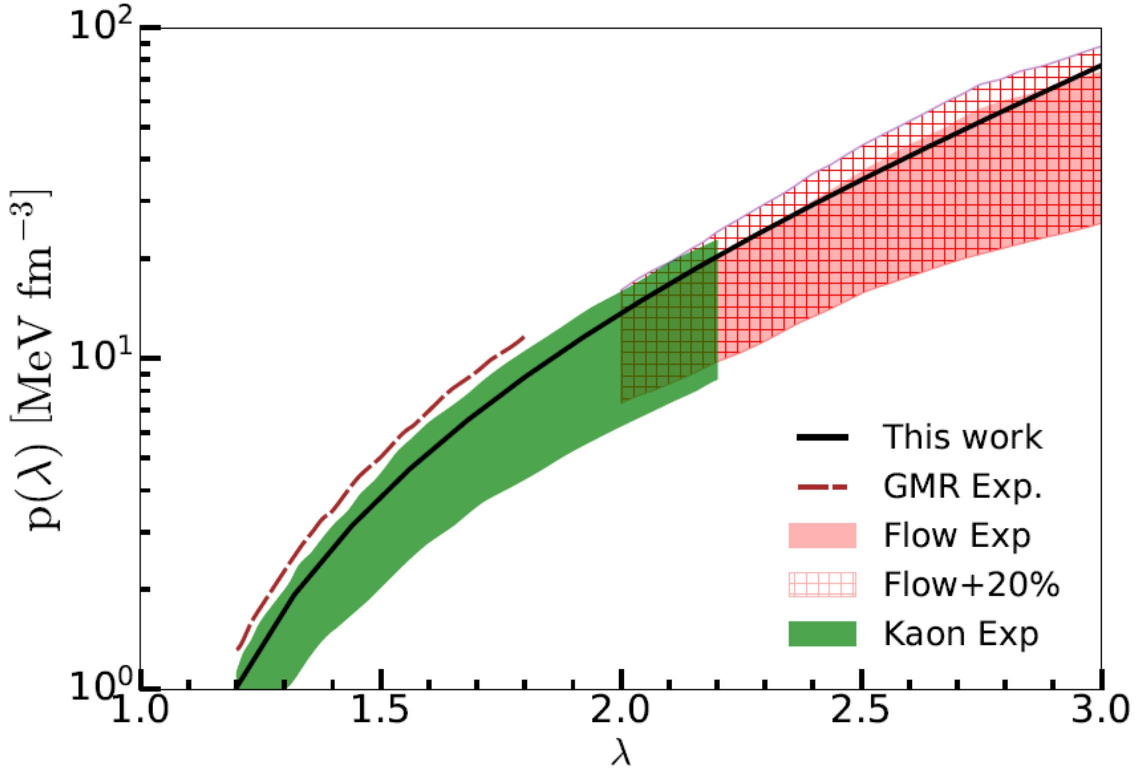
$$K_0 = 9\lambda^2 \left.\frac{\partial^2 \varepsilon_V}{\partial \lambda^2}\right|_{\lambda=1} = 220\,\mathrm{MeV}$$

