

Determination of Spin-Parity Quantum Numbers for the Narrow Structure near the $p\bar{\Lambda}$ Threshold in $e^+e^- \rightarrow pK^-\bar{\Lambda} + c.c.$

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A narrow structure in the $p\bar{\Lambda}$ system near the mass threshold, named as $X(2085)$, is observed in the process $e^+e^- \rightarrow pK^-\bar{\Lambda}$ with a statistical significance greater than 20σ . Its spin and parity are determined for the first time to be $J^P = 1^+$ in an amplitude analysis, with a statistical significance greater than 5σ over other quantum numbers ($0^-, 1^-$ and 2^+). The pole positions of $X(2085)$ are measured to be $M_{\text{pole}} = (2084_{-2}^{+4} \pm 9)$ MeV and $\Gamma_{\text{pole}} = (58_{-3}^{+4} \pm 25)$ MeV, where the first uncertainties are statistical and the second ones are systematic. The analysis is based on the study of the process $e^+e^- \rightarrow pK^-\bar{\Lambda}$ and uses the data samples collected with the BESIII detector at the center-of-mass energies $\sqrt{s} = 4.008, 4.178, 4.226, 4.258, 4.416, \text{ and } 4.682$ GeV with a total integrated luminosity of 8.35 fb^{-1} .

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Quantum chromodynamics, the theory of the strong interaction, allows the existence of bound states beyond conventional mesons and baryons. Searching for these exotic states is one of the main interests in experimental hadron physics. An anomalous enhancement near the mass threshold of the $p\bar{\Lambda}$ system was first observed by the BES Collaboration in the decay of $J/\psi \rightarrow pK^-\bar{\Lambda}$ [1]. This enhancement is consistent with an S -wave Breit-Wigner function with a mass of $m = [2075 \pm 12(\text{stat}) \pm 5(\text{syst})]$ MeV and a constant width of $\Gamma = [90 \pm 35(\text{stat}) \pm 9(\text{syst})]$ MeV, but can also be described with a P -wave Breit-Wigner resonance. Therefore, the spin and parity of this structure were not determined. Similar evidence of a structure in $p\bar{\Lambda}$ was reported in several decays of B mesons and charmonium states, such as $B^0 \rightarrow p\bar{\Lambda}\pi^-$ [2], $B^0 \rightarrow \bar{p}\Lambda\pi^-$ [3], $B^+ \rightarrow p\bar{\Lambda}\gamma$ [4], $B^+ \rightarrow p\bar{\Lambda}\pi^0$ [5], $\psi(3686) \rightarrow pK^-\bar{\Lambda}$ [1], $\chi_{cJ} \rightarrow pK^-\bar{\Lambda}$ [6], and their charge conjugations. However, the mass and width of the structure in B decays were not determined. By replacing the s quark with a c quark, a similar structure is also observed in the $\bar{p}\Lambda_c^+$ system in the decay of $B^- \rightarrow \Lambda_c^+ \bar{p}\pi^-$ [7].

Theoretically, the near-threshold enhancement in the $p\bar{\Lambda}$ system was investigated in scenarios of $q^3\bar{q}^3$ meson [8], baryon-antibaryon SU(3) nonets [9], final state interaction [10], or chiral effective field theory [11]. The quantum numbers $J^P = 0^-$ are excluded by combining C and P symmetries with SU(3) flavor symmetry [12]. The

hypothesis of an S -wave $p\bar{\Lambda}$ bound state was rejected in the quark model by considering the annihilation interaction [13]. The mass spectrum of $p\bar{\Lambda}$ in B meson decays was not fully understood in the naive factorization picture with limited statistics [14,15]. Further experimental studies of the near-threshold enhancement in the $p\bar{\Lambda}$ system in various processes are critical for validating different theoretical models.

In this Letter, we report the observation of a narrow structure near the $p\bar{\Lambda}$ mass threshold, named as $X(2085)$, in the process $e^+e^- \rightarrow pK^-\bar{\Lambda}$ at the center-of-mass energies $\sqrt{s} = 4.008, 4.178, 4.226, 4.258, 4.416, \text{ and } 4.682$ GeV. The quantum numbers and resonance parameters of $X(2085)$ are determined from an amplitude analysis. A detailed measurement of the energy dependence of the $e^+e^- \rightarrow pK^-\bar{\Lambda}$ cross sections can be found in a separate paper [16]. Throughout this Letter, charged conjugated modes are always implied.

