Ξ^- capture events in light emulsion nuclei constraining the Ξ-nuclear potential

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based on E. Friedman, A, Gal, PLB 820 (2021) 136555

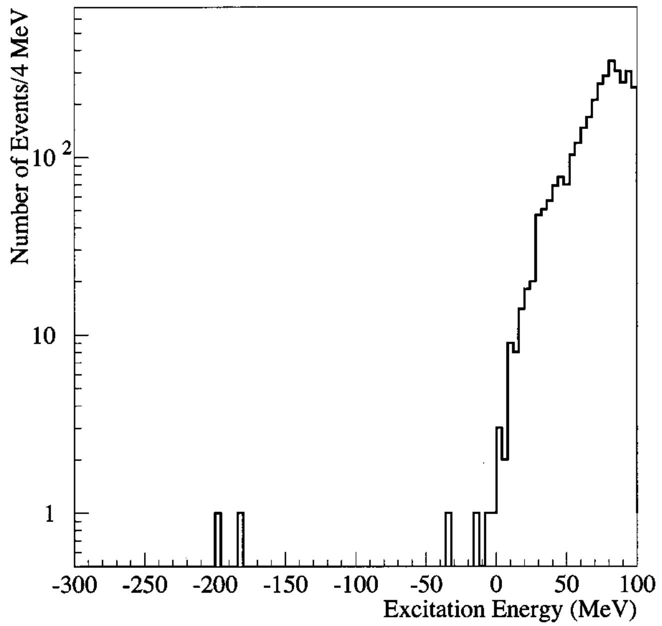
Abstract: All five KEK & J-PARC two-body $\Xi^- + {}^{A}\mathrm{Z} \rightarrow {}^{A'}_{\Lambda}\mathrm{Z'} + {}^{A''}_{\Lambda}\mathrm{Z''}$ capture events in light emulsion nuclei are considered, confirming that they occur from Coulomb-assisted $1p_{\Xi^-}$ nuclear states. The underlying Ξ-nuclear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

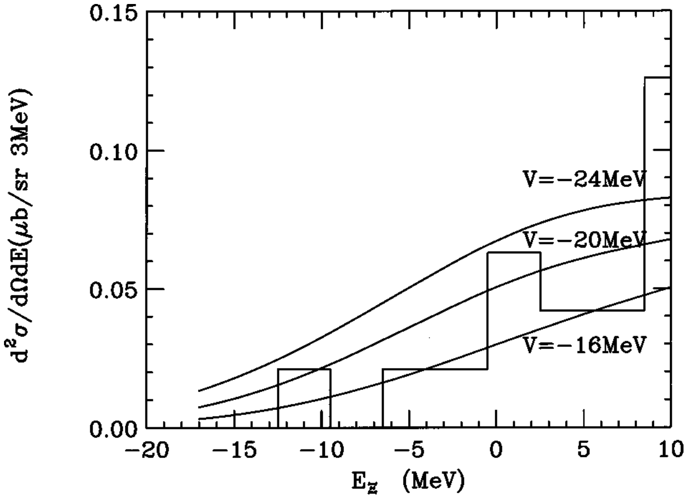
Ξ^- brief overview

from counter experiments

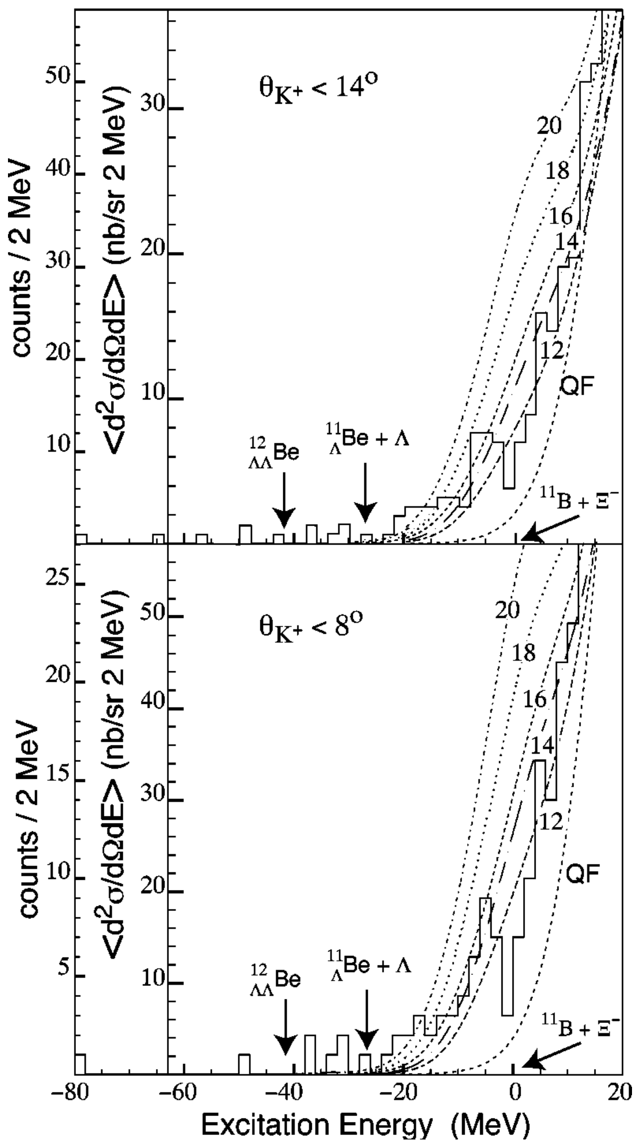
and femtoscopy

E224 (KEK)



