On the stability of $\Lambda(1405)$-matter

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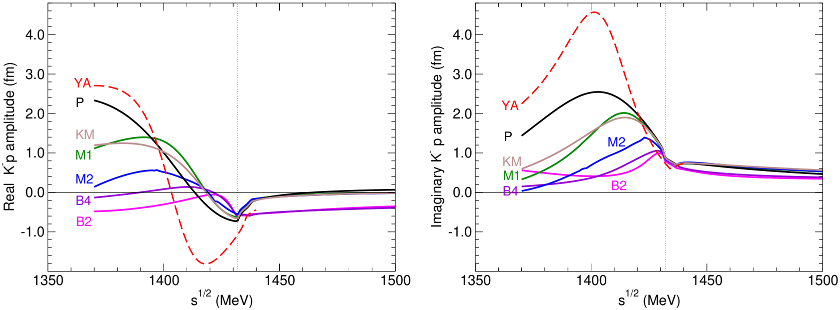
Motivation

- formation of stable hadronic matter composed of Λ^* [$\Lambda(1405)$] baryons
  Y. Akaishi, T. Yamazaki, Phys. Lett. B 774 (2017) 522
- strong energy-independent $\bar{K}N$ potential producing $(\bar{K}N)_{I=0}$ quasibound state [$\Lambda(1405)$] 27 MeV below the K^-p threshold
  S. Maeda, Y. Akaishi, T. Yamazaki, Proc. Jpn. Acad. Ser. B 89 (2013) 418
- implications for stable Λ^*-matter based on few-body calculations, no reliable many-body calculations have been done

$$\Downarrow$$

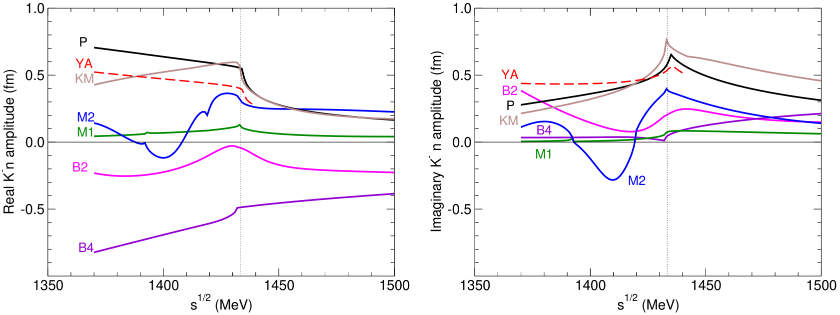
- we have performed many-body calculations of Λ^* nuclei within the Relativistic Mean-Field approach
  J. Hrtankova et al., Phys. Lett. B 785 (2018) 90.

$\bar{K}N$ interaction models



Yamazaki-Akaishi (YA)	*T. Yamazaki, Y. Akaishi, Phys. Rev. C 76 (2007) 045201*
Prague (P)	*A. Cieply, J. Smejkal, Nucl. Phys. A 881 (2012) 115*
Kyoto-Munich (KM)	*Y. Ikeda, T. Hyodo, W. Weise, Nucl. Phys. A 881 (2012) 98*
Murcia (M1 and M2)	*Z. H. Guo, J. A. Oller, Phys. Rev. C 87, 035202 (2013)*
Bonn (B2 and B4)	*M. Mai, U.-G. Meißner, Nucl. Phys. A 900 (2013) 51*

$\bar{K}N$ interaction models



Kaonic atoms test

→ energy-independent $\bar{K}N$ potential (AY) confronted with kaonic atom data:

- optical potential constructed from corresponding $\bar{K}N$ amplitudes supplemented by phenomenological K^- multinucleon potential

model	B2	B4	M1	M2	P	KM	AY
$\chi^2(65)$	111	105	121	109	125	123	150

- calculated K^- single-nucleon absorption fractions at threshold and compared with experimental data