The BESIII detector is a magnetic spectrometer [17] located at the Beijing Electron Positron Collider (BEPCII) [18]. The cylindrical core of the BESIII detector consists of a main drift chamber filled with a helium-based gas (MDC), a plastic scintillator time-of-flight system, and a CsI(Tl) electromagnetic calorimeter, which are all enclosed in a superconducting solenoidal magnet providing a 1.0 T magnetic field. The flux-return yoke is instrumented with resistive plate chambers arranged in nine layers in the barrel and eight layers in the end caps for muon identification. The acceptance for charged particles and photons is 93% of 4π solid angle. The charged-particle momentum resolution at 1.0 GeV/c is 0.5%. The electromagnetic calorimeter measures photon energies with a resolution of 2.5% (5%) at 1 GeV in the barrel (end cap) region.

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Monte Carlo (MC) simulated samples produced with a GEANT4-based [19] software package, which includes the geometric description of the BESIII detector and the detector response, are used to determine the detection efficiencies and to estimate the backgrounds. The simulation includes the beam energy spread and initial state radiation in the e^+e^- annihilations modeled with the KKMC generator [20]. The inclusive MC sample consists of the production of open-charm processes, the initial state radiation of vector charmonium(-like) states, and the continuum process incorporated in KKMC [20]. The known decay states are modeled with BESEVTGEN [21] using branching fractions taken from the Particle Data Group [22], and the remaining unknown decays from the charmonium states with LUNDCHARM [23]. Final state radiation from charged final state particles is incorporated with PHOTOS [24] package.

The candidates for $e^+e^- \rightarrow pK^-\bar{\Lambda}$ are required to have four charged tracks with zero net charge. Charged tracks are required to start from the region $|d_z| < 20$ cm and $|\cos\theta| < 0.93$, where $|d_z|$ is the distance of closest approach to the interaction point along the z axis, and θ is the polar angle relative to the z axis, which is taken to be the symmetry axis of the MDC.

To reconstruct $\Lambda(\bar{\Lambda})$, all possible track pairs with opposite charges are assigned as $p\pi^-(\bar{p}\pi^+)$. The $p\pi^-(\bar{p}\pi^+)$ trajectories are constrained to originate from a common vertex by applying a vertex fit, the χ^2 of which is required to be less than 100. The decay length of any $\Lambda(\bar{\Lambda})$ candidate must be greater than twice the standard deviation of the vertex resolution. The invariant mass of $p\pi^-(\bar{p}\pi^+)$ is required to be within the $\Lambda(\bar{\Lambda})$ signal mass window of $|M_{p\pi^-(\bar{p}\pi^+)} - M_\Lambda| < 6$ MeV/ c^2 . In each event, exactly one $\Lambda(\bar{\Lambda})$ candidate is allowed. The other two charged tracks are assigned according to their charges as proton and kaon not from $\Lambda(\bar{\Lambda})$ decays. To ensure that these tracks originate from the interaction point, an additional requirements of $|d_z| < 10$ cm and $|d_r| < 1$ cm is imposed, where $|d_r|$ is the distance of closest approach to the interaction point in the transverse plane. A four-constraint kinematic fit is imposed on the selected charged particles under the hypothesis $e^+e^- \rightarrow pK^-\bar{\Lambda}$. The χ^2 of the four-constraint kinematic fit is required to be less than 100.

The background from $e^+e^- \rightarrow (\gamma)e^+e^-$ is suppressed by rejecting events with $|\cos\theta_K| > 0.83$, where θ_K is the polar angle of the kaon candidate.

After applying all the above selection criteria, a total of 3883 candidate events for $e^+e^- \rightarrow pK^-\bar{\Lambda}$ survives in the data sample at $\sqrt{s} = 4.178$ GeV, which is the largest dataset under consideration. A study of the inclusive MC leads to an estimated background yield of 52 events. Figure 1 shows the Dalitz plot of the selected events, where a significant near-threshold enhancement in the $p\bar{\Lambda}$ system is observed. In addition, contributions of some excited Λ and nucleon states can also be seen.

