$\Xi^- p \to \Lambda\Lambda$ in light emulsion nuclei constraining the Ξ-nuclear potential

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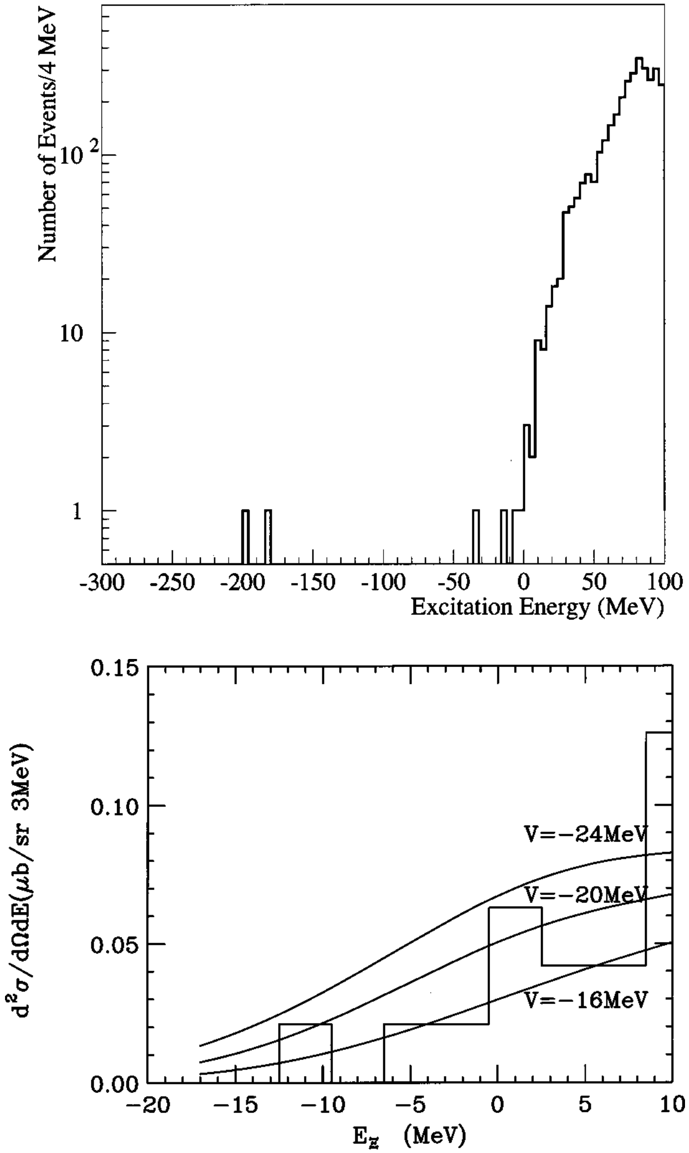
based on E. Friedman, A, Gal, arXiv:2104.00421

Abstract: All five KEK & J-PARC two-body $\Xi^- + {}^{A}$Z $\to {}^{A'}_{\Lambda}$Z'$+{}^{A''}_{\Lambda}$Z" capture events in light emulsion nuclei are considered, confirming that they occur from Coulomb-assisted $1p_{\Xi^-}$ nuclear states. The underlying Ξ-nuclear potential is strongly attractive, with nuclear-matter depth V_Ξ larger than 20 MeV.