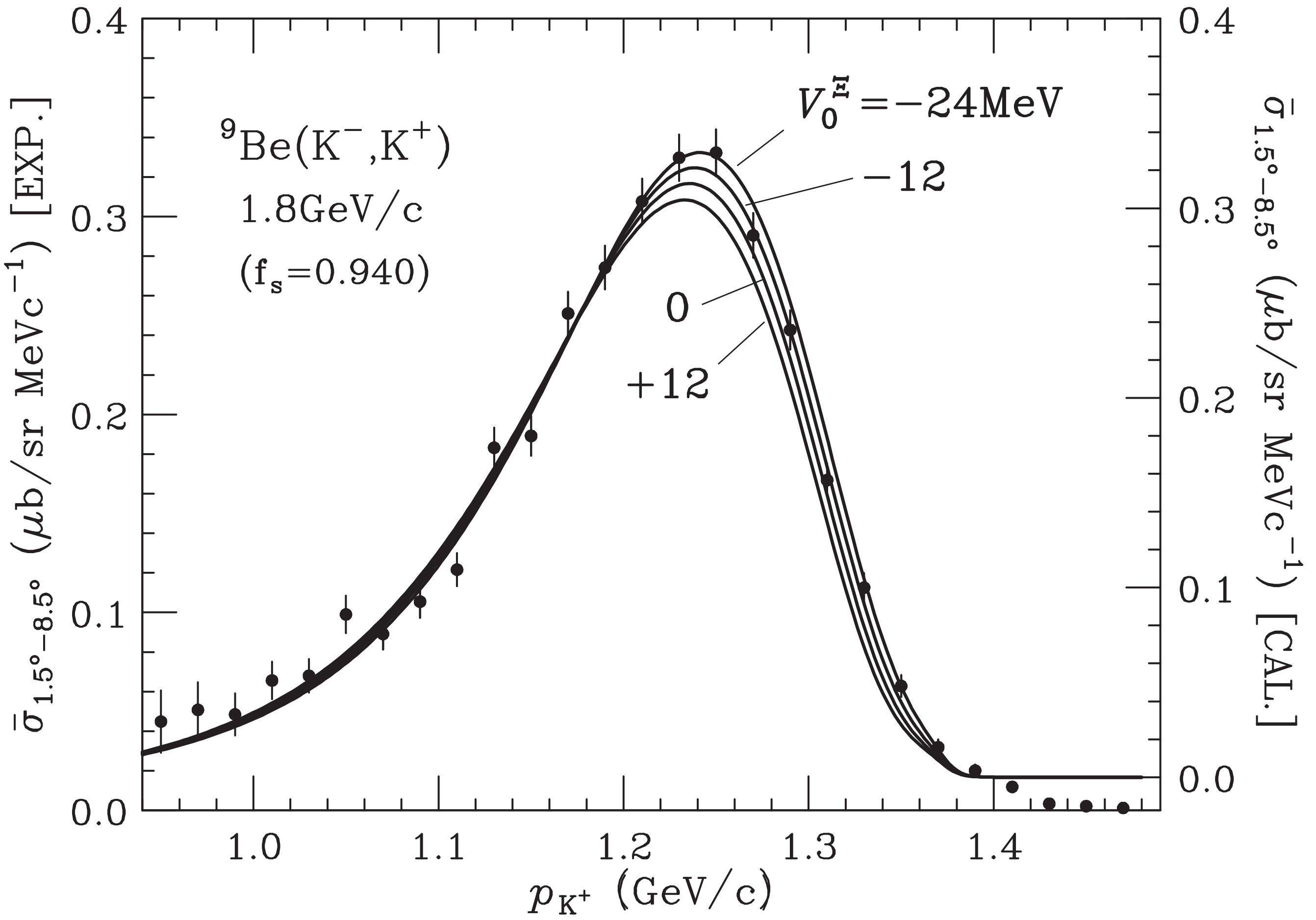


E885 (BNL)



