$\Lambda N$ correlations from the stopped $K^-$ reaction on $^4$He

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(Dated: February 2, 2008)

We have investigated correlations of coincident $\Lambda N$ pairs from the stopped $K^-$ reaction on $^4$He, and clearly observed $\Lambda p$ and $\Lambda n$ branches of the two-nucleon absorption process in the $\Lambda N$ invariant mass spectra. In addition, non-mesonic reaction channels, which indicate possible exotic signals for the formation of strange multibaryon states, have been identified.

PACS numbers: 13.75.Jz, 21.45.+v, 25.80.Nv, 36.10.Gv

Recently, the existence of strongly bound $\bar{K}$-nuclear states, in particular, in few baryon systems $^3$He, $^3$H, has been intensively discussed. On the experimental side, possible candidates of few-body kaonic systems reported in stopped $K^-$ experiments $^3, 4, 5, 6$ were investigated in relation to their non-mesonic decay modes. Inclusive and semi-inclusive missing-mass spectroscopy using the $^3$He($\bar{K}^-$/$N$, $N$) reaction $^3, 5, 6$ showed its limitation in identifying relatively broad states due to the poorly known physical background shape originating from non-mesonic processes. Invariant mass spectroscopy via $\Lambda\pi$ and $\Lambda d$ correlations in stopped $K^-$ reactions $^3, 6, 9$ faced ambiguity in the discrimination of the signal from the direct and indirect contributions of the non-mesonic absorption processes, which are also poorly known. Thus a detailed study of the contribution of non-mesonic multi-nucleon absorption processes of stopped $K^-$ is crucial for the identification of strange multibaryon states, especially for those with relatively broad widths. From the theoretical point of view, these processes are expected to be the primary source of the imaginary part of the $\bar{K}$-nuclear potential in the deeply-bound energy region where $K N \to Y \pi$ channels are suppressed, thus dominating the widths of possible bound states. Hence, the dynamics of the absorption processes play an important role in the decay mechanism of possible $\bar{K}$-nuclei. The presently available information is from bubble chamber experiments which are mainly confined to measurements of total non-pionic capture rates of stopped $K^-$ $^{10}$, and the dynamical nature or even their existence are still speculative, except for those on deuterium $^{11}$. Therefore, comprehensive studies of non-mesonic reactions are indispensable to clarify whether or not the two-nucleon absorption (2NA) exist as well-separable processes and to see whether or not any signatures for multibaryonic states can be clearly identified.

The dynamics of the multinucleon absorption processes are most directly investigated by means of a coincidence measurement of back-to-back-correlated $YN$ pairs from stopped $K^-$ reactions, as

$$K^- "NN"(NN) \to YN(\bar{N}N) : 2\text{NA}, \quad (1)$$

$$K^- "NNNN"(N) \to YNN(\bar{N}N) : 3\text{NA}, \quad (2)$$

where $X$ ($X = N, d, \pi, \text{or } \gamma$) denotes an undetected particle $X$, and we adopt the terminology and notations introduced in Ref. $^9$ throughout the paper. Furthermore, the possible di/tri-baryonic signals are expected to appear most clearly in the $YN$ spectra, as

$$(K^-^4\text{He})_{\text{atomic}} \to 2S_T^{0/+}_{T=\frac{1}{2}^{+}} + \bar{N}N,$$

and

$$(K^-^4\text{He})_{\text{atomic}} \to 3S_T^{0/+}_{T=0/1} + N,$$

This Letter presents the successful measurement of $\Lambda N$ pairs from the stopped $K^-$ reaction in $^4$He in the KEK-PS E549 experiment.

Detailed descriptions of the experiment and analysis procedures for proton and neutron channels are given in Refs. $^5$ and $^8$, respectively, and the present analysis scheme is covered by Ref. $^6$. The $p\pi^\pm$ invariant mass ($M_{p\pi}$) spectra obtained from $p\pi$ back-to-back and
while components must be produced in non-mesonic final states, zones, and distinct physics processes. We classify the events into three divided zones as defined in the text.

