Search for the $\Theta(1540)^+$ pentaquark using kaon secondary interactions at Belle

K. Abe,9 K. Abe,47 I. Adachi,9 H. Aihara,49 K. Aoki,23 K. Arinstein,2 Y. Asano,54 T. Aso,53 V. Aulchenko,2 T. Aushev,13 T. Aziz,45 S. Bahinipati,5 A. M. Bakich,44 V. Balagura,13 Y. Ban,36 S. Banerjee,45 E. Barberio,22 M. Barbero,8 A. Bay,19 I. Bedny,2 U. Bitenc,14 I. Bizjak,14 S. Blyth,25 A. Bondar,2 A. Bozek,29 M. Bračko,9,21,14 J. Brodzicka,29 T. E. Browder,8 M.-C. Chang,48 P. Chang,28 Y. Chao,28 A. Chen,25 K.-F. Chen,28 W. T. Chen,25 B. G. Cheon,4 C.-C. Chiang,28 R. Chistov,13 S.-K. Choi,7 Y. Choi,43 Y. K. Choi,43 A. Chuvikov,37 S. Cole,44 J. Dalseno,22 M. Danilov,13 M. Dash,56 L. Y. Dong,11 R. Dowd,22 J. Dragic,9 A. Drutskek,5 S. Eidelman,2 Y. Enari,23 D. Epifanov,2 F. Fang,8 S. Fratina,14 H. Fujii,9 N. Gabyshev,2 A. Garmash,37 T. Gershon,9 A. Go,25 G. Gokhroo,45 P. Goldenzweig,5 B. Golob,20,14 A. Gorišek,14 M. Grosse Perdekamp,38 H. Guler,8 R. Guo,26 J. Haba,9 K. Haraguchi,16 P. Kapusta,29 S. U. Kataoka,24 N. Katayama,9 H. Kawai,3 N. Kawamura,1 T. Kawasaki,31 S. Kazi,5 N. Kent,8 H. R. Khan,50 A. Kibayashi,50 H. Kichimi,9 H. J. Kim,18 H. O. Kim,43 J. H. Kim,43 S. K. Kim,41 S. M. Kim,43 T. H. Kim,57 K. Kinoshita,5 N. Kishimoto,23 S. Korpar,21,14 Y. Kozakai,23 P. Krizan,20,14 P. Krokovny,9 T. Kubota,23 R. Kulasiri,5 C. C. Kuo,25 H. Kurashiro,50 E. Kurihara,3 A. Kusaka,9 A. Kuzmin,2 Y.-J. Kwon,57 J. S. Lange,6 G. Leder,12 S. E. Lee,41 Y.-J. Lee,28 T. Lesiak,29 J. Li,40 A. Limosani,9 S.-W. Lin,28 D. Liventsev,13 J. MacNaughton,12 G. Majumder,45 F. Mandl,12 D. Marlow,37 H. Matsumoto,31 T. Matsumoto,51 A. Matyja,29 Y. Mikami,48 W. Mitaroff,12 K. Miyabayashi,24 H. Miyake,34 H. Miyata,31 Y. Miyazaki,23 R. Mizuk,13 D. Mohapatra,56 G. R. Moloney,22 T. Mori,50 A. Murakami,39 T. Nagamine,48 Y. Nagasaka,10 T. Nakagawa,51 I. Nakamura,9 E. Nakano,33 M. Nakao,9 H. Nakazawa,9 Z. Natkaniec,20 K. Neichi,47 S. Nishida,9 O. Nitoh,52 N. Noguchi,24 T. Nozaki,9 A. Ogawa,38 S. Ogawa,46 T. Ohshima,23 T. Okabe,23 S. Okuno,15 S. L. Olsen,8 Y. Onuki,31 W. Ostrowicz,29 H. Ozaki,9 P. Pakhlov,13 H. Palka,29 C. W. Park,43 H. Park,18 K. S. Park,43 N. Parslow,44 L. S. Peak,44 M. Pernicka,12 R. Pestotnik,14 M. Peters,8 L. E. Piilonen,56 A. Poluektov,2 F. J. Ronga,9 N. Root,2 M. Rozanska,29 H. Sahoo,8 M. Saigo,48 S. Saitoh,9 Y. Sakai,9 H. Sakamoto,17 H. Sakaue,33 T. R. Sarangi,9 M. Satapathy,55 N. Sato,23 N. Satoyama,42 T. Schietinger,19 O. Schneider,19 P. Schönherr,48 J. Schömann,28 C. Schwanda,12 A. J. Schwartz,5 T. Seki,51 K. Senyo,23 R. Seuster,8 M. E. Severij,22 T. Shibata,31 H. Shibuya,46 J.-G. Shi,28 B. Shwartz,2 V. Sidorov,2 J. B. Singh,35 A. Somov,5 N. Soni,35 R. Stamen,9 S. Stanić,32 M. Starić,14 A. Sugiyama,39 K. Sumisawa,9 T. Sumiyoshi,51 S. Suzuki,39
S. Y. Suzuki, O. Tajima, N. Takada, F. Takasaki, K. Tamai, N. Tamura, K. Tanabe, M. Tanaka, G. N. Taylor, Y. Teramoto, X. C. Tian, K. Trabelsi, Y. F. Tse, T. Tsuboyama, T. Tsukamoto, K. Uchida, Y. Uchida, S. Uehara, T. Uglov, K. Ueno, Y. Unno, S. Uno, P. Urquijo, Y. Ushiroda, G. Varner, K. E. Varvell, S. Villa, C. C. Wang, C. H. Wang, M.-Z. Wang, M. Watanabe, Y. Watanabe, L. Widhalm, C.-H. Wu, Q. L. Xie, B. D. Yabsley, A. Yamaguchi, H. Yamamoto, S. Yamamoto, Y. Yamashita, M. Yamauchi, Heyoung Yang, J. Ying, S. Yoshino, Y. Yuan, Y. Yusa, H. Yuta, S. L. Zang, C. C. Zhang, J. Zhang, L. M. Zhang, Z. P. Zhang, V. Zhilich, T. Ziegler, and D. Zürcher