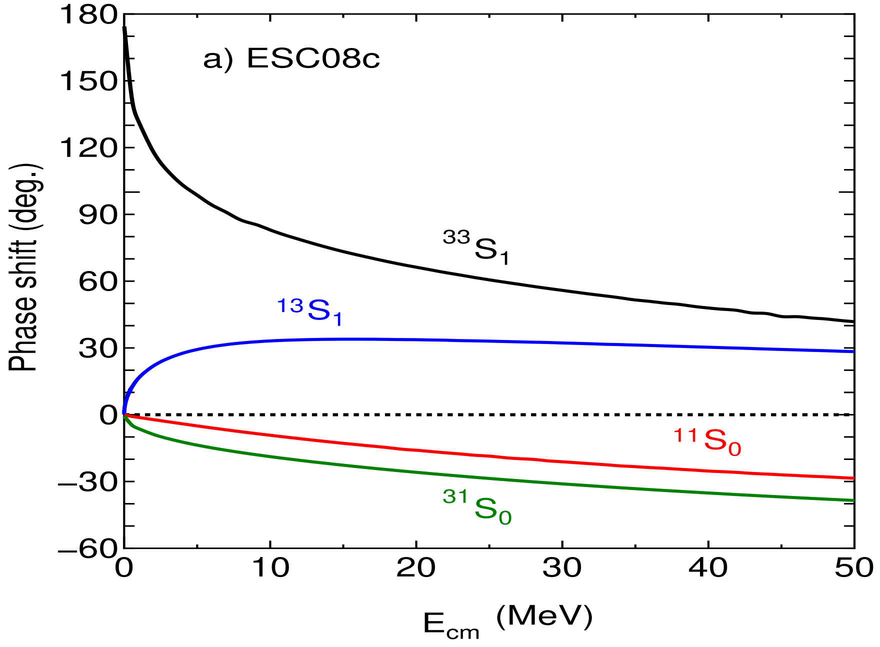
^{12}C(K$^-$,K$^+$) counter experiments, end of 1990s.

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

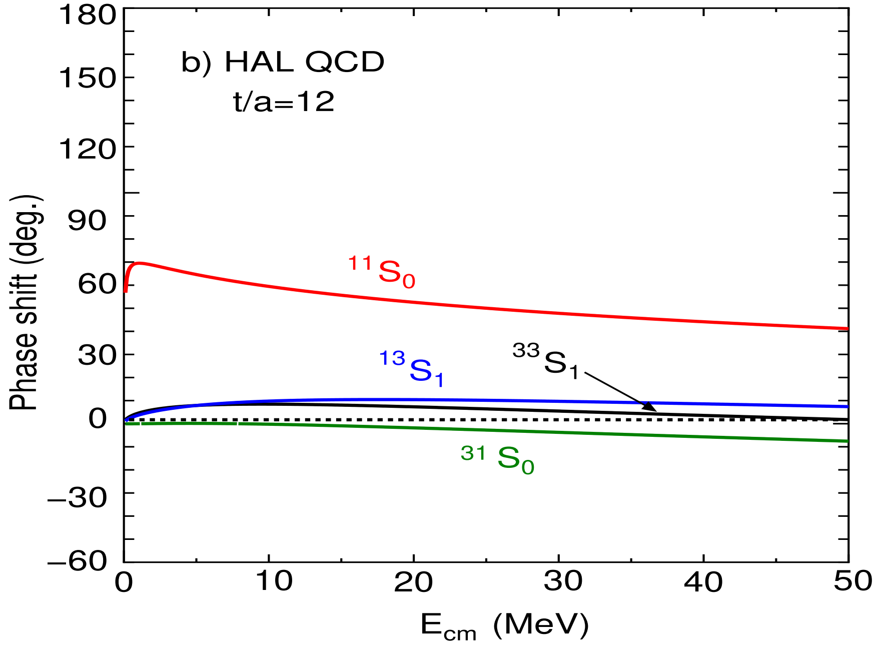


BNL AGS-906 on ^{9}Be claiming a stable $^{4}_{\Lambda\Lambda}$H.
QF calculation, Harada-Hirabayashi (PRC 2021),
concludes V_Ξ=17±6 MeV. Yet, no Ξ^- bound state
smoking gun from (K$^-$, K$^+$) experiments.
Await J-PARC final E05 & future E70 results.

ΞN s-wave model interactions



Nijmegen ESC08c version



HAL-QCD version

Hiyama et al. PRL 124 (2020) 092501: A≤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: $V_\Xi^{\rm LQCD}=4\pm2$ MeV

