Ξ-nuclear constraints from Ξ^- emulsion capture events

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Abstract. All five KEK and J-PARC two-body $\Xi^-+{}^{A}$Z $\rightarrow {}^{A'}_{\Lambda}$Z'+ ${}^{A''}_{\Lambda}$Z" capture events in light emulsion nuclei, including KISO and IBUKI in ^{14}N, are consistent with Coulomb-assisted $1p_{\Xi^-}$ nuclear states. The underlying Ξ-nuclear potential is strongly attractive, with nuclear-matter depth V_Ξ larger than 20 MeV. The recent ^{14}N capture events KINKA and IRRAWADDY assigned by J-PARC E07 to $1s_{\Xi^-}$ nuclear states, and implying considerably shallower V_Ξ, have also another interpretation as $1p_{\Xi^0}$ nuclear states.

1 Introduction: Ξ^- capture events

The nuclear interactions of Ξ hyperons are poorly known [1, 2]. Because of the large momentum transfer in the standard (K^-, K^+) production reaction, induced by the two-body $K^-p \rightarrow K^+\Xi^-$ strangeness exchange reaction, the Ξ^- hyperons are produced dominantly in the quasi-free continuum region, with less than 1% expected to form Ξ^--nuclear bound states that decay by a $\Xi^-p \rightarrow \Lambda\Lambda$ strong-interaction capture reaction. In fact, no Ξ^- or $\Lambda\Lambda$ hypernuclear bound states have ever been observed unambiguously in such experiments, e.g., KEK-PS E224 [3] and BNL-AGS E885 [4], both on ^{12}C, and BNL-AGS E906 [5] on ^{9}Be. A potential depth of $V_\Xi = 17 \pm 6$ MeV was deduced recently from the quasi-free Ξ^- spectrum taken in the ^{9}Be(K^-, K^+) reaction [6].

Here we focus on Ξ nuclear constraints derived by observing Ξ^- capture events in exposures of light-emulsion CNO nuclei to the (K^-, K^+) reaction. A small fraction of the produced high-energy Ξ^- hyperons slows down in the emulsion, undergoing an Auger process to form high-n atomic states, and cascades down radiatively. Strong-interaction capture takes over atomic radiative cascade in a 3D atomic orbit bound by 126, 175, 231 keV in C, N, O, respectively, affected to less than 1 keV by the strong interaction [7]. Interestingly, all two-body Ξ^- capture events $\Xi^- + {}^{A}Z \rightarrow {}^{A'}_{\Lambda}$Z'+${}^{A''}_{\Lambda}$Z" to twin single-$\Lambda$ hypernuclei reported in KEK and J-PARC light-emulsion K^- exposure experiments [8–12] are consistent with Ξ^- capture from a lower orbit: a Coulomb-assisted $1p_{\Xi^-}$ nuclear state bound by $\sim$1 MeV. These capture events are listed in Table 1. Expecting the final two Λ hyperons in $\Xi^-p \rightarrow \Lambda\Lambda$ capture to form in a spin $S = 0$, $1s^2_\Lambda$ configuration, the initial Ξ^- hyperon and the proton on which it is captured must satisfy $l_{\Xi^-} = l_p$ [13], which for p-shell nuclear targets favors the choice $l_{\Xi^-} = 1$. Not listed in the table are multi-body capture events that require for their interpretation undetected capture products, usually neutrons, on top of a pair of single-Λ hypernuclei. Several of these new J-PARC E07 events [12], like KINKA and IRRAWADDY, imply Ξ^- capture from $1s_{\Xi^-}$ nuclear states, with estimated capture rates of order 1% of capture rates from the $1p_{\Xi^-}$ nuclear states considered here [13, 14]. We discuss these states below.

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Table 1. Two-body Ξ^- capture emulsion events from KEK and J-PARC experiments.

Experiment	Event	^{A}Z	$^{A'}_{\Lambda}$Z'+$^{A''}_{\Lambda}$Z"	B_{Ξ^-} (MeV)
KEK E176 [8]	10-09-06	^{12}C	$^{4}_{\Lambda}$H+$^{9}_{\Lambda}$Be	0.82±0.17
KEK E176 [8]	13-11-14	^{12}C	$^{4}_{\Lambda}$H+$^{9}_{\Lambda}$Be*	0.82±0.14
KEK E176 [8]	14-03-35	^{14}N	$^{3}_{\Lambda}$H+$^{12}_{\Lambda}$B	1.18±0.22
KEK E373 [10]	KISO	^{14}N	$^{5}_{\Lambda}$He+$^{10}_{\Lambda}$Be*	1.03±0.18
J-PARC E07 [11]	IBUKI	^{14}N	$^{5}_{\Lambda}$He+$^{10}_{\Lambda}$Be	1.27±0.21

