Indication of a Deeply Bound and Compact $K^- pp$ State Formed in the $pp \to p\Lambda K^+$ Reaction at 2.85 GeV

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(Received 27 December 2009; published 1 April 2010)

We have analyzed data of the DISTO experiment on the exclusive $pp \to p\Lambda K^+$ reaction at 2.85 GeV to search for a strongly bound compact $K^- pp (\equiv X)$ state to be formed in the $pp \to K^+ + X$ reaction. The observed spectra of the K^+ missing mass and the $p\Lambda$ invariant-mass with high transverse momenta of p and K^+ revealed a broad distinct peak of 26-σ confidence with a mass $M_X = 2267 \pm 3$(stat) $\pm$ 5(syst) MeV/c^2 and a width $\Gamma_X = 118 \pm 8$(stat) $\pm$ 10(syst) MeV. The enormously large cross section indicates formation of a compact $K^- pp$ with a large binding energy of $B_K = 103$ MeV, which can be a possible gateway toward cold and dense kaonic nuclear matter.

Recently, it was predicted that a strongly bound $K^- pp$ system with a short p-p distance [1,2] can be formed in a $p + p \to p + \Lambda^* + K^+$ reaction with an enormously large sticking probability between $\Lambda^* \equiv \Lambda(1405)$ and p due to the short range and high momentum transfer of the pp reaction [3,4]. Thus, the issue whether the $K^- pp$ and other kaonic nuclei have ultra high nuclear density or not can be answered by examining this prediction experimentally. Here, we report that existing data of a DISTO experiment show an evidence for this "exotic" formation. Preliminary reports have been published [5,6].

$K^- pp$ [a symbolical notation; more generally, $(\bar{K}NN)_{S=0,I=1/2}$] is the simplest kaonic nuclear bound system, predicted to be a quasistable state with a mass $M = 2322$ MeV/c^2, a binding energy $B_K = 48$ MeV, and a partial decay width $\Gamma_{\Sigma \pi p} = 61$ MeV [1,2]. A detailed theoretical analysis, based on the Ansatz (called "strong binding regime") that the $\Lambda(1405)$ resonance is an $I = 0$ $\bar{K}N$ quasibound state embedded in a $\Sigma \pi$ continuum, has shown that $K^- pp$ has a moleculelike structure in which the K^- migrates between the two protons, causing a *super-strong nuclear force* [3,4,7]. The strongly bound nature of $K^- pp$ is also supported by recent Faddeev calculations [8,9]. On the other hand, recent theories based on chiral dynamics predict the $K^- p$ pole to be located at 1420–1430 MeV/c^2, close to the $\bar{K} + N$ threshold, leading to a "weak" $\bar{K}N$ interaction [10,11] ("weak-binding regime"), and thus to a very shallow $K^- pp$ state [12]. Since the issue is pertinent to the existence of dense kaonic nuclear states [1,2,13,14] and eventually to the problem of kaon condensation [15], it is of vital importance to distinguish between the "strong binding" and the "weak binding" regimes by studying the $K^- pp$ formation in the pp reaction experimentally. So far, only little experimental information is available. A FINUDA experiment of K^- absorption at rest in light nuclei [16] reported that the observed invariant-mass spectrum, $M(p\Lambda)$, showed a peaklike structure with $M = 2255 \pm 7$ MeV/c^2, $B_K = 115 \pm 7$ MeV, and $\Gamma = 67 \pm 14$ MeV/c^2, but unfortunately, its lower part is suppressed by the detector acceptance, and no information for the shape of possible physical background is available.