Kaonic atoms test

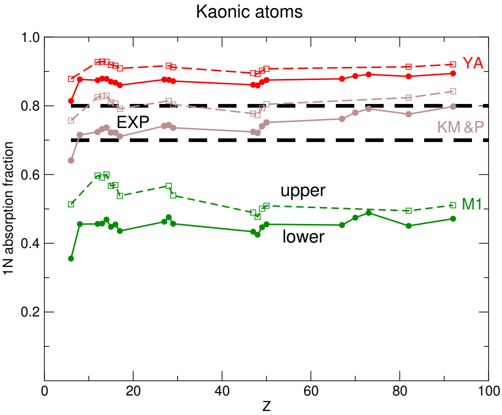


Fig.1: Calculated K^- single-nucleon absorption fractions in the AY model (denoted by YA) compared with KM, P, and M1 chiral models. The range of experimentally deduced fractions is marked by the two horizontal dashed lines.

$\bar{K}N$ interaction & quasibound states

Table: $(\bar{K}N)_{I=0}$, $(\bar{K}NN)_{I=1/2}$ and $(\bar{K}\bar{K}NN)_{I=0}$ binding energies B calculated using energy dependent (E-dep.) and energy independent (E-indep.) $\bar{K}N$ potentials. The binding energies listed for $(\bar{K}\bar{K}NN)_{I=0}$ are transformed in the last row to $B_{\Lambda^*\Lambda^*} = B(\bar{K}\bar{K}NN)_{I=0} - 2B(\bar{K}N)_{I=0}$.

B (MeV)	(E-dep.) [1]	(E-indep. A) [2]	(E-indep. B) [2]
$(\bar{K}N)_{I=0}$	11.4	26.6	64.2
$(\bar{K}NN)_{I=1/2}$	15.7	51.5	102 [3]
$(\bar{K}\bar{K}NN)_{I=0}$	32.1	93	190
$\Lambda^*\Lambda^*$	9.3	40	62

[1] *N. Barnea, A. Gal, E.Z. Liverts, Phys. Lett. B 712 (2012) 132*

[2] *S. Maeda, Y. Akaishi, T. Yamazaki, Proc. Jpn. Acad. Ser. B 89 (2013) 418*

[3] *T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 132502*

$\Lambda^*\Lambda^*$ interaction

- $\Lambda^*\Lambda^*$ interaction described by Yukawa meson-exchange potentials:
  1) Dover-Gal *C.B. Dover, A. Gal, Prog. Part. Nucl. Phys. 12 (1984) 171*

$$V_{\Lambda^*\Lambda^*}(r) = \alpha_\omega^2 g_{\omega\Lambda^*}^2 \left(1 - \frac{1}{8}\frac{m_\omega^2}{M_{\Lambda^*}^2}\right) Y_\omega(r) - \alpha_\sigma^2 g_{\sigma\Lambda^*}^2 \left(1 - \frac{1}{8}\frac{m_\sigma^2}{M_{\Lambda^*}^2}\right) Y_\sigma(r) + \alpha_\omega^2 g_{\omega\Lambda^*}^2 \frac{1}{6}\left(\frac{m_\omega}{M_{\Lambda^*}}\right) Y_\omega(r)(\vec{\sigma}_1 \cdot \vec{\sigma}_2) \, ,$$

2) Machleidt *R. Machleidt, Adv. Nucl. Phys. 19 (1989) 189*

$$V_{\Lambda^*\Lambda^*}(r) = \alpha_\omega^2 g_{\omega\Lambda^*}^2 \left(1 - \frac{1}{2}\frac{m_\omega^2}{M_{\Lambda^*}^2}\right) Y_\omega(r) - \alpha_\sigma^2 g_{\sigma\Lambda^*}^2 \left(1 - \frac{1}{4}\frac{m_\sigma^2}{M_{\Lambda^*}^2}\right) Y_\sigma(r) + \alpha_\omega^2 g_{\omega\Lambda^*}^2 \frac{1}{6}\left(\frac{m_\omega}{M_{\Lambda^*}}\right) Y_\omega(r)(\vec{\sigma}_1 \cdot \vec{\sigma}_2) \, ,$$

where $Y_{i=\sigma,\omega}(r) = \exp(-m_i r)/(4\pi r)$ and $M_{\Lambda^*} = 1405$ MeV

