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Impurity effect of Λ hyperon on collective excitation of atomic nuclei

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Outline

1. **Introduction**
    - Importance of Λ hypernuclei
    - γ-ray spectroscopy of Λ hypernuclei
    - Towards symmetry restored EDF for Λ hypernuclei
2. **The Skyrme EDF based 5DCH for Λ effect on nuclear collectivity**
    - The Skyrme EDF based 5D collective Hamiltonian
    - Impurity effect of Λ on nuclear collectivity: an example
    - A systematical study of Λ impurity effect
3. **A new parametrization for effective ΛN interaction in Covariant EDF**
    - Effective Lagrangian density
    - Parametrization for ΛN interaction
    - Some results with the new PK1-Y1 interaction
4. **Summary and perspective (2 min.)**

Importance of Λ hypernuclei

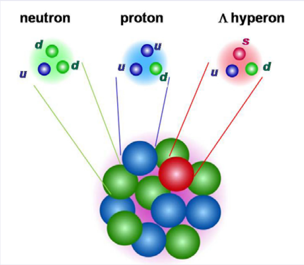
- Λ-hypernucleus: nucleus with either a neutron or proton being replaced by a Λ hyperon (Λ: $\tau \sim 2.6 \times 10^{-10}$s, no charge, no isospin)
- First discovery of Λ hypernucleus: pionic decay in emulsion produced by cosmic rays

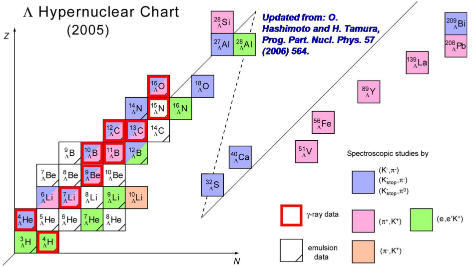
Danysz and Pniewski, Bull. Acad. Pol. Sci. III **1***, 42 (1953); Phil. Mag.* **44***, 348 (1953).*

- **What can we learn from Λ hypernuclei?**
  - — ΛN effective interaction in nuclear medium
  - — EoS and neutron star with Λ hyperons

N. K. Glendenning, Compact Stars (Springer-Verlag, New York, 2000)

Single-Λ hypernucleus





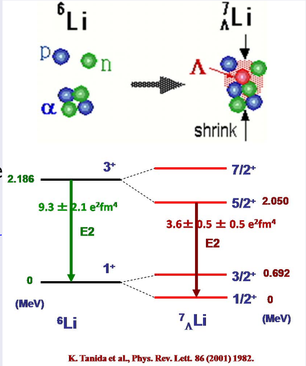
— Impurity (shrinkage) effect of Λ on atomic nuclei:
size, shape, binding/sepataion energy, density distribution, single-particle energy, shell effect, fission barrier, · · ·

Tanida(2001), Hashimoto (2006), · · · .

Spectroscopy of Λ-hypernuclei

Experimental measurement of γ-ray spectroscopy

- In the past decade, many high-resolution γ-ray spectroscopy experiments (with Hyperball) have been carried out for Λ hypernuclei to understand the nature of ΛN interaction in nuclear medium and the impurity effect of a Λ on nuclear structure. *O. Hashimoto and H. Tamura, PPNP* **57***, 564 (2006).*
  - ▶ $^{7}_{\Lambda}$Li: reduced $B(E2)$ value $\Rightarrow$ about 19% reduction of nuclear size/collectivity! Shrinkage effect *Tanida (2001)*



K. Tanida et al., Phys. Rev. Lett. 86 (2001) 1982.

- The facilities built at J-PARC provide an opportunity to perform hypernuclear γ-ray spectroscopy study with high precision by improving the quality of the secondary mesonic beam *Tamura09*. These facilities offer useful tools to study the low-lying states of hypernuclei.

Spectroscopy of Λ-hypernuclei

Theoretical studies of low-lying excited states in Λ-hypernuclei

- Few-body model *Nemura (2002)*
- Cluster model *Motoba (1983), Yamada (1984), Hiyama (2003), Hiyama (2010)*
- Shell model *Dalitz (1978), Millener (2010)*.

More recently,

- the antisymmetrized molecular dynamics (AMD) has been extended for studying the deformation and low-lying states of hypernuclei *Isaka (2011)*.

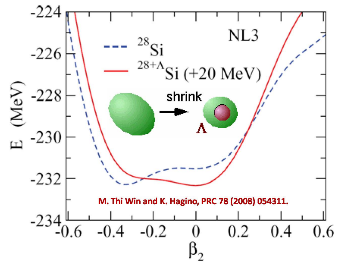
Extension of nuclear SR-EDF for hypernuclei

- Energy density functional (EDF) theory in nuclear physics is nowadays the most important microscopic approach for large-scale nuclear structure calculations in medium and heavy nuclei. *M. Bender, P.-H. Heenen, P.-G. Reinhard, Rev. Modern Phys. 75 (2003) 121. G. A. Lalazissis, P. Ring, D. Vretenar (Eds.), Extended Density Functionals in Nuclear Structure Physics, in: Lecture Notes in Physics, vol. 641, Springer, Heidelberg, 2004.*
- In the past decades, the nuclear single-reference(SR)-EDF has been extended to study hypernuclei extensively, but mostly focused on g.s. properties *Rayet (1976), Yamamoto (1988), Millener (1988), Rufa (1990), Mares (1994), Schaffner (1994), Sugahara (1994), Vretenar (1998), Lv (2003), Tan (04), Shen (2006), · · ·* .

