Observation of Coulomb-assisted nuclear bound state of $\Xi^{-#14}$N system

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An emulsion–counter hybrid experiment was performed at J-PARC. We observed a $\Xi^{-}$ absorption event decaying into twin single-$\Lambda$ hypernuclei in nuclear emulsion. The reaction process was uniquely identified to be $\Xi^{-} + ^{12}$C -> $^{10}$Be + $^{3}$He by kinematic calculation. The binding energy of the $\Xi^{-}$ hyperon in the $\Xi^{-} + ^{14}$N system was measured to be 1.27 ± 0.21 MeV. The energy level of $\Xi^{-}$ is likely a nuclear 1p state. This indicates that the $\Xi N$–$\Lambda \Lambda$ coupling is weak.

For further understanding of the baryon–baryon interaction, the use of SU(3) flavor symmetry has been investigated. In contrast to a relatively large amount of information on $S = -1$ hypernuclei, the experimental data regarding $S = -2$ systems are still scarce. The $\Lambda \Lambda$ interaction has been studied by measurements of double-$\Lambda$ hypernuclei. The binding energy of $^{6}$AHe revealed that the $\Lambda \Lambda$ interaction is weakly attractive [1, 2]. The study of $\Xi$ hypernuclei provides meaningful information on the $\Xi N$ interaction. The missing-mass spectroscopy was performed using the ($K^{-}, K^{+}$) reaction at KEK E224 and BNL E885 experiments. In both experiments, a peak in the bound state reaction could not be observed due to the low energy resolution [3, 4]. The BNL E885 estimated the potential depth of the $\Xi$ to be about 14 MeV assuming the Woods-Saxon type potential, for which the binding energy was about 4.5 MeV. The missing-mass of the $^{12}$C($K^{-}, K^{+}$) reaction was measured at J-PARC [5]. A new improved experiment is planned at J-PARC with an expected energy...
resolution of better than 2 MeV FWHM [6]. Furthermore, the $\Xi^-$–$p$ interaction was studied by ALICE [7]. From the two-body correlations, the presence of a strong and attractive interaction was presented.

Several emulsion experiments reported the possibility of an attractive $\Xi$–nucleus interaction. The remarkable event named “KISO” was found by the KEK E373 experiment [8]. The decay mode of that event was uniquely identified to be $\Xi^- + ^{14}_{\Lambda} \text{N} \rightarrow ^{10}_{\Lambda} \text{Be} + ^{5}_{\Lambda} \text{He}$. The binding energy of the $\Xi^-$ hyperon in the nucleus, $B_{\Xi^-}$, was measured at $3.87 \pm 0.21$ MeV or $1.03 \pm 0.18$ MeV for production of $^{10}_{\Lambda} \text{Be}$ in either the ground state or the first excited state, respectively [9]. In both cases, the bound state of the $\Xi^- + ^{14}_{\Lambda} \text{N}$ system is expected to be deeper than the atomic $3D$ orbit. The $\Xi N$ interaction can also be extracted by measuring the energy shift and width of X-rays from $\Xi$-atoms. Two experiments involving $\Xi$-atomic X-ray measurements using Ge detectors have been proposed at J-PARC [10, 11], E07 being the one described in this paper.

A theoretical calculation of the binding energy of the $\Xi^- + ^{14}_{\Lambda} \text{N}$ system was presented by Yamaguchi et al. using the $\Xi N$ one-boson-exchange potential called the Ehlme potential [12]. In this calculation, the coupling constants are adjusted so as to reproduce the experimental result of the $\Xi^- + ^{12}_{\Lambda} \text{C}$ bound states with $B_{\Xi^-} \sim 0.6$ MeV observed in the KEK E176 experiment [9, 13]. The calculation for the $\Xi^- + ^{11}_{\Lambda} \text{B}$ system predicts the binding energy of the ground state, which is in agreement with the excitation energy spectrum in the BNL E885 experiment. T. T. Sun et al. performed a theoretical calculation with the relativistic-mean-field (RMF) and Skyrme-Hartree-Fock (SHF) models [14]. The preferred interpretation of the Kiso event was an observation of an excited state of the $^{10}_{\Lambda} \text{Be}$. When the $\Xi N$ interaction was adjusted so as to reproduce the binding energy for the KISO event assuming the $1p$ state in the case of $^{10}_{\Lambda} \text{Be}$ being in the excited state, the predicted $\Xi^-$ removal energy of $^{15}_{\Lambda} \text{C}$ in the $1s$ state was 7.2–9.4 MeV. In a recent study of Lattice QCD calculations [15], the $\Xi N$ interaction potentials are available for various $S = -2$ channels with almost physical quark masses ($m_\pi =$ 146 MeV). The lattice calculations indicated that the coupling between $\Lambda\Lambda$ and $\Xi N$ states is weak.

