# Evidence for a Kaon-Bound State $K^- pp$ Produced in $K^-$ Absorption Reactions at Rest

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(Received 4 March 2005; published 3 June 2005)

We have searched for a deeply bound kaonic state by using the FINUDA spectrometer installed at the $e^+e^-$ collider DAΦNE. Almost monochromatic $K^-$'s produced through the decay of $\phi(1020)$ mesons are used to observe $K^-$ absorption reactions stopped on very thin nuclear targets. Taking this unique advantage, we have succeeded to detect a kaon-bound state $K^- pp$ through its two-body decay into a $\Lambda$ hyperon and a proton. The binding energy and the decay width are determined from the invariant-mass distribution as $115^{+6}_{-5}(\text{stat})^{+3}_{-4}(\text{syst})$ MeV and $67^{+14}_{-11}(\text{stat})^{+2}_{-3}(\text{syst})$ MeV, respectively.

DOI: 10.1103/PhysRevLett.94.212303 PACS numbers: 21.45.+v, 21.30.Fe, 21.80.+a, 25.80.Nv

At the last conference on hypernuclei and strangeness production HYP2003, two groups reported possible signatures of deeply bound kaonic states in two different reactions: $^{16}$O($K^-$, $n$) [1] and $^4$He($K^-_{\text{stop}}$, $nX$) [2,3]. The observed signals were interpreted as the productions of $^{15}_{K^-}$O and $K^- ppn$, respectively. Later, the latter group has also reported the observation of a much clearer signal of the production of a tribaryonic state $S^0(3115)$ in the $^4$He($K^-_{\text{stop}}$, $pX$) reaction [3,4]. If these interpretations are true, the $K^-$ nucleus potential seems to be deeper than 100 MeV.

Thus, it is an urgent experimental subject to verify or confirm if these signals really correspond to the production of kaon-bound states or not. Unfortunately, all of these measurements used the missing-mass method, so that there exist some ambiguities whether a kaon was really bound in the system. In the FINUDA (acronym for "Fisica Nucleare a DAΦNE") experiment, we can stop $K^-$'s in very thin nuclear targets, and detect multitracks in the FINUDA spectrometer. It enables us to detect a $\Lambda$ hyperon through its decay to proton and $\pi^-$. We can clearly identify the formation of bound states with strangeness from their decays to $\Lambda + X$.

As for the $K^- p$ interaction in free space, the existing experimental information on low-energy $K^- p$ scattering [5], $K^- p$ threshold branching ratios [6], a kaonic-hydrogen atomic x-ray measurement [7,8], etc., leaves rooms for different theoretical analyses.

The information on the $K^-$ nucleus interaction has been obtained with the kaonic atomic data [9]. Unfortunately,

0031-9007/05/94(21)/212303(4)$23.00

we have qualitatively two different predictions for the depth of the $K^-$ nucleus potential at normal nuclear matter density: very deep attractive potentials $[-\mathrm{Re}V_{\mathrm{opt}}(\rho_0) \approx$ 150–200 MeV] [10,11] and much shallower potentials $[-\mathrm{Re}V_{\mathrm{opt}}(\rho_0) \approx$ 50–75 MeV] [12–16]. Both types of potentials reasonably describe the shifts and widths of the x-ray data.

Recently, an interesting idea has been proposed suggesting the possible existence of deeply bound nuclear $\overline{K}$ states in light nuclei [17,18], for which the potential is very deep. Since the potential is strongly attractive in the $I = 0$ $\overline{K}N$ interaction, proton-rich $\overline{K}$ nuclei such as $K^-pp$ and $K^-ppn$ are predicted to have large binding energies of 50–100 MeV. A further interesting suggestion is that the nucleus might be shrunk because of the large binding energy and form a high-density state, which is also confirmed with the method of antisymmetrized molecular dynamics for the cases of $K^-ppn$ and $K^{-8}$Be [19]. Since there is no Pauli blocking effect for a $K^-$ boson, it can attract the nucleus at its center. If such a $\overline{K}$ nucleus is observed, it would give us direct information of the $K^-$ nucleus potential at nuclear matter density.

The experiment is performed at an intersection region of the $e^+e^-$ collider DAΦNE at the Laboratori Nazionali di Frascati (LNF), which produces copious $\phi(1020)$ mesons. A key characteristic of the FINUDA spectrometer is the achievement of high resolution through the use of very thin nuclear targets of $\approx 200$ mg/cm$^2$ and low-mass chambers in a He atmosphere [20]. The nearly monochromatic $K^-$ from the $\phi$ decays are fully stopped in these targets. The spectrometer covers a solid angle larger than $2\pi$ sr. This good performance enables us to carry out the spectroscopy of $\Lambda$ hypernuclei with a good energy resolution better than 1 MeV FWHM and their weak decay studies as the main objective of the FINUDA experiment.