The nature of the mysterious components \( B_{p/n} \) for
which no single step reaction scheme of conventional processes accounts, could include signals of di- or tri-baryonic states, and it should be mentioned that $A_p$ corresponds to the strength which had been attributed to a $K^-pp$ bound state in the FINUDA experiment [5], and thus, further investigation is absolutely needed, as discussed in what follows. On the other hand, the $C_{p/n}$ components with $M_{\text{miss}} > 2M_N + m_n$ are considered to be dominated by the quasi-free hyperon production processes, $K^- "N"(NNN) \rightarrow Y\pi(NNN)$, and successive $\Sigma(N) \rightarrow \Lambda N$ conversion, which dominate the stopped $K^-$ reaction [10].

The correlations between the momenta of the $\Lambda$ and $N$ are shown in Fig. 3 together with the overall and selected projections and acceptance curves. There, the $A_{p/n}$ components appear as correlated pairs with the highest momenta. The nucleon momentum ($P_N$) spectra of $A_{p/n}$ components are centered at $\sim 540/580$ MeV/c, respectively, with the FWHM $> 100$ MeV/c reflecting the Fermi motion, as predicted by PWIA calculation taking the nuclear form factor into account [15] as well as in Ref. [13]. This contradicts the claim for the mono-energetic emission of $N$ and $Y$ [16] (this aspect is clearly different from the situation observed on $^6$Li [17], in which a deuteron with a very small momentum ($\sim 50$ MeV/c) leads to the reaction, $K^- "d"(^4\text{He}) \rightarrow \Sigma^-p(^4\text{He})$ with monoenergetic protons).

The $B_p$ and $B_n$ components show somewhat different behavior. The low-momentum tail of $P_n$, which was detected due to the wide momentum acceptance, is produced by spectators of any reaction. The $B_p$ component is centered at $\sim 470$ MeV/c on both $P_p$ and $P_{\Lambda}$. The re-scattering processes proposed to explain the FUNUDA bump [18],

\[ K^- "N"(NN) \rightarrow \Lambda \tilde{N}(\tilde{N}\tilde{N}) \]
\[ \tilde{N}(\tilde{N}) \rightarrow N'\tilde{N}, \] 

or

\[ K^- "N"(NN) \rightarrow \tilde{\Lambda} N(\tilde{N}\tilde{N}) \]
\[ \tilde{\Lambda}(\tilde{N}) \rightarrow \Lambda'\tilde{N}, \] 

where $N'$ and $\Lambda'$ are re-scattered particles produced in the primary $2NA$ processes, account neither for the fact that both momenta are shifted toward lower values by
FIG. 3: A correlation diagram between 3-momenta of \( p \) and \( n \) (horizontal) and \( \Lambda \) (vertical). On the correlations, \( M_{\text{miss}} = m_L^N \), \( = m_H^N \), and \( = m_d \) are drawn by black, thick-gray, and thin-gray, with solid and dashed curves for \( \cos \theta_{\Lambda N} = -1.0 \) and \(-0.6\), respectively. On the projections, the \( \Lambda_N \), \( B_N \), and \( C_N \) components are shown by green, red, and blue lines, respectively, and acceptance curves calculated for inclusive \( N \) and \( \Lambda \) events are drawn by brown dotted curves on \( P_p \), \( P_n \), and \( P_\Lambda \) (\( \Lambda p \) side) spectra. 

4He(stopped \( K^- \), \( N \)) missing mass (tribaryon mass) scales are shown on the top sides of the \( P_N \) spectra.

The observed distributions of masses and momenta are qualitatively consistent with this reaction chain. The possible contribution originates from the \( \Sigma N \) branches of the 2NA processes and successive \( \Sigma \Lambda \) conversion,

\[
K^-\overline{NN}'(NN) \rightarrow \tilde{\Sigma}N(\tilde{N}\tilde{N}), \\
\tilde{\Sigma}(\tilde{N}) \rightarrow \Lambda\tilde{N}.
\]  

(9)

for which its \( \Lambda d \) branch has been observed very recently \[9\], is another possible source. However, this would require an even larger branching ratio of the 3NA compared to that of the 2NA to account for the entire observed strength.

