Energy spectra of $^{15}{}_{\Xi}C$ and $^{12}{}_{\Xi}Be$, and ΞN two-body interaction

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GPPU GRADUATE PROGRAM ON PHYSICS FOR THE UNIVERSE

宇宙創成物理学国際共同大学院

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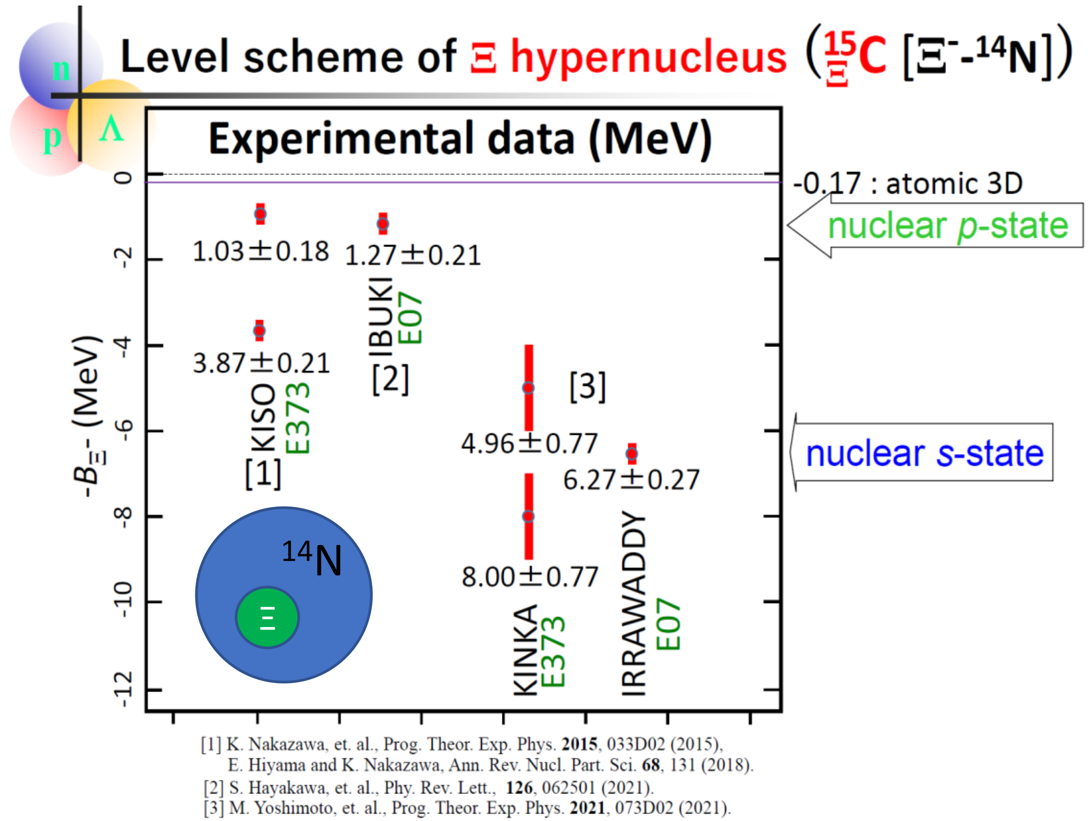
Information on NΞ interactions