(The Belle Collaboration)

1 Aomori University, Aomori
2 Budker Institute of Nuclear Physics, Novosibirsk
3 Chiba University, Chiba
4 Chonnam National University, Kwangju
5 University of Cincinnati, Cincinnati, Ohio 45221
6 University of Frankfurt, Frankfurt
7 Gyeongsang National University, Chinju
8 University of Hawaii, Honolulu, Hawaii 96822
9 High Energy Accelerator Research Organization (KEK), Tsukuba
10 Hiroshima Institute of Technology, Hiroshima
11 Institute of High Energy Physics, Chinese Academy of Sciences, Beijing
12 Institute of High Energy Physics, Vienna
13 Institute for Theoretical and Experimental Physics, Moscow
14 J. Stefan Institute, Ljubljana
15 Kanagawa University, Yokohama
16 Korea University, Seoul
17 Kyoto University, Kyoto
18 Kyungpook National University, Taegu
19 Swiss Federal Institute of Technology of Lausanne, EPFL, Lausanne
20 University of Ljubljana, Ljubljana
21 University of Maribor, Maribor
22 University of Melbourne, Victoria
23 Nagoya University, Nagoya
24 Nara Women’s University, Nara
25 National Central University, Chung-li
26 National Kaohsiung Normal University, Kaohsiung
27 National United University, Miao Li
28 Department of Physics, National Taiwan University, Taipei
29 H. Niewodniczanski Institute of Nuclear Physics, Krakow
30 Nippon Dental University, Niigata
31 Niigata University, Niigata
32 Nova Gorica Polytechnic, Nova Gorica
33 Osaka City University, Osaka
34 Osaka University, Osaka
35 Panjab University, Chandigarh
Abstract

Using kaon secondary interactions in the material of the Belle detector, we search for both inclusive and exclusive production of the $\Theta(1540)^{+}$. We set an upper limit of 2.5\% at the 90\% C.L. on the ratio of the $\Theta(1540)^{+}$ to $\Lambda(1520)$ inclusive production cross sections. We also search for the $\Theta(1540)^{+}$ as an intermediate resonance in the charge exchange reaction $K^{+}n \rightarrow pK_{S}^{0}$. An upper limit of $\Gamma_{\Theta^{+}} < 0.64 \text{MeV}$ at the 90\% C.L. at $m_{\Theta^{+}} = 1.539 \text{MeV}/c^{2}$ is set. These results are obtained from a $397 \, \text{fb}^{-1}$ data sample collected with the Belle detector near the $\Upsilon(4S)$ resonance, at the KEKB asymmetric energy $e^{+}e^{-}$ collider.