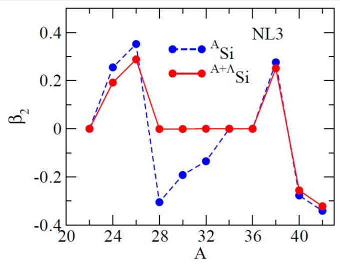
Λ-hypernuclei in SR-EDF theory

Recent investigations of polarization effect of Λ on nuclear deformation

- Both the non-relativistic Skyrme-Hartree-Fock (SHF) *Zhou (2007), Schulze (2010), Thi Win (2011)* and the relativistic mean-field (RMF) approaches *Thi Win (2008), Lu (2011)* have been applied to study the impurity effect of Λ hyperon on the deformation of sd-shell Λ hypernuclei.
- It has been found that, generally, the shape polarization effect of the Λ hyperon is small, but with several exceptions, including ${}^{13}_{\Lambda}$C, ${}^{23}_{\Lambda}$C, and ${}^{29,31}{}_{\Lambda}$Si.
  - ${}^{29,31}_{\Lambda}$Si: minimum is shifted from oblate to spherical shape *Thi Win (2008)*



M. Thi Win and K. Hagino, PRC 78 (2008) 054311.



Quantitatively study of Λ impurity effect on nuclear collectivity

Towards symmetry restored MR-EDF approach for hypernuclei

- The SR-EDF calculations *Zhou07, Thi Win08, Schulze10, Thi Win11, Lu11* showed that the Λ hyperon could soften the potential energy surface, in which case, however, a large shape fluctuation effect of collective vibration might be expected.
- Furthermore, symmetry (e.g., translation, rotation, particle number) is spontaneously broken in the static SR-EDF. The symmetry restoration becomes important for studying the spectrum of low-lying states.

Alternative methods to solve the above problems:

- 3D Projection + GCM: Non-Rel.: *Bender(2008), Rodriguez(2010)*; Rel.: *Yao(2009,2010)*
- 5D Collective Hamiltonian *Libert (1999), Prochniak (2004), Niksic (2009), Li (2010)*

The first step of this work

- Construction of a 5DCH with the parameters derived from the SHF+BCS calculations for the nuclear core in a single-Λ hypernucleus and calculate the corresponding low-spin excitation spectra.
- The impurity effect of Λ hyperon on the collective motion of an atomic nucleus is examined by studying the modifications of collective excitation spectrum. *JMY, Z.P. Li, K. Hagino, M. Thi Win, Y. Zhang, J. Meng, NPA 868-869, 12 (2011)*

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The Skyrme EDF based 5D collective Hamiltonian

Collective Hamiltonian in five dimension

The collective Hamiltonian that describes the nuclear excitations of quadrupole vibrations, 3D rotations, and their couplings can be written in the form: *Libert (1999), Prochniak (2004), Niksic (2009), Li (2010)*

$$\hat{H} = \hat{T}_{\text{vib}} + \hat{T}_{\text{rot}} + V_{\text{coll}}. \tag{1}$$

- The vibrational kinetic energy is given by,

$$\begin{aligned}\hat{T}_{\text{vib}} &= -\frac{\hbar^2}{2\sqrt{wr}}\left\{\frac{1}{\beta^4}\left[\frac{\partial}{\partial\beta}\sqrt{\frac{r}{w}}\beta^4 B_{\gamma\gamma}\frac{\partial}{\partial\beta} - \frac{\partial}{\partial\beta}\sqrt{\frac{r}{w}}\beta^3 B_{\beta\gamma}\frac{\partial}{\partial\gamma}\right]\right.\\ &\left.+\frac{1}{\beta\sin 3\gamma}\left[-\frac{\partial}{\partial\gamma}\sqrt{\frac{r}{w}}\sin 3\gamma B_{\beta\gamma}\frac{\partial}{\partial\beta} + \frac{1}{\beta}\frac{\partial}{\partial\gamma}\sqrt{\frac{r}{w}}\sin 3\gamma B_{\beta\beta}\frac{\partial}{\partial\gamma}\right]\right\}\end{aligned} \tag{2}$$

where $r = B_1 B_2 B_3$, and $w = B_{\beta\beta}B_{\gamma\gamma} - B_{\beta\gamma}^2$.

- Rotational kinetic energy,

$$\hat{T}_{\text{rot}} = \frac{1}{2}\sum_{\kappa=1}^{3}\frac{\hat{J}_\kappa^2}{\mathcal{I}_\kappa}, \tag{3}$$

where $\mathcal{I}_\kappa$ are the moments of inertia.

Parameters in 5DCH: $B_{\beta\beta}$, $B_{\beta\gamma}$, $B_{\gamma\gamma}$; $\mathcal{I}_{\kappa=1,2,3}$; V_{coll} (function of β, γ).