The DISTO experiment, originally aimed at comprehensive studies of strangeness exchange reactions in pp collisions, was carried out at the SATURNE accelerator at Saclay [17,18]. We have analyzed the experimental data set of exclusive reaction products, $p\Lambda K^+$, at the incident kinetic energy of 2.85 GeV (see details in [6]). For this

purpose, Λ events were preselected by identification of the $\Lambda \to p\pi^-$ decay, and a missing-mass spectrum of $\Delta M(pK^+)$ showed peaks of Λ, Σ^0, and $\Sigma^0(1385) + \Lambda(1405)$. Then, they were used for a kinematical refit of four particles, p, p, K^+, π^-, where the reconstructed invariant mass $M_{p\pi^-}$ is constrained to the Λ mass and the four-body missing mass is constrained to 0 or M_{π^0}. The reaction products are selected by asking for the Dalitz regions kinematically accessible by the $p\Lambda K^+$ and $p\Sigma^0 K^+$ final states. The missing-mass spectrum, $\Delta M(pK^+)$, thus obtained, is shown in Fig. 1 (left). We selected about 177 thousands exclusive $p\Lambda K^+$ events by setting the Λ gate as shown. The impurity of Σ^0 in this Λ gate is estimated to be 4.5%. It is found to be reduced to 2.6% for events in final spectra to be shown later.

The exclusive $p\Lambda K^+$ data not only correspond to the "ordinary" Λ production process,

$$p + p \to p + \Lambda + K^+ \quad \text{(ordinary)}, \qquad (1)$$

but also may include the exotic process involving the $K^- pp$ bound state ($\equiv X$),

$$p + p \to K^+ + X, \qquad X \to p + \Lambda \quad \text{(exotic)}. \qquad (2)$$

We show in Fig. 1 (right) an acceptance-corrected Dalitz plot of all the $p\Lambda K^+$ events in the plane of $x = M(p\Lambda)^2$ vs $y = M(\Lambda K)^2$. The expected Dalitz distribution of the ordinary process (1) is continuous without any local bump structure [19]. On the other hand, the observed distribution, Fig. 1 (right), reveals some structure that cannot be explained by the ordinary process. However, the Dalitz plot alone cannot discriminate between the ordinary and the exotic processes. It is important to study the angular distributions and momentum spectra of p, Λ, and K^+, with respect to the incident beam, which are hidden in the Dalitz presentation.

Hereafter, we show uncorrected experimental spectral distribution of a kind α [UNC$^{(\alpha)}$] together with *simulated* data [SIM$^{(\alpha)}$]. Each SIM$^{(\alpha)}$ distribution is calculated for events of the ordinary $pK^+\Lambda$ process (1) according to a uniform phase-space distribution, folded with the DISTO acceptance, and then fed to the complete reconstruction and analysis chain for UNC$^{(\alpha)}$, fulfilling hence the same cuts and refitting procedure. In view of possible uncertainties in the efficiency matrix, we adopt a method to obtain an efficiency-compensated presentation of the experimental data, that is, by calculating a *deviation-spectrum* for each bin as defined by

$$\text{DEV}^{(\alpha)} \equiv \text{UNC}^{(\alpha)} / \text{SIM}^{(\alpha)}. \qquad (3)$$

Each DEV$^{(\alpha)}$ spectrum is, of course, different from the intensity distribution, which is generally bell shaped due to the phase-space density. DEV$^{(\alpha)}$ is free, not only from the phase-space density, but also from possible uncertainty in the efficiency. A DEV$^{(\alpha)}$ distribution is generally flat, but indicates a structure when a physically meaningful deviation from the uniform phase-space distribution occurs. This deviation-spectrum method is valid when the selected events are 100% exclusive $p\Lambda K^+$ [6]. The actual purity of the Λ selection is about 95%, and is even higher for events taken in the final spectra. The validity can be examined from the equivalence of $M(p\Lambda)$ and $\Delta M(K^+)$, which are in fact found to be nearly identical to each other.

