First Study of Reaction $\Xi^0 n \to \Xi^- p$ Using Ξ^0-Nucleus Scattering at an Electron-Positron Collider

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Using $(1.0087 \pm 0.0044) \times 10^{10}$ J/ψ events collected with the BESIII detector at the BEPCII storage ring, the process $\Xi^0 n \to \Xi^- p$ is studied, where the Ξ^0 baryon is produced in the process $J/\psi \to \Xi^0 \bar{\Xi}^0$ and the neutron is a component of the ^{9}Be, ^{12}C, and ^{197}Au nuclei in the beam pipe. A clear signal is observed with a statistical significance of 7.1σ. The cross section of the reaction $\Xi^0 + {}^9\text{Be} \to \Xi^- + p + {}^8\text{Be}$ is determined to be $\sigma(\Xi^0 + {}^9\text{Be} \to \Xi^- + p + {}^8\text{Be}) = (22.1 \pm 5.3_{\text{stat}} \pm 4.5_{\text{sys}})$ mb at the Ξ^0 momentum of 0.818 GeV/c, where the first uncertainty is statistical and the second is systematic. No significant H-dibaryon signal is observed in the $\Xi^- p$ final state. This is the first study of hyperon-nucleon interactions in electron-positron collisions and opens up a new direction for such research.

Scattering experiments of high energy particle beams bombarding target materials have been of great significance for studying the inner structure of matter and the fundamental interactions [1–3]. Charged long-lived particle beams such as $\pi^\pm$ and $K^\pm$ can be easily produced, and relevant research results have been very rich. On the other hand, due to significantly shorter lifetimes and higher masses, particle beams of hyperons, such as Λ, Σ, or Ξ, are more difficult to produce and corresponding experiments are rare, although measurements of these beams bombarding target materials are crucial for understanding nonperturbative QCD.

The experimental study on the interaction between hyperons and different target materials began in the 1960s and has lasted for more than half a century [4–13]. However, the intensities of hyperon beams produced by these experiments are relatively low and relevant experimental measurements are very scarce. After stagnating for decades, in 2021 and 2022, the CLAS and J-PARC E40 collaborations reported the latest results of Λ/Σ and nucleon interaction, respectively, including the reactions $\Lambda p \to \Lambda p$ [14], $\Sigma^- p \to \Sigma^- p$ [15], $\Sigma^+ p \to \Sigma^+ p$ [16], and $\Sigma^- p \to \Lambda n$ [17]. More research on hyperon-nucleon interaction is still strongly needed. Compared with other hyperons, relevant experimental measurements on Ξ-nucleon interaction are even more limited. Only a few events were observed for each reaction [7–13]. The interaction of Ξ and nucleons has been studied in some theoretical models, such as the constituent quark model [18–20], the meson-exchange picture [21], and the chiral effective field theory approach [22–24]. More experimental measurements are needed to constrain the theoretical models, which can greatly promote research in this field.

The study of Ξ-nucleon interaction also can be used to search for the H-dibaryon, which has strangeness -2 and valence quark structure $uuddss$. This H-dibaryon was first predicted according to the bag model in the 1970s [25,26].

Later studies by two lattice QCD groups also predicted the existence of the H-dibaryon [27–29]. Although the H-dibaryon has been searched for by many experiments, no convincing signal has been found so far [30–37]. The H-dibaryon can also be searched for in Ξ-nucleon scattering processes, for example, in the $\Xi^- p$ final state in the process $\Xi^0 n \to \Xi^- p$. Especially, Refs. [25,26] predict an H-dibaryon may appear as a bound state of $\Sigma\Sigma$ decaying strongly into ΞN or $\Lambda\Lambda$, where N represents n or p. Furthermore, the study of hyperon-nucleon interactions is important to understand the role of hyperons in dense neutron-star matter, to determine the equation of state of nuclear matter at supersaturation densities and to understand the so-called "hyperon puzzle" of neutron stars [38–40]. The study of Ξ-nucleon interaction is also helpful to understand the formation of Ξ hypernuclei, on which experimental information is very scarce [41–43].