The Skyrme EDF based 5D collective Hamiltonian

Skyrme EDF for Λ hypernucleus

The Skyrme EDF for Λ hypernucleus is given by,

$$E^{\mathrm{SR}}_{\mathrm{tot}} = \int d^3r[\mathcal{E}_N(\mathbf{r}) + \mathcal{T}_\Lambda(\mathbf{r}) + \mathcal{E}_{N\Lambda}(\mathbf{r})], \tag{4}$$

- Nuclear part: $\mathcal{E}_N(\mathbf{r})$ is the standard EDF, including the Skyrme force in *ph*-channel, δ-force in *pp*-channel and kinetic term *Vautherin (1972), Bonche (2005)*.
- Kinetic part for Λ: $\mathcal{T}_\Lambda(\mathbf{r}) = \frac{\hbar^2}{2m_\Lambda}\tau_\Lambda$
- Interaction part related to the Λ: *M. Rayet, Ann. Phys. (N.Y.) 102, 226 (1976)*

$$\begin{aligned}\mathcal{E}_{N\Lambda} \quad = \quad & t_0^\Lambda(1+\frac{1}{2}x_0^\Lambda)\rho_\Lambda\rho_N + \frac{1}{4}(t_1^\Lambda + t_2^\Lambda)(\tau_\Lambda\rho_N + \tau_N\rho_\Lambda) \\ & +\frac{1}{8}(3t_1^\Lambda - t_2^\Lambda)(\nabla\rho_N\cdot\nabla\rho_\Lambda) + \frac{1}{4}t_3^\Lambda\rho_\Lambda(\rho_N^2 + 2\rho_n\rho_p) \\ & +\frac{1}{2}W_0^\Lambda(\nabla\rho_N\cdot\mathbf{J}_\Lambda + \nabla\rho_\Lambda\cdot\mathbf{J}_N)\tau_N\rho_\Lambda, \end{aligned} \tag{5}$$

where $\rho_\Lambda, \tau_\Lambda$ and $\mathbf{J}_\Lambda$ are respectively the particle density, the kinetic energy density, and the spin density of the Λ hyperon.

Parameters in ΛN interaction: $t_0^\Lambda, x_0^\Lambda, t_1^\Lambda, t_2^\Lambda, t_3^\Lambda$, and W_0^Λ.

The Skyrme EDF based 5D collective Hamiltonian

Pairing correlation between nucleons

The density-dependent δ-force is adopted in the *pp*-channel,

$$V(\mathbf{r}_1, \mathbf{r}_2) = -g\frac{1-\hat{P}^\sigma}{2}\left[1-\frac{\rho(\mathbf{r}_1)}{\rho_0}\right]\delta(\mathbf{r}_1-\mathbf{r}_2), \tag{6}$$

where $\hat{P}^\sigma$ is the spin-exchange operator, and $\rho_0 = 0.16\ \mathrm{fm}^{-3}$.

Collective potential in 5DCH

The collective potential $V_{\rm coll}$ in the collective Hamiltonian is obtained by subtracting the zero-point-energy (ZPE) from the total mean-field energy,

$$V_{\rm coll}(\beta,\gamma) = E^{\rm core}_{\rm tot}(\beta,\gamma) - \Delta V_{\rm vib}(\beta,\gamma) - \Delta V_{\rm rot}(\beta,\gamma), \tag{7}$$

where $E^{\rm core}_{\rm tot}$ is the total energy for the nuclear core in Λ hypernucleus. We will investigate two options, that is, those with (w) or without (w/o) the interaction part of energy $\mathcal{E}_{N\Lambda}$ between the Λ and nucleons,

$$E^{\rm core}_{\rm tot} = \begin{cases} \int d^3r\,\mathcal{E}_N(\mathbf{r}), & w/o \\ \int d^3r[\mathcal{E}_N(\mathbf{r}) + \mathcal{E}_{N\Lambda}(\mathbf{r})], & w \end{cases} \tag{8}$$

Polarization effect of Λ on collective properties of ^{24}Mg

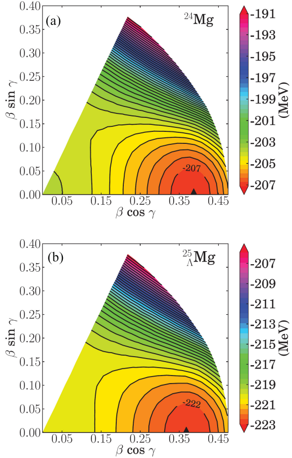


Figure: Potential energy surfaces by SHF+BCS calculations with the SGII force. Each contour line is separated by 0.5 MeV. *M. Thi Win, K. Hagino, and T. Koike, PRC83, 014301 (2011)*

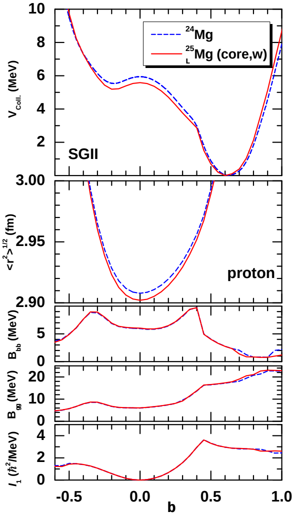
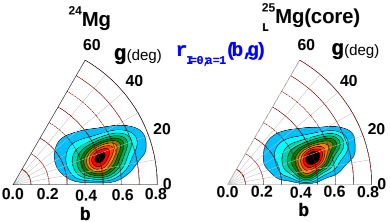
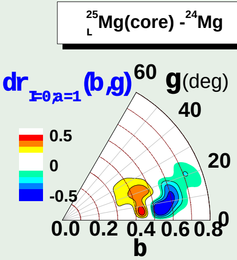


Figure: Parameters in 5DCH for ^{24}Mg and nuclear core of $^{25}_{\Lambda}$Mg. *JMY, Z. P. Li, K. Hagino, M. Thi Win, Y. Zhang, and J. Meng, NPA 868-869 (2011) 12-24.*

Polarization effect of Λ on collective properties of ^{24}Mg



Shift in collective wavefunction of g.s.