J-PARC E07 is an emulsion–counter hybrid experiment designed to identify the decay modes of around 10 events of $S = -2$ hypernuclei [11]. The experiment was carried out using a 1.81 GeV/c $K^-$ beam at the K1.8 beam line of the Hadron Experimental Facility at J-PARC [16, 17]. The beam intensity and purity were $2.8 \times 10^5$ kaons per spill (2s duration) and 82%, respectively. The $\Xi^-$ hyperons produced in the quasi-free "p"$(K^-, K^+)\Xi^-$ reaction in a diamond target of 9.87 g/cm$^2$ thickness were injected into an emulsion module. The emulsion module consisted of two 380-µm-thick sheets and eleven 1-mm-thick sheets with $34.5 \times 35.0$ cm$^2$ area. Positions and angles of the produced $\Xi^-$ hyperons were measured with silicon strip detectors (SSD) located between the target and the emulsion. Hyperfragments emitted from the $\Xi^-$ hyperon absorption points were observed in the emulsion using a microscope. Charged particles emitted from the hyperfragments and escaping out of the emulsion modules were detected by two SSDs placed both upstream and downstream of the emulsion. Both SSDs had the same strip pitch of 50 µm and 4 layers with a thickness of 320 µm. The incident $\Xi^-$ hyperons were eventually slowed down and captured at rest in the atomic orbit of a nucleus in the emulsion material. $\Xi$ hypernuclei or double-$\Lambda$ hypernuclei are generated at the capture point with some probability [16], and the decay tracks of charged particles are recorded in the emulsion module. A total amount of 118 emulsion modules were exposed to $1.13 \times 10^{11}$ $K^-$ particles. About 100 events of $S = -2$ hypernuclei were expected to be produced among $10^4$ $\Xi^-$ stopped in the emulsion. Refer to [19] for more information on the experimental setup and the analysis. The $\Xi$-atomic X-rays were also measured by using Germanium detectors. Details are presented in Ref. [20].

A remarkable event forming a twin-$\Lambda$ hypernuclear topology was found in the tenth sheet of module #047. Figure 1 shows a superimposed image and a schematic drawing of the event. We named the event “IBUKI” [21]. The $\Xi^-$ traced in sequence from upstream was
points were found inside of the emulsion module. No charged daughter particles were found at the ends of tracks #5, #6, and #9 in the eleventh, the third, and the ninth sheets, respectively. Track #8 ended in the twelfth sheet as shown in Figure 2. The thick track #8 accompanied by particle emission at the stopping point indicates a negative particle. Additional support for this comes from the observed Auger emission. Thus, a twin Λ hypernuclei event was observed. Table I summarizes measured values of ranges and emission angles of the nine tracks. The angles are expressed by a zenith angle (θ) and an azimuthal angle (φ) with respect to the axis perpendicular to the emulsion sheet. For tracks #6, #8, and #9, the ranges in the base film were converted to those in the emulsion layer.

FIG. 2. Photograph of the end point of track #8. The range of a charged particle emitted from the end point was measured to be 178.13 ± 1.04 μm. An Auger electron was also observed.

Since the energy calibration and the range correction were necessary for the kinematic analysis, the density of the emulsion was measured using 132 α tracks with a monochromatic energy of 8.785 MeV from the decay of 212Po. The mean range and the emulsion density were measured to be 50.25±0.11 μm and 3.544±0.012 g/cm³, respectively.

For each vertex point, all possible decay modes were kinematically examined considering both mesonic and non-mesonic decays. Among various nuclear species in the emulsion, C, N, and O were taken into account as nuclei to capture the Ξ hyperon. Emission of neutral particles also needed to be considered. The possibility of the emission of up to three neutral particles was included in the kinematic calculation. As for the mass of the Λ hypernuclei, the values obtained from the experimental data were utilized [22–30]. Mass values of some possible Λ hypernuclei were also taken into account via a calculation with linear interpolation and extrapolation of BΛ, where a typical error in the fitting of the masses of 0.5 MeV/c² was uniformly assumed.