Recent experimental data of $^{15}_{\Xi}C$ →

Provide information on **S=-2** sector of B-B force

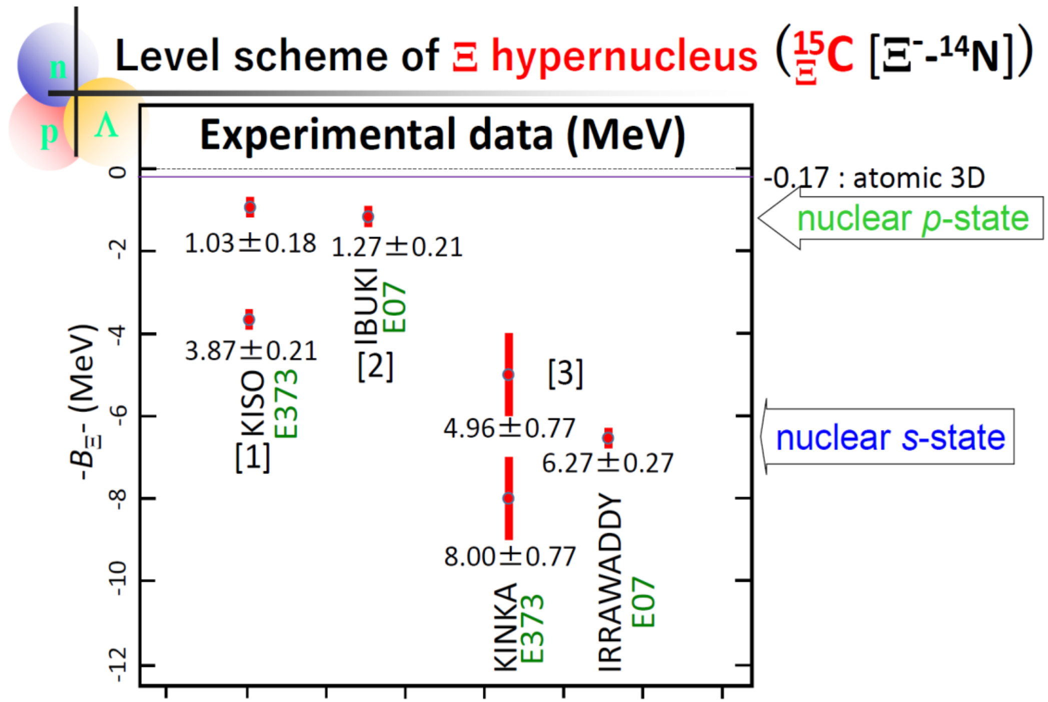


Yoshimoto et al., PTEP **2021**, 073D02 (2021).

Courtesy of Prof. Nakazawa

Purpose

- Interpretation of $^{15}{}_{\Xi}C$ data
- Estimate of spin-dependent ΞN interaction
- Spectrum $^{12}{}_{\Xi}Be$? (future expt. at J-PARC)



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[2] S. Hayakawa, et. al., Phy. Rev. Lett., **126**, 062501 (2021).
[3] M. Yoshimoto, et. al., Prog. Theor. Exp. Phys. **2021**, 073D02 (2021).

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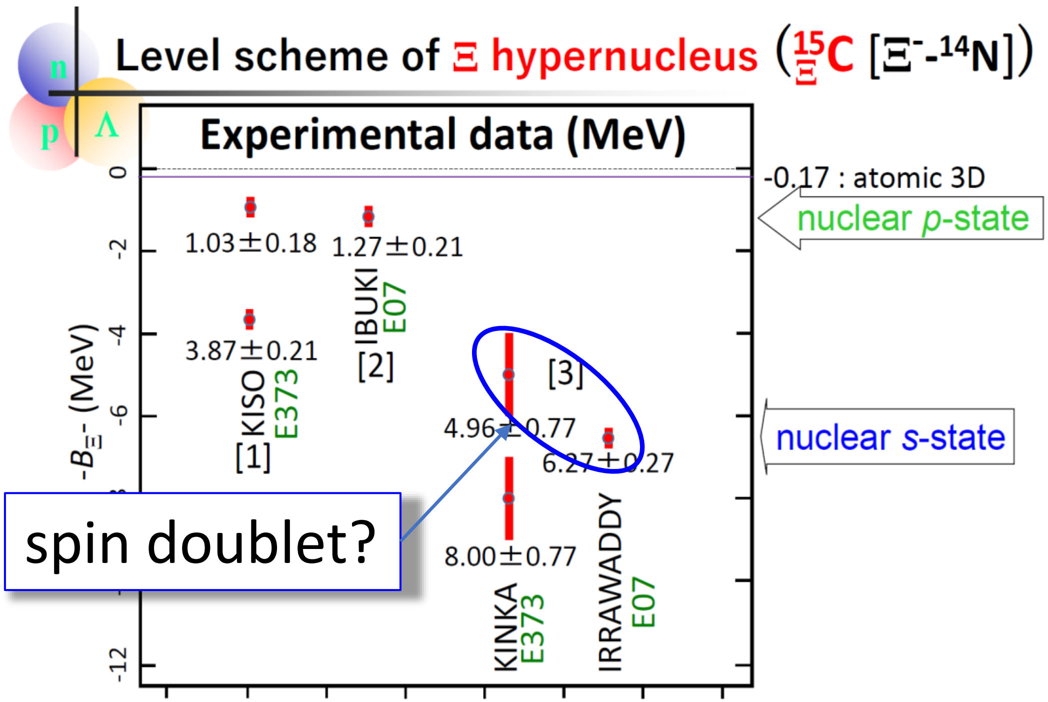
$V_{N\Xi} \sim \boldsymbol{\sigma}_N . \boldsymbol{\sigma}_\Xi$