The Λ hyperon shifts the collective wave function of ground state to a smaller deformation region by softening the nuclear collective potential surface in the neighborhood of spherical shape.

Low-lying spectrum of ^{24}Mg with and without Λ

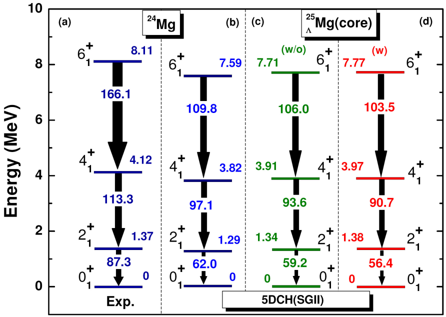


Figure: The spectrum calculated with two options: $V_{\mathrm{coll.}}$ with (without) the contribution of $\mathcal{E}_{N\Lambda}$ term.

JMY, Z. P. Li, K. Hagino, M. Thi Win, Y. Zhang, and J. Meng, NPA 868-869 (2011) 12-24.

- Comparing columns (b) and (d), one finds that the Λ increases excitation energy of 2^+_1 state by $\sim 7\%$ and reduces $B(E2: 2^+_1 \to 0^+_1)$ by $\sim 9\%$.
- However, the shrinkage effect on the rms proton radius is only $\sim 0.5\%$.
- In other words, Λ reduces the collectivity of ^{24}Mg, mainly by softening the PEC around spherical shape, rather than by shrinking the rms radius of protons.

Table: Excitation energies (MeV) of 2^+_2, 4^+_2 and 0^+_2 states.

	$E_x(2^+_2)$	$E_x(4^+_2)$	$E_x(0^+_2)$
Exp.	4.24	6.01	6.43
^{24}Mg	4.44	7.11	3.13
$^{25}_{\Lambda}$Mg (core, w)	4.68	7.45	3.11

The Skyrme EDFs for a systematical study

Effective interactions in *ph*-channel for both nucleons and Λ

Table: Parameters in the Skyrme-type ΛN effective interactions for a systematical study of Λ impurity effect.

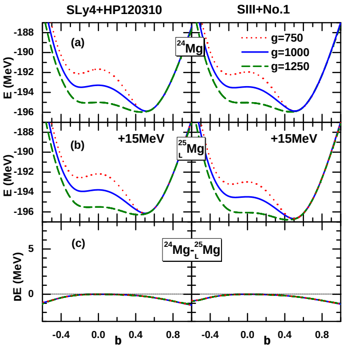
Parameter	t_0^Λ	x_0^Λ	t_1^Λ	t_2^Λ	t_3^Λ	W_0^Λ
SIII-No.1	-349.0	-0.108	67.61	37.39	2000.000	0.0
SLy4-HP120310	-346.6	-0.135	98.90	50.38	1617.566	0.0

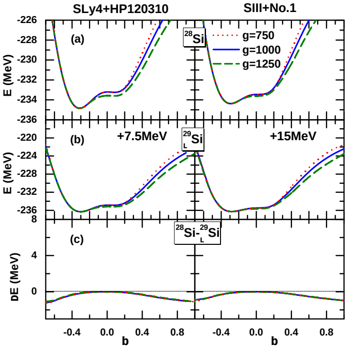
- SIII-No.1:
  M. Beiner, H. Flocard, Nguyen Van Giai, P. Quentin, Nucl. Phys. A238, 29 (1975);

  Y. Yamamoto, H. Bandō, and J. Žofka, Prog. Theor. Phys. 80, 757 (1988)
- SLy4-HP120310:
  E. Chabanat, P. Bonche, P. Haensel, J. Meyer, and R. Schaeffer, Nucl. Phys. A 635, 231 (1998);