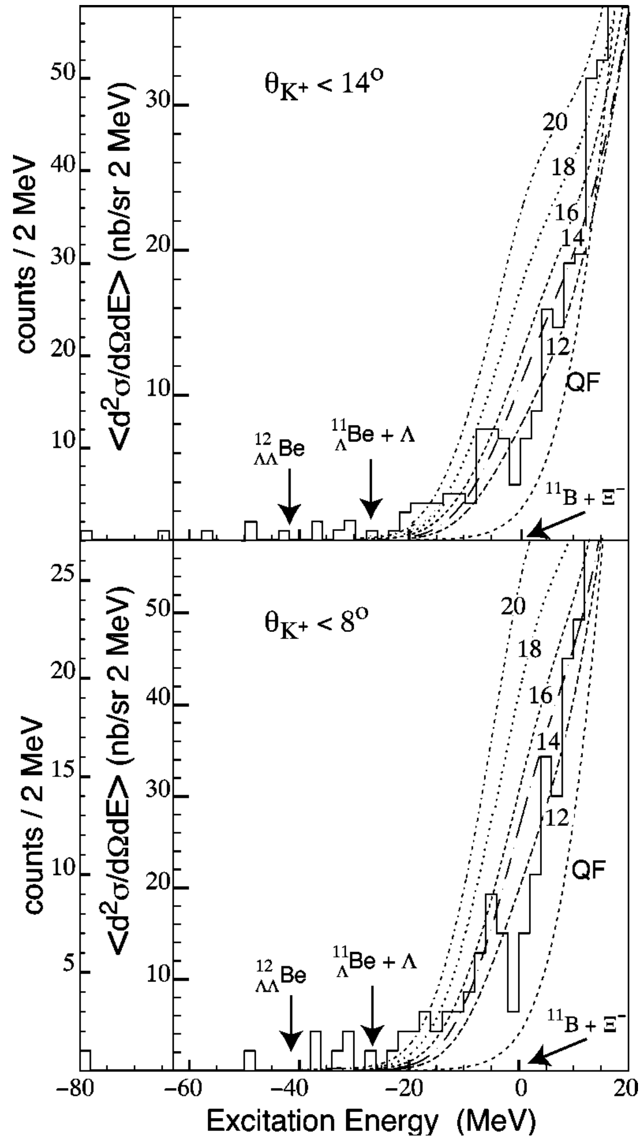
Ξ^- brief overview

mostly experimental

E224 (KEK)

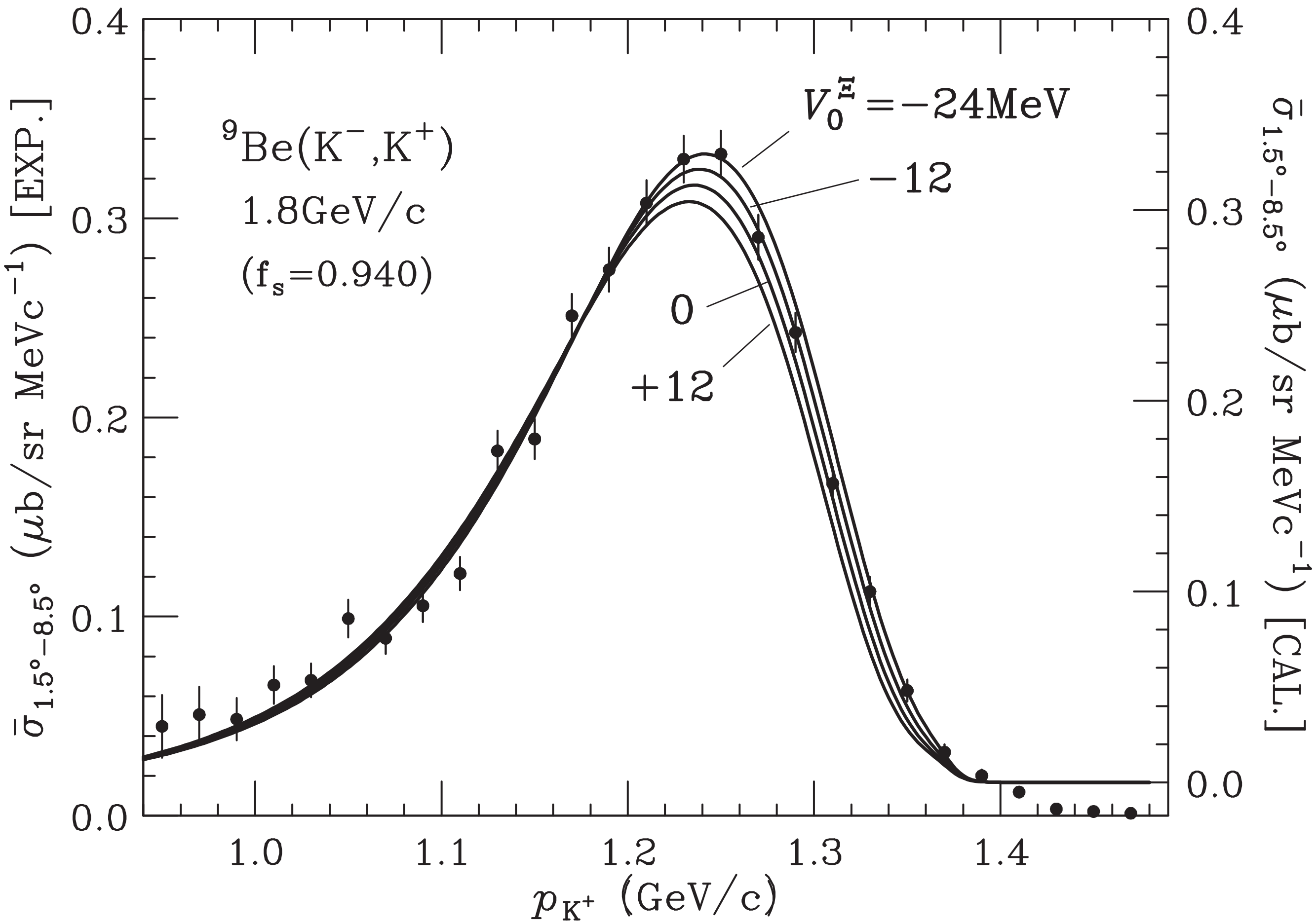


E885 (BNL)