$\Lambda^*\Lambda^*$ interaction

- scaling either $g_{\sigma\Lambda^*}$ or $g_{\omega\Lambda^*}$ in order to get $B_{\Lambda^*\Lambda^*} = 40$ MeV
- few-body calculations ($A \leq 6$) performed using Stochastic Variational Method (SVM) with Machleidt and Dover-Gal potentials
- similar SVM calculations done by Akaishi and Yamazaki using Machleidt potential but neglecting the spin-spin interaction
  Y. Akaishi, T. Yamazaki, arXiv:1903.10687 [nucl-th]

Table: The values of the scaling parameters α_σ and α_ω for σ and ω fields, respectively.

$V_{\Lambda^*\Lambda^*}$	α_σ	α_ω
Machleidt	1.0913	0.8889
Dover-Gal	1.0332	0.9750

Few-body SVM calculations

The effect of spin-spin interaction is sizable!

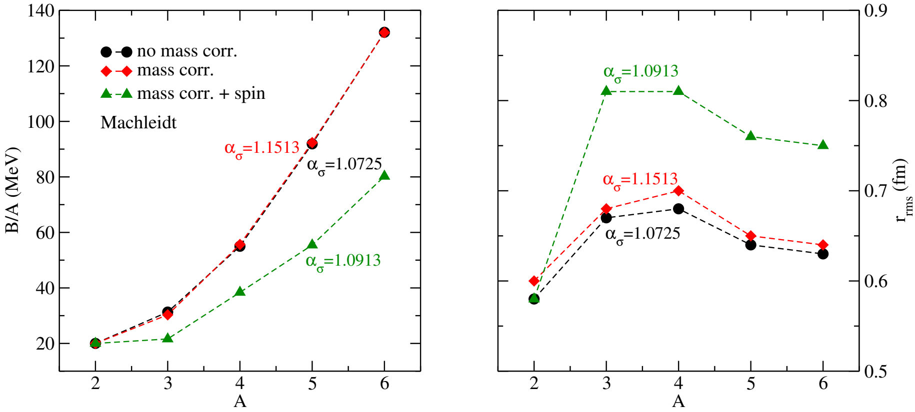


Fig.2: Binding energy per Λ^* (left), B/A, and RMS radius (right), r_{rms}, as a function of mass number, calculated within the SVM method using the Machleidt type potential and scaling of σ coupling constant.

RMF calculations of Λ^* nuclei

- many-body systems composed of Λ^* hyperons (neutral, $I = 0$) calculated within the Relativistic Mean-Field (RMF) approach
  J. Hrtankova et al., Phys. Lett. B 785 (2018) 90.

$$\mathcal{L} = \bar{\Lambda}^* \left[\mathrm{i}\gamma^\mu D_\mu - (M_{\Lambda^*} - g_{\sigma\Lambda^*}\sigma) \right] \Lambda^* + (\sigma, \omega_\mu \text{ free-field terms})$$

where $D_\mu = \partial_\mu + \mathrm{i}\, g_{\omega\Lambda^*}\, \omega_\mu$, M_{Λ^*} - mass of Λ^*, $g_{i\Lambda^*}$ - coupling constants

- coupling constants $g_{i\Lambda^*}$ and meson masses m_i $(i = \sigma, \omega)$ taken from the HS model *C.J. Horowitz, B.D. Serot, Nucl. Phys. A 368 (1981) 503*

$$m_\omega = 783 \text{ MeV}, \quad m_\sigma = 520 \text{ MeV}, \quad g_{\omega\Lambda^*} = 13.80, \quad g_{\sigma\Lambda^*} = 10.47$$