  N. Guleria, S. K. Dhiman and R. Shyam, arXiv:1108.0787v1 [nucl-th] (2011)

Comparison of PECs by different Skyrmes forces and pairing strengths

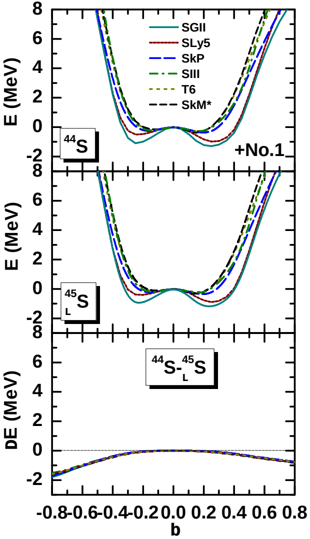


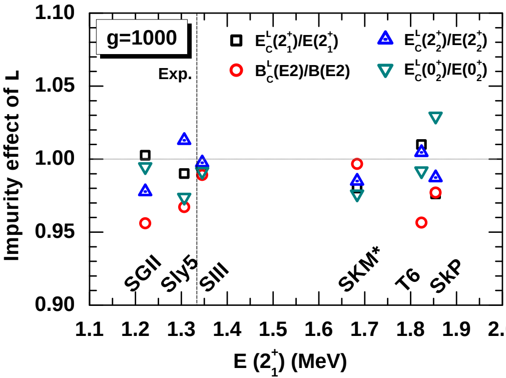


- The Sly4 and SIII forces gives similar polarization effect of Λ hyperon.
- Pairing strength for nucleons has significant influence on the topology of potential energy curves for atomic nuclei, but negligible effect on the polarization effect of Λ hyperon.

H. Mei, JMY, K. Hagino, Z.P. Li, et al., in preparation.

Λ impurity effect in shape-coexistence nucleus: ^{44}S

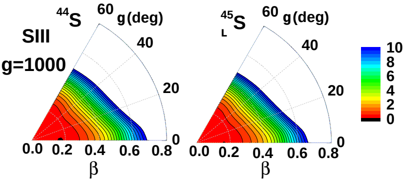


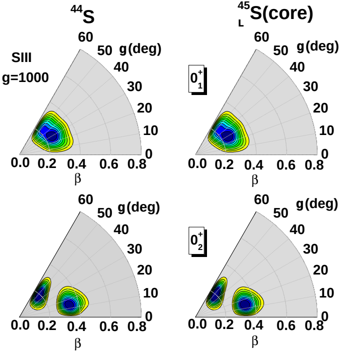


- All forces of concerned give similar results of Λ impurity effect in ^{44}S, i.e., the Λ impurity effect on collectivity of ^{44}S is within 5%.

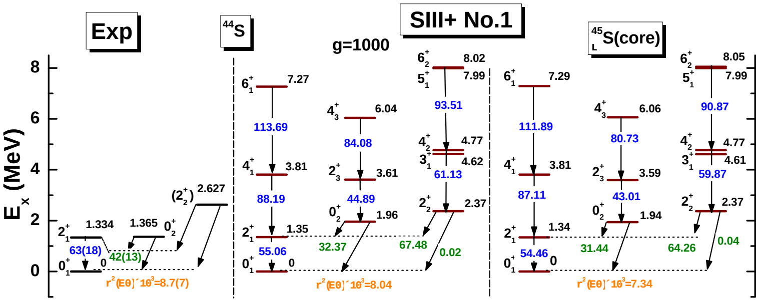
H. Mei, JMY, K. Hagino, Z.P. Li, et al., in preparation.

PES, WF, Spectra for ^{44}S and nuclear core of $^{45}_{\Lambda}$S





PES, WF, Spectra for ^{44}S and nuclear core of $^{45}_{\Lambda}$S



- The spectrum of ^{44}S is reproduced quite well by the 5DCH calculation with the SIII force.
- The impurity effect of Λ is very small.
- As pointed out in Refs. *M. Thi Win (2008); H.-J. Schulze (2010)*, the polarization effect of Λ particle might be stronger in the calculations with covariant EDFs. It is very interesting to extend this work to the relativistic case.

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Effective Lagrangian density

Effective Lagrangian density for hypernucleus

$$\mathcal{L} = \mathcal{L}_N + \mathcal{L}_\Lambda, \tag{9}$$

For nuclear part

$$\begin{aligned}\mathcal{L}_N \quad = \quad & \bar{\psi}_N \left[i\partial\!\!\!/ - m_N - g_{N\sigma}\sigma - g_{N\omega}\gamma^\mu\omega_\mu - g_{N\rho}\gamma^\mu\vec{\tau}\cdot\vec{\rho}_\mu - e\gamma^\mu A_\mu \frac{1-\tau_3}{2} \right] \psi_N \\ & + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{3}g_2\sigma^3 - \frac{1}{4}g_3\sigma^4 \\ & - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \frac{1}{4}c_3(\omega_\mu\omega^\mu)^2 \\ & - \frac{1}{4}\vec{R}_{\mu\nu}\vec{R}^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\cdot\vec{\rho}^\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}. \end{aligned} \tag{10}$$

For Λ hyperon part

The Lagrangian density $\mathcal{L}_\Lambda$ related to the Λ hyperon is as follows,

$$\mathcal{L}_\Lambda = \bar{\psi}_\Lambda \left(i\gamma^\mu\partial_\mu - m_\Lambda - g_{\Lambda\sigma}\sigma - g_{\Lambda\omega}\gamma^\mu\omega_\mu \right) \psi_\Lambda + \frac{f_{\omega\Lambda\Lambda}}{4m_\Lambda}\bar{\psi}_\Lambda\sigma^{\mu\nu}\Omega_{\mu\nu}\psi_\Lambda. \tag{11}$$

Parameters in ΛN interaction

m_Λ, $g_{\Lambda\sigma}$, $g_{\Lambda\omega}$ and $f_{\omega\Lambda\Lambda}$ (much less than that of Skyrme force!).