2 Ξ nuclear optical potential

Ξ^- atomic and nuclear bound states are calculated using a standard $t\rho$ optical-potential form [15]

$$V_{\rm opt}(r) = -\frac{2\pi}{\mu}\,(1+\frac{A-1}{A}\,\frac{\mu}{m_N})\,[b_0\,\rho(r)+b_1\,\rho_{\rm exc}(r)], \tag{1}$$

where μ is the Ξ^--nucleus reduced mass and the complex strength parameters b_0 and b_1 are effective, generally density dependent ΞN isoscalar and isovector c.m. scattering amplitudes respectively. The density $\rho = \rho_n + \rho_p$ is a nuclear density distribution normalized to the number of nucleons A and $\rho_{\rm exc} = \rho_n - \rho_p$ is a neutron-excess density with $\rho_n = (N/Z)\rho_p$, implying that $\rho_{\rm exc} = 0$ for the $N = Z$ emulsion nuclei ^{12}C and ^{14}N considered here. A finite-size Coulomb potential V_c, including vacuum-polarization terms is added. For densities we used mostly harmonic-oscillator (HO) densities [16] where the r.m.s. radius of ρ_p was set equal to that of the nuclear charge density [17]. Folding reasonably chosen ΞN interaction ranges other than corresponding to the proton charge radius, or using Modified Harmonic Oscillator densities, or replacing HO densities by realistic three-parameter Fermi density distributions, made little difference: all the calculated binding energies changed by a small fraction, about 0.03 MeV, of the uncertainty imposed by the ±0.15 MeV experimental uncertainty of the 0.82 MeV $1p_{\Xi^-}$ binding energy in ^{12}C listed in Table 1. This holds also for adding a $\rho_{\rm exc} \neq 0$ term induced by considering realistic differences of neutron and proton r.m.s. radii.

Accepting the binding energy interval $B^{1p}_{\Xi^-}$=0.82±0.15 MeV for the two KEK E176 events listed in Table 1, a Ξ-nuclear potential strength of ${\rm Re}\,b_0 = 0.32 \pm 0.01$ fm follows for a fixed value ${\rm Im}\,b_0 = 0.01$ fm. The sensitivity to variations of ${\rm Im}\,b_0$ is minimal: choosing ${\rm Im}\,b_0 = 0.04$ fm [7] instead of 0.01 fm increases ${\rm Re}\,b_0$ by 0.01 fm to 0.33 ± 0.01 fm. The value ${\rm Re}\,b_0 = 0.32 \pm 0.01$ fm implies in the limit $A \to \infty$ and $\rho(r) \to \rho_0$=0.17 fm^{-3} a depth value $V_\Xi = 24.3 \pm 0.8$ MeV in nuclear matter, compatible with that derived from AGS-E906 in Ref. [6] and in agreement with the range of values 21–24 MeV extracted from old emulsion events [18].

So far we have discussed a density independent t-matrix element b_0 in $V_{\rm opt}$, Eq. (1), to fit the Ξ^- capture events in ^{12}C from Table 1. To explore how robust the deduced Ξ potential-depth value $V_\Xi = 24.3 \pm 0.8$ MeV is, we introduce the next to leading-order density dependence of $V_{\rm opt}$, replacing ${\rm Re}\,b_0$ in Eq. (1) by

$${\rm Re}\,b_0(\rho) = \frac{{\rm Re}\,b_0}{1+\frac{3k_F}{2\pi}{\rm Re}\,b_0^{\rm lab}}, \qquad k_F = (3\pi^2\rho/2)^{\frac{1}{3}}, \tag{2}$$

where k_F is the Fermi momentum corresponding to nuclear density ρ and $b_0^{\rm lab} = (1+\frac{m_{\Xi^-}}{m_N})b_0$ is the lab transformed form of the c.m. scattering amplitude b_0. Eq. (2) accounts for Pauli exclusion correlations in ΞN in-medium multiple scatterings [19, 20]. Shorter-range correlations, disregarded here, were shown in Ref. [21] to contribute less than ~30% of the long-range Pauli correlation term. Applying Eq. (2) in the present context, $B^{1p}_{\Xi^-}(^{12}{\rm C})$=0.82 MeV is refitted by ${\rm Re}\,b_0$=0.527 fm. The nuclear-matter Ξ-nuclear potential depth V_Ξ decreases from 24.3±0.8 to 21.9±0.7 MeV, a decrease of merely 10%.