Figure 2 shows the UNC, SIM, and DEV distributions of the momentum P vs $\cos\theta$ in c.m. of p and K^+. The UNC data as well as the SIM data show that the p distribution is extremely backward, which arises from the large accep-
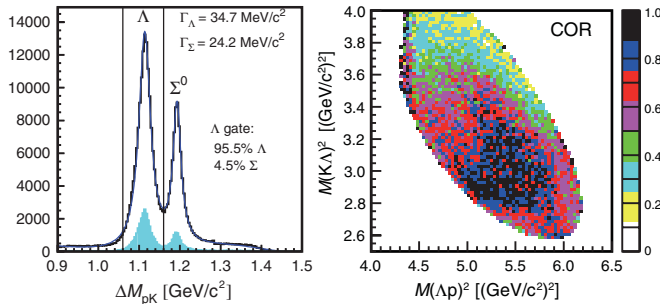

FIG. 1 (color). (Left) A $\Delta M(pK^+)$ spectrum of raw data after the kinematically constrained refit, acceptance uncorrected; the small shaded histogram includes events after p and K^+ cuts applied to obtain final spectra. (Right) An acceptance-corrected Dalitz plot of the exclusive $pp \to p\Lambda K^+$ reaction products at 2.85 GeV.
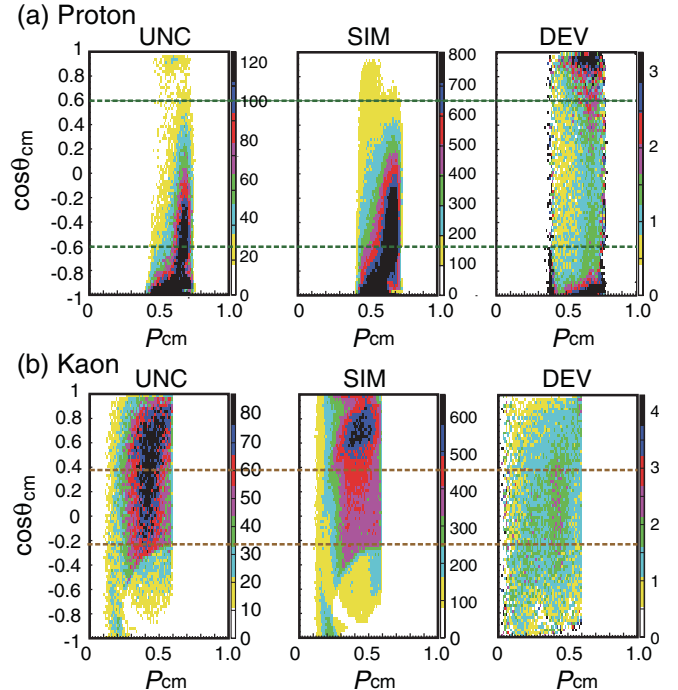

FIG. 2 (color). Momentum distributions, P, versus $\cos\theta$ in c.m. of (a) p and (b) K^+. Each block consists of UNC (uncorrected), SIM (simulated), and DEV (deviation) data. The horizontal dotted lines define $-0.6 < \cos\theta_{\text{cm}}(p) < 0.6$ and $-0.2 < \cos\theta_{\text{cm}}(K) < 0.4$, to be used for proton-angle and K^+-angle cuts.

tance of the DISTO detector for $\Lambda \to p + \pi^-$ decay in the forward direction. The DEV distributions of p and Λ (not shown), both peaked at $\cos\theta = \pm 1$ in c.m., are remarkably symmetric, as expected from the symmetric pp collision in c.m. This fact justifies the present acceptance correction on SIM.

Since the maximum momentum of p in the ordinary process of $p\Lambda K^+$ is 0.751 GeV/c, the dominating proton group at extremely backward angles [$\cos\theta_{cm}(p) < -0.9$] has a transverse momentum, $P_T < 0.3$ GeV/c. This fact is understood as the ordinary process of low transverse momentum P_T [19]. On the other hand, since the proton group of large-angle emission includes a much less amount of the ordinary process, the relative contribution of the exotic process, involving the decay of X with a transverse momentum of around 0.4 GeV/c, is expected to be larger. So, it is extremely interesting to distinguish X from the dominant ordinary process by applying proton-angle cuts, such as "large-angle proton" (LAP) cut: $|\cos\theta_{cm}(p)| < 0.6$ and "small-angle proton" (SAP) cut: $|\cos\theta_{cm}(p)| > 0.6$.