The BESIII detector records symmetric $e^+ e^-$ collisions at the BEPCII collider [44]. Details of the BESIII detector can be found in Ref. [45]. With a sample of $(1.0087 \pm 0.0044) \times 10^{10}$ J/ψ events collected by the BESIII detector [46], an intense monoenergetic Ξ baryon can be produced by the decay $J/\psi \to \Xi^0 \bar{\Xi}^0$. The Ξ baryon can interact with the material in the beam pipe adjacent to the $e^+ e^-$ beam, providing a novel source to study the Ξ-nucleon interaction [47,48]. The material of the beam pipe is composed of gold (^{197}Au), beryllium (^{9}Be), and oil (^{12}C : ^{1}H = 1 : 2.13), as shown in Fig. 1, with more details in Ref. [45].

In this Letter, we describe a study of the reaction $\Xi^0 n \to \Xi^- p$, where the Ξ^0 baryon is produced in the process $J/\psi \to \Xi^0 \bar{\Xi}^0$, and the neutron is a component of the ^{9}Be, ^{12}C, and ^{197}Au nuclei in the beam pipe. This is the first study of hyperon-nucleon interaction at an electron-positron collider. The cross section of the reaction $\Xi^0 + {}^9\text{Be} \to \Xi^- + p + {}^8\text{Be}$ is also determined. Since the momentum of the monoenergetic, incident Ξ^0 is relatively high ($P_{\Xi^0} = 0.818$ GeV/c), its interaction with atomic nuclei tends to be a direct nuclear reaction. It is assumed that a Ξ^0 reacts with a neutron in the ^{9}Be directly in the reaction, and that afterward a residual nucleus ^{8}Be, a Ξ^-, and a proton are
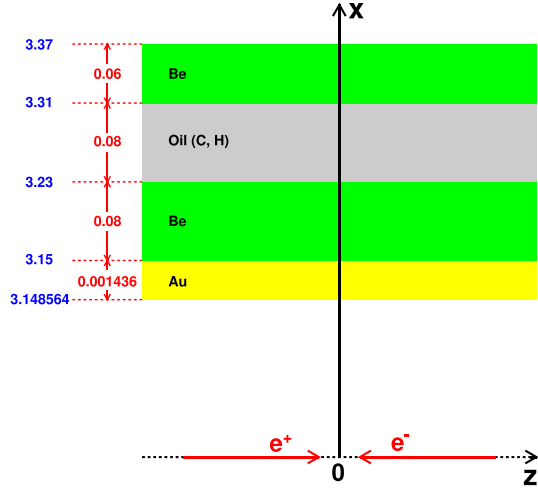
FIG. 1. Schematic diagram of the beam pipe, the length units are centimeter (cm). The z axis is the symmetry axis of the MDC, and the x axis is perpendicular to the e^+e^- beam direction.

left over. To determine the cross section of $\Xi^0 + {}^9\text{Be} \to \Xi^- + p + {}^8\text{Be}$ from the composite material, the reaction is assumed to be a pure surface process.

In this analysis, simulated data samples that are produced with a GEANT4-based [49] Monte Carlo (MC) package, which includes the geometric description of the BESIII detector [50] and the detector response, are used to determine detection efficiencies and to estimate backgrounds. The inclusive MC sample includes both the production of the J/ψ resonance and the continuum process incorporated in KKMC [51]. All particle decays are modeled with EVTGEN [52] using branching fractions either taken from the Particle Data Group (PDG) [53], where available, or otherwise estimated with LUNDCHARM [54]. Final state radiation from charged final state particles is incorporated using the PHOTOS package [55].