The residual of the reconstructed invariant mass from the initial mass was calculated for each decay mode. In the case of vertex A, the sum of the masses of Ξ− and a capturing nucleus was used as the initial mass. Regarding vertex B and C, the mass of a Λ hypernuclei was assumed. The binding energy of Ξ− (BΞ−) was obtained by subtracting the reconstructed mass from the initial mass at vertex A. In decay modes containing only one neutral particle, the invariant mass was obtained by assuming that the neutral particle was emitted in such a direction as to conserve the total momentum. If decay modes include multiple neutral particles, such neutral particles were treated as to be emitted in the same direction. Therefore, those multiple neutral particles were treated as a single particle such as '2n' and '3n'. Since this assumption provided the minimum kinetic energy of the neutral particles, the obtained BΞ− represents maximum values.

Figure 3 shows BΞ−, and the magnitude of the total momentum, p_total, for all possible decay modes for vertex A. The black dots and open circles indicate the decay modes including known and possible Λ hypernuclei, respectively. The p_total value was required to be zero within 3σ tolerance. Since the stopped Ξ− cascades down atomic orbitals before being absorbed by the nucleus, the binding energy will be positive, at least within the experimental error. The value of BΞ− was required to be more than zero with 3σ tolerance, even if multiple neutral particles are emitted. Finally, only one decay mode of

$$\Xi^- + ^{14}\text{N} \rightarrow ^{10}_\Lambda\text{Be}(\#1) + ^3\text{He}(\#2)$$

was accepted around the position of p_total ~ 40 MeV/c and BΞ− ~ 1 MeV in Figure 3.

FIG. 3. Correlation plot of the binding energy and the magnitude of the total momentum at vertex A. Black dots and open circles indicate the decay modes including known and possible Λ hypernuclei, respectively.

At vertex B, the kinematic calculation was also performed using tracks #3–6. 358 possible decay modes
remained within $3\sigma$ tolerance of the energy and the momentum conservation law independent of the result of vertex A. Among them, thirteen decay modes for the case of track #1 being $^8\text{Be}$ are listed in Table II. Many decay modes were accepted due to the large $Q$ value of non-mesonic decay. Moreover, at least two neutral particles were likely to be emitted. The listed thirteen decay modes were consistent with vertex A.

TABLE II. Possible decay modes at vertex B for the case of track #1 being $^8\text{Be}$.

| #3 | #4 | #5 | #6 | $Q$ [MeV] | $B_\Lambda$ [MeV] |
|----|----|----|----|----------|-----------------|
| $p$ | $d$ | $t$ | $p$ | 3$n$ | 120.06 | < 11.81 |
| $p$ | $t$ | $d$ | $p$ | 3$n$ | 120.06 | < 11.81 |
| $p$ | $t$ | $t$ | $p$ | 2$n$ | 126.32 | < 12.83 |
| $d$ | $p$ | $t$ | $p$ | 3$n$ | 120.06 | < 12.71 |
| $d$ | $d$ | $d$ | $p$ | 3$n$ | 116.03 | < 12.89 |
| $d$ | $d$ | $t$ | $p$ | 2$n$ | 122.28 | < 10.04 |
| $d$ | $t$ | $t$ | $p$ | 3$n$ | 120.06 | < 20.07 |
| $d$ | $d$ | $d$ | $p$ | 2$n$ | 122.28 | < 15.27 |
| $t$ | $p$ | $d$ | $p$ | 3$n$ | 120.06 | < 17.31 |
| $t$ | $d$ | $p$ | $p$ | 2$n$ | 126.32 | < 15.09 |
| $t$ | $d$ | $d$ | $p$ | 3$n$ | 120.06 | < 20.15 |
| $t$ | $d$ | $d$ | $p$ | 2$n$ | 122.29 | < 15.88 |
| $t$ | $t$ | $p$ | $p$ | 2$n$ | 126.32 | < 22.48 |

Since the length of track #3 was very short, the topology without track #3 was also tested. The coplanarity of three tracks is defined as $(\hat{r}_1 \times \hat{r}_2) \cdot \hat{r}_3$, where $\hat{r}_i$ represents the unit vector of $i$-th track direction. The coplanarity of tracks #4–6 was obtained to be $-0.500 \pm 0.034$. This makes some neutron(s) emission likely. The accepted decay modes for the case of track #1 being $^8\text{Be}$ are listed in Table III. From forty-eight candidates, the listed three decay modes were consistent with the result at vertex A. Since no track from $\beta$ decay of $^6\text{He}$ to $^6\text{Li} + e^- + \bar{\nu}$ is visible at the end of track #4, the case of track #4 being $^6\text{He}$ was rejected. Even though the decay mode at vertex B was ambiguous, track #6 was most likely a proton. At least two neutrons were probably emitted.