One possible exotic interpretation for \( B_p \) and \( B_n \) is the production of tribaryon states \( 3^S_{T=1} \) and \( 3^S_{T=0,1/2} \), respectively, and their decay to \( \Delta NN \) or \( \Sigma^0NN \). The scales of the masses corresponding to the momenta of \( N \) in the reaction \[4\] are shown parallel to the momentum scales. If the peaks in the nucleon momentum spectra (red histograms) are interpreted in this way, their masses would be close to 3140 MeV/c\(^2\). Another possibility is the production of the \( 3^S_{T=4} \) dibaryon and its decay to \( \Delta N \). The possible multibaryonic states enumer-
ated above are considered to have fairly broad spectrum shapes, and hence further investigations are required to allow such interpretations and deduce their binding energies and widths.

In summary, we have investigated $\Lambda p$ and $\Lambda n$ correlations from the stopped $K^-$ reaction on $^4$He, and observed at least two kinds of non-mesonic components in each of the channels. One consists of well-correlated fast $\Lambda p$ and $\Lambda n$ pairs, which are evidence for $\Lambda p$ and $\Lambda n$ branches of the 2NA process in $^4$He, and their dynamical properties have been revealed for the first time. The others are made of slower $\Lambda N$ pairs, which could be interpreted as exotic signals of $^3S_{T=0/1}$ and/or $^3S_{T=0/1}$ as well as the cascade of $\Sigma N$ branches of the 2NA and successive $\Sigma \Lambda$ conversion processes.

We are grateful to the KEK staff members of the beam channel group, accelerator group, and electronics group, for support of the present experiment. We also owe much to T. Taniguchi and M. Sekimoto for their continuous contribution and advices for electronics. This work was supported by KEK, RIKEN, and Grant-in-Aid for Scientific Research (S) 14102005 of the Ministry of Education, Culture, Sports, Science and Technology of Japan.

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[1] Y. Akaishi and T. Yamazaki, Phys. Rev. C 65, 044005 (2002).
[2] T. Yamazaki and Y. Akaishi, Phys. Lett. B 535, 70 (2002).
[3] M. Iwasaki et al., nucl-ex/0310018.
[4] T. Suzuki et al., Phys. Lett. B 597, 263 (2004).
[5] M. Agnello et al., Phys. Rev. Lett. 94, 212303 (2005).
[6] M. Agnello et al., Phys. Lett. B 654, 80 (2007).
[7] M. Sato et al., Phys. Lett. B (2007), in press, nucl-ex/0708.2968.
[8] H. Yim et al., in Proceedings of The IX International Conference on Hypernuclear and Strange Particle Physics (Mainz, Germany, 2006), p. 201.
[9] T. Suzuki et al., Phys. Rev. C (2007), in press, nucl-ex/0709.0996.
[10] P. A. Katz et al., Phys. Rev. D 1, 1267 (1970).
[11] V. R. Veirs and R. A. Burnstein, Phys. Rev. D 1, 1883 (1970).
[12] R. Roosen and J. H. Wickens, Nuovo Cimento A 66, 101 (1981).
[13] T. Yamazaki and Y. Akaishi, Nucl. Phys. A 792, 229 (2007).
[14] T. Onaga, H. Narumi, and T. Kohmura, Prog. Theor. Phys. 82, 222 (1989).
[15] M. Iwasaki et al., Nucl. Instrum. Methods Phys. Res. A 473, 286 (2001).
[16] E. Oset and H. Toki, Phys. Rev. C 74, 015207 (2006).
[17] M. Agnello et al., Nucl. Phys. A 775, 35 (2006).
[18] V. K. Magas, E. Oset, A. Ramos, and H. Toki, Phys. Rev. C 74, 025206 (2006).