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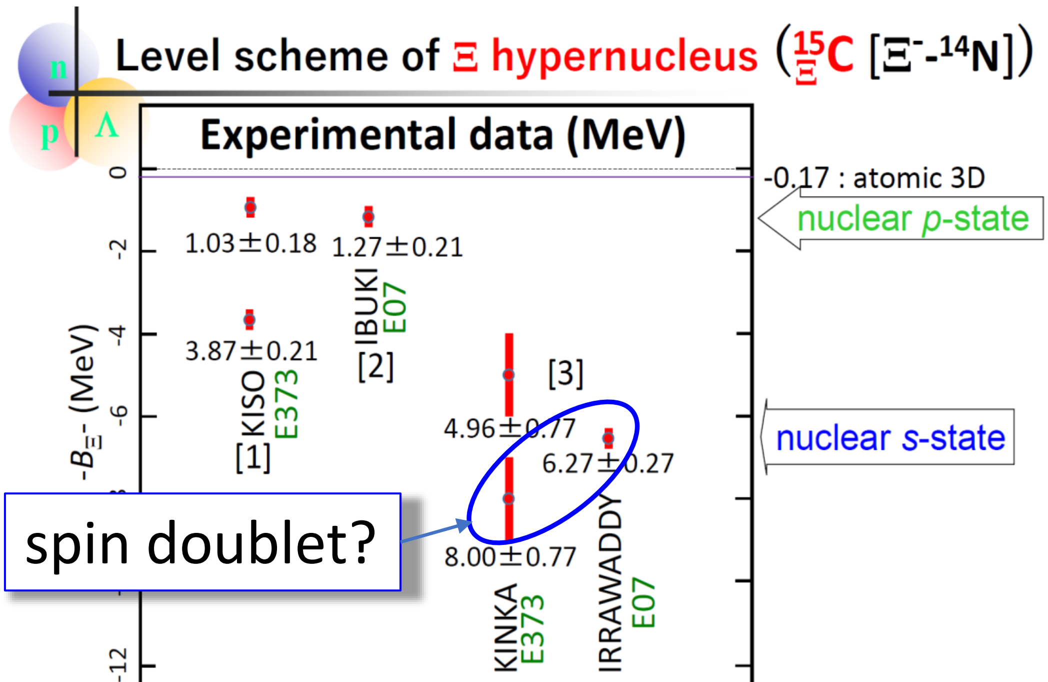

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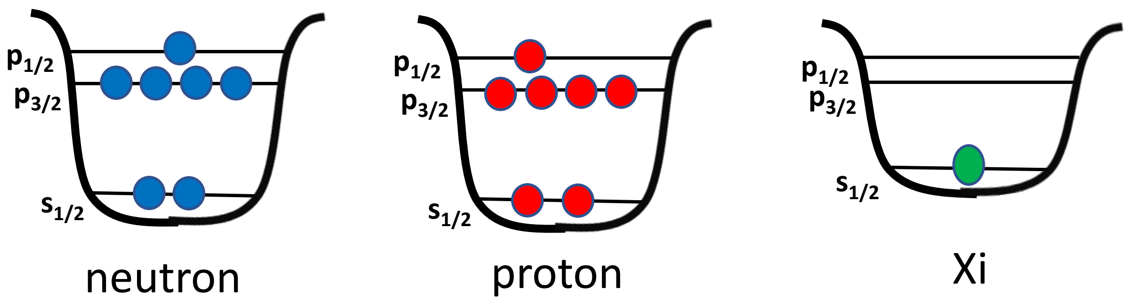
Method

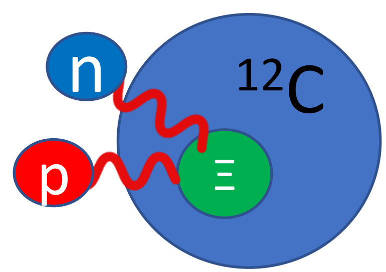
1. Relativistic mean-field (RMF) calculation

→ single-particle levels



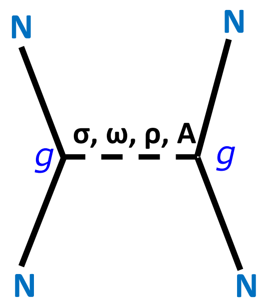
2. N-Ξ residual interaction (simple shell model)