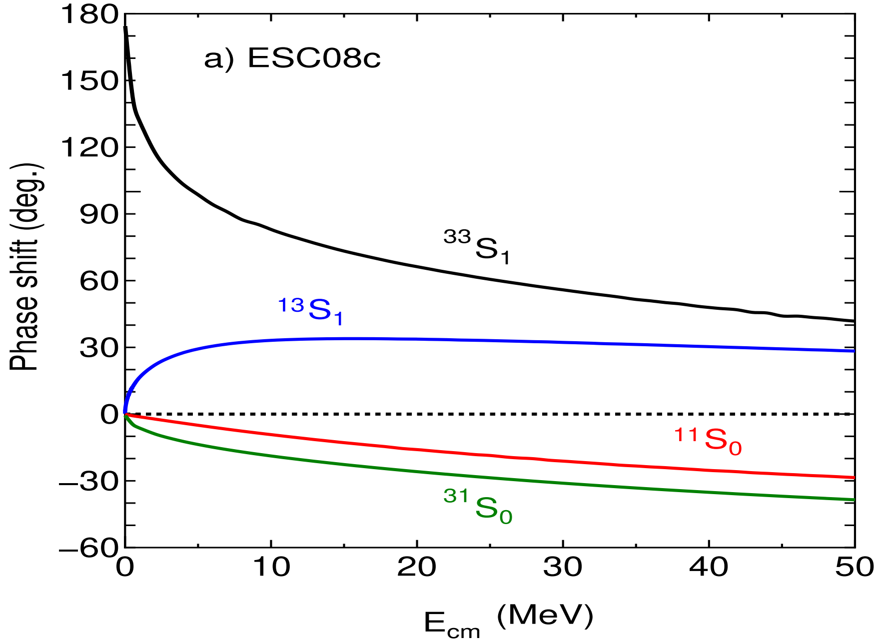
^{12}C(K$^-$,K$^+$) counter experiments, end of 1990s.

Unresolved bound states, if any, V_Ξ of order 15 MeV

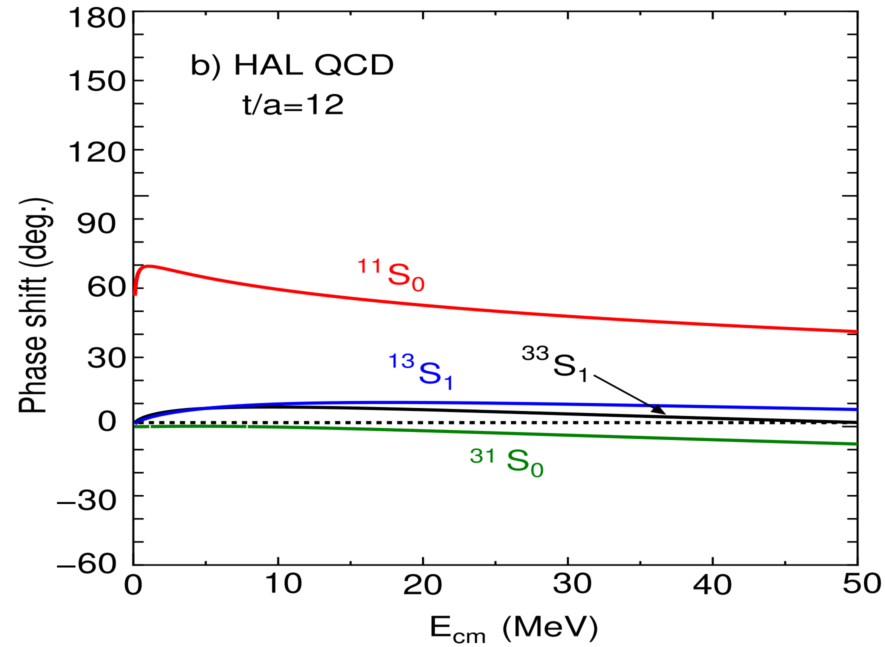


BNL AGS-906 on ^{9}Be claiming a stable $^{4}_{\Lambda\Lambda}$H.
QF calculation, Harada-Hirabayashi (PRC 2021),
concludes V_{Ξ}=17±6 MeV. Yet, no Ξ^- bound state
smoking gun from (K$^-$, K$^+$) experiments.
Await J-PARC final E05 & future E70 results.