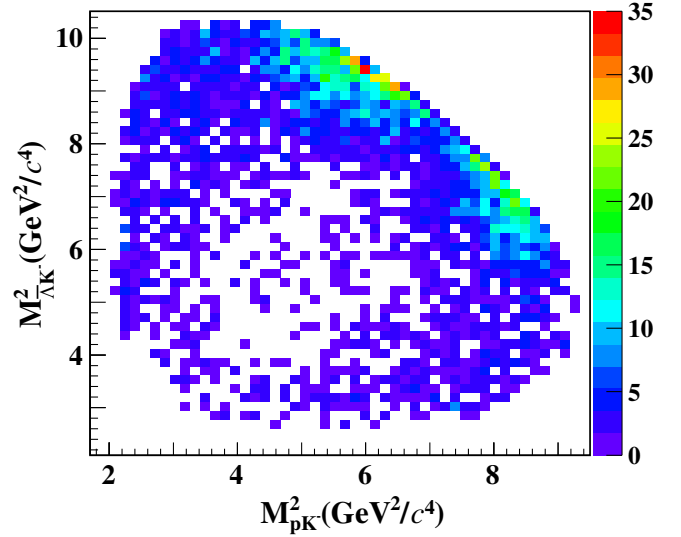


FIG. 1. Dalitz plot of the selected $e^+e^- \rightarrow pK^-\bar{\Lambda}$ events in data at $\sqrt{s} = 4.178$ GeV.

The structures are investigated via an amplitude analysis, in which the amplitudes for the sequential processes $e^+e^- \rightarrow \gamma^* \rightarrow X^+K^- (X^+ \rightarrow p\bar{\Lambda})$, $e^+e^- \rightarrow \gamma^* \rightarrow N^{*+}\bar{p} (N^{*+} \rightarrow K^+\bar{\Lambda})$, $e^+e^- \rightarrow \gamma^* \rightarrow \Lambda^*\bar{\Lambda} (\Lambda^* \rightarrow pK^-)$, and their charge conjugates, are constructed using the relativistic covariant tensor amplitude formalism [25]. These effective vertices Γ are deduced from an effective Lagrangian by considering C - and P -parity invariance, Lorentz invariance, and the combination of charge conjugation (C), parity (P), and time reversal (T) invariance.

The amplitude of a process containing a specific resonance is written as

$$\mathcal{A}_j = \epsilon_\alpha^*(p_0, m) \bar{u}(p_1, \lambda_1) \Gamma_1^{\alpha\mu_1\mu_2\cdots} \mathcal{P}_{\mu_1\mu_2\cdots\nu_1\nu_2\cdots} \Gamma_2^{\nu_1\nu_2\cdots} \times v(p_2, \lambda_2) BW(s), \quad (1)$$

where ϵ^* is the γ^* polarization vector; $u(p_1, \lambda_1)$ and $v(p_2, \lambda_2)$ are the free Dirac spinors for proton and $\bar{\Lambda}$, respectively; Γ_1 and Γ_2 are the two strong interaction vertices describing the resonance couplings with γ^* , p , K^- , and $\bar{\Lambda}$, which are summarized in Supplemental Material [26]; $BW(s)$ is a Breit-Wigner function for an intermediate states with a spin projection operator \mathcal{P} .

The line shape of $X(2085)$ is parametrized by a relativistic Breit-Wigner function

$$BW(m^2) = \frac{1}{m_0^2 - m^2 - im_0\Gamma(m)}, \quad (2)$$

with a mass dependent width given by

$$\Gamma(m) = \Gamma_0 \left(\frac{q}{q_0}\right)^{2l+1} \frac{m_0}{m} B_l^2(q, q_0, d). \quad (3)$$

Here, m is the invariant mass of the $p\bar{\Lambda}$ system; m_0 and Γ_0 are the mass and width of $X(2085)$, respectively; $q(q_0)$ is

TABLE I. The $\Delta \ln \mathcal{L}$, Δndf , and estimated statistical significances of 1^+ over the other hypotheses. See text for details.

	$\Delta \ln \mathcal{L}$	Δndf	Significance
1^+ over 0^-	40.6	4	8.3
1^+ over 1^-	30.2	2	7.5
1^+ over 2^+	44.8	2	9.2
1^+ over 2^-	13.8	0	5.3

the three-momentum of the proton in the rest frame of $p\bar{\Lambda}$, which is calculated with the invariant mass $m(m_0)$; l is the orbital angular momentum of the $p\bar{\Lambda}$ system; $B_l(q, q_0, d)$ is the reduced Blatt-Weisskopf barrier factor [27]; d is the radius of the centrifugal barrier chosen as $d = 0.73$ fm [28], corresponding to the range of the strong interaction in hadronic decays. The other intermediate states are described with a constant width, i.e., $\Gamma(m) = \Gamma_0$.