- self-consistent solution of coupled Dirac and Klein-Gordon equations
- calculations with the NL-SH model for comparison
  M.M. Sharma, M.A. Nagarajan, P. Ring, Phys. Lett. B 312 (1993) 377

Binding energy per Λ*

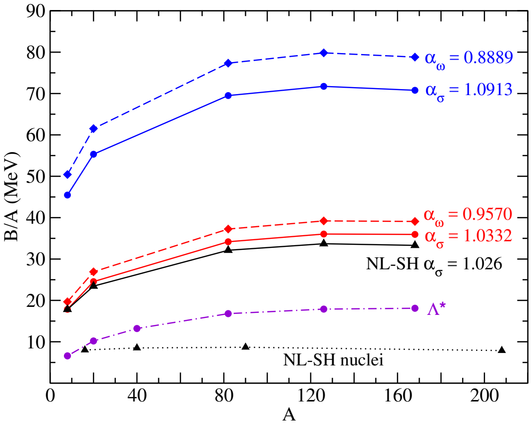


Fig.3: Binding energy of Λ^* nuclei per Λ^*, B/A, as a function of mass number A, calculated within the HS and NL-SH RMF models for various strengths of scalar and vector fields. The binding energy per nucleon in atomic nuclei is shown for comparison (NL-SH nuclei).

Λ* nuclei density distribution and radii

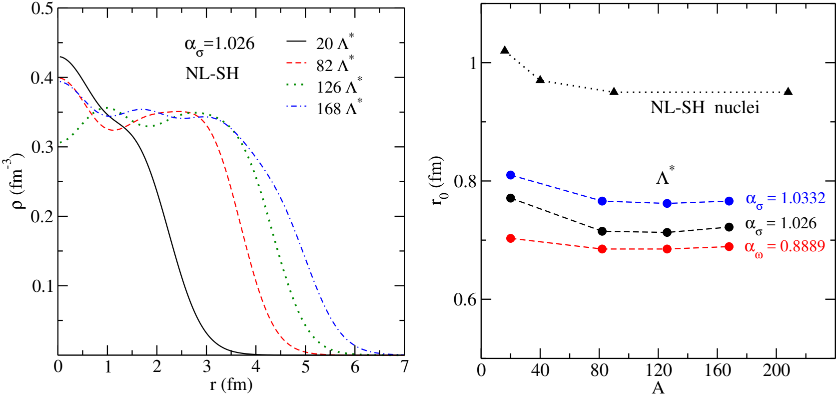


Fig.4: Left: Λ^* density distribution in various systems calculated within the NL-SH model. Right: Values of rms radius parameter r_0, $r_{\rm rms} = r_0 A^{1/3}$, in Λ^* nuclei for various interaction strengths. Values of r_0 in atomic nuclei (NL-SH nuclei) are shown for comparison.

Λ^* decay

- nonmesonic decay channel $\Lambda^*\Lambda^* \to YY$ $(Y = \Sigma, \Lambda)$
- decay of $\Lambda^*\Lambda^* \to \Lambda\Lambda$ in $1s$ state described by imaginary potential

$$\mathrm{Im}\, V_{\rm opt} = -\frac{4\pi}{2E_{\Lambda^*}} \frac{\sqrt{s}}{M_{\Lambda^*}} \mathrm{Im}\, b_0 \; f_{\rm supp} \; \rho$$

where $E_{\Lambda^*} = M_{\Lambda^*} - B_{\Lambda^*}$, $\sqrt{s} = \sqrt{(E_{\Lambda^*} + E_{\Lambda^*})^2 - (\vec{p}_{\Lambda^*} + \vec{p}_{\Lambda^*})^2}$,
$\mathrm{Im}\, b_0 = 0.85$ fm (fitted to $\Gamma_{\Lambda^*\Lambda^*} = 100$ MeV at threshold),
and $f_{\rm supp}$ is phase space suppression factor

Table: $1s$ single-particle energy ϵ_{Λ^*} and width $\Gamma_{\Lambda^*\Lambda^*}$ (in MeV) of Λ^* in systems composed of 8 and 168 Λ^* baryons, calculated using the HS model with $\alpha_\sigma = 1.0913$.