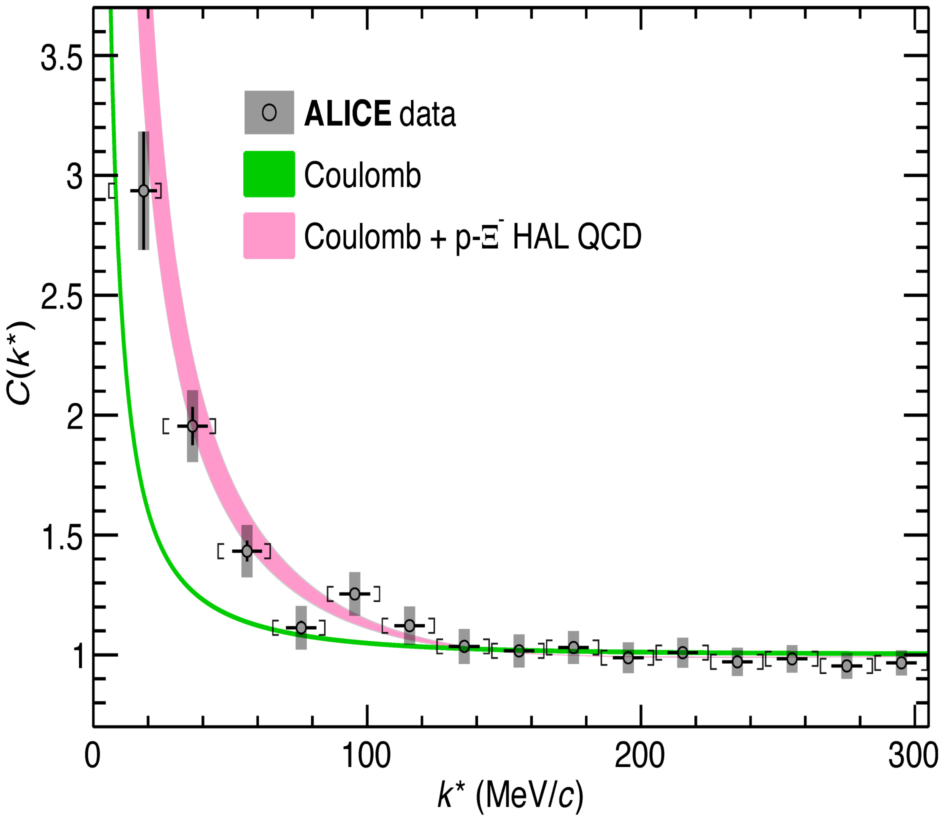
Kohno, PRC 100 (2019) 024313: $V_\Xi^{\rm EFT}\approx 10$ MeV