The DEV K^+ spectrum of Fig. 2(b) already shows that the $P_{cm}(K)$ has a monoenergetic component around 0.4 GeV/c even before applying the proton-angle cut, which could be a signature for a two-body process, $pp \to K^+ X$. It is to be noted that this component is present in the UNC data, and thus, the component appearing in the DEV data cannot be a fake that might originate from the correction, since SIM is smooth in this region.

Figure 3 shows DEV spectra of $M(p\Lambda)^2$ and $\Delta M(K)^2$ and their correlations with $\cos\theta_{cm}(K)$ for (a) LAP and (b) SAP. Clearly, the vertical band in the $P_{cm}(K)$ vs $\cos\theta_{cm}(K)$ plot, now converted into $M(p\Lambda)^2$ and $\Delta M(K)^2$, is enhanced with LAP. A distinct peak is seen at around $x \sim 5.15$, corresponding to $M_X \approx 2.27$ GeV/c^2. We have demonstrated that the proton-angle cut is very effective in discriminating the X formation process (monoenergetic emission of K^+) from the ordinary process. The DEV spectra of SAP, as shown in Fig. 3(b), are remarkably flat. The linear shape with a positive gradient of (b) is well accounted for by the ordinary $pp \to p\Lambda K^+$ mechanism with a collision length of $\hbar/m_B c$ with $m_B \sim 0.2$ GeV/c^2, which explains the proton angular distribution as well [19]. In great contrast, the observed DEV spectra of LAP (a) reveal a large bump on a flat horizontal background.

We find from Fig. 2(b) that the geometrical acceptance of K^+ is not flat in the forward and backward c.m. zones of K^+ emission, as seen in both UNC and SIM. Thus, we applied cuts, $-0.2 < \cos\theta_{cm}(K) < 0.4$, to obtain final DEV spectra, where enhanced monoenergetic X events are observed at large K^+ c.m. angles.

In summary, we have observed a large broad peak in the DEV spectrum of $\Delta M(K^+)$ [and $M(p\Lambda)$], as shown in Fig. 4(a), which is associated with LAP. On the other hand, in Fig. 4(b) for SAP, a linear background dominates. We made simple fitting of the DEV spectrum of $\Delta M(K^+)$ with LAP (a) by a Gaussian + linear background, and obtained
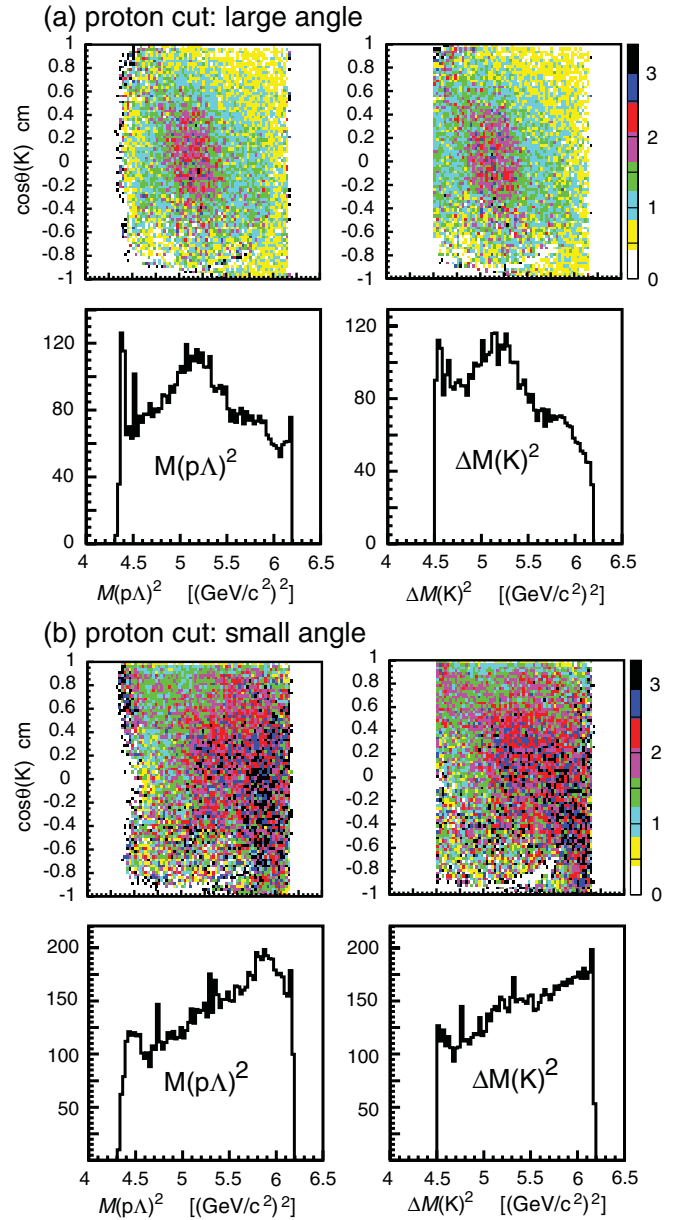