For vertex C, consistency with the conservation laws was checked using tracks #7–9. In total, 263 candidates were accepted within $3\sigma$ tolerance of energy and momentum conservation. Almost all were non-mesonic decay modes with multiple neutral particles. Among them, the decay mode for the case of track #2 being $^\Lambda\text{He}$ was the only reasonable one, obtained as the following decay mode,

$$^\Lambda\text{Be} \rightarrow ^4\text{He}(\#7) + \pi^- (\#8) + p(\#9).$$

This decay mode is consistent with a charged-particle emission at the end point of track #8. Since the value of the coplanarity of tracks #7–9 was $0.061 \pm 0.030$ at vertex C, no neutral particle was likely emitted at vertex C.

From the above discussions, the reaction process of the IBUKI event was obtained as follows,

$$\Xi^- + ^{14}\text{N} \rightarrow ^{10}\text{Be}(\#1) + ^\Lambda\text{He}(\#2),$$

$$^{10}\text{Be} \rightarrow (3 \text{ or } 4 \text{ nuclei, } \#3-6) + (2 \text{ or } 3 \text{ } n),$$

$$^\Lambda\text{He} \rightarrow ^4\text{He}(\#7) + \pi^- (\#8) + p(\#9).$$

Thus, the formation process of twin $\Lambda$ hypernuclei was uniquely identified as $^{10}\text{Be}$ and $^\Lambda\text{He}$. Since the final state was a two-body system at vertex A, the momenta of the twin $\Lambda$ hypernuclei should balance if the initial state is at rest. The range from vertex B to C was measured to be $97.12 \pm 0.35 \mu$m. To minimize the measurement errors, a kinematic fitting was applied at vertex A [31]. The fitting result is summarized in Table IV. From the constraint of the total length between vertex B and C, the ranges of track #1 and 2 were calculated to be $9.40 \pm 0.25 \mu$m and $87.72 \pm 0.25 \mu$m, respectively, so that their momenta correspond to each other. Straggling was taken into account in this fitting. For long tracks such
as tracks #8 and #9, the range error increases due to the straggling. The angles represent twin Λ hypernuclei being emitted back to back. The χ² value was obtained to be 2.409 with 3 degrees of freedom. Considering the effects of straggling and the error in the emulsion density, the error of Bzte was estimated to be 0.08 MeV. The mass errors of Ξ⁻ hyperon (1321.71 ± 0.07 MeV/c²[32]), Λ⁰Be (9499.88 ± 0.13 MeV/c²[23]), and ³He (4839.94 ± 0.02 MeV/c²[24]) were also taken into account. The mass of ¹⁰Be was presented as the average of the 1⁻ and 2⁻ states in the ground-state doublet. The energy spacing between these two states is expected to be less than 0.1 MeV. Therefore, the binding energy of the Ξ⁻ hyperon in the Ξ⁻–¹⁴N system, Bzte, was obtained to be 1.27 ± 0.21 MeV, where the error includes the spin-doublet uncertainty of ¹⁰Be. Kinematic fitting was also applied at vertex C. The result is listed in Table V. The χ² value was obtained to be 6.622 with 4 degrees of freedom. The binding energy of the Λ hyperon in ⁵ΛHe, BΛ, was obtained to be 2.77 ± 0.23 MeV, which agrees well with the world average [24].