The compressibility of the symmetric matter

III. Results

Binding energy & pressure





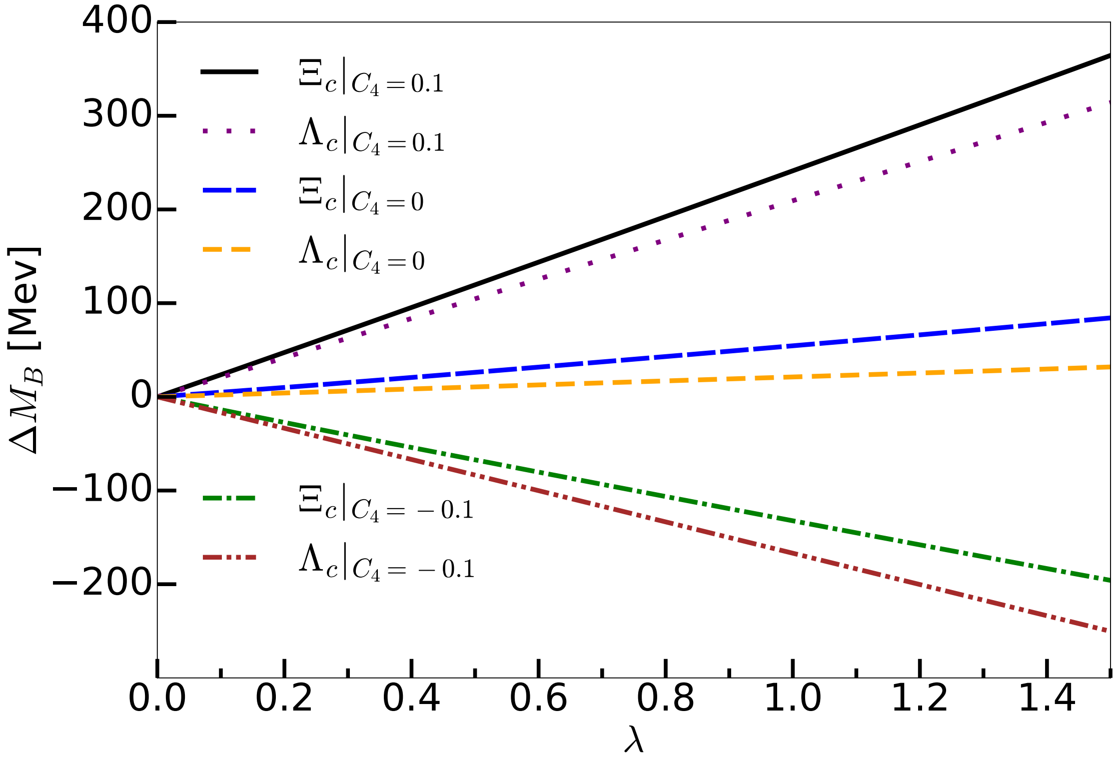
Singly charmed baryons mass splitting

$$M^* \equiv M_D^* = (1 + C_4\lambda)M_D \qquad \Delta M_B = M_B^* - M_B$$

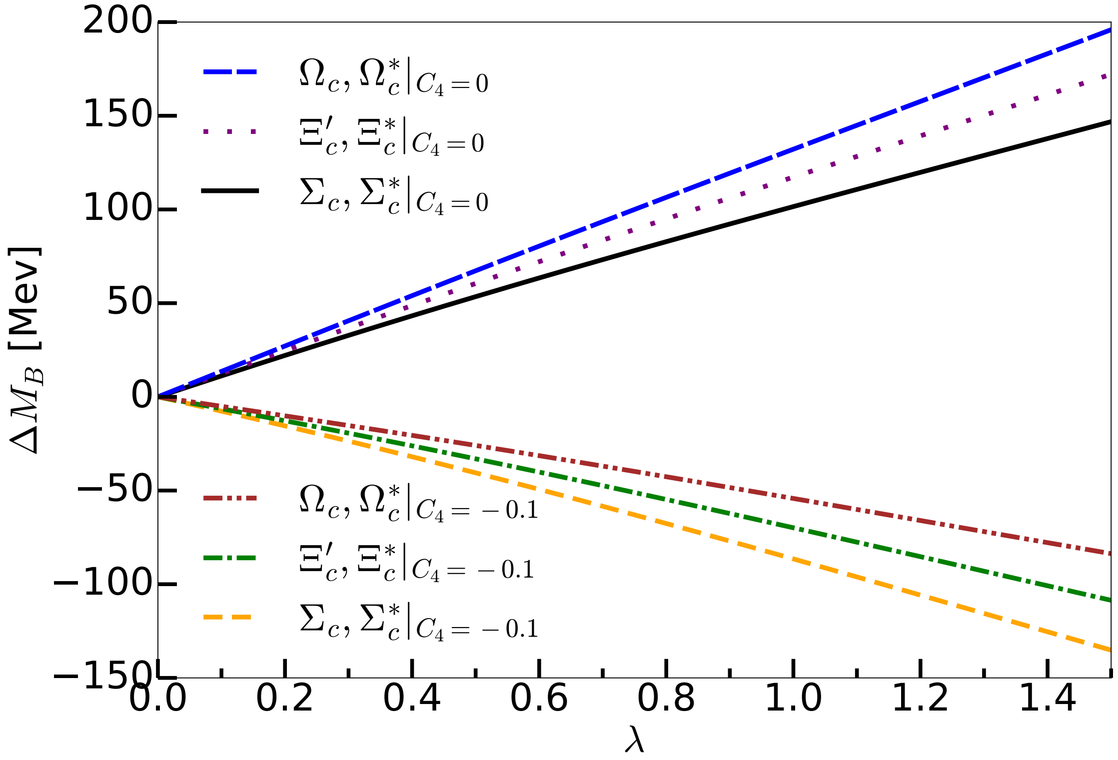
Baryon	$M_B,\ \rho = 0$		$\Delta M_B,\ \rho = \rho_0$		
	Exp. [5]	This work	$C_4 = -0.1$	$C_4 = 0$	$C_4 = 0.1$
Λ_c	2286.5	2286.0	-166.91	21.22	209.34
Ξ_c	2469.4	2437.8	-132.30	54.48	241.25
Σ_c	2453.5	2564.5	-86.50	101.54	289.57
Ξ_c'	2576.8	2646.8	-69.89	117.27	304.43
Ω_c	2695.2	2721.6	-54.23	132.17	318.56

Singly charmed baryons mass splitting

Antitriplet baryons



Sextet baryons



All of the singly charmed baryons are quite sensitive to the change of the heavy meson mass in nuclear matter.