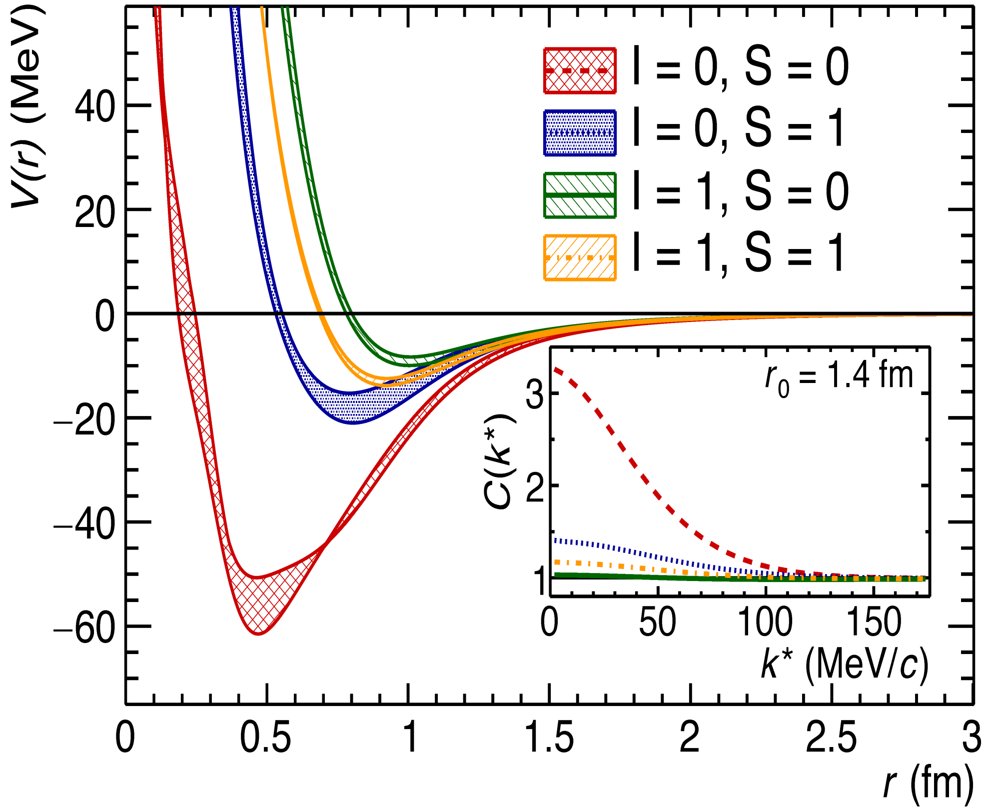
Femtoscopy study of p-Ξ^- correlations

ALICE, PRL 123 (2019) 112002

attractive HAL-QCD – yes

repulsive Nijmegen ESC16 – no





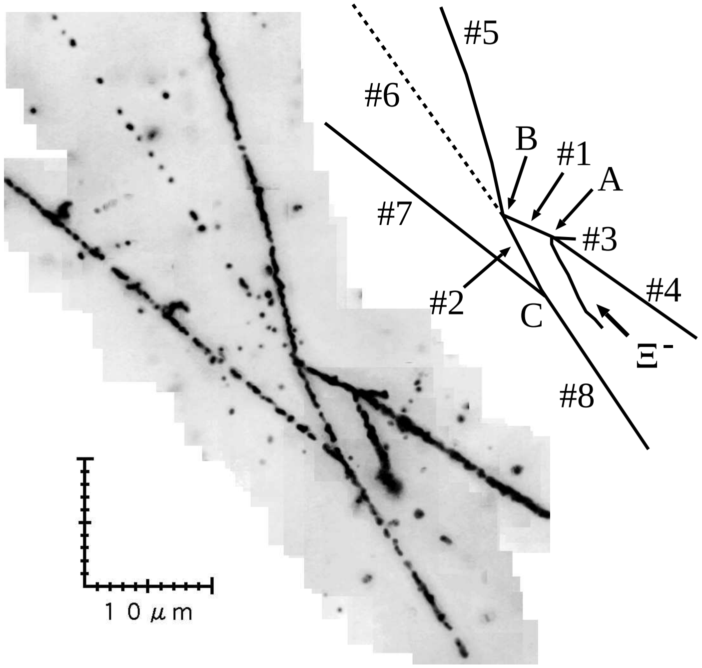
S=$-$2 production at KEK & J-PARC

p(K$^-$, K$^+$)Ξ^- on diamond target,

Ξ^- stops in light emulsion nuclei,

captured & e.m. cascades in a Ξ^- atom,

captured strongly: $\Xi^- p \rightarrow \Lambda\Lambda$.



Nagara event, $_{\Lambda\Lambda}^{\;\;6}\mathrm{He}$, (KEK-E373) PRL (2001), PRC (2013)

$B_{\Lambda\Lambda}(_{\Lambda\Lambda}^{\;\;6}\mathrm{He})$=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:** ${}_{\Lambda}^{5}\mathrm{He}$ **nonmesonic weak decay to 2 Z=1 recoils + n.**

KEK-E373 $\Lambda\Lambda$ events: Mikage vs. Nagara

Solution	^{A}Z	$_{\Lambda\Lambda}^{\ A}Z$	$B_{\Lambda\Lambda}$ (MeV)	Hiyama's $B_{\Lambda\Lambda}$
(1)	^{12}C	$_{\Lambda\Lambda}^{\ 6}He$	10.01±1.71	6.91±0.16
(2)	^{12}C	$_{\Lambda\Lambda}^{\ 11}Be$	20.86±3.06	18.23±0.16
(3)	^{14}N	$_{\Lambda\Lambda}^{\ 11}Be$	22.12±2.67	18.23±0.16

Solution 1: $\Xi^-_{3D} + {}^{12}C \rightarrow {}_{\Lambda\Lambda}^{\ 6}He + {}^{6}Li + n$

${}_{\Lambda\Lambda}^{\ 6}He \rightarrow {}_{\Lambda}^{3}H + p + 2n,\qquad {}_{\Lambda}^{3}H \rightarrow {}^{3}He + \pi^-$

Sol. 2(3): $\Xi^-_{3D} + {}^{12}C({}^{14}N) \rightarrow {}_{\Lambda\Lambda}^{\ 11}Be + p({}^{3}He) + n$

${}_{\Lambda\Lambda}^{\ 11}Be \rightarrow {}_{\Lambda}^{9}Li + p + n,\qquad {}_{\Lambda}^{9}Li \rightarrow {}^{9}Be + \pi^-$

- Unobserved neutrons → large uncertainties, all solutions acceptable within 2σ.
- Similar to uncertainties met in assigning Hida to ${}_{\Lambda\Lambda}^{\ 11}Be$ or ${}_{\Lambda\Lambda}^{\ 12}Be$ (Gal-Millener, 2011).
- Ξ^- capture from a p state is weaker.