3 $1p_{\Xi^-}$ states in ^{14}N

Applying Eqs. (1,2) to ^{14}N, with $\mathrm{Re}\, b_0$ fitted to $B^{1p}_{\Xi^-}(^{12}\mathrm{C})$=0.82±0.15 MeV, results in $B^{1p}_{\Xi^-}(^{14}\mathrm{N})$=1.96±0.26 MeV, Pauli correlations included. This binding energy is considerably higher than the value B_{Ξ^-}=1.15±0.20 MeV obtained from the three events assigned in Table 1 to Ξ^- capture in ^{14}N. To resolve this apparent dicrepancy, we note that the calculated $B^{1p}_{\Xi^-}(^{14}\mathrm{N})$ corresponds to a $(2\Lambda + 1)$-average of binding energies for a triplet of states $\Lambda^\pi = (0^-, 1^-, 2^-)$ obtained by coupling a $1p_{\Xi^-}$ state to $J^\pi(^{14}\mathrm{N}_{\mathrm{g.s.}})=1^+$, as shown in Fig. 1.

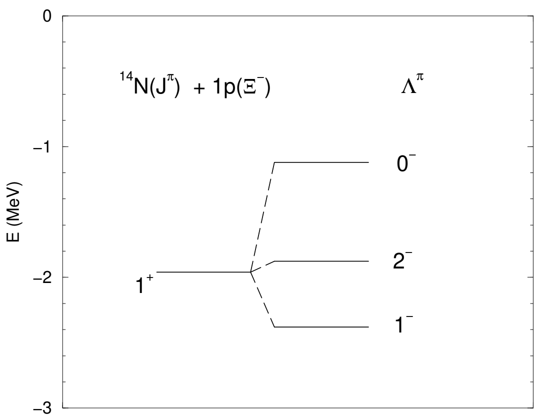

Figure 1. Energies (in MeV) of $\Lambda^\pi = (0^-, 1^-, 2^-)$ triplet of $^{14}\mathrm{N}_{\mathrm{g.s.}} + 1p_{\Xi^-}$ states, split by a $Q_N \cdot Q_\Xi$ residual interaction (3). The $(2\Lambda + 1)$-averaged energy −1.96 MeV was calculated using the same Pauli-corrected optical potential parameter b_0 that yields a $^{12}\mathrm{C}_{\mathrm{g.s.}} + 1p_{\Xi^-}$ state at −0.82 MeV, corresponding to the Ξ^- capture events in ^{12}C listed in Table 1. Figure updating Fig. 2 in Ref. [15].

The energy splittings marked in Fig. 1 follow from a shell-model quadrupole-quadrupole spin independent residual interaction $\mathcal{V}_{\Xi N}$,

$$\mathcal{V}_{\Xi N} = F^{(2)}_{\Xi N} Q_N \cdot Q_\Xi, \quad Q_B = \sqrt{\frac{4\pi}{5}} Y_2(\hat{r}_B), \tag{3}$$

where $F^{(2)}$ is the corresponding Slater integral. A representative value of $F^{(2)}_{\Xi N} = -3$ MeV is used here, smaller than the value $F^{(2)}_{\Lambda N} = -3.7$ MeV established empirically for p-shell Λ hypernuclei [22], in accordance with a ΞN strong interaction somewhat weaker than the ΛN strong interaction. A single $^3D_1$ $^{14}\mathrm{N}_{\mathrm{g.s.}}$ component providing a good approximation to the full intermediate-coupling g.s. wavefunction [23] was assumed in the present evaluation.

Fig. 1 shows a triplet of $^{14}\mathrm{N}_{\mathrm{g.s.}} + 1p_{\Xi^-}$ levels, spread over more than 1 MeV. The least bound of these states, $\Lambda^\pi = 0^-$, is shifted upward by 0.84 MeV from the $(2\Lambda + 1)$ averaged position at -1.96 ± 0.26 MeV to $E(0^-) = -1.12 \pm 0.26$ MeV. This is consistent with the averaged position $\bar{E} = -1.15 \pm 0.20$ MeV of the three Ξ^- $^{14}\mathrm{N}_{\mathrm{g.s.}}$ capture events listed in Table 1. The $\Lambda^\pi = 0^-$ state assumes spin-parity $J^\pi = \frac{1}{2}^-$ when Pauli-spin $s_{\Xi^-} = \frac{1}{2}$ is introduced, but its position is unaffected by spin dependent ΞN residual interactions in leading order. We are not aware of any good reason why capture has not been seen from the other two states with $\Lambda^\pi = 1^-, 2^-$. This may change when more events are collected at the next stage of the ongoing J-PARC E07 emulsion experiment.