ΞN s-wave model interactions



Nijmegen ESC08c version



HAL-QCD version

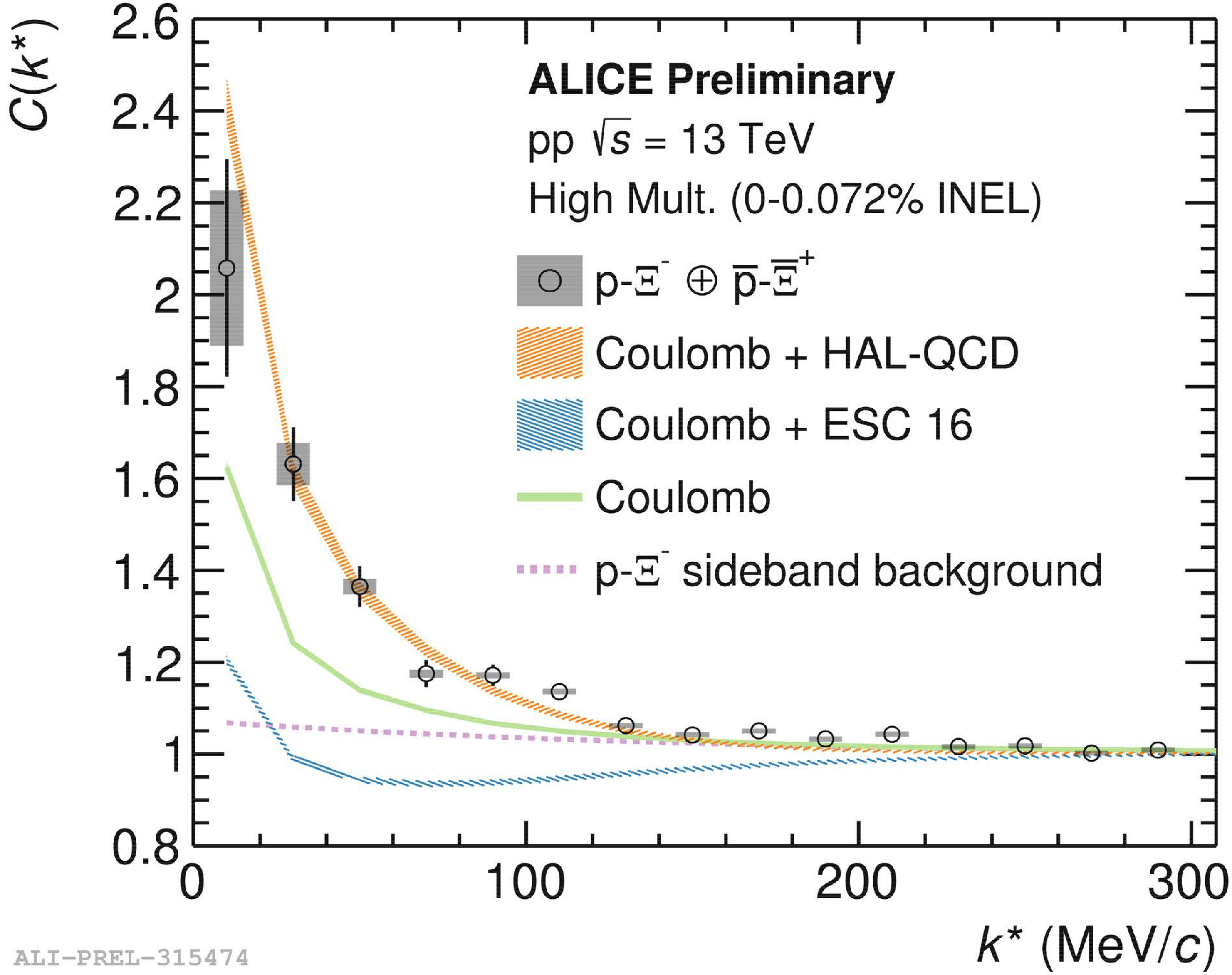
Hiyama et al. PRL 124 (2020) 092501: A$\leq$4 Ξ hypernuclei