The complex coupling constants of the amplitudes are determined by an unbinned maximum likelihood fit using MINUIT [29]. The number of free parameters are 50, including 48 coupling parameters and two resonance parameters for the $X(2085)$. The background contribution is estimated with the inclusive MC sample and subtracted from the likelihood. The efficiency correction is performed based on MC simulation. The amplitude analysis is first performed to the data taken at $\sqrt{s} = 4.178$ GeV, which has the largest integrated luminosity among the six datasets. The contributions from $X(2085)$ as well as from other excited kaon, Λ , and nucleon states are evaluated. The baseline solution is obtained with only amplitudes having a statistical significance greater than 5σ , including $X(2085)$, $K_2^*(1980)$, $K_4^*(2045)$, $K_2(2250)$, $\Lambda(1520)$, $\Lambda(1890)$, $\Lambda(2350)$, $N(1720)$, and $N(2570)$. The resonance parameters of excited kaon, Λ , and nucleon states are fixed to individual world average values [22]. When the resonance parameters are presented as a range, the midpoint of the

range is considered as the nominal value, and half of the range is taken as its uncertainty.

Possible J^P assignments, 0^- , 1^- , 1^+ , 2^+ , and 2^- , for $X(2085)$ are tested. The statistical significance of $J^P = 1^+$ over the other four quantum numbers is estimated with $\Delta \ln \mathcal{L} = \ln \mathcal{L}_{1^+} - \ln \mathcal{L}_{J^P}$ and Δndf . Here, the log-likelihood difference $\Delta \ln \mathcal{L}$ is determined with the fit to data; the Δndf is the change of number of degrees of freedom. For $J^P = 2^-$ hypothesis with $\Delta ndf = 0$, the method in Ref. [30] is applied. The Δndf is assumed to be 1, which allows the calculation of a lower limit on the statistical significance of its rejection [31] as $\sqrt{2(\ln \mathcal{L}_{1^+} - \ln \mathcal{L}_{2^-})}$. The approach is also verified through a likelihood test using a series of pseudodatasets [32]. Based on the likelihood ratio $t \equiv -2 \ln(\mathcal{L}_{2^-}/\mathcal{L}_{1^+})$ distribution, the 2^- hypothesis is rejected with a statistical significance $(t_{\text{data}} - \langle t \rangle_{2^-})/\sigma(t)_{2^-} = 5.6\sigma$, which is consistent with the nominal result. As summarized in Table I, the other four J^P hypotheses are rejected with statistical significances larger than 5σ .

The $X(2085)$ is observed with statistical significance greater than 20σ . As the mass and width of a mass-dependent-width Breit-Wigner function can be model-dependent and deviate from the actual resonance properties, we determine the pole position in the complex (M, Γ) plane as a position where the denominator of the Breit-Wigner function is zero. The pole position is denoted as $P = M_{\text{pole}} - i\Gamma_{\text{pole}}/2$. M_{pole} and Γ_{pole} are then used to characterize the mass and width of the $X(2085)$ resonance. In the case of the 1^+ hypothesis, the pole mass and width are determined to be $M_{\text{pole}} = (2083_{-4}^{+6})$ MeV and $\Gamma_{\text{pole}} = (63_{-7}^{+8})$ MeV, respectively. The results of the 1^+ amplitude fit are consistent with the data presented in M_{pK^-} , $M_{p\bar{\Lambda}}$, and $M_{K^-\bar{\Lambda}}$ distributions, as demonstrated in Fig. 2.

The fit with the same set of amplitudes is performed to datasets taken at the other energy points. The obtained