4 $1s_{\Xi^-}$ states in ^{14}N?

In addition to the Ξ^-_{1p}–^{14}N capture events listed as KISO and IBUKI in Table 1, the J-PARC light-nuclei emulsion experiment E07 reported also two other events KINKA and IRRAWADDY, assigned as Ξ^-_{1s}–^{14}N states, see Fig. 2. We note that $2P \to 1S$ radiative decay rates are of order 1% of $3D \to 2P$ radiative decay rates [13, 14] suggesting that Ξ^- capture from a nuclear Ξ^-_{1s}–^{14}N state is suppressed to this order relative to capture from a nuclear Ξ^-_{1p}–^{14}N state. Assigning a Ξ^-_{1s}–^{14}N bound state to IRRAWADDY, and by default also KINKA which–given its large uncertainty–is not inconsistent with IRRAWADDY, is therefore questionable.

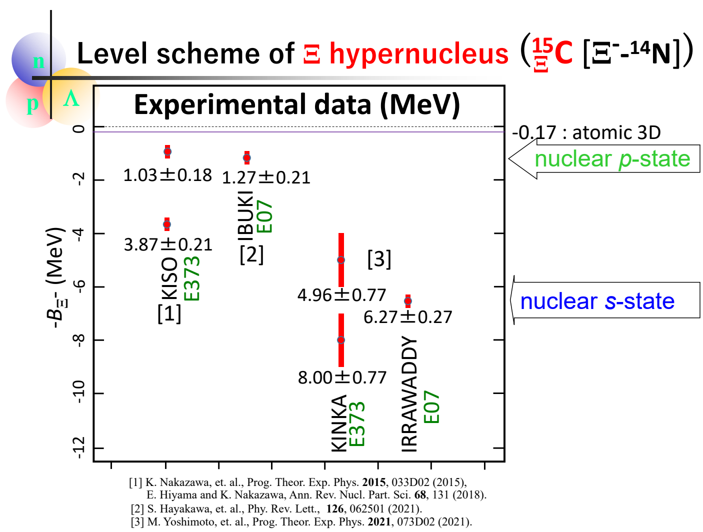

Figure 2. Ξ^-_{1s} and Ξ^-_{1p} nuclear states in ^{14}N, assigned in KEK-E373 and J-PARC E07 emulsion experiments by interpreting Ξ^- capture events that lead to observed twin-Λ hypernuclear decays. Figure provided by Dr. K. Nakazawa, based on recent results from Refs. [10–12].

It has been conjectured by us recently [24] that IRRAWADDY is a near-threshold Ξ^0_{1p}–^{14}C bound state that has nothing to do with a Ξ^-_{1s}–^{14}N bound state suggested by E07. The mixing induced by the ΞN strong interaction between a Ξ^-_{1p}–^{14}N bound state identified with IBUKI and a Ξ^0_{1p}–^{14}C bound state lying about 5 MeV below IBUKU, within the J-PARC E07 experimental uncertainty of IRRAWADDY, is sufficiently strong to make the $E1$ radiative deexcitation of the Ξ^-_{3D}–^{14}N atomic state populate equally well *both* Ξ^-_{1p}–^{14}N and Ξ^0_{1p}–^{14}C nuclear states.

5 Discussion

Two Ξ-nuclear scenarios are listed in Table 2. In the first one, two KEK-E176 ^{12}C events [8], with $B^{1p}_{\Xi^-} = 0.82 \pm 0.15$ MeV, serve as input for setting up the strength of the Ξ-nuclear optical potential. Other Ξ^- binding energies are then predicted, as listed in the first row of Table 2. We note that a value $V_\Xi \gtrsim 20$ MeV implies a substantially stronger in-medium ΞN attraction than reported by some recent free-space model evaluations (HAL-QCD [25], EFT@NLO [26, 27] and RMF [28]), all of which satisfy $V_\Xi \lesssim 10$ MeV. A notable exception is provided by versions ESC16*(A,B) of the latest

Table 2. Ξ^-–^{12}C and Ξ^-–^{14}N binding energies in $1s$ and $1p$ states, $B^{1s}_{\Xi^-}$ and $B^{1p}_{\Xi^-}$, plus Ξ nuclear potential depths $V_\Xi(\rho_0)$ at nuclear-matter density $\rho_0 = 0.17\,\mathrm{fm}^{-3}$ calculated using a density-dependent optical potential Eqs. (1,2) with Re b_0 fitted to binding energies underlined for each input choice. All entries are in MeV.