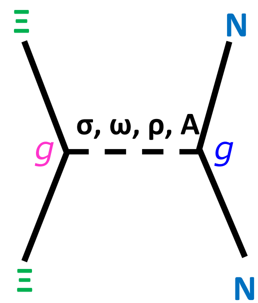
→ **energy spectrum of $^{15}_{\Xi}C$**

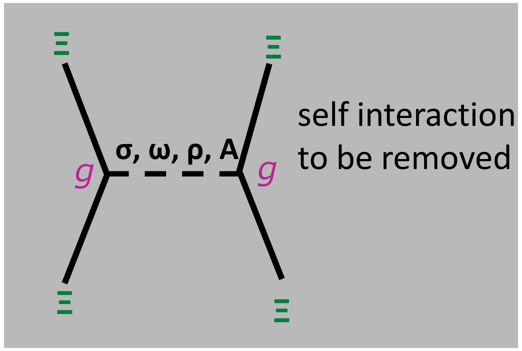


Relativistic mean field (RMF) theory

$$
\begin{aligned}
\mathcal{L} = &\bar{\psi}_N(i\partial\!\!\!/ - m_N)\psi_N + \bar{\psi}_\Xi(i\partial\!\!\!/ - m_\Xi)\psi_\Xi \\
&+\frac{1}{2}(\partial_\mu\sigma)(\partial^\mu\sigma) - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{c_3}{3}\sigma^3 - \frac{c_4}{4}\sigma^4 \\
&-\frac{1}{4}G^{\mu\nu}G_{\mu\nu} + \frac{1}{2}m_\omega^2\omega^\mu\omega_\mu + \frac{d_4}{4}(\omega^\mu\omega_\mu)^2 \\
&-\frac{1}{4}\vec{R}^{\mu\nu}\cdot\vec{R}_{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}^{\mu}\cdot\vec{\rho}_\mu + \frac{g_4}{4}(\vec{\rho}^{\mu}\cdot\vec{\rho}_\mu)^2 \\
&-\frac{1}{4}F^{\mu\nu}F_{\mu\nu} \\
&-\bar{\psi}_N\left(g_{\sigma N}\sigma + g_{\omega N}\omega\!\!\!/ + g_{\rho N}\vec{\rho}\!\!\!/\cdot\vec{\tau} + eA\!\!\!/\frac{1-\tau_3}{2}\right)\psi_N \\
&-\bar{\psi}_\Xi\left(g_{\sigma\Xi}\sigma + g_{\omega\Xi}\omega\!\!\!/ + g_{\rho\Xi}\vec{\rho}\!\!\!/\cdot\vec{\tau}\right. \\
&\qquad\left. + \frac{f_{\omega\Xi}}{4m_\Xi}G_{\mu\nu}\sigma^{\mu\nu} - A\!\!\!/\frac{\tau_3 - 1}{2}\right)\psi_\Xi
\end{aligned}
$$







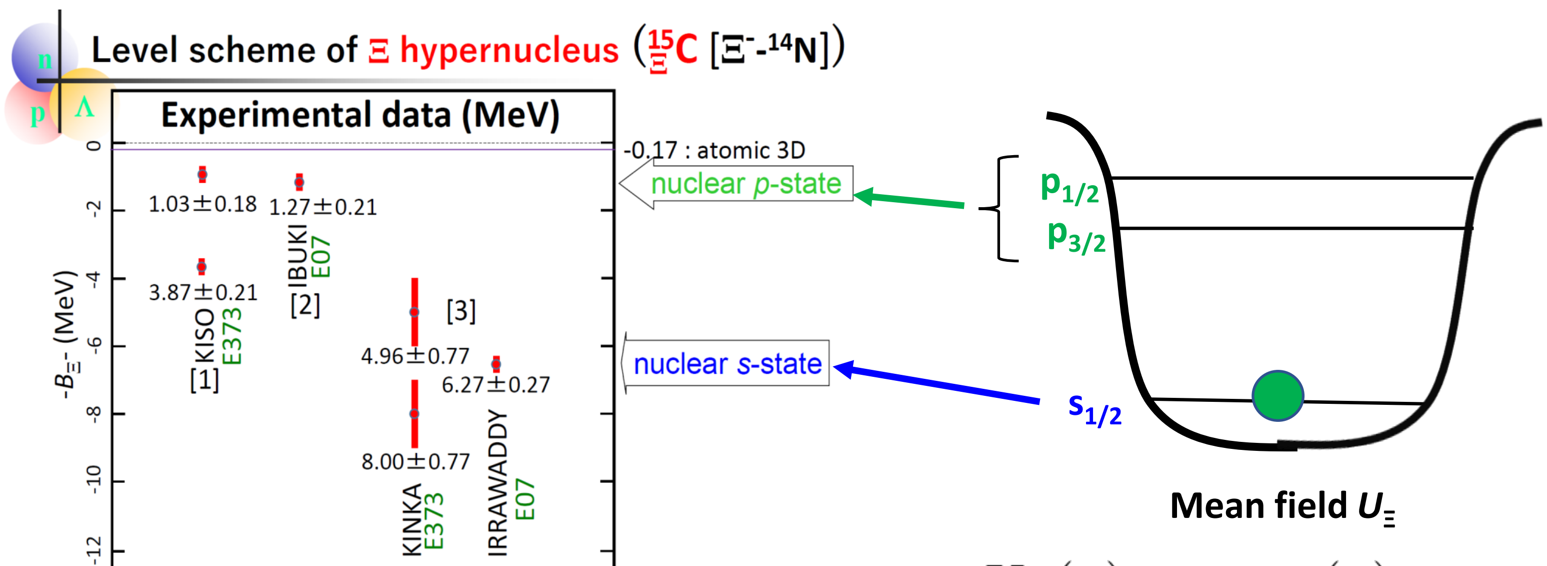
Nucleon sector: PK1 Long et al., PRC **69** 034319 ('04)