Substantial model dependence

HAL-QCD: LQCD calculation at $m_{\pi(K)}$=146(525) MeV

Sasaki et al. NPA 998 (2020) 121737

Inoue et al. AIPCP 2130 (2019) 020002: $V_\Xi^{\rm LQCD}$=4±2 MeV



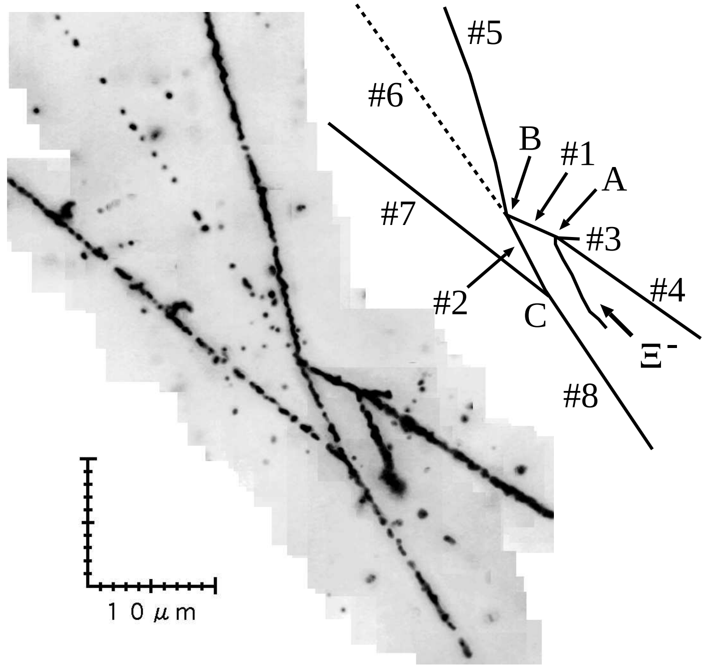
Femtoscopy study of p-Ξ^- correlations

ALICE, PRL 123 (2019) 112002

attractive HAL-QCD – yes, repulsive Nijmegen ESC16 – no

$(\mathrm{K}^-, \mathrm{K}^+)$ in light emulsion nuclei

Ξ^- stopped and captured



Nagara event, ${}_{\Lambda\Lambda}^{\;6}$He, (KEK-E373) PRL 87 (2001) 212502

$B_{\Lambda\Lambda}({}_{\Lambda\Lambda}^{\;6}\mathrm{He})$=6.91±0.16 MeV unambiguously determined.

- **A:** Ξ^- **atomic capture** $\Xi^-_{3D} + {}^{12}\mathrm{C} \rightarrow {}_{\Lambda\Lambda}^{\;6}\mathrm{He} + t + \alpha$
- **B: weak decay** ${}_{\Lambda\Lambda}^{\;6}\mathrm{He} \rightarrow {}_{\Lambda}^{5}\mathrm{He} + p + \pi^-$
- **C:** ${}_{\Lambda}^{5}$He **nonmesonic weak decay to 2** Z**=1 recoils + n.**

Twin Λ: capture & decay vertices

Include IBUKI (J-PARC E07) PRL 126 (2021) 062501

- **A: capture** $\Xi^-_{1p} + {}^{14}\mathrm{N} \to {}^{5}_{\Lambda}\mathrm{He} + {}^{10}_{\Lambda}\mathrm{Be}$
- **B: decay** ${}^{5}_{\Lambda}\mathrm{He} \to {}^{4}\mathrm{He} + \mathrm{p} + \pi^-$
- **C: decay** ${}^{10}_{\Lambda}\mathrm{Be} \to$ 3 or 4 nuclei + neutrons