Input	$B^{1s}_{\Xi^-}(^{12}\mathrm{C})$	$B^{1p}_{\Xi^-}(^{12}\mathrm{C})$	$B^{1s}_{\Xi^-}(^{14}\mathrm{N})$	$B^{1p}_{\Xi^-}(^{14}\mathrm{N})$	$V_\Xi(\rho_0)$
KEK E176 [8]	9.82	$\underline{0.82}$	11.78	1.96	21.9
J-PARC E07 [12]	4.94	0.31	$\underline{6.27}$	0.50	13.8

Nijmegen extended-soft-core ΞN interaction model [29], in which values of V_Ξ higher than 20 MeV are derived. However, these large values are reduced substantially by ΞNN three-body contributions within the same ESC16* model.

Choosing instead the J-PARC E07 ^{14}N IRRAWADDY event, with $B^{1s}_{\Xi^-} = 6.27 \pm 0.27$ MeV [12] as input, gives rise to different predictions as listed in the second row of the table. The difference between the two sets of predictions is striking, particularly for the Ξ^-_{1s} binding energies. This large difference is reflected also in the Ξ-nuclear potential depths at nuclear matter density, $V_\Xi(\rho_0)$, listed in the last column of the table. Equally interesting is the difference between the two sets with regard to Ξ^-_{1p} bound states. In particular, the Ξ^-_{1p}–^{12}C binding energy constrained by $B^{1s}_{\Xi^-}(^{14}\mathrm{N})$=6.27±0.27 MeV comes out in the second row exceedingly small, substantially disagreeing with that determined from the two KEK E176 capture events [8] underlined in the first row. As for the calculated Ξ^-_{1p}–^{14}N binding energies, since $J(^{14}\mathrm{N}) \neq 0$, see Fig. 1, these cannot be compared *directly* with IBUKI's binding energy of 1.27±0.21 MeV from Fig. 2.

Recent Skyrme-Hartree-Fock (SHF) calculations [30] presented global fits to comprehensive Ξ-nuclear data, including $B^{1s}_{\Xi^-}$=8.00 MeV for KINKA and $B^{1p}_{\Xi^-}$=1.13 MeV for the mean of KISO and IBUKI. Apart from small nonlocal potential terms and effective mass corrections, the SHF Ξ-nuclear mean-field potential $V_\Xi(\rho_N)$ consists of two terms: $V^{(2)}_\Xi(\rho_N) \propto \rho_N$ & $V^{(3)}_\Xi(\rho_N) \propto \rho_N^2$. Large-scale SHF fits of the corresponding Ξ potential depths, and their sum, are listed in the first row of Table 3. Listed in the lower rows are Ξ potential depths obtained in the optical potential methodology [31] when fitting just the two Ξ^- states in ^{14}N as used in the SHF calculations [30]. Good agreement is observed between the two methods, with $V_\Xi(\rho_0) \approx 14$ MeV, similar to the depth value listed in the second row of Table 2 using IRRAWADDY alone. We note that the Ξ^-_{1p} state in ^{12}C (see Table 2) comes out unbound in the SHF calculations unless ^{12}C is made artificially deformed [30].

Table 3. Ξ-nuclear potential depths (in MeV) from a large-scale SHF fit [30] and from our V_{opt} two-parameter fits to just $B^{1s}_{\Xi^-}$=8.00 MeV (KINKA) and $B^{1p}_{\Xi^-}$=1.13 MeV (KISO,IBUKI) in ^{14}N. 'Pauli' refers to Eq. (2).

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

The solution proposed here to the difficulty of interpreting IRRAWADDY as a Ξ^-_{1s} bound state in ^{14}N is by pointing out that it could correspond to a Ξ^0_{1p}–^{14}C bound state, something that cannot occur kinematically in the other light-emulsion nuclei ^{12}C and ^{16}O. Given that in this nuclear mass range capture rates from $1s_{\Xi^-}$ states are estimated to be two orders of magnitude below capture rates from $1p_{\Xi^-}$ states [13, 14], this Ξ^0_{1p}–^{14}C new assignment addresses satisfactorily the capture rate hierarchy.

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