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I. INTRODUCTION

The observation of the \( \Theta(1540)^+ \) pentaquark, an exotic bound state with the quark content \( uudd\bar{s} \), is one of the most puzzling mysteries of recent years (see [1] for an experimental overview). The \( \Theta(1540)^+ \) was first observed in exclusive reactions at low energy [1]. Later several groups reported observation in inclusive reactions at higher energies [1]. Conversely, other experiments at high energies do not see the \( \Theta(1540)^+ \) pentaquark although they do observe significantly larger yields of conventional hyperons than seen at the experiments that observe the \( \Theta(1540)^+ \). In order to resolve this discrepancy it is frequently assumed that pentaquark production decreases rapidly with energy. A high statistics experiment at low energies is therefore important. In order to achieve this, Belle utilises the small fraction of tracks that interact with the material of the inner part of the detector. These secondary interactions are used to search for pentaquarks. Particles produced in \( e^+e^- \) annihilation at Belle have quite low momenta; the most probable kaon momentum is only 0.6 GeV/c.

Results from two analyses are presented. In the first, we search for inclusive production of the \( \Theta(1540)^+ \) via the \( KN \rightarrow \Theta(1540)^+X \), \( \Theta(1540)^+ \rightarrow pK^0_S \) process, using the signal from inclusive \( \Lambda(1520) \) production as a reference. In the second, we search for exclusive \( \Theta(1540)^+ \) production in the charge exchange reaction \( K^+n \rightarrow \Theta(1540)^+ \rightarrow pK^0_S \). For this search, the yield of charge exchange reactions is used as a reference, allowing a direct comparison to the results of the DIANA experiment [2].

II. DETECTOR AND DATA SET

These studies are performed using a 357 fb\(^{-1} \) data sample collected at the \( \Upsilon(4S) \) resonance and 40 fb\(^{-1} \) at an energy 60 MeV below the resonance. The data were collected with the Belle detector [3] at the KEKB asymmetric energy \( e^+e^- \) storage rings [4].

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer cylindrical drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like array of time-of-flight scintillation counters (TOF), and an array of CsI(Tl) crystals (ECL) located inside a superconducting solenoidal coil that produces a 1.5 T magnetic field. An iron flux return located outside the coil is instrumented to detect muons and \( K_L \) mesons (KLM). Two different inner detector configurations were used. For the first sample of 155 fb\(^{-1} \), a 2.0 cm radius beampipe and a 3-layer silicon vertex detector (SVD1) were used; for the second sample of 242 fb\(^{-1} \), a 1.5 cm radius beampipe, and a four-layer silicon vertex detector (SVD2), and a small-cell inner drift chamber were used [5].

A GEANT [6] based Monte-Carlo (MC) simulation is used to model the production of secondary \( pK \) pairs, and to determine the detector resolution and acceptance.

III. SELECTION OF SECONDARY \( pK \) PAIRS

The analyses are performed by identifying \( pK^- \), \( pK^+ \) and \( pK^0_S \) produced at secondary vertices. Charged particle candidates are required to be positively identified based on the CDC \( (dE/dx) \), TOF and ACC information. In addition, proton and charged kaon candidates are removed if they are consistent with being electrons based on ECL, CDC and ACC information. \( K^0_S \) candidates are reconstructed from \( \pi^+\pi^- \) pairs that have masses within
±10 MeV/c² of the nominal $K_S^0$ mass ($3\sigma$ window). Additional selection requirements are imposed on the quality of the $K_S^0$ vertex, on the impact parameters of the daughter tracks and on the angle between the momentum and the direction from the interaction point (IP) to the vertex.

The proton and kaon candidates are required to have an origin that is displaced from the IP. The $pK^-$, $pK^+$ and $pK_S^0$ vertices are fitted and those with a radial distance $1 < R < 11$ cm are selected. Additional criteria on the quality of the $pK$ vertex are applied. We consider secondary $pK$ pairs only in the central part of the detector $-0.74 < \cos \theta < 0.9$, where $\theta$ is the polar angle of the secondary $pK$ vertex. The distributions of the secondary $pK^0_S$ vertices in the $xy$ plane are shown in Fig. 1 for the SVD1 and SVD2 data samples, where the $z$-axis passes through the IP and is antiparallel to the $e^+$ beam. The beam pipe, the SVD layers, the SVD cover and the CDC support cylinders are clearly visible.