	8 Λ^*	168 Λ^*
ϵ_{Λ^*}	-133.8	-202.6
$\Gamma_{\Lambda^*\Lambda^*}$	72.1	99.9

Saturation mechanism in RMF

- decisive role of Lorentz covariance in producing saturation within the RMF model
- Klein-Gordon equations for meson fields

$$
\begin{aligned}
(-\triangle + m_\sigma^2)\sigma &= -g_{\sigma B}\rho_{\mathrm{s}} \\
(-\triangle + m_\omega^2)\omega_0 &= g_{\omega B}\rho_{\mathrm{v}}
\end{aligned}
$$

scalar density $\rho_{\mathrm{s}} = \bar{B}B$ decrease in dense matter with respect to vector (baryon) density $\rho_{\mathrm{v}} = B^\dagger B$

$$
\rho_{\mathrm{s}} \sim \frac{M^*}{E^*}\rho_{\mathrm{v}} \quad \text{where} \quad \frac{M^*}{E^*} < 1
$$

and $M^* = M - g_{\sigma B}\langle\sigma\rangle$ is baryon effective mass

Saturation mechanism in RMF

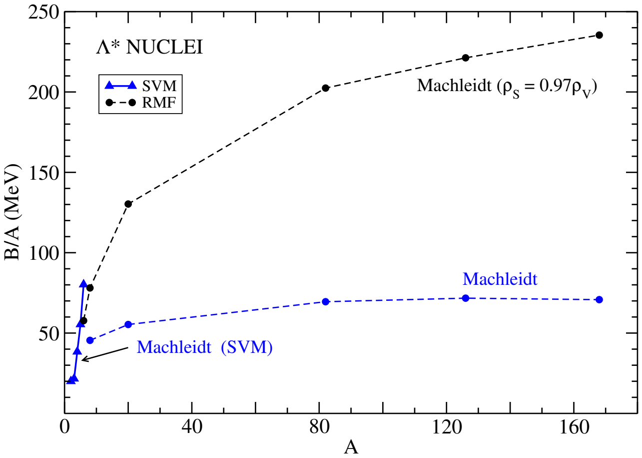


Fig.5: Binding energy of Λ^* nuclei per Λ^*, B/A as a function of mass number A, calculated within the RMF and SVM approaches for $\alpha_\sigma = 1.0913$ (Machleidt).

Conclusions

- we explored the possibility of existence of stable Λ^* matter based on energy independent $\bar{K}N$ interaction model (AY)
- the AY model was confronted with kaonic atom data $\longrightarrow$ it does not reproduce experimental values of single-nucleon absorption fractions
- we performed RMF calculations of Λ^* nuclei with various Λ^* interaction strengths compatible with $B_{\Lambda^*\Lambda^*} = 40$ MeV
- binding energy per Λ^* in many-body systems saturates below 100 MeV for $A \geq 120$ leaving Λ^* aggregates unstable against strong interaction decay

Backup slides

Backup slides

- energy-independent $\bar{K}N$ potentials by Yamazaki and Akaishi

  T. Yamazaki, Y. Akaishi, Phys. Rev. C 76 (2007) 045201

$$V^{I=0}_{\bar{K}N}(r) = (-595 - i83)\exp[-(r/0.66\ \mathrm{fm})^2]\ ,$$
$$V^{I=1}_{\bar{K}N}(r) = (-175 - i105)\exp[-(r/0.66\ \mathrm{fm})^2]\ .$$