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) PTEP 2021 073D02

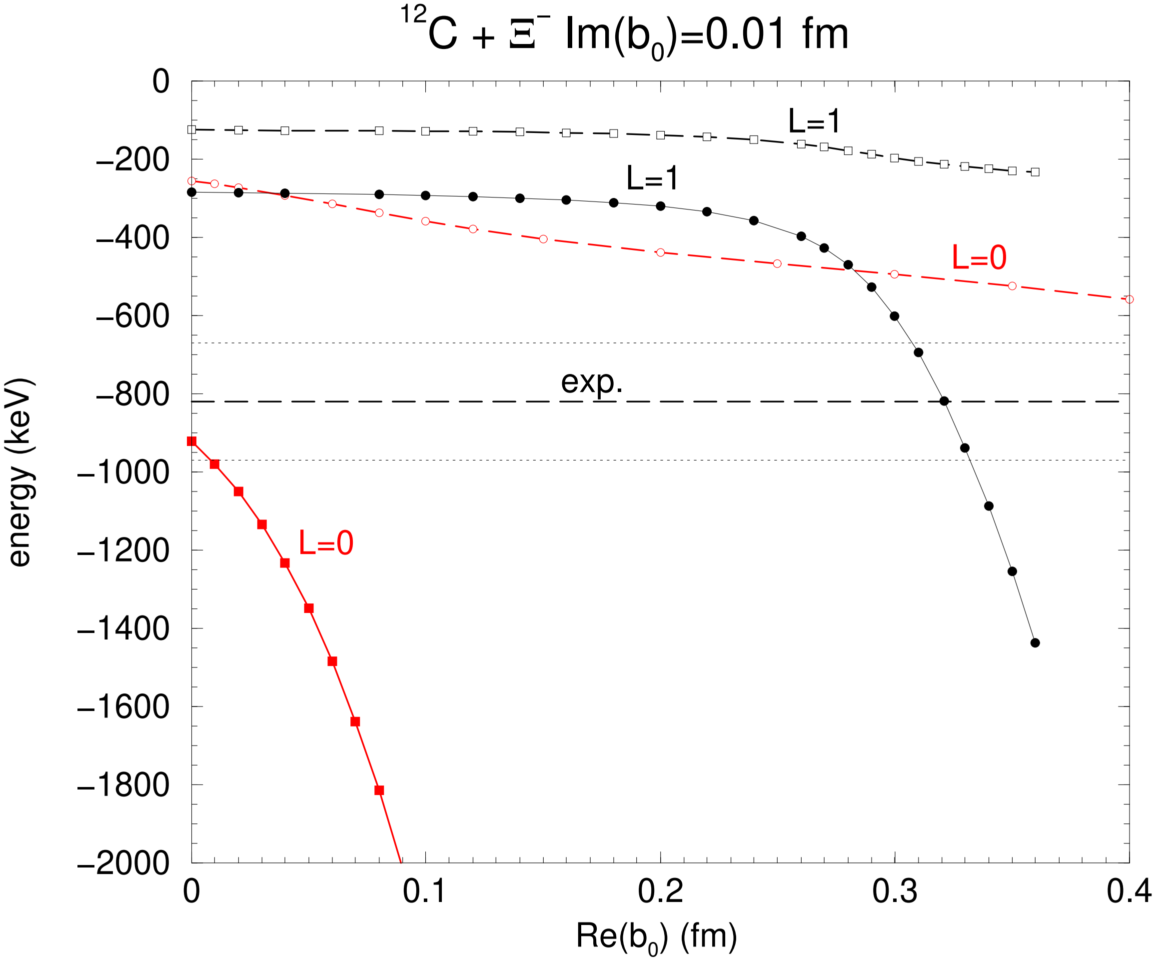
- **A: capture** $\Xi^-_{1s} + {}^{14}\mathrm{N} \to {}^{9}_{\Lambda}\mathrm{Be} + {}^{5}_{\Lambda}\mathrm{He} + \mathrm{n}$
- **B: decay** ${}^{9}_{\Lambda}\mathrm{Be} \to {}^{6}\mathrm{He} + 2\mathrm{p} + \mathrm{n}$
- **C: decay** ${}^{5}_{\Lambda}\mathrm{He} \to$ 2 nuclei + neutrons

Furthermore, $1\mathrm{s}_{\Xi^-}$ capture rate is only a few % of $1\mathrm{p}_{\Xi^-}$ 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 ∼1 MeV, evolving by Strong Interaction from a 2P atomic state.