The signal process considered in this analysis is $J/\psi \to \Xi^0\bar\Xi^0$, $\Xi^0 n \to \Xi^- p$, $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$, $\bar\Xi^0 \to \bar\Lambda\pi^0$, $\bar\Lambda \to \bar p\pi^+$, $\pi^0 \to \gamma\gamma$. In order to determine the detection efficiency, 1.0×10^6 signal MC events are simulated, with the angular distribution of $J/\psi \to \Xi^0\bar\Xi^0$ generated according to the measurement in Ref. [56]. We simulate the reaction process $\Xi^0 n \to \Xi^- p$ assuming the neutron to be free, regardless of its Fermi momentum. Since the momentum of the monoenergetic, incident Ξ^0 is much greater than the Fermi momentum, this approximation is reasonable. The effect of this approximation is considered in the systematic uncertainty evaluation. Since the distribution of the $\Xi^- p$ invariant mass, $M(\Xi^- p)$, is almost flat in data from 2.26 to 2.40 GeV/c^2, the mass of free neutron in MC simulation is tuned to change the center-of-mass energy of the reaction system to make the $M(\Xi^- p)$ distribution consistent between data and MC. The angular distribution of the reaction process is generated using an isotropic phase-space distribution.

Charged tracks detected in the multilayer drift chamber (MDC) are required to be within a polar angle (θ) range of $|\cos\theta| < 0.93$, where θ is defined with respect to the z axis taken to be the symmetry axis of the MDC. Photon candidates are identified using showers in the electromagnetic calorimeter (EMC). The deposited energy of each shower must be more than 25 MeV in the barrel region ($|\cos\theta| < 0.8$) and more than 50 MeV in the end cap region ($0.86 < |\cos\theta| < 0.92$). To exclude showers that originate from charged tracks, the angle enclosed by the EMC shower and the position of the closest charged track at the EMC must be greater than $10°$ as measured from the interaction point. To suppress electronic noise and showers unrelated to the event, the difference between the EMC time and the event start time is required to be within [0, 700] ns. Particle identification (PID) for charged tracks combines measurements of the energy deposited in the MDC (dE/dx) and the flight time in the time-of-flight system to form likelihoods $\mathcal{L}(h)$ ($h = p, K, \pi$) for each hadron h hypothesis. Tracks are identified as protons when the proton hypothesis has the greatest likelihood [$\mathcal{L}(p) > \mathcal{L}(\pi)$ and $\mathcal{L}(p) > \mathcal{L}(K)$], while tracks are identified as pions when the pion hypothesis has the greatest likelihood [$\mathcal{L}(\pi) > \mathcal{L}(K)$ and $\mathcal{L}(\pi) > \mathcal{L}(p)$].

Since the final state of the signal process is $pp\pi^-\pi^-\bar p\pi^+\gamma\gamma$, candidate events must have six charged tracks with zero net charge and at least two photon candidates. We require that there are two p, two π^-, one $\bar p$, and one π^+. For the decay $\bar\Xi^0 \to \bar\Lambda\pi^0$ with $\bar\Lambda \to \bar p\pi^+$, we perform a vertex fit to the $\bar p\pi^+$ combination, and the $\bar\Lambda$ signal region is defined as $|M(\bar p\pi^+) - m_{\bar\Lambda}| < 0.003$ GeV/c^2, where $m_{\bar\Lambda}$ is the nominal mass of the $\bar\Lambda$. In this Letter, all nominal masses are taken from PDG [53]. The invariant mass of the two photons is required to be in the π^0 mass window [0.11, 0.15] GeV/c^2, and the invariant mass of the two photons is constrained to the nominal mass of the π^0 using a 1C kinematic fit. If there is more than one π^0 candidate in an event, only the one with the minimum value of $|M(\bar\Lambda\pi^0) - m_{\bar\Xi^0}|$ is retained. The $\bar\Xi^0$ signal region is defined as -0.015 GeV/$c^2 < (M(\bar\Lambda\pi^0) - m_{\bar\Xi^0}) < 0.010$ GeV/c^2, where $m_{\bar\Xi^0}$ is the $\bar\Xi^0$ nominal mass. For the reaction $\Xi^0 n \to \Xi^- p$ with subsequent decay $\Xi^- \to \Lambda\pi^-$, we first perform the vertex fit of Λ by considering all $p\pi^-$ combinations. The $p\pi^-$ combination with the smallest value of $|M(p\pi^-) - m_\Lambda|$, where m_Λ is the Λ nominal mass, is taken as Λ candidate. The Λ signal region is also defined as $|M(p\pi^-) - m_\Lambda| < 0.003$ GeV/c^2. Then, a vertex fit of Ξ^- is performed for the combination of the Λ and the remaining π^-. Finally, a vertex fit is performed for the combination of the Ξ^- and the remaining p.