Exclude KINKA (KEK E373) arXiv:2103.08793

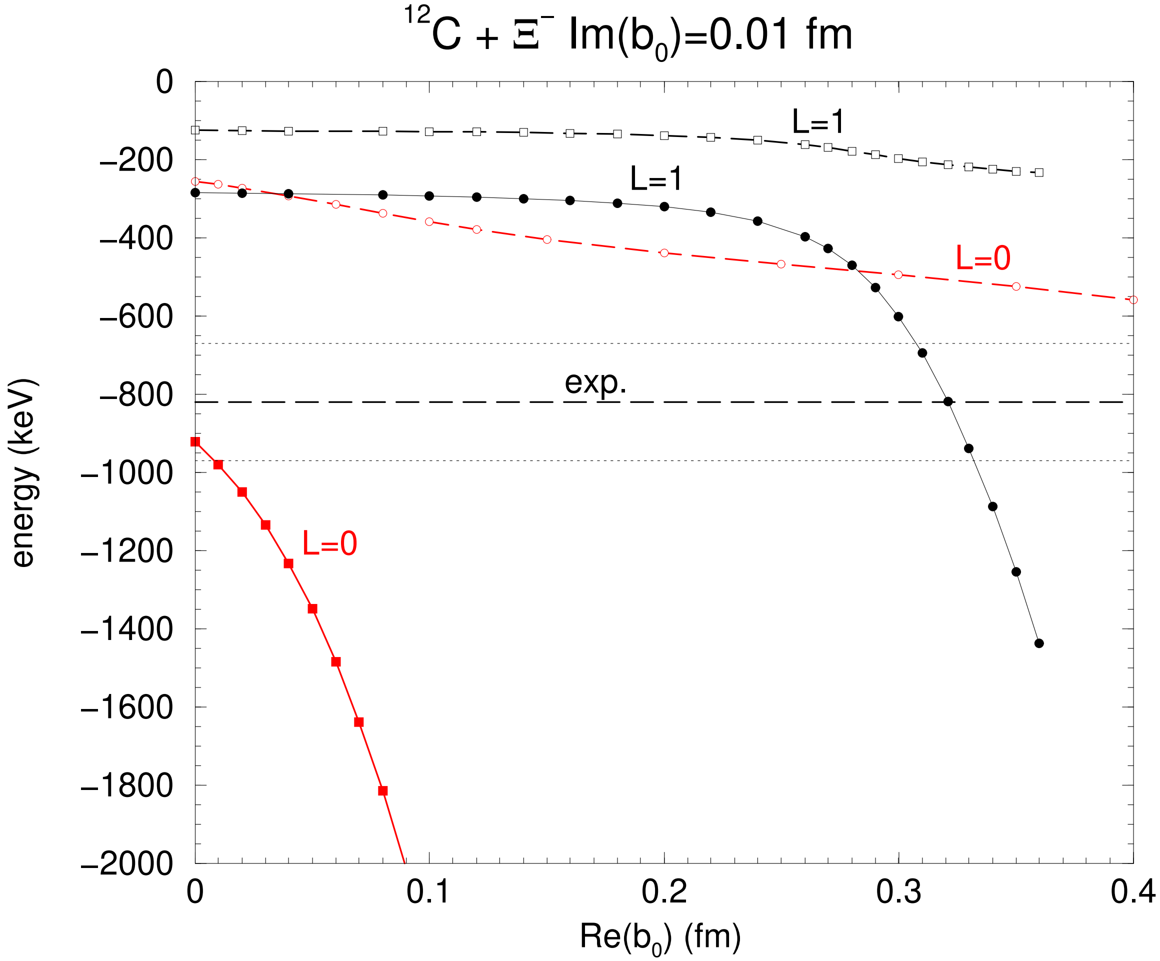
- **A: capture** $\Xi^-_{1s} + {}^{14}\mathrm{N} \to {}^{9}_{\Lambda}\mathrm{Be} + {}^{5}_{\Lambda}\mathrm{He} + \mathrm{n}$
- **B: decay** ${}^{9}_{\Lambda}\mathrm{Be} \to {}^{6}\mathrm{He} + 2\mathrm{p} + \mathrm{n}$
- **C: decay** ${}^{5}_{\Lambda}\mathrm{He} \to$ 2 nuclei + neutrons

Furthermore, $1s_{\Xi^-}$ capture rate is only a few % of $1p_{\Xi^-}$ capture rate

Two-body Ξ^- capture emulsion events

Experiment	Event	^{A}Z	$^{A'}_{\Lambda}$Z'$+^{A''}_{\Lambda}$Z"	B_{Ξ^-} (MeV)
KEK E176	10-09-06	^{12}C	$^{4}_{\Lambda}$H$+^{9}_{\Lambda}$Be	0.82±0.17
KEK E176	13-11-14	^{12}C	$^{4}_{\Lambda}$H$+^{9}_{\Lambda}$Be*	0.82±0.14
KEK E176	14-03-35	^{14}N	$^{3}_{\Lambda}$H$+^{12}_{\Lambda}$B	1.18±0.22
KEK E373	KISO	^{14}N	$^{5}_{\Lambda}$He$+^{10}_{\Lambda}$Be*	1.03±0.18
J-PARC E07	IBUKI	^{14}N	$^{5}_{\Lambda}$He$+^{10}_{\Lambda}$Be	1.27±0.21

- Ξ^- capture occurs mostly from 3D atomic state ($B_{\Xi^-} = 126, 175$ keV in ^{12}C, ^{14}N, respectively).
- To form 1s$^2_{\Lambda}$ in $\Xi^- p \to \Lambda\Lambda$ need $l_{\Xi^-} = l_p$, hence expect capture from a Coulomb-assisted $1p_{\Xi^-}$ nuclear state bound by $\sim$1 MeV, evolving thru Strong Interaction from a 2P atomic state.