Hyperon sector: Fit to $_{\Xi}^{15}$C spectrum

Relativistic mean field (RMF) theory

Parameter fitting:

- $g_{\sigma\Xi}$, $g_{\sigma\Xi}$: $B_{\Xi s} \approx 6$ MeV, $B_{\Xi p} \approx 1$ MeV
- ($f_{\omega\Xi}$: $p_{3/2}$-$p_{1/2}$ splitting as small as Λ)



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Mean field U_Ξ

$$U_\Xi(\boldsymbol{r}) \approx g_{\sigma\Xi}\sigma(\boldsymbol{r}) + g_{\omega\Xi}\omega(\boldsymbol{r})$$

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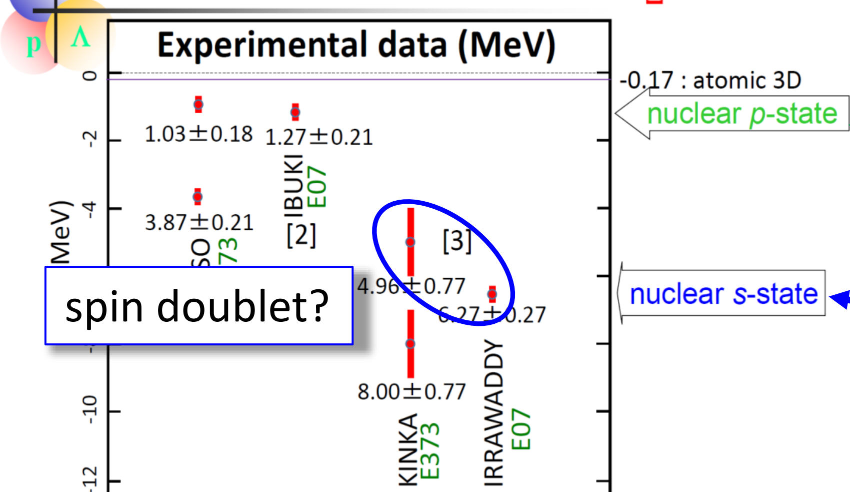
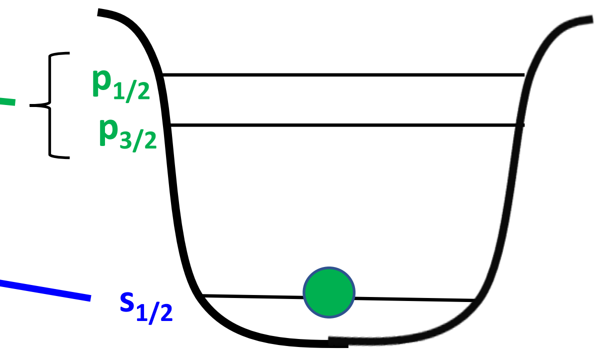
Coupling	Fitted (a)	Fitted (b)
$g_{\sigma\Xi}/g_{\sigma N}$	0.497	0.497
$g_{\omega\Xi}/g_{\omega N}$	0.5733	0.5663
$f_{\omega\Xi}/g_{\omega\Xi}$	−0.8	−0.8

cf. Hu et al., J. Phys. G**49**, 025104 (2022), QMF calculation

Level scheme of Ξ hypernucleus ($^{15}_{\Xi}C$ [Ξ^--^{14}N])





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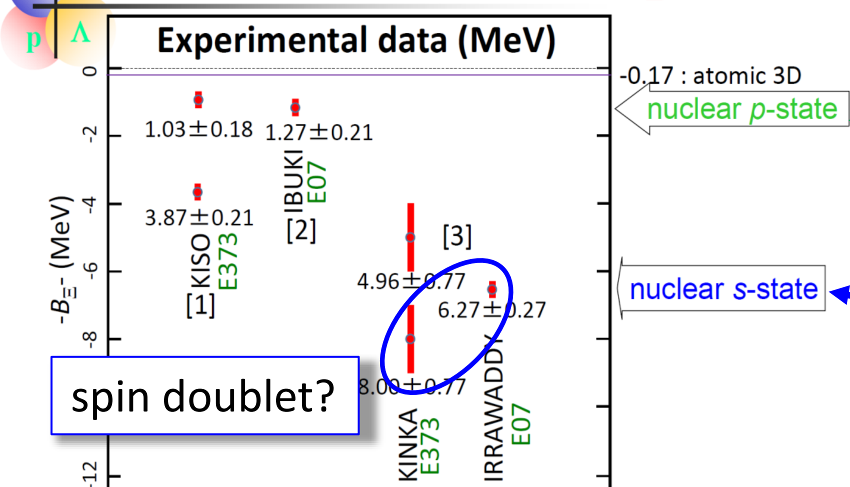