Parametrization procedure

Obsevables in fitting

- Single-Λ energies $\varepsilon^{\Lambda}_{1s1/2}$ of 13 selected hypernuclei from ${}^{12}_{\Lambda}\mathrm{C}$ to ${}^{208}_{\Lambda}\mathrm{Pb}$
- Spin-orbit splittings $\varepsilon^{\Lambda}_{1p1/2} - \varepsilon^{\Lambda}_{1p3/2}$ of ${}^{13}_{\Lambda}\mathrm{C}$ *Ajimura01*, and ${}^{9}_{\Lambda}\mathrm{Be}$ *Ukai04*

Fitting strategy

- Choosing the PK1 *Long04* for NN part and fixing $m_\Lambda = 1115.6$ MeV
- Adjusting R_σ, R_ω by fixing $R_{\omega\Lambda\Lambda} = 0$ or $R_{\omega\Lambda\Lambda} = 1$ *Cohen (1991)*, where $R_\sigma \equiv g_{\Lambda\sigma}/g_{N\sigma}$, $R_\omega \equiv g_{\Lambda\omega}/g_{N\omega}$ and $R_{\omega\Lambda\Lambda} \equiv f_{\omega\Lambda\Lambda}/g_{\Lambda\omega}$.
- Minimizing the square deviation between the experimental observable $O_i^{\rm exp}$ and the calculated value $O_i^{\rm cal}$

$$\chi^2 = \sum_i^N \frac{(\mathcal{O}_i^{\rm exp.} - \mathcal{O}_i^{\rm cal.})^2}{(\Delta\mathcal{O}_i^{\rm exp.}/\mathcal{O}_i^{\rm exp.})^2}, \tag{12}$$

where $\Delta\mathcal{O}_i^{\rm exp.}$ is the experimental uncertainty of the observable.

The ΛN effective interaction in covariant EDF

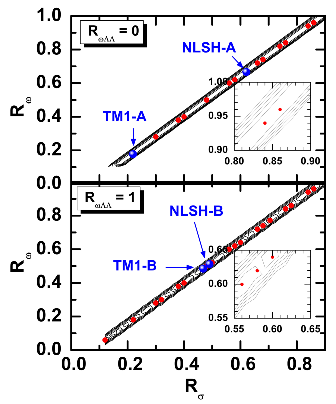


Figure: The contour plot of χ^2 distribution ($\mathcal{O} = \varepsilon^{\Lambda}_{1s1/2}$) in RMF calculations as a function of the ratios R_σ and R_ω. Local minima are indicated with red points.

- The χ^2 distribution: a sharp deep valley $\Rightarrow$ R_σ and R_ω are linearly correlated approximately as

$$R_\omega = 1.22 R_\sigma - 0.09 \tag{13}$$

for $R_{\omega\Lambda\Lambda} = 0$ and 1, consistent with the DD-RMF results *Keil (2000)*.

The ΛN effective interaction in covariant EDF

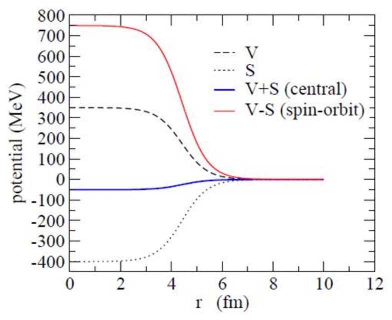


Figure: Distribution of vector V and scalar S potentials.

H.F. Lu, JMY, J. Meng, et al., in prepation (2011). C.Y. Song, JMY, H.F. Lu, and J. Meng, IJMPE 19, 2538 (2010).

- The χ^2 distribution: a sharp deep valley $\Rightarrow$ R_σ and R_ω are linearly correlated approximately as

$$R_\omega = 1.22 R_\sigma - 0.09 \tag{13}$$

  for $R_{\omega\Lambda\Lambda} = 0$ and 1, consistent with the DD-RMF results *Keil (2000)*.

- Reason: Cancelation of potentials V and S mainly determines single-particle energy of $\Lambda_{1s1/2}$. ($\Rightarrow$ not sufficient to fix the effective ΛN interaction).

The ΛN effective interaction in covariant EDF

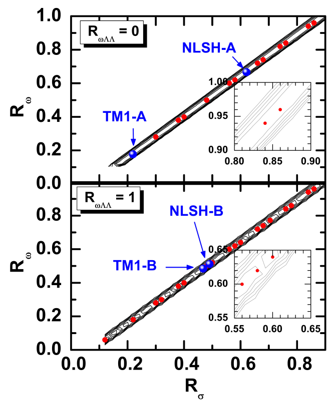


Figure: The contour plot of χ^2 distribution ($\mathcal{O} = \varepsilon^{\Lambda}_{1s1/2}$) in RMF calculations as a function of the ratios R_σ and R_ω. Local minima are indicated with red points.