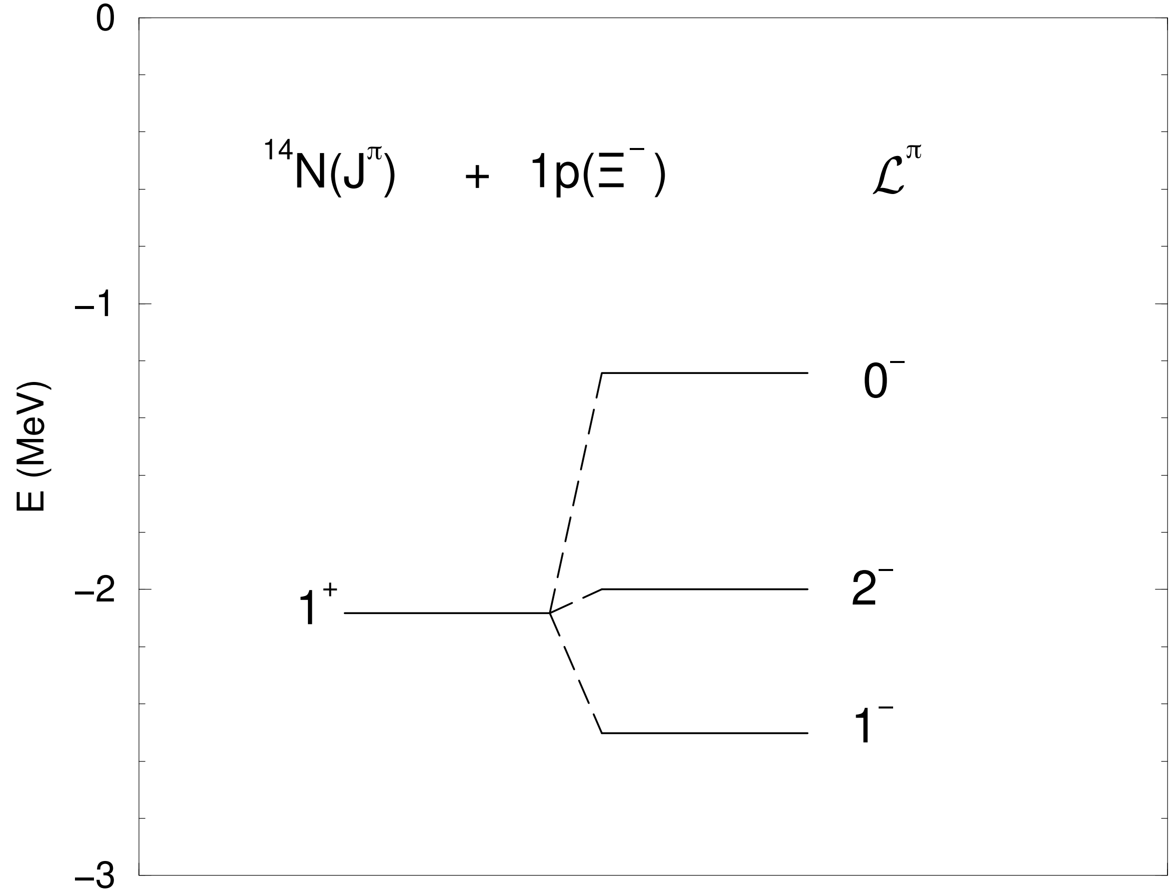
$V_{opt} = t\rho \sim b_0\rho(r)$: scan over Re b_0

Rearrangement: 3P→2P, 2S→1S, 2P→1p, 1S→1s

Fit exp.: Re $b_0 = 0.32 \pm 0.01$ fm ⇒ $V_\Xi = 24.3 \pm 0.8$ MeV

However, it fails in ^{14}N:

$B^{\Xi^-}_{1p}$(calc.)$=2.08 \pm 0.28$ vs. $B^{\Xi^-}_{1p}$(exp.)$=1.15 \pm 0.20$ MeV