IV. Summary

Summary

We considered the modification of the parameters of the framework of the in-medium modified SU(3) Skyrme model with π, ρ and ω mesons, using empirical information on nuclear phenomenology.

We obtained the results for the in-medium mass spectrum of the singly charmed baryons in terms of the in-medium modified heavy meson mass.

The values of the mass of singly charmed baryons on both the antitriplet and sextet was much influenced by the heavy meson mass.

Thank you for listening

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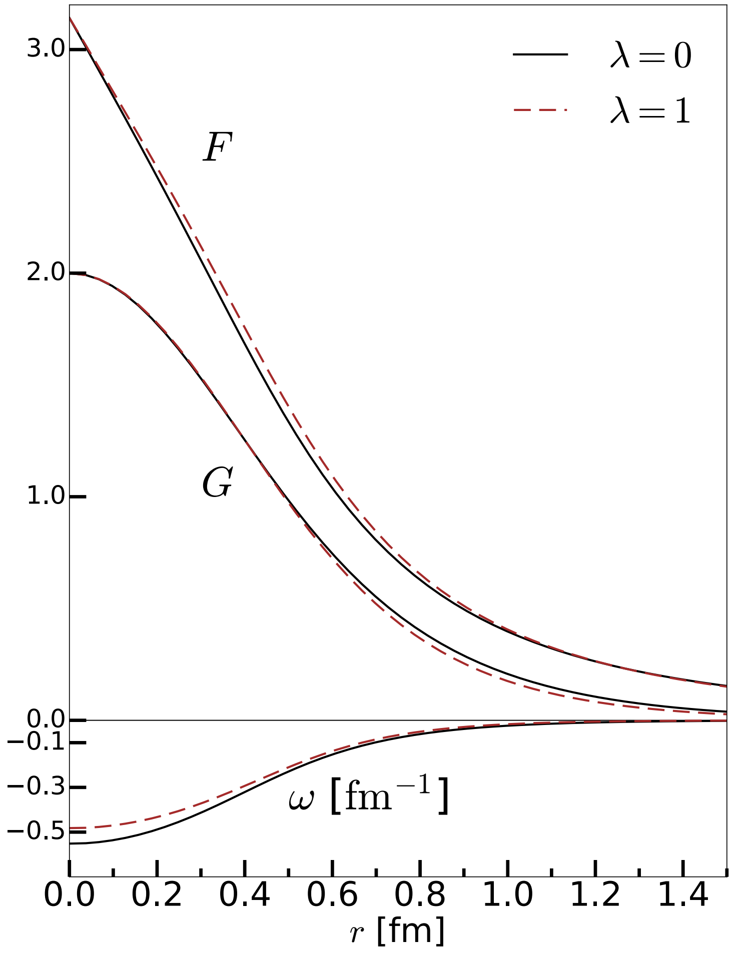
Classical soliton mass in nuclear matter

$$
\begin{aligned}
M_{cl}^* &= 4\pi \int dr \left[\alpha_p^s \frac{F_\pi^2}{4}(2\sin^2 F + r^2 F'^2) + \frac{1}{2} m_\pi^2 F_\pi^2 \alpha_m r^2 (1-\cos F) + \frac{k}{2} F_\pi^2 (G - 1 + \cos F)^2 \right. \\
&\left. + \frac{1}{\zeta_s}\frac{1}{2g^2}\left(G'^2 + \frac{G^2(G-2)^2}{2r^2}\right) - \frac{r^2}{2}(\zeta_s m_v^2 \omega^2 + \omega'^2) + \sqrt{\zeta_s}\frac{3g}{2\sqrt{2}\pi^2}\omega F' \sin^2 F \right] \\
&\equiv E_\pi^* + E_\pi^{m*} + E_{\pi\rho}^* + E_\rho^* + E_{\omega,1}^* + E_{\omega,2}^* + E_{\pi\omega}^*
\end{aligned}
$$

Classical soliton mass in nuclear matter

	$\lambda = 0$	$\lambda = 0.5$	$\lambda = 1$	$\lambda = 1.5$
E_π^*	772.0	762.3	752.0	740.1
E_π^{m*}	41.5	43.8	46.5	49.4
$E_{\pi\rho}^*$	37.1	25.5	18.5	14.0
E_ρ^*	411.3	336.2	282.9	243.3
E_ω^*	-237.4	-246.2	-248.7	-247.3
$E_{\pi\omega}^*$	473.1	490.4	495.4	492.7
M_{cl}^*	1497.6	1388.5	1299.5	1221.3



Model dependent parameters