![Distribution of reconstructed secondary $pK^0_S$ vertices](image)

**FIG. 1**: Distribution of reconstructed secondary $pK^0_S$ vertices in the Belle detector for the SVD1 (left) and SVD2 (right) data samples.

IV. SEARCH FOR INCLUSIVE $\Theta(1540)^+$ PRODUCTION

The mass spectra for $pK^-$ and $pK_S^0$ secondary vertices are shown in Fig. 2. We apply an additional selection requirement on the angle between the $pK$ momentum and the direction from the IP to the $pK$ vertex $d\phi < 1$ rad. In the $pK^-$ sample we reject $\Lambda \to p\pi^-$ and $K_S^0 \to \pi^+\pi^-$ decays misidentified as secondary $pK^-$ vertices. No significant structures are observed in the $m_{pK^-}$ spectrum, while in the $m_{pK^-}$ spectrum a $\Lambda(1520)$ signal is clearly visible. The $pK^-$ mass spectrum is fitted to a sum of a $\Lambda(1520)$ signal function and a threshold function. The signal function is a $D$-wave Breit-Wigner shape convolved with a detector resolution function, determined from MC. The detector resolution function is parametrized by a double Gaussian with widths of 2 MeV and 5 MeV with approximately equal contributions from each Gaussian component. The $\Lambda(1520)$ parameters obtained from the fit are consistent with the
FIG. 2: (a) Mass spectra of \( pK^- \) (points with error bars) and \( pK^0_S \) (histogram) secondary pairs. The fit is described in the text. (b) Momentum spectrum of the \( \Lambda(1520) \).

PDG values [7]. The \( \Lambda(1520) \) yield, defined as the fit function signal component integrated over the 1.48–1.56 GeV/c\(^2\) mass interval \((2.5\Gamma)\), is \((4.02 \pm 0.08) \cdot 10^4 \) events.

The \( pK^0_S \) mass spectrum is fitted to a sum of a \( \Theta(1540)^+ \) signal component and a third order polynomial. The \( \Theta(1540)^+ \) is assumed to be narrow and its shape is determined by the detector resolution function, which is again a double Gaussian with similar parameters to those used for the \( pK^- \) mode. The MC resolution is checked against data using the \( \Omega^- \rightarrow \Lambda K^- \) signal, which has a topology similar to the secondary \( pK^0_S \) vertices. It is found that the \( \Omega^- \) width is 4% percent larger in data than in MC, and this correction factor is applied to the mass resolution of secondary \( pK^0_S \) vertices. For \( m = 1540 \text{ MeV}/c^2 \) the fit yield is 58 \( \pm 129 \) events. Using the Feldman-Cousins method of upper limit evaluation [8], we find \( N < 270 \) events at the 90% C.L. The upper limit is below 320 events for a wide range of possible \( \Theta(1540)^+ \) masses. We set an upper limit on the ratio of \( \Theta(1540)^+ \) to \( \Lambda(1520) \) production cross sections:

\[
\frac{N_{\Theta(1540)^+}}{N_{\Lambda(1520)}} \frac{\epsilon_{pK^-}}{\epsilon_{pK^0_S}} \frac{\mathcal{B}(\Lambda(1520) \rightarrow pK^-)}{\mathcal{B}(\Theta(1540)^+ \rightarrow pK^0_S)\mathcal{B}(K^0_S \rightarrow \pi^+\pi^-)} < 2.5\% \text{ at the 90\% C.L.}
\]

It is assumed that \( \mathcal{B}(\Theta(1540)^+ \rightarrow pK^0_S) = 25\% \). We take \( \mathcal{B}(\Lambda(1520) \rightarrow pK^-) = \frac{1}{2}\mathcal{B}(\Lambda(1520) \rightarrow N\bar{K}) = \frac{1}{2}(45 \pm 1)\% \) [7]. The ratio of efficiencies for \( \Theta(1540)^+ \rightarrow pK^0_S \) and \( \Lambda(1520) \rightarrow pK^- \) of about 41\% is obtained from MC simulation assuming that the two processes have similar kinematics. Our limit is much lower than the results reported by many experiments that observe the \( \Theta(1540)^+ \). For example it is two orders of magnitude lower than the value reported by the HERMES Collaboration [9].