FIG. 3 (color).   (a) Events with LAP cut [$|\cos\theta_{cm}(p)| < 0.6$] and (b) events with SAP cut [$|\cos\theta_{cm}(p)| > 0.6$]. Each frame consists of (upper) DEV spectra of 2-dimensional $M(p\Lambda)^2$ and $\Delta M(K)^2$ vs $\cos\theta_{cm}(K)$ and (lower) DEV spectra of 1-dimensional $M(p\Lambda)^2$ and $\Delta M(K)^2$.

$$M_X = 2267 \pm 3(\text{stat}) \pm 5(\text{syst}) \text{ MeV}/c^2, \qquad (4)$$

$$\Gamma_X = 118 \pm 8(\text{stat}) \pm 10(\text{syst}) \text{ MeV}. \qquad (5)$$

The best-fit χ^2/ndf value is $34.2/24 = 1.4$. The peak height amounts to about 26-σ statistical significance. The DEV spectrum of $\Delta M(K^+)$ with SAP (b) can be fitted with the same Gaussian shape and another linear background, as shown. The very different background slopes of (a) and (b) are accounted for by a simple reaction model [19]. The Gaussian-like peak persists in (b) despite the larger background for SAP. The observed mass of X is close to
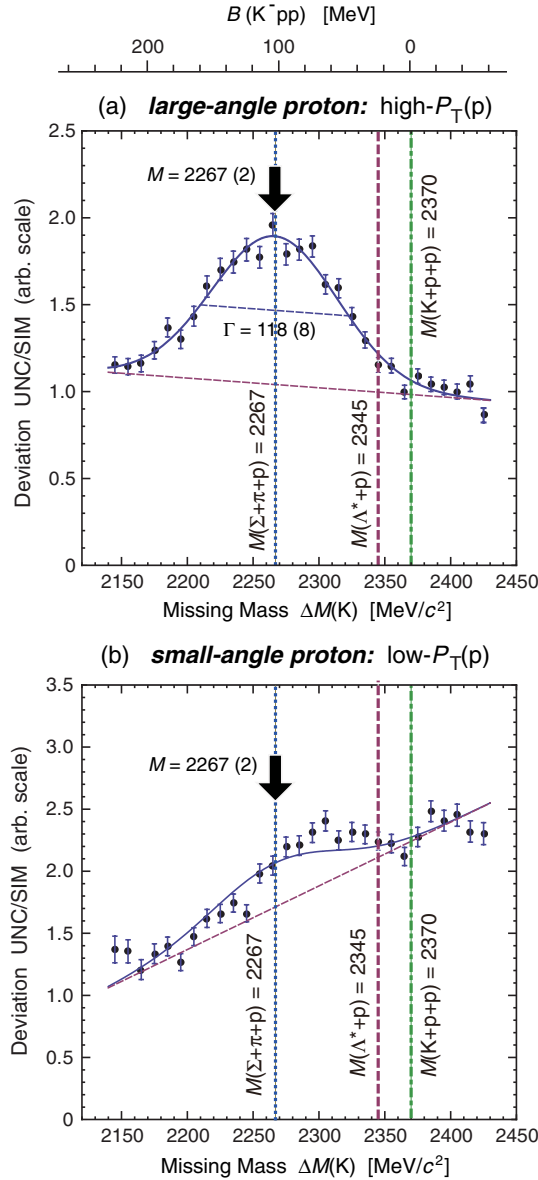
FIG. 4 (color online). (a) Observed DEV spectra of $\Delta M(K^+)$ of events with LAP emission $[|\cos\theta_{cm}(p)| < 0.6]$ and (b) with SAP emission $[|\cos\theta_{cm}(p)| > 0.6]$. Both selected with large-angle K^+ emission $[-0.2 < \cos\theta_{cm}(K^+) < 0.4]$.