To select the signal events of $J/\psi \to \Xi^0\bar\Xi^0$, the invariant mass of the system recoiling against the $\bar\Xi^0$, $M_{\text{recoil}}(\bar\Xi^0)$, is required to be in the Ξ^0 signal region,
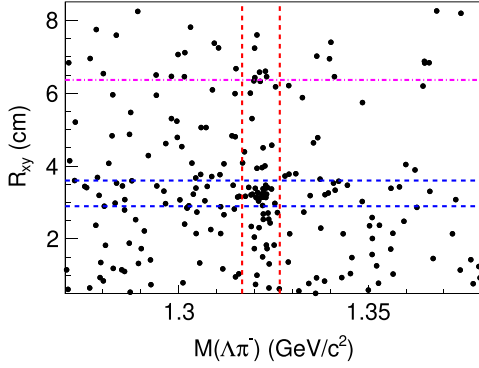
FIG. 2. Distribution of R_{xy} versus $M(\Lambda\pi^-)$ for data. The blue horizontal dashed lines denote the beam pipe region, the pink horizontal dashed-dotted line denotes the position of inner wall of MDC, and the red vertical dashed line marks the Ξ^- signal region.
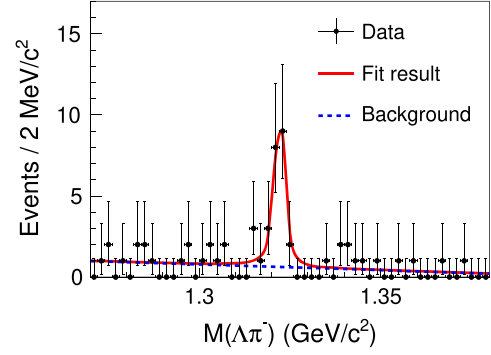

FIG. 3. Distribution of $M(\Lambda\pi^-)$ in data (dots with error bars). The red solid curve is the total fit result and the blue dashed curve is the background component.

defined as $[1.295, 1.325]$ GeV/c^2, where $M_{\mathrm{recoil}}(\bar{\Xi}^0) \equiv \sqrt{E_{\mathrm{beam}}^2 - |\vec{p}_{\bar{\Xi}^0}c|^2}/c^2$, E_{beam} is the e^+ or e^- beam energy for data, and $\vec{p}_{\bar{\Xi}^0}$ is the measured momentum of the $\bar{\Xi}^0$ candidate in the e^+e^- rest frame. The main background is $J/\psi \to \Xi^0\bar{\Xi}^0$, $\Xi^0 \to \Lambda\pi^0$, $\bar{\Xi}^0 \to \bar{\Lambda}\pi^0$. To suppress this background, the recoil mass of $\bar{\Xi}^0\Lambda$, $M_{\mathrm{recoil}}(\bar{\Xi}^0\Lambda)$, is obtained from the four-momenta of the initial e^+e^- system and the $\bar{\Xi}^0$ and Λ candidates. $M_{\mathrm{recoil}}(\bar{\Xi}^0\Lambda)$ should be around the nominal π^0 mass for this background, so we require $M_{\mathrm{recoil}}(\bar{\Xi}^0\Lambda) < 0$ GeV/c^2 to remove these events.