Figure 1 (top) shows an overview of the FINUDA spectrometer. It consists of three regions: the interaction/target region, the tracking system, and the external time-of-flight system. The $K^+K^-$ pair from the $\phi$ decay is detected by a barrel of 12 thin scintillator slabs (TOFINO) and an octagonal array of silicon microstrip detectors (ISIM). The kaon loses its energy through the beam pipe, TOFINO, and ISIM, and finally stops in one of thin targets. After $K^-$ absorption in the target, the emitted particles are detected by the external tracking system. Charged particles are detected with a second layer of silicon microstrip detectors (OSIM), two layers of low-mass drift chambers (LMDC), and six layers of aluminized mylar straw tubes, arranged in three groups, the first one beam oriented, and the others tilted by ±12°. The $dE/dx$ information obtained in the OSIM detector is used for particle identification. Seventy-two external scintillator slabs (TOFONE) are installed in the outermost part, which are used to measure the time of flight of a charged or neutral particle and for triggering purpose.

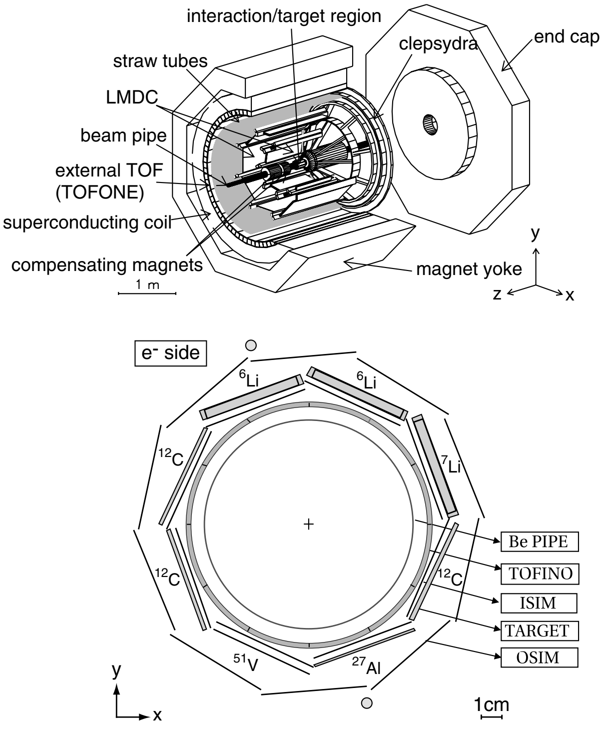

FIG. 1. Global views (top, complete apparatus; bottom, interaction/target region) of the FINUDA apparatus.

In the first data taking in 2003–2004, five kinds of targets ($^6$Li, $^7$Li, $^{12}$C, $^{27}$Al, and $^{51}$V) were installed as shown in Fig. 1 (bottom). The integrated luminosity during the run reached $\sim$250 pb$^{-1}$, of which $\sim$190 pb$^{-1}$ was effectively used in the present analyses.

The momentum resolution of the FINUDA spectrometer at this stage of analysis was determined from the two monochromatic peaks corresponding to $K_{\mu 2}(K^+ \rightarrow \mu^+\nu_\mu)$ and $K_{\pi 2}(K^+ \rightarrow \pi^+\pi^0)$ decays of $K^+$ stopping in the targets. It was found to be $\Delta p/p \sim 0.6\%$ FWHM. It is remarkable that the spectrometer delivered the right momenta of the monochromatic particles to a precision better than 200 keV/$c$, without the need of further correction.

$\Lambda$ hyperons are produced with a sizable fraction in kaon absorption through various processes. The quasifree process ($K^-N \rightarrow \Lambda\pi$) emits a slow $\Lambda$ with a momentum $\sim$300 MeV/$c$. Above $\sim$400 MeV/$c$, the main contribution comes from the $\Lambda$ hyperons emitted from two-nucleon absorptions ($K^- +$ “$NN$” $\rightarrow \Lambda N$, $\Sigma^0 N$). The acceptance of the FINUDA spectrometer cuts the $\Lambda$ hyperons with a momentum lower than 300 MeV/$c$, which is restricted by the low momentum threshold for $\pi^-$ from the $\Lambda \rightarrow p + \pi^-$ decay. Therefore, the $\Lambda$ from the quasifree process is hardly observed in the FINUDA spectrometer.

$\Lambda$ particles can be identified by reconstructing the invariant mass of a proton and a negative pion as shown in Fig. 2(a). The peak position agrees well with the known $\Lambda$ mass, and the width of the peak is as narrow as 6 MeV/$c^2$ FWHM.