$M(p\Lambda) \sim 2255$ MeV/c^2 of the $K^- pp$ candidate reported by FINUDA [16].

The X production rate is found to be as much as the $\Lambda(1405)(= \Lambda^*)$ production rate, which is roughly 20% of the total Λ production rate. Such a large formation is theoretically possible only when the p-p (or Λ^*-p) rms distance in X is shorter than 1.7 fm [3,4], whereas the average N-N distance in ordinary nuclei is 2.2 fm. The $pp \rightarrow \Lambda^* + p + K^+ \rightarrow X + K^+$ reaction produces Λ^* and p of large momenta, which can match the internal momenta of the off-shell Λ^* and p particles in the bound state of $X = \Lambda^*$-p, only if X exists as a dense object. Thus, the dominance of the formation of the observed X at high

momentum transfer ($\sim$1.6 GeV/c) gives direct evidence for its compactness of the produced $K^- pp$ cluster.

As shown in Fig. 4, the peak is located nearly at the $\Sigma\pi$ emission threshold, below which the $N\Sigma\pi$ decay is not allowed. The expected partial width of $K^- pp$, $\Gamma_{N\Sigma\pi}$, must be much smaller than the predicted value of 60 MeV [2], when we take into account the pionic emission threshold realistically by a Kapur-Peierls procedure (see [20]). Thus, $\Gamma_{non-\pi} = \Gamma_{p\Lambda} + \Gamma_{N\Sigma} = \Gamma_{obs} - \Gamma_{N\Sigma\pi} \approx 100$ MeV, which is much larger than recently calculated nonpionic widths for the normal nuclear density, $\Gamma_{non-\pi} \sim 20$–30 MeV [7,21]. The observed enhancement of $\Gamma_{non-\pi}$ roughly by a factor of 3 seems to be understood with the compact nature of $K^- pp$ [4].

The observed mass of X corresponds to a binding energy $B_K = 103 \pm 3$(stat) ± 5(syst) MeV for $X = K^- pp$. It is larger than the original prediction [2,8,9]. It could be accounted for if the $\bar{K}N$ interaction is effectively enhanced by 25%, thus suggesting additional effects to be investigated [4,22]. On the other hand, the theoretical claims for shallow $\bar{K}$ binding [10–12] do not seem to be in agreement with the observation. We emphasize that the deeply bound and compact $K^- pp$ indicated from the present study is an important gateway toward cold and dense kaonic nuclear matter [15,23].

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