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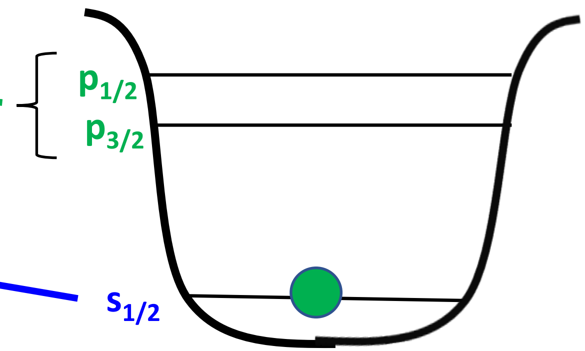

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$$U_\Xi(\boldsymbol{r}) \approx g_{\sigma\Xi}\sigma(\boldsymbol{r}) + g_{\omega\Xi}\omega(\boldsymbol{r})$$

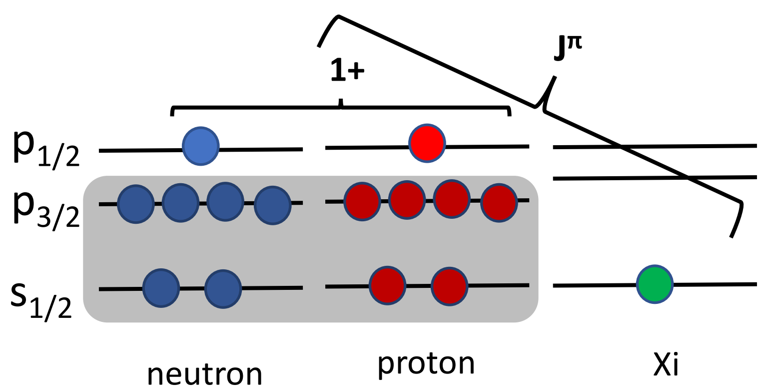
Spin-isospin dependent residual interaction

s-wave interaction

$$V = \sum_{i \in \text{nucleons}} (v_\sigma \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_\Xi + v_\tau \vec{\tau}_i \cdot \vec{\tau}_\Xi + v_{\sigma\tau} \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_\Xi \vec{\tau}_i \cdot \vec{\tau}_\Xi) \delta(\boldsymbol{r}_i - \boldsymbol{r}_\Xi)$$

Energy shift due to V (first-order perturbation)

$$\Delta E = \langle V \rangle = \left\langle \left[\left[\nu 1p_{1/2}\, \pi 1p_{1/2} \right]_{1^+} \xi n l_j \right]_{J^\pi} \middle| V \middle| \left[\left[\nu 1p_{1/2}\, \pi 1p_{1/2} \right]_{1^+} \xi n l_j \right]_{J^\pi} \right\rangle$$



$_{\Xi}^{15}$C (σ.σ only)

g.s. doublet (Ξ in $s_{1/2}$):
$J^\pi = 3/2^+$ and $1/2^+$

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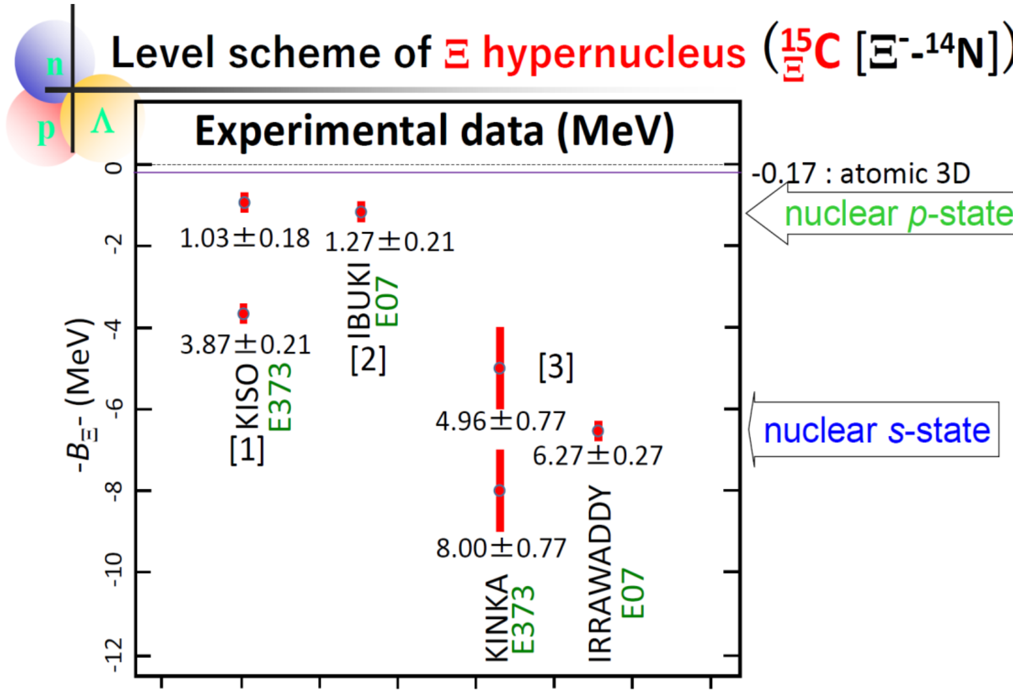
The strength parameters are estimated based on HAL QCD N-Ξ s-wave potential

Sasaki et al., NPA**998**, 121737 (2020).