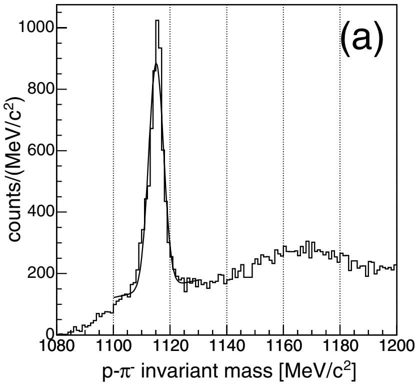

FIG. 2. (a) Invariant-mass distribution of a proton and a $\pi^-$ for all the events in which these two particles are observed, fitted by a single Gaussian together with a linear background in the invariant-mass range of 1100–1130 MeV/$c^2$. (b) Opening angle distribution between a $\Lambda$ and a proton: solid line, $^6$Li, $^7$Li, and $^{12}$C; dashed line, $^{27}$Al and $^{51}$V. The shaded area ($\cos\theta^{\mathrm{Lab}} < -0.8$) is selected as the back-to-back event.

When a $K^-$ interacts with two protons, one expects that a hyperon-nucleon pair ($\Lambda + p$, $\Sigma^0 + p$, or $\Sigma^+ + n$) is emitted in the opposite direction, ignoring a final state interaction inside the nucleus. The angular correlation between a $\Lambda$ and a proton from the same point in the target [Fig. 2(b)] clearly indicates the existence of this kind of reaction. Even for heavy nuclei such as $^{27}$Al and $^{51}$V the similar correlations were observed, which might suggest the absorption would take place at the surface of a nucleus.

In the following analysis, we use the $\Lambda$-$p$ pairs emitted in the opposite direction ($\cos\theta^{\mathrm{Lab}} < -0.8$) only from the light nuclear targets ($^6$Li, $^7$Li, and $^{12}$C).

Since the back-to-back angular correlation between a $\Lambda$ and a proton is so clear, it is naturally expected that the two particles are emitted from a "$K^-pp$" intermediate system. The angular correlation is smeared out due to the Fermi motions of the two protons at the surface of a nucleus by which the $K^-$ is absorbed after cascading down the atomic orbits by emitting x rays. If the reaction process were simply a two-nucleon absorption process, the mass of the system should be close to the sum of a kaon and two proton mass, namely, 2.370 GeV/$c^2$. The initial motion of the two protons does not affect the invariant-mass distribution.

The invariant-mass distribution of the $\Lambda$-$p$ pairs is shown in Fig. 3. A significant mass decrease of the $K^-pp$ system with respect to its expected mass is observed. It can be interpreted as a bound state composed of a kaon and two protons, hereafter abbreviated as $K^-pp$.

In the inset of Fig. 3, the acceptance corrected invariant-mass distribution for events with two well-defined long-track protons is shown. Since the trigger and detection acceptance are monotonically increasing functions of the invariant mass in this mass region, the peak further shifts to a lower mass side. The binding energy $B_{K^-pp} = 115^{+6}_{-5}(\mathrm{stat})^{+3}_{-4}(\mathrm{syst})$ MeV and the width $\Gamma = 67^{+14}_{-11}(\mathrm{stat})^{+2}_{-3}(\mathrm{syst})$ MeV are obtained from the fitting with a Lorentzian function (folded with a Gaussian with $\sigma = 4$ MeV/$c^2$, corresponding to the detector resolution, estimated with a Monte Carlo simulation) in the region of 2.22–2.33 GeV/$c^2$. Here, the systematic errors were estimated by changing the event selections in the $\Lambda$ invariant mass and the $\Lambda$-$p$ opening angle cut as well as by taking account of the detector acceptance change due to possible systematic deviations in absolute momentum scale, reaction vertex distributions, etc. Although we still have ambiguities on absolute normalization, a rough estimate on the yield of $K^-pp \rightarrow \Lambda + p$ is of the order of 0.1% per stopped $K^-$. Consistency of the Monte Carlo simulation used for estimations of the acceptance and the resolutions was examined by producing the $K^-pp$ events according to the obtained mass and width. The same simulation conditions were applied to these events; the momentum distributions of $\Lambda$'s and protons, the $\Lambda$-$p$ opening angle