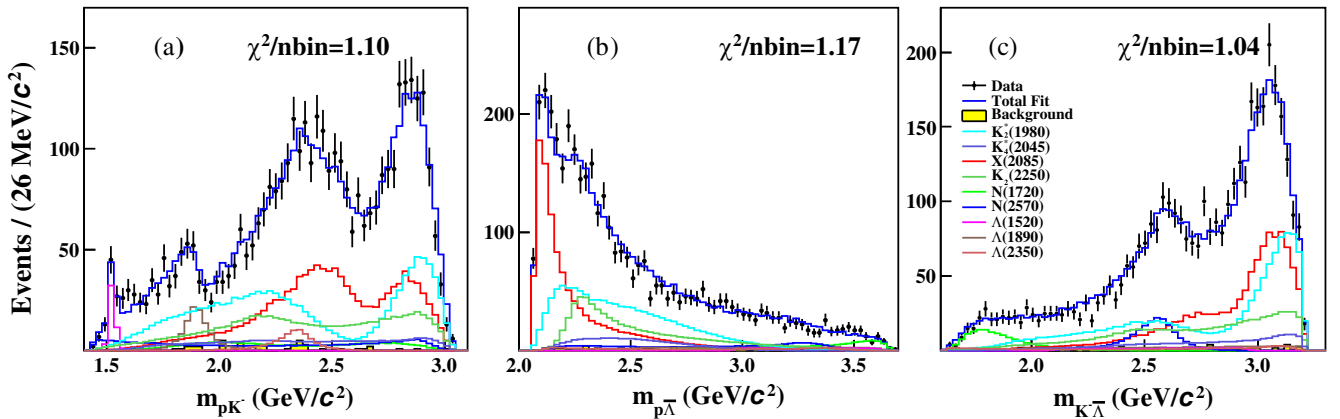


FIG. 2. Fit projections of the amplitude fit result on the (a) pK^- , (b) $p\bar{\Lambda}$, and (c) $K^-\bar{\Lambda}$ invariant mass distributions of the $e^+e^- \rightarrow pK^-\Lambda$ candidate events in data taken at $\sqrt{s} = 4.178$ GeV. The points with errors are data, the blue curve is the fit result, the curves in various colors denote different resonant components, and the yellow filled histogram is the simulated background.

TABLE II. The integrated luminosity \mathcal{L}_{int} (in pb^{-1}) and obtained pole parameters of $X(2085)$ (in MeV) at various energy points \sqrt{s} (in GeV). The uncertainties are statistical only.

\sqrt{s}	\mathcal{L}_{int}	M_{pole}	Γ_{pole}
4.008	482.0 ± 4.7	2082_{-9}^{+13}	56_{-14}^{+15}
4.178	3189.0 ± 31.9	2083_{-4}^{+6}	63_{-7}^{+8}
4.226	1100.9 ± 7.0	2086_{-8}^{+11}	71_{-13}^{+15}
4.258	828.4 ± 5.5	2081_{-6}^{+9}	52_{-9}^{+10}
4.416	1090.7 ± 7.2	2085_{-7}^{+10}	59_{-9}^{+11}
4.682	1669.3 ± 9.0	2090_{-7}^{+9}	55_{-5}^{+8}
Average	—	2084_{-2}^{+4}	58_{-3}^{+4}

results are summarized in Table II. The pole position of $X(2085)$ is stable and independent of \sqrt{s} . The averaged pole parameters are determined to be $M_{\text{pole}} = (2084_{-2}^{+4})$ MeV and $\Gamma_{\text{pole}} = (58_{-3}^{+4})$ MeV.

The systematic uncertainties on the resonance parameters of $X(2085)$ are summarized in Table III. The uncertainties, except those associated with the background estimation, are considered to be correlated among various energy points and studied at $\sqrt{s} = 4.178$ GeV. The systematic uncertainty arising from taking the radius $d = 0.73$ fm is estimated with alternative radii 0.20 fm and 0.99 fm [22]. To estimate the systematic uncertainty associated with the Breit-Wigner line shapes of $K_2(2250)$ and $N(1720)$, whose $M_0 - 2\Gamma_0$ falls below the mass threshold, we replaced their line shapes with the mass-dependent model given by Eq. (3). The systematic uncertainty due to the Breit-Wigner line shapes of $K_2^*(1980)$ and $K_4^*(2045)$, whose mass center M_0 is lower than the mass threshold, is estimated by modeling their line shape with $\Gamma(s) = (1/M_{\text{BW}})g_{p\bar{\Lambda}}^2\rho_{p\bar{\Lambda}}(s)n_{p\bar{\Lambda}}^2(s)$. Here, g is the coupling constant, $\rho(s) = q/\sqrt{s}$ is the two-body phase space factor, and $n = (q/q_0)^l B_l(q/q_0)$ with momentum

 TABLE III. Systematic uncertainties on the pole positions of $X(2085)$.