Table IV. Ranges and emission angles for vertex A with the kinematic fitting. The value of χ²/ndf is 2.409/3.

| Vertex | Track | Range [μm] | θ [deg] | φ [deg] |
|--------|-------|-----------|--------|--------|
| Λ      | #1    | 9.40 ± 0.06 | 88.65 ± 1.35 | 302.52 ± 1.19 |
|        | #2    | 87.72 ± 0.70 | 91.35 ± 1.35 | 122.52 ± 1.19 |

The Bzte value of 1.27 ± 0.21 MeV represents a bound Ξ⁻–¹⁴N system. However, the case of ¹⁰Be being produced in an excited state must be considered. In a missing mass experiment at JLab the energy spectrum of ¹⁰Be was measured [23]. A low-lying excited state at 2.78 ± 0.11 MeV was observed. In case of the KISO event, the production of the ¹⁰Be in that excited state could not be excluded so that the Ξ⁻ binding energy was not uniquely determined (see Table VI). In case of the IBUKI event, the small Ξ⁻ binding energy of 1.27 MeV excludes a production of ¹⁰Be in the 2.78 MeV state. Instead, the ¹⁰Be is produced in one of the levels of the ground-state doublet. Thus, the reaction process of the IBUKI event was determined to be a bound state of Ξ⁻–¹⁴N decaying into ground states of both ¹⁰Be and ³He, having a Bzte value of 1.27 ± 0.21 MeV. This is the first observation of a twin-Λ hypernuclei event in which the binding energy was precisely determined. In the following, the energy level of the Ξ⁻ in the bound state is discussed in comparison with theoretical calculations.

Table V. Ranges and emission angles for vertex C with the kinematic fitting. The value of χ²/ndf is 6.622/4.

| Vertex | Track | Range [μm] | θ [deg] | φ [deg] |
|--------|-------|-----------|--------|--------|
| C      | #7    | 19.11 ± 0.20 | 87.04 ± 1.03 | 308.85 ± 0.87 |
|        | #8    | 2145.67 ± 71.02 | 29.54 ± 1.46 | 236.29 ± 2.19 |
|        | #9    | 2194.37 ± 27.57 | 105.72 ± 0.98 | 121.63 ± 0.84 |

In the calculation of Yamaguchi et al. using the Eihime potential [12], the Bzte values for the Ξ⁻–¹⁴N system are 5.93 MeV and 1.14 MeV in the nuclear 1s (atomic 1S) and nuclear 1p (atomic 2P) states, respectively. The bound states of both the IBUKI and the KISO events are consistent with the calculation for the 1p state. In the nuclear 1p state both Coulomb and nuclear forces are at work, resulting in a binding energy of 0.39 MeV and 0.75 MeV, respectively, according to this calculation. Thus the result is a Coulomb-assisted nuclear bound state. The calculated Bzte of ¹²C and ¹⁰Be by T. T. Sun et al. [14] are also consistent with the experimental data.

From the above considerations, in order to satisfy the experimental results of KEK E176, BNL E885, the KISO event, and the IBUKI event, the interpretation of the KISO event likely results in Bzte = 1.03 ± 0.18 MeV. In that case, the energy level of Ξ⁻ in both KISO and IBUKI events is considered to be the 1p state, although several spins are possible. Here, the isospin dependence of the ΞN interaction (Lane potential) is proportional to 1/A and has a weak effect. Assuming that the initial state is the same in both KISO and IBUKI events, the weighted average of the binding energy of Ξ⁻ in the 1p state is obtained to be 1.13 ± 0.14 MeV for the Ξ⁻–¹⁴N system. This now gives the depth of the Ξ⁻ potential for the first time. On the other hand, in the case of the binding energy of Ξ⁻ in the 1p state being 3.87 ± 0.21 MeV in the KISO event, the indicated width is too wide, despite the large contribution of the Coulomb potential. Thus, the present result is the first observation of the Coulomb-assisted bound state for the Ξ⁻–¹⁴N system. The probabilities of Ξ⁻ hyperon capture from the s, p, and d orbits for ¹⁴N atom were estimated to be 0.00–0.07%, 0.2–5.7%, and 47.9–75.7%, respectively [33, 34]. Therefore, the observation of a Ξ⁻ capture event in the p orbit experimentally indicates the ΞN–Λ coupling is weak, which agrees with the recent study of the Lattice QCD calculations [15].

In summary, the J-PARC E07 experiment observed a twin-Λ hypernuclei event, named IBUKI. The reaction process was clearly identified as Ξ⁻ + ¹⁴N → ¹⁰Be + ³ΛHe. The binding energy of the Ξ⁻ + ¹⁴N system was determined to be 1.27 ± 0.21 MeV by applying kinematic fitting. By considering an excited state, the energy level for ¹⁰Be was interpreted to be the ground state (1⁻) or
the other state of the spin doublet (2−). This is the first observation of twin-Λ hypernuclei in which the binding energy is precisely determined. By considering the experimental data and the theoretical calculations, the energy level of Ξ− is likely to be the Coulomb-assisted nuclear 1p state for both the KISO and IBUKI events. From the energies of both IBUKI and KISO events, a binding energy of 1.13 ± 0.14 MeV was obtained as the weighted average, assuming the same initial state for both KISO and IBUKI events. Furthermore, the observation of a Ξ− capture event in the p orbit indicates that the ΞN–ΛΛ coupling is weak.