- The χ^2 distribution: a sharp deep valley $\Rightarrow$ R_σ and R_ω are linearly correlated approximately as

$$R_\omega = 1.22 R_\sigma - 0.09 \qquad (13)$$

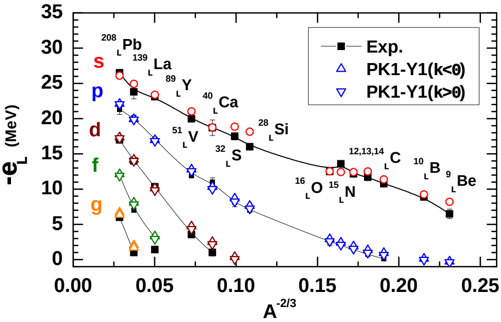
  for $R_{\omega\Lambda\Lambda} = 0$ and 1, consistent with the DD-RMF results *Keil (2000)*.
- Reason: Cancelation of potentials V and S mainly determines single-particle energy of $\Lambda_{1s1/2}$. ($\Rightarrow$ not sufficient to fix the effective ΛN interaction).
- Such a strong balance is not changed by the $\omega\Lambda\Lambda$ tensor coupling.
- The spin-orbit splittings of Λ s.p. states are mainly determined by derivative of $V + S$, $\Rightarrow$ constraining the values of R_σ, R_ω and $R_{\omega\Lambda\Lambda}$. The spin-orbit splitting of Λ single-particle requires the $R_{\omega\Lambda\Lambda} = 1$.

Noble (1980), Jennings (1990), Cohen (1991), ..., Yao (2008)

The ΛN effective interaction in covariant EDF

Table: Parameters for the ΛN effective interaction, in comparison with the previous adopted values in different covariant EDFs.

	PK1			TM1		NLSH		
Parameter	Y1	Y2	Y0	A *Sugahara94*	B *Sugahara94*	A *Mares94*	B *Ma96*	$SU(3)_f$
R_σ	0.580	0.705	0.840	0.219	0.468	0.621	0.490	0.667
R_ω	0.620	0.772	0.940	0.177	0.485	0.667	0.512	0.667
$R_{\omega\Lambda\Lambda}$	1.0	1.0	0.0	0.0	1.21	0.0 (1.0)	0.616	0.0 (1.0)



- $\kappa > 0$ and $\kappa < 0$ denote the states of $\ell = j - 1/2$ and $\ell = j + 1/2$ respectively. A is the baryon number of the hypernucleus.
- The experimental data are taken from Refs. [*Davis86, Hotchi01, Pile91, Nagae00, Hasegawa96, Tamura02*]
- Good quality of PK1-Y1 effective interaction for ε_Λ, not only in s state, but also in other states.

H.F. Lu, JMY, J. Meng, et al., in prepation (2011). C.Y. Song, JMY, H.F. Lu, and J. Meng, IJMPE 19, 2538 (2010).

The ΛN effective interaction in covariant EDF

Table: The calculated spin-orbit splittings of p_Λ states with the PK1-Y1, PK1-Y2, and PK1-Y0, in comparison with the data *Tamura02,Ukai04,Ajimura01* and those obtained with the TM1-A *Sugahara94*, TM1-B *Sugahara94*, NLSH-A *Mares94*, and NLSH-B *Ma96*. All energies are given in MeV. The bold-faced quantities denote the data used in the parametrization fitting.

		PK1			TM1		NLSH	
Nuclei	Exp.	Y1	Y2	Y0	A *Sugahara94*	B *Sugahara94*	$A^{R_{\omega\Lambda\Lambda}=1.0}$ *Mares94*	B *Ma96*
${}^{9}_{\Lambda}$Be	**0.045(5)**	0.039	0.085	0.250	0.016	0.004	0.057	0.053
${}^{13}_{\Lambda}$C	**0.152(65)**	0.233	0.320	1.345	0.334	0.012	0.293	0.516

H.F. Lu, JMY, J. Meng, et al., in prepation (2011). C.Y. Song, JMY, H.F. Lu, and J. Meng, IJMPE 19, 2538 (2010).

Polarization effect of Λ on carbon isotopes

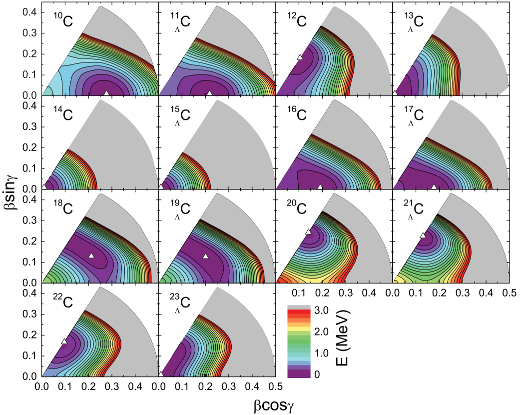


Figure: The potential energy surfaces of carbon isotopes and those of corresponding single-Λ hypernuclei, calculated with the PK1-Y1 effective interactions.

- The deformations of the carbon hypernuclei are similar to their corresponding core nuclei
- Two exceptions: $^{13}_{\Lambda}\mathrm{C}$ and $^{23}_{\Lambda}\mathrm{C}$, the minima of which are shifted from the oblate shape to spherical one.
- Quantitative (Covariant EDF based) evaluation of Λ effect on nuclear collectivity needs to be done to constrain further the strengths R_σ, R_ω.

Bing-Nan Lu, En-Guang Zhao, and Shan-Gui Zhou, PRC84, 014328 (2011).