The distribution of R_{xy} versus the invariant mass $M(\Lambda\pi^-)$ of data is shown in Fig. 2, where R_{xy} is the distance from the reconstructed Ξ^-p vertex to the z axis. The beam pipe signal region is defined as $[2.9, 3.6]$ cm, taking into account the detector resolution. This requirement also removes the influence from additional supporting materials. Clear enhancements are seen in the beam pipe and Ξ^- signal regions, due to Ξ^0 interactions with material in the beam pipe producing Ξ^- via the process $\Xi^0 n \to \Xi^- p$. A cluster of events can be seen in the inner wall of MDC region, defined as $[6.0, 6.8]$ cm, but the signal is not statistically significant.

Figure 3 shows the $M(\Lambda\pi^-)$ distribution from data after final event selection. A clear Ξ^- signal is observed, corresponding to the reaction $\Xi^0 n \to \Xi^- p$. A detailed study of the J/ψ inclusive MC sample indicates that there is no peaking background contribution in the Ξ^- signal region. Additionally, no significant peak is found in beam pipe sideband events from data. To determine the signal yield, an unbinned maximum likelihood fit is performed to the $M(\Lambda\pi^-)$ distribution. We use the MC-determined shape to describe the Ξ^- signal, where the yield acts as a free fit parameter. The background is described by a linear function with the number of events and the slope as free parameters. The fit result is shown in Fig. 3; the Ξ^- signal yield returned by the fit is $N^{\mathrm{sig}} = 22.9 \pm 5.5$. The statistical significance is determined to be 7.1σ by comparing the

likelihood values for the fits with and without the Ξ^- signal and taking the change of the number of degrees of freedom into account.

Since the beam pipe is composed of layers of composite material, as shown in Fig. 1, the cross section of the reaction between Ξ^0 baryons and ^{9}Be nuclei $\sigma(\Xi^0 + {}^9\mathrm{Be} \to \Xi^- + p + {}^8\mathrm{Be})$ is extracted using

$$\sigma(\Xi^0 + {}^9\mathrm{Be} \to \Xi^- + p + {}^8\mathrm{Be}) = \frac{N^{\mathrm{sig}}}{\epsilon\mathcal{B}\mathcal{L}_{\mathrm{eff}}}, \quad (1)$$

where ϵ is the selection efficiency, $\mathcal{B}$ is the product of the branching ratios of all intermediate resonances, defined as $\mathcal{B} \equiv \mathcal{B}(\bar{\Xi}^0 \to \bar{\Lambda}\pi^0)\mathcal{B}(\bar{\Lambda} \to \bar{p}\pi^+)\mathcal{B}(\pi^0 \to \gamma\gamma)\mathcal{B}(\Xi^- \to \Lambda\pi^-)\mathcal{B}(\Lambda \to p\pi^-)$, and $\mathcal{L}_{\mathrm{eff}}$ is the effective luminosity of the Ξ^0 flux produced from $J/\psi \to \Xi^0\bar{\Xi}^0$ and the distribution of target materials, as shown in the following formula:

$$\mathcal{L}_{\mathrm{eff}} = \frac{N_{J/\psi}\mathcal{B}_{J/\psi}}{2 + \frac{2}{3}\alpha} \int_a^b \int_0^\pi (1 + \alpha\cos^2\theta)e^{-\frac{x}{\sin\theta\beta\gamma L}}N(x)C(x)d\theta dx. \quad (2)$$

In the formula for the effective luminosity, the angular distribution of the Ξ^0 flux, the attenuation of the Ξ^0 flux, the number of target nuclei, and the weight of different target materials are considered in turn. $N_{J/\psi}$ is the number of J/ψ events [46], $\mathcal{B}_{J/\psi}$ is the branching fraction of $J/\psi \to \Xi^0\bar{\Xi}^0$, α is the parameter of the angular distribution of $J/\psi \to \Xi^0\bar{\Xi}^0$ [56], $\beta\gamma \equiv (\sqrt{E_{\mathrm{beam}}^2 - m_{\Xi^0}^2c^4}/m_{\Xi^0}c^2)$ is the ratio of the momentum and the mass of the Ξ^0, $L \equiv c\tau$ is the product of the light speed and the mean lifetime of the Ξ^0, $N(x)$ is the number of target nuclei per unit volume, a and b are the distances from the inner surface and outer surface of the beam pipe to the z axis, θ and x are the angle and distance to the z axis. The beam pipe can be regarded as infinitely long with respect to the product

TABLE I. Input parameters for the cross section calculation using Eq. (1). The nominal values of $C(x)$ are obtained based on the pure surface process assumption, and the values in brackets are obtained based on the assumption that the cross section is proportional to the number of neutrons in the nucleus.