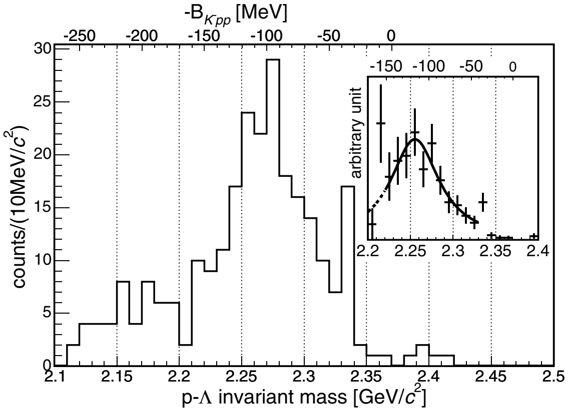

FIG. 3. Invariant mass of a $\Lambda$ and a proton in back-to-back correlation ($\cos\theta^{\mathrm{Lab}} < -0.8$) from light targets before the acceptance correction. The inset shows the result after the acceptance correction for the events which have two protons with well-defined good tracks. Only the bins between 2.22 and 2.33 GeV/$c^2$ are used for the fitting.

distribution, the momentum distribution of the $K^-pp$ system, etc., were in good agreement with the observed ones.

The $K^-pp$ decay into $\Sigma^0 + p$ should still have a back-to-back correlation between a $\Lambda$ and a proton, but a $\gamma$ from the $\Sigma^0$ decay is missing when reconstructing the invariant mass ($\Sigma^0$ at rest emits a 74 MeV $\gamma$). An excess in a low-mass region below $\sim$2.2 GeV/$c^2$ may be attributed to this decay mode. An analysis of this decay mode is under way for future publication.

From old bubble chamber and emulsion data [21], it is known that kaon two-nucleon absorption processes take place in 15%–20% per stopped $K^-$ in the broad range of the periodic table. However, the experimental information was statistically too limited to further investigate the reaction mechanism, and nobody has identified the kaon two-nucleon absorption process experimentally. Several theoretical analyses were performed in the 1960s to understand the reaction mechanism. A more recent theoretical analysis [22] roughly explained it with the two-nucleon absorption process including meson-rescattering diagrams. Here, it should be noted that the main mode for the kaon two-nucleon absorption is on a $pn$ pair with $S = 1$ and $T = 0$ and not on a $pp$ pair, which contributes only by $\sim$10% according to the calculation. Thus, there is no *a priori* reason that the two-nucleon absorption processes are to be observed in the $\Lambda$-$p$ coincidence events.

On the other hand, the detector system is very sensitive to the existence of the two-nucleon absorption mode $K^- +$ "$pp$" $\rightarrow \Lambda p$ since its invariant-mass resolution is 10 MeV/$c^2$ FWHM. The effect of the nuclear binding of two protons is only to move the peak position to the lower mass side of the order of separation energies of two protons ($\sim$30 MeV), and not to broaden the peak. A sharp spike around 2.34 GeV/$c^2$ may be attributed to this process. There could be, in addition, the two-nucleon absorption mode $K^- +$ "$pp$" $\rightarrow \Sigma^0 p$. In this case, the $\Lambda$-$p$ invariant-mass distribution is shifted to the lower mass region by about 74 MeV and broadened because a $\gamma$ from the $\Sigma^0 \rightarrow \Lambda + \gamma$ decay is missing. However, the observed invariant-mass distribution is too broad to be attributed to this process only. Also, according to the old data in the helium bubble chamber [23], the branching ratios of $K^-NN \rightarrow \Lambda N$ and $\Sigma^0 N$ are estimated to be 9.3% ± 2.6% and 2.3% ± 1.0% per stopped $K^-$ in $^4$He, respectively. The theoretical calculation [22] also suggests the $\Lambda N$ mode has a larger branching ratio than the $\Sigma^0 N$ mode. Therefore, we can assume that the kaon two-nucleon absorption mode is not dominant in this channel, nor in the $\Sigma^0 + p$ one which has even a lower branching ratio. Thus, we attribute the observed events in the bound region to the formation of the deeply bound $K^-pp$ state.

In summary, we have successfully observed evidence of the kaon-bound state $K^-pp$ through its decay into a $\Lambda$ and a proton. The invariant-mass distribution of the $\Lambda$-$p$ pair shows a significant mass decrease with respect to the mass of the system expected in the case of a simple kaon two-nucleon absorption. The state $K^-pp$ has a binding energy of $115^{+6}_{-5}$(stat)$^{+3}_{-4}$(syst) MeV and a decay width of $67^{+14}_{-11}$(stat)$^{+2}_{-3}$(syst) MeV.

We are greatly indebted to Dr. S. Bertolucci, former Director of LNF, for his continuous encouragement and help. Dr. P. Raimondi and the DAΦNE machine staff are warmly acknowledged for their very skillful handling of the DAΦNE collider. This work is supported in part by the Grant-In-Aid for Scientific Research (B) 15340087 of Ministry of Education, Culture, Sports, Science and Technology (MEXT).

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