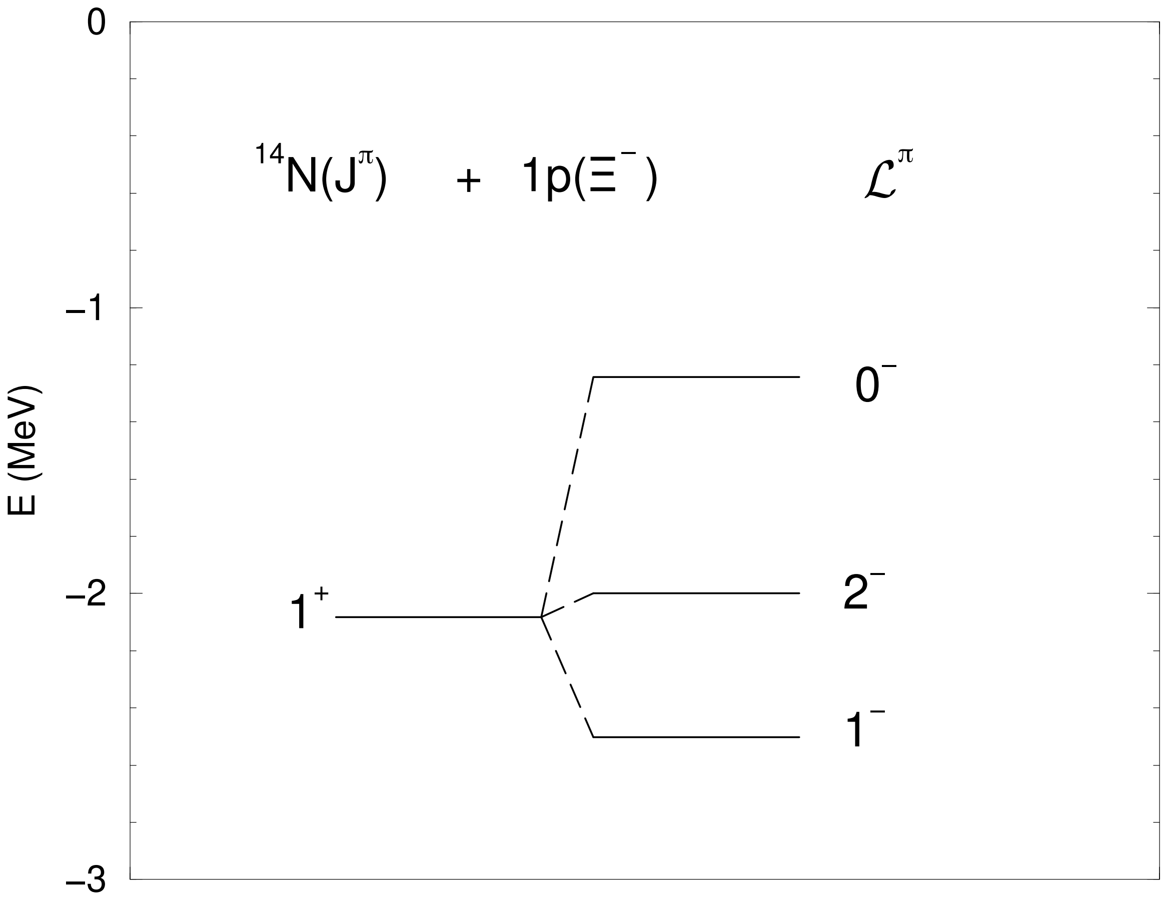
V_{opt}=t$\rho \sim b_0\rho(r)$: scan over Re b_0

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

Fit exp.: Re b_0=0.32±0.01 fm ⇒ V_Ξ=24.3±0.8 MeV

However, it fails in ^{14}N:

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

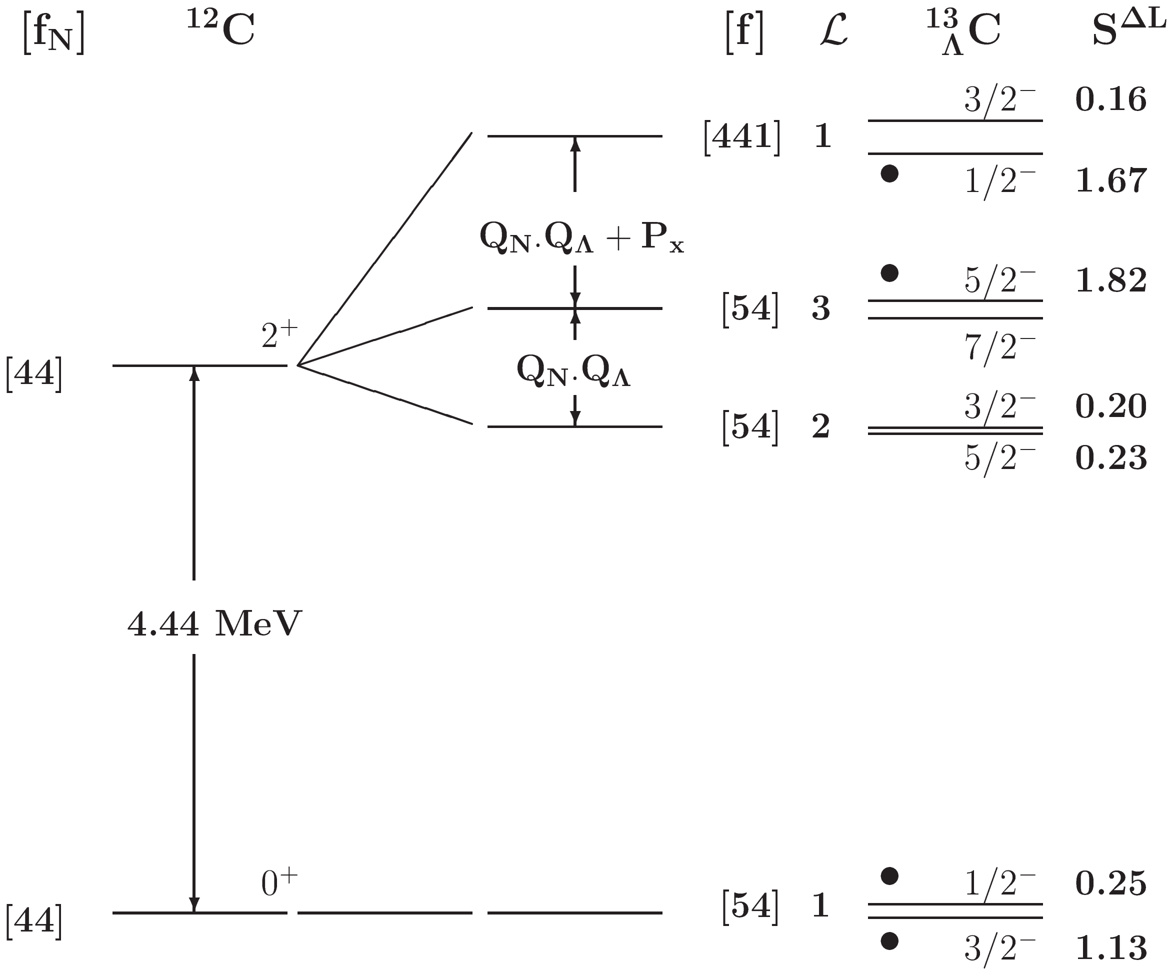


$^{14}\mathrm{N}_{\mathrm{g.s.}}(1^+)$ **split by shell-model residual interaction**

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

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

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



$Q_N \cdot Q_\Lambda$ split ^{12}C(2^+) × $1p_\Lambda$ triplet

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

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

Density Dependence of V_Ξ

$$b_0 \to b_0(\rho): \quad \mathrm{Re}\, b_0(\rho) = \frac{\mathrm{Re}\, b_0}{1 + \frac{3k_F}{2\pi}\mathrm{Re}\, b_0^{\mathrm{lab}}}$$

for Pauli correlations, with $k_F = (3\pi^2\rho/2)^{1/3}$, reducing $V_\Xi(\rho_0) = 24.3 \pm 0.8$ to 21.9±0.7 MeV, with a systematic uncertainty of ≈1 MeV.

- **A similar procedure fitting both 1s & 1p states in ${}^{16}_{\Lambda}$N: $V_\Lambda(\rho_0) \approx 30$ MeV (FG22).**
- **$B_{1s}(\Xi^-) \approx 10$ MeV in ^{12}C, ≈11.5 MeV in ^{14}N, much larger than Kinka's 8.0±0.8 MeV.**
- **Expect $B_{1s}(\Xi^-) \approx 8$–9 MeV in ^{12}C(K^-, K^+) (J-PARC E05→E70).**
- **Could ΞNN contributions prove useful?**

Remarks on SHF Calculations

Guo-Zhou-Schulze, PRC 104 (2021) L061307

Suppressing SHF nonlocal terms and assuming $m^*_\Xi = m_\Xi$, the SHF Ξ mean field depth $V_\Xi(\rho_0)$ in n.m. density ρ_0=0.17 fm^{-1} is fixed by fitting

$$V_\Xi(\rho_N) = [V^{(2)}_\Xi(\rho_N) = a_0\rho_N] + [V^{(3)}_\Xi(\rho_N) = a_3\rho_N^2]$$

in ^{14}N to $B_{\Xi^-}(1s) \approx$ 8.00 MeV (KINKA) and $B_\Xi(1p) \approx$ 1.13 MeV (KISO & IBUKI).

Method	Pauli	$V^{(2)}_\Xi(\rho_0)$	$V^{(3)}_\Xi(\rho_0)$	$V_\Xi(\rho_0)$ (MeV)
SHF	No	34.1	−20.4	13.7
$V_{\rm opt}$	No	27.5	−12.6	14.9
$V_{\rm opt}$	Yes	24.6	−11.0	13.6

Summary & Outlook

- All five twin-Λ two-body capture events: $V_{\Xi}(\rho_0)$=24.3±0.8 MeV, down to 21.9±0.7 MeV with Pauli correlations.
- KEK-E224 & BNL-E885: $V_{\Xi}(\rho_0)\approx$16±2 MeV.
- BNL-E906: $V_{\Xi}(\rho_0)$=17±6 MeV (recent HH).
- EFT & LQCD suggest $V_{\Xi}(\rho_0)\leq$10 MeV.
- SHF using E07 ^{14}N input: $V_{\Xi}\approx$14±1 MeV, with attractive ΞN & repulsive ΞNN terms.
- Why all E07-assigned $1s_{\Xi^-}$ events (Kinka...) are in ^{14}N? Need just one good $1s_{\Xi^-}$ event in ^{12}C.
- Implications to dense neutron-star matter?