→ Too weak to reproduce KINKA-IRRAWADDY splitting



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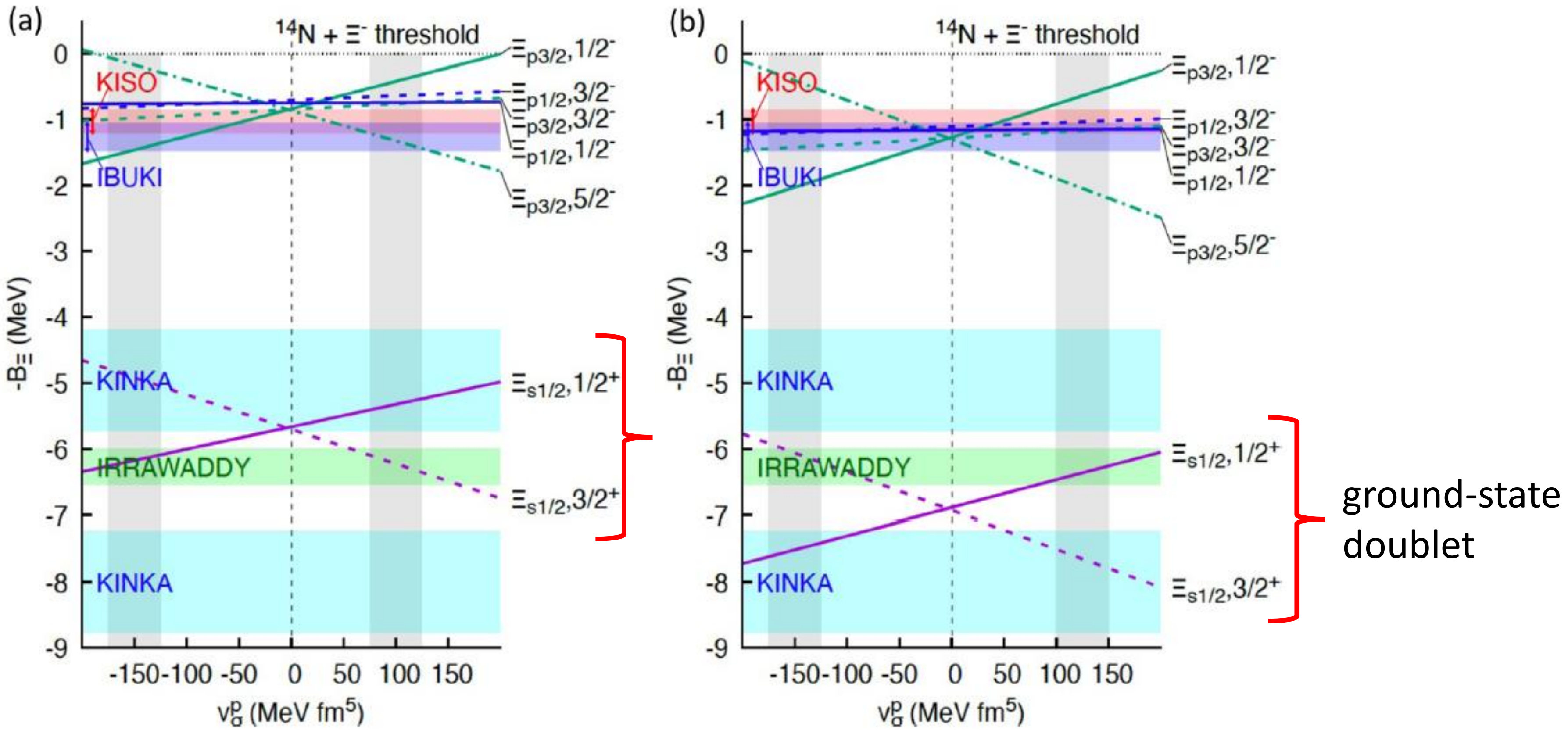
***p*-wave interaction**

$$V^p = \sum_{i \in \mathrm{nucleons}} v_\sigma^p \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_\Xi \overleftarrow{\boldsymbol{\nabla}} \cdot \delta(\boldsymbol{r}_i - \boldsymbol{r}_\Xi) \overrightarrow{\boldsymbol{\nabla}}$$

$$\boldsymbol{\nabla} = \boldsymbol{\nabla}_i - \boldsymbol{\nabla}_\Xi$$

→ Energy spectra of $^{15}{}_{\Xi}$C as functions of *p*-wave interaction strength