Outline

1. Introduction
   - Importance of Λ hypernuclei
   - γ-ray spectroscopy of Λ hypernuclei
   - Towards symmetry restored EDF for Λ hypernuclei
2. The Skyrme EDF based 5DCH for Λ effect on nuclear collectivity
   - The Skyrme EDF based 5D collective Hamiltonian
   - Impurity effect of Λ on nuclear collectivity: an example
   - A systematical study of Λ impurity effect
3. A new parametrization for effective ΛN interaction in Covariant EDF
   - Effective Lagrangian density
   - Parametrization for ΛN interaction
   - Some results with the new PK1-Y1 interaction
4. **Summary and perspective (2 min.)**

Summary and perspective

Impurity effect of Λ on nuclear collectivity

Based on several different Skyrme EDFs, the impurity effect of Λ on nuclear collectivity have been studied systematically with 5D collective Hamiltonian.

- The impurity effect of Λ hyperon on nuclear collectivity (^{24}Mg, ^{44}S, $\cdots$) is generally small (within $5-10\%$).
- The searching for possible large Λ impurity effect on nuclear collectivity (e.g., in ^{28,30}Si) is in progress.

New parametrization of ΛN effective interaction based on a Rel. EDF

A new parametrization PK1-Y1 of ΛN effective interaction has been proposed based on the PK1 covariant EDF for nuclear part. Both the s.p. energy of Λ of 13 hypernuclei and the spin-orbit splitting of p_Λ states of 2 hypernuclei have been used to constrain the ΛN effective interaction.

- The $\Lambda\omega\omega$ tensor coupling is essential for small s.o. splitting of p_Λ state.
- Only s.p. energy of Λ cannot uniquely constrain the ΛN interaction.
- A quantitative evaluation of Λ effect on nuclear collectivity should be done to constrain further the strengths R_σ, R_ω.

Summary and perspective

Impurity effect of Λ on nuclear collectivity

Based on several different Skyrme EDFs, the impurity effect of Λ on nuclear collectivity have been studied systematically with 5D collective Hamiltonian.

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The further steps of this work to be done in the future...

- develop a 5DCH for hypernuclei (suitable for odd-mass/-odd nuclei)
- develop a 3D projection+GCM approach for hypernuclei (suitable for odd-mass/-odd nuclei)

Collaboration

Acknowledgments

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Hua Mei, Zhipan Li	Southwest Univ. China
Kouichi Hagino, Myaing Thi Win	Tohoku Univ. Japan

Thanks for Your attention!

The ΛN effective interaction in covariant EDF

Table: The calculated single-particle energies (MeV) of $\Lambda_{1s1/2}$ in selected hypernuclei with the PK1-Y1, PK1-Y2 and PK1-Y0, in comparison with the data. *Tamura02* and those obtained with the TM1-A *Sugahara94*, TM1-B *Sugahara94*, NLSH-A *Mares94*, and NLSH-B *Ma96*.

		PK1			TM1		NLSH	
Nuclei	Exp.	Y1	Y2	Y0	A *Sugahara94*	B *Sugahara94*	A *Mares94*	B *Ma96*
${}^{12}_{\Lambda}$C	−10.76(17)	−11.319	−11.055	−11.364	−11.412	−10.258	−11.731	−11.420
${}^{13}_{\Lambda}$C	−11.69(12)	−12.415	−12.008	−12.248	−12.569	−11.162	−12.791	−12.564
${}^{14}_{\Lambda}$C	−12.17(33)	−12.315	−12.028	−12.223	−12.627	−11.357	−12.738	−12.380
${}^{14}_{\Lambda}$N	−12.17(33)	−12.315	−12.054	−12.256	−12.602	−11.359	−12.766	−12.402
${}^{15}_{\Lambda}$N	−13.59(15)	−12.340	−12.137	−12.305	−12.746	−11.576	−12.793	−12.340
${}^{16}_{\Lambda}$O	−12.50(35)	−12.442	−12.290	−12.437	−12.936	−11.812	−12.908	−12.396
${}^{28}_{\Lambda}$Si	−16.00(29)	−17.957	−17.815	−17.642	−17.314	−16.618	−18.608	−17.739
${}^{32}_{\Lambda}$S	−17.5(5)	−18.611	−18.401	−18.170	−18.372	−16.942	−19.202	−18.395
${}^{40}_{\Lambda}$Ca	−18.7(11)	−18.382	−18.352	−18.077	−18.218	−17.519	−19.166	−18.244
${}^{51}_{\Lambda}$V	−19.97(13)	−20.730	−20.794	−20.394	−19.820	−19.454	−21.477	−20.280
${}^{89}_{\Lambda}$Y	−23.11(10)	−22.984	−23.211	−22.671	−21.685	−21.560	−23.804	−22.362
${}^{139}_{\Lambda}$La	−23.8(10)	−24.347	−24.846	−24.432	−22.217	−22.722	−25.296	−23.566
${}^{208}_{\Lambda}$Pb	−26.5(5)	−25.605	−26.146	−25.735	−23.360	−23.872	−26.573	−24.778
Δ		0.851	0.815	0.749	1.229	1.209	1.200	0.906
δ		0.054	0.051	0.048	0.062	0.069	0.075	0.055

$$\Delta = \sqrt{\sum_{i}^{N} \frac{1}{N}(E_i^{\rm exp} - E_i^{\rm cal})^2}, \delta = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \frac{(E_i^{\rm exp} - E_i^{\rm cal})^2}{(E_i^{\rm exp})^2}}.$$

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