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[1] K. Nakazawa and H. Takahashi, Prog. Theor. Phys. Suppl. 185, 335 (2010).
[2] J. K. Ahn et al., Phys. Rev. C 88, 014003 (2013).
[3] T. Fukuda et al., Phys. Rev. C 58, 1306 (1998).
[4] P. Khaustov et al., Phys. Rev. C 61, 054603 (2000).
[5] T. Nagae et al., AIP Conf. Proc. 2130, 020015 (2019).
[6] T. Nagae et al., J-PARC E70 experiment. Proposal for the next E05 run with the S-2S spectrometer (http://j-parc.jp/researcher/Hadron/en/pac_1801/pdf/P70_2018-10.pdf, 2018).
[7] S. Acharya et al., Phys. Rev. Lett. 123, 112002 (2019).
[8] K. Nakazawa et al., Prog. Theor. Exp. Phys. 2015, 033D02 (2015).
[9] E. Hiyama and K. Nakazawa, Ann. Rev. Nucl. Part. Sci. 68, 131 (2018).
[10] K. Tanida et al., J-PARC E03 experiment. Proposal for J-PARC 50 GeV Proton Synchrotron: Measurement of X Rays from Ξ−-Atom (http://j-parc.jp/researcher/Hadron/en/pac_0606/pdf/p03-Tanida.pdf, 2006).
[11] K. Imai, K. Nakazawa, H. Tamura, et al., J-PARC E07 experiment. Systematic Study of Double-Strangeness System with an Emulsion-Counter Hybrid Method (http://j-parc.jp/researcher/Hadron/en/pac_0606/pdf/p07-Nakazawa.pdf, 2006).
[12] M. Yamaguchi, K. Tominaga, Y. Yamamoto, and T. Ueda, Prog. Theor. Phys. 105, 627 (2001).
[13] S. Aoki et al., Nucl. Phys. A 828, 191 (2009).
[14] T. T. Sun, E. Hiyama, H. Sagawa, H.-J. Schulze, and J. Meng, Phys. Rev. C 94, 064319 (2016).
[15] K. Sasaki et al., Nucl. Phys. A 998, 121737 (2020).
[16] K. Agari et al., Prog. Theor. Exp. Phys. 2012, 02B009 (2012).
[17] T. Takahashi et al., Prog. Theor. Exp. Phys. 2012, 02B010 (2012).
[18] A. M. M. Theint et al., Prog. Theor. Exp. Phys. 2019, 021D01 (2019).
[19] H. Ekawa et al., Prog. Theor. Exp. Phys. 2019, 021D02 (2019).
[20] M. Fujiwara, Ph.D. thesis, Tohoku University (2019).
[21] IBUKI is the name of a mountain on the east-west boundary of the Japanese main island.
[22] O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. 57, 564 (2006).
[23] T. Gogami et al., Phys. Rev. C 93, 034314 (2016).
[24] M. Jurić et al., Nucl. Phys. B 52, 1 (1973).
[25] R. Bertini et al., Nucl. Phys. A 368, 365 (1981).
[26] M. May et al., Phys. Rev. Lett. 47, 1106 (1981).
[27] D. H. Davis, Contemp. Phys. 27, 91 (1986).
[28] P. D. užewski et al., Nucl. Phys. A 484, 520 (1988).
[29] F. Cusanno et al., Phys. Rev. Lett. 103, 202501 (2009).
[30] T. Gogami et al., Phys. Rev. C 94, 021302 (2016).
[31] P. Avery, Applied Fitting Theory I: General Least Squares Theory, CLEO Note CBX 91-72 (https://www.phys.ufl.edu/~avery/fitting.html, 1991).
[32] Particle data group, Phys. Lett. B 667, 1061 (2008).
[33] D. Zhu, C. B. Dover, A. Gal, and M. May, Phys. Rev. Lett. 67, 2268 (1991).
[34] T. Koike, JPS Conf. Proc. 17, 033011 (2017).