Parameter	Result
N^{sig}	22.9 ± 5.5
ϵ	1.873%
$\mathcal{B}$	$(40.114 \pm 0.444)\%$ [53]
$N_{J/\psi}$	$(1.0087 \pm 0.0044) \times 10^{10}$ [46]
$\mathcal{B}_{J/\psi}$	$(0.117 \pm 0.004)\%$ [53]
α	0.514 ± 0.016 [56]
L	(8.69 ± 0.27) cm [53]
E_{beam}	1.5485 GeV
m_{Ξ^0}	(1.31486 ± 0.00020) GeV/c^2 [53]
a	3.148564 cm [45]
b	3.37 cm [45]
$N(x)$	$\begin{cases} 5.91 \times 10^{22} \text{ cm}^{-3}, & 3.148564 \le x \le 3.15 \text{ cm} \\ 1.24 \times 10^{23} \text{ cm}^{-3}, & 3.15 < x \le 3.23 \text{ cm} \\ 3.45 \times 10^{22} \text{ cm}^{-3}, & 3.23 < x \le 3.31 \text{ cm} \\ 1.24 \times 10^{23} \text{ cm}^{-3}, & 3.31 < x \le 3.37 \text{ cm} \end{cases}$
$C(x)$	$\begin{cases} 8.437(23.6), & 3.148564 \le x \le 3.15 \text{ cm} \\ 1.000(1.00), & 3.15 < x \le 3.23 \text{ cm} \\ 1.090(1.20), & 3.23 < x \le 3.31 \text{ cm} \\ 1.000(1.00), & 3.31 < x \le 3.37 \text{ cm} \end{cases}$

$\beta\gamma L$ of Ξ^0. $C(x)$ is the cross section ratio relative to $\sigma(\Xi^0 + {}^9\text{Be} \to \Xi^- + p + {}^8\text{Be})$, where we assume the reaction is dominated by the interaction of a Ξ^0 baryon with a single neutron on the ^{9}Be nucleus surface [57–61]. The derivation of the formula can be found in Sec. I of the Supplemental Material [62], and the relevant parameters are listed in Table I. The corresponding cross sections are determined to be $\sigma(\Xi^0 + {}^9\text{Be} \to \Xi^- + p + {}^8\text{Be}) = (22.1 \pm 5.3_{\text{stat}} \pm 4.5_{\text{sys}})$ mb, or $\sigma(\Xi^0 + {}^{12}\text{C} \to \Xi^- + p + {}^{11}\text{C}) = (24.1 \pm 5.8_{\text{stat}} \pm 4.6_{\text{sys}})$ mb, which are not independent and are derived from the same basic quantities.

We also search for H-dibaryon signals in the $\Xi^- p$ final state. The mean lifetime of the H-dibaryon is unknown; it may decay in the beam pipe region, or after flying some distance. Figure 4 shows the $M(\Xi^- p)$ distributions for selected Ξ^- signal events inside or outside the beam pipe region. Based on the available statistics, we do not see any obvious peaks in the two $M(\Xi^- p)$ distributions, so no significant short-lifetime or long-lifetime H-dibaryon signal is observed in the process $\Xi^0 n \to \Xi^- p$ with ^{9}Be, ^{12}C and ^{197}Au.