Source	M_{pole} (MeV)	Γ_{pole} (MeV)
Radius d	5.8	19.8
Breit-Wigner line shape	5.6	14.7
Excited Σ states	1.3	1.6
Insignificant resonance	1.5	2.1
Resonance parameters	0.8	1.7
$ \cos\theta_K $ requirement	0.5	0.6
$\Lambda(\bar{\Lambda})$ signal mass window	0.6	1.3
Background estimation	1.4	2.8
Mass resolution	0.3	0.2
Total	8.5	25.0

scale $q_0 = 0.2708$ GeV. The parameters M_{BW} and $g_{p\bar{\Lambda}}^2$ are determined by solving $M_{\text{BW}}^2 - s - iM_{\text{BW}}\Gamma(s) = 0$ with the measured Breit-Wigner poles, where $\sqrt{s} = M_{\text{PDG}} - i\Gamma_{\text{PDG}}/2$. The systematic uncertainty related to possible contributions from excited Σ states is estimated by adding Σ^* states with the similar masses as that of Λ^* states in the nominal solution. The systematic uncertainty caused by insignificant resonance with statistical significance within 3 to 5σ , is studied by including them into fit. The systematic uncertainty due to quoted resonance parameters of the other eight resonances is estimated by sampling their parameters according to their uncertainties simultaneously, repeating the fit, and taking the width of the resulting distribution as systematic uncertainty. The systematic uncertainty of the requirement $|\cos\theta_K| < 0.83$ is estimated by removing this cut. The maximum change between resonance parameters of $X(2085)$ is taken to be the corresponding uncertainty. The systematic uncertainty related to the $\Lambda(\bar{\Lambda})$ signal mass window is estimated by varying it by 1 MeV. The systematic uncertainty due to the background estimation is evaluated by performing another amplitude fit without considering the background contribution. For each of these sources, the largest change of the $X(2085)$ resonance parameters is assigned as the systematic uncertainty. The systematic uncertainty due to the mass resolution is estimated with a simulation study as described in Ref. [33]. This study is used to derive a relation between the measured pole parameters and their true values, and the difference between the parameters from the fit to data and the derived true values is taken as the corresponding systematic uncertainty.

Analogous systematic variations are conducted to verify the reliability of J^P assignment. Further details can be found in the Supplemental Material [26]. The hypothesis of $J^P = 1^+$ continues to be favored with a statistical significance exceeding 5σ over 0^- , 1^- , and 2^+ hypotheses, while for the 2^- hypothesis the statistical significance falls within the range of $3.1 \sim 7.5\sigma$.

In summary, with 8.35 fb $^{-1}$ of e^+e^- collision data taken at $\sqrt{s} = 4.008, 4.178, 4.226, 4.258, 4.416,$ and 4.682 GeV, the process $e^+e^- \rightarrow pK^-\bar{\Lambda}$ is studied. The enhancement near the mass threshold of $p\bar{\Lambda}$ system, $X(2085)$, is observed with a statistical significance greater than 20σ . The spin and parity of $X(2085)$ are determined with an amplitude analysis to be 1^+ with a statistical significance greater than 5σ over quantum numbers of 0^- , 1^- , and 2^+ , while the statistical significance of 1^+ over 2^- falls within $3.1 \sim 7.5\sigma$. Under the assignment of $J^P = 1^+$, the pole positions of $X(2085)$ are measured to be $M_{\text{pole}} = (2086_{-2}^{+4} \pm 9)$ MeV and $\Gamma_{\text{pole}} = (56_{-3}^{+4} \pm 25)$ MeV, respectively. They match neither any known excited kaon state observed in experiments [22] nor any state predicted by the potential model [34–38] without considering possible mixing between states with the same quantum

numbers. The anomalous narrow width and the mass near the $p\bar{\Lambda}$ threshold may suggest exotic properties of $X(2085)$. No conclusion can be drawn that $X(2085)$ is the same structure as the one observed in Ref. [1] since limited information was given. Further studies about the properties of $X(2085)$ in the decays of $J/\psi \rightarrow pK^-\bar{\Lambda}$ and $\psi(3686) \rightarrow pK^-\bar{\Lambda}$ with larger J/ψ and $\psi(3686)$ data samples [39] are desirable to provide more precise information. Searching for its isospin partner in $e^+e^- \rightarrow nK_S^0\bar{\Lambda}$ final state is crucial to check if $X(2085)$ has an isospin of $1/2$.

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