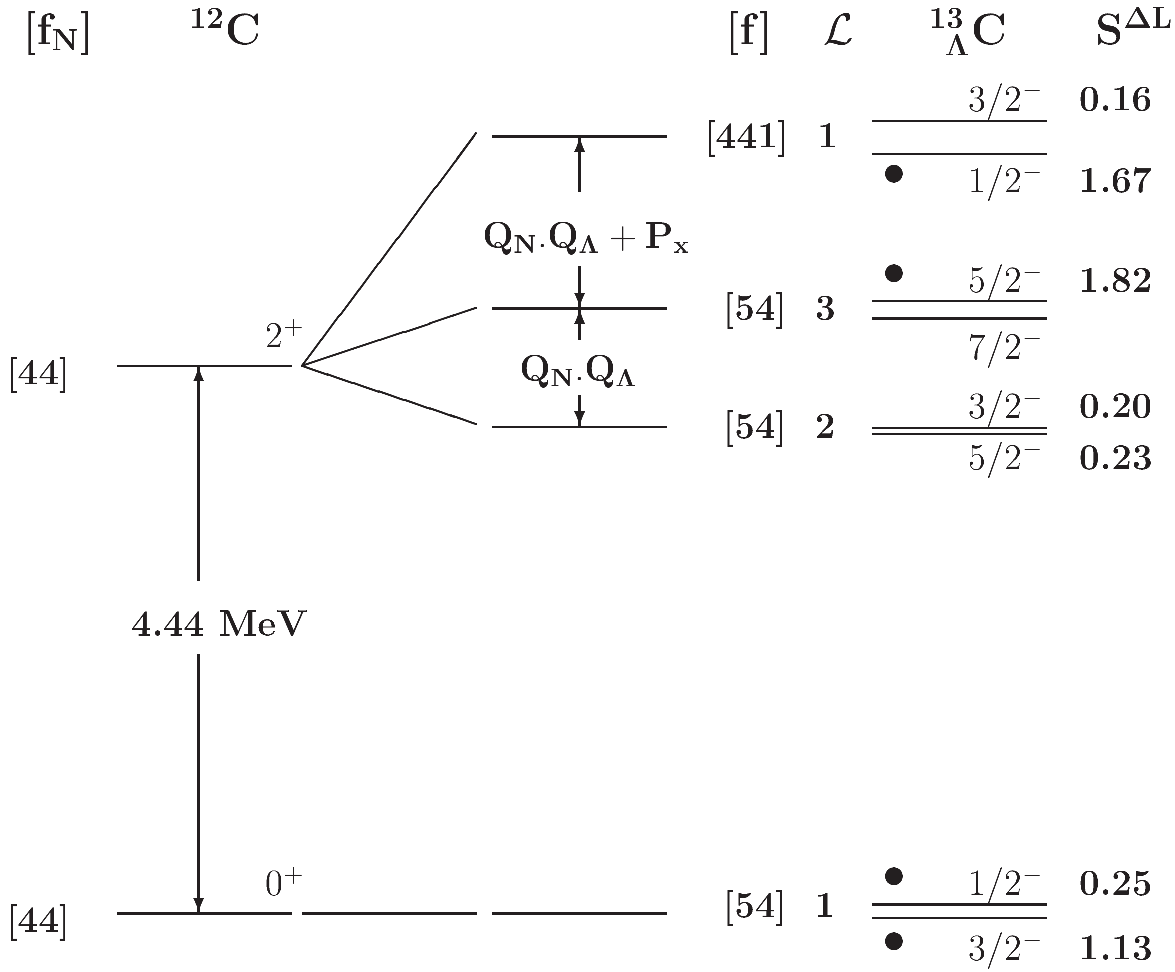


$^{14}\mathbf{N}_{\rm g.s.}(\mathbf{1}^+)$ **split by shell-model residual interaction**

$$\mathbf{F}^{(2)}_{\Xi N}\ \mathbf{Q}_N \cdot \mathbf{Q}_\Xi \qquad\qquad \mathbf{Q}=\sqrt{\frac{4\pi}{5}}\,\mathbf{Y}_2(\hat{r})$$

$$\mathbf{F}^{(2)}_{\Xi N}=-\mathbf{3}\ \mathbf{MeV} \Rightarrow \mathbf{B}^{\Xi^-}_{1p}(\mathbf{0}^-)=\mathbf{1.24\pm0.28\ MeV}$$

agrees with $\mathbf{B}^{\Xi^-}_{1p}(\mathbf{exp.})=\mathbf{1.15\pm0.20\ MeV}$



$\mathbf{Q}_N \cdot \mathbf{Q}_\Lambda$ split ^{12}C(2^+) $\times$ 1p$_\Lambda$ triplet

Auerbach...Dover, Gal...Millener, PRL 1981, AOP 1983

Verified in ^{13}C(K$^-$, π^-)$^{13}_{\Lambda}$C BNL-AGS experiment

Summary & Outlook

- **Consistency reached among all five twin-Λ two-body capture events.**
- **V_{Ξ}=24.3±0.8 MeV in nuclear matter ($\rho_0 = 0.17$ fm^{-3}), down to 21.9±0.7 MeV upon including Pauli correlations.**
- **$B_{1s}(\Xi^-) \approx$ 10 MeV in C.**
- **Likely implications to dense neutron-star matter.**

Thanks to Eli Friedman, partner in this project,

and to all of you in the audience for attention!