The sources of systematic uncertainties related to the determined cross sections come from the tracking efficiency (6.0%) [63], photon efficiency (2.0%), PID efficiency (6.0%), track number requirement (3.0%), mass windows (7.8%), R_{xy} requirement (6.6%), $M_{\text{recoil}}(\bar{\Xi}^0\Lambda)$ requirement (4.3%), $(\Xi^- + p)$ momentum (10.0%), $M(\Xi^- p)$ distribution (0.6%), angular distribution of $\Xi^0 n \to \Xi^- p$ (1.0%), MC

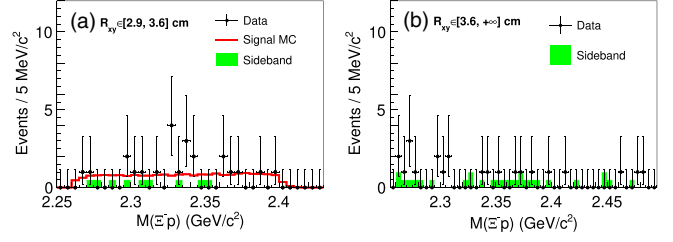FIG. 4. Distributions of $M(\Xi^- p)$ for data in $2.9 < R_{xy} < 3.6$ cm (a) and $R_{xy} > 3.6$ cm (b). The green shaded histograms correspond to the normalized events from the Ξ^- sideband region, and the red line corresponds to the signal MC distribution that is normalized by the total number of events for data.

statistics (0.7%), efficiency curve parametrization (0.5%), fit procedure (5.0%), number of J/ψ (0.4%), branching fractions (3.6%), angular distribution of $J/\psi \to \Xi^0\bar{\Xi}^0$ (0.1%), Ξ^0 mean lifetime (2.7%), e^+e^- interaction point (2.7%), and cross section ratios (7.2% or 2.1% for different nuclei). All systematic uncertainties are discussed in detail in Sec. II of the Supplemental Material [62]. The total systematic uncertainties are 20.4% and 19.2% for $\sigma(\Xi^0 + {}^9\text{Be} \to \Xi^- + p + {}^8\text{Be})$ and $\sigma(\Xi^0 + {}^{12}\text{C} \to \Xi^- + p + {}^{11}\text{C})$, respectively.

In summary, using $(1.0087 \pm 0.0044) \times 10^{10}$ J/ψ events collected with the BESIII detector operating at the BEPCII storage ring, the reaction $\Xi^0 n \to \Xi^- p$ is observed with a statistical significance of 7.1σ, where Ξ^0 is from the process $J/\psi \to \Xi^0\bar{\Xi}^0$ and n is from materials in the beam pipe. The cross section of the reaction $\Xi^0 + {}^9\text{Be} \to \Xi^- + p + {}^8\text{Be}$ at the momentum of the Ξ^0 of $P_{\Xi^0} = 0.818$ GeV/c is determined to be $\sigma(\Xi^0 + {}^9\text{Be} \to \Xi^- + p + {}^8\text{Be}) = (22.1 \pm 5.3_{\text{stat}} \pm 4.5_{\text{sys}})$ mb, where the first uncertainty is statistical and the second is systematic. If the effective number of reaction neutrons in a ^{9}Be nucleus is taken as 3 [13], the cross section of $\Xi^0 n \to \Xi^- p$ for a single neutron is determined to be $\sigma(\Xi^0 n \to \Xi^- p) = (7.4 \pm 1.8_{\text{stat}} \pm 1.5_{\text{sys}})$ mb, consistent with theoretical predictions in Refs. [20,23,24]. Furthermore, we do not observe any significant H-dibaryon signal in the $\Xi^- p$ final state for this reaction process.

This work is the first study of hyperon-nucleon interaction in electron-positron collisions, and opens up a new direction for such research. Other hyperons and nucleon interactions can also be studied, such as Λ and Σ. Furthermore, we may be able to design targets of specific materials to study hyperon-nucleon interaction in future super tau-charm facilities [64,65]. With more statistics at that time, we can also study the momentum-dependent cross section distribution based on the hyperons from multibody decays of J/ψ or other charmonia.

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