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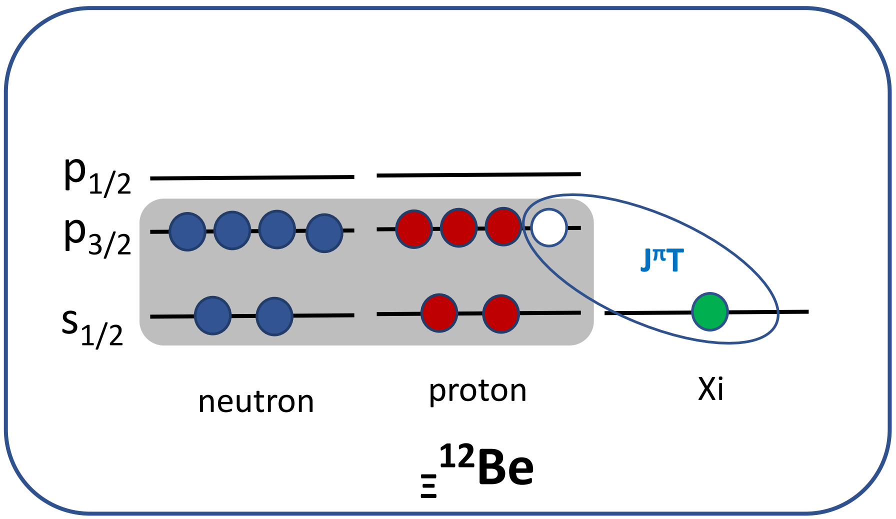
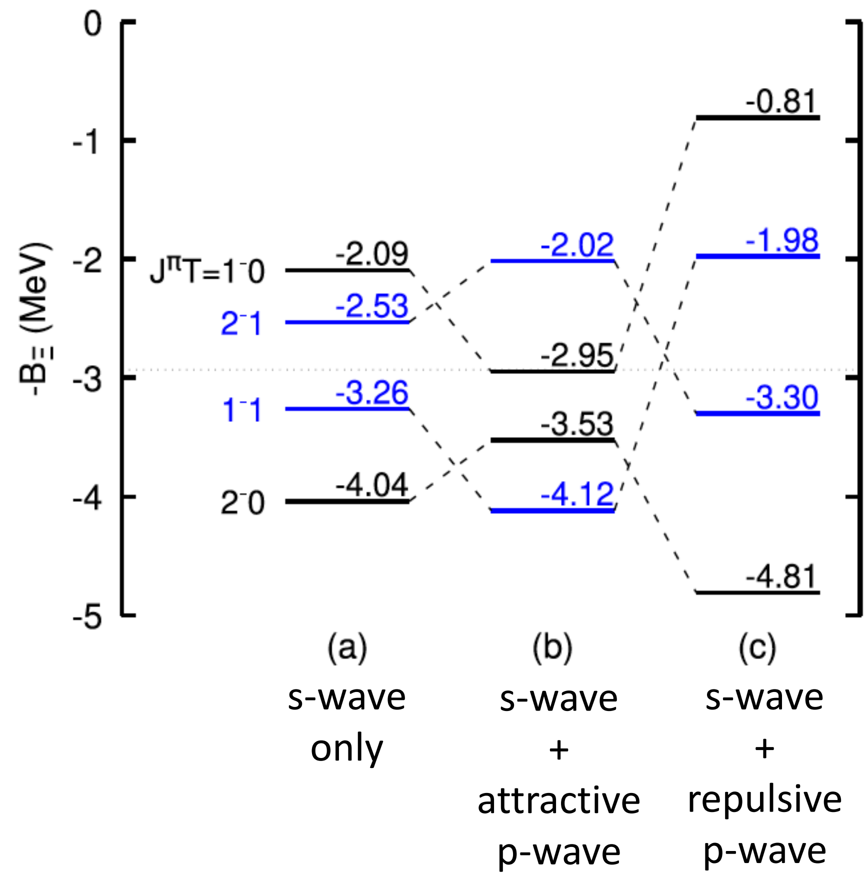
Both positive (~100 MeV.fm^5)
and negative (~-150 MeV.fm^5) $v_\sigma{}^p$ can
reproduce KINKA and IRRAWADDY
as spin-doublet states

Spectrum of $^{12}_{\Xi}Be$





Summary

Qualitative interpretation of new data of $^{15}{}_{\Xi}C$

→KINKA and IRRAWADDY: g.s. spin doublet

Spin-dependent p-wave NΞ interaction is important?