The momentum spectrum of the produced \( \Lambda(1520) \) is shown in Fig. 2 (b). This spectrum is obtained by fitting \( m_{pK^-} \) in momentum bins and correcting for the efficiency obtained from the MC. If a \( \Lambda(1520) \) is produced as an intermediate resonance in the elastic scattering of a \( K^- \) on a free proton, then its momentum is around 400 MeV/c. As such, the observed hard momentum spectrum of the \( \Lambda(1520) \) confirms that they are produced in inelastic interactions. We find that non-strange particles do not produce \( \Lambda(1520) \) since the secondary \( pK^- \) pairs are accompanied by an additional \( K^+ \) from the same vertex in only about 0.5\% of events.
The projectiles that can produce Λ(1520) are K−, K0 S, K+ and Λ. The Λ needs a momentum of about 1.8 GeV/c to produce the Λ(1520). The number of such Λ’s in e+e− annihilations is small. The observed number of Λ(1520) can not be produced by Λ projectiles even if the total ΛN cross section is assumed to be saturated by inclusive Λ(1520) production. We therefore conclude that our Λ(1520) signal is due to kaon interactions, with a contribution of Λ interactions no larger than a few percent.

V. SEARCH FOR EXCLUSIVE Θ(1540)+ PRODUCTION

Possible exclusive pentaquark production is studied using the K+n → pK0 S reaction, searching for the Θ(1540)+ as an intermediate resonance. Since the projectile is not reconstructed, it is not possible to distinguish this reaction from the reactions KS0p → pK0 S, KLp → pK0 S, and inelastic reactions with a π0 or undetected tracks in the final state. Therefore we apply selection criteria which suppress the contribution of the inelastic reactions in the sample of secondary pK0 S pairs (see section V E), and determine the contribution of the charge exchange reaction indirectly, as described below in this section. The cross section of the KS0p → Θ(1540)+ → pK0 S reaction is expected to be similar to the cross section of the K+n → Θ(1540)+ → pK0 S reaction [10], however the flux of KS0 is decreased by decays in flight and we conservatively neglect the contribution of this reaction. The KLp → pK0 S reaction can produce a dip in the Θ(1540)+ region because of the interference of resonant and nonresonant amplitudes. However, the size of the dip is expected to be negligible [10].

The number of charge exchange reactions can be estimated in a straightforward way using the known flux of primary K+, ΦK+, the reaction cross section, σch, the amount of material, M, and the reconstruction efficiency for the secondary pK0 S pair, εpK0 S, and taking into account nuclear effects:

\[
N_{ch}^{el}(m_{pK}) = \int \Phi_{K^+} \sigma_{ch} M \epsilon_{pK_0^S} B(S(E_N, |\vec{p}_F|) \delta(\sqrt{s} - m_{pK}) P \ dE_N \ d^3p_F \ dp_{K^+} \ dR \ d\theta, \ (1)
\]

where B is the product of K0 branching fractions \( B = B(K^0 \rightarrow K^0_S) B(K^0_S \rightarrow \pi^+\pi^-) \), \( S(E_N, |\vec{p}_F|) \) is a nuclear spectral function which is a joint probability to find in a nucleus a nucleon with energy \( E_N \) and Fermi momentum \( |\vec{p}_F| \), \( s = (E_{K^+} + E_N)^2 - (|\vec{p}_{K^+} + |\vec{p}_F|^2) \) is the centre of mass (c.m.) energy of the reaction squared, \( E_{K^+} \) is the energy and \( |\vec{p}_{K^+}| \) is the momentum of the projectile, \( m_{pK} \) is the mass of the produced pair, \( P \) is the probability that the produced pair is not rescattered in the nucleus and \( R \) and \( \theta \) are the radial distance and polar angle of the secondary vertex, respectively.

However, it is difficult to accurately estimate the systematic errors in this calculation because \( M \) and \( \epsilon_{pK_0^S} \) are complicated functions of the coordinates and the estimation of \( S \) and \( P \) is model dependent. This problem is solved by reconstructing the decay chain \( D^{*-} \rightarrow \overline{D}^{0}\pi^- \), \( \overline{D}^{0} \rightarrow K^+\pi^- \) for events where a \( K^+ \) interacts elastically in the detector material. The reconstruction procedure is explained in detail in section VA. The yield of such decays, \( N_{D^*}^{el} \), is expressed as

\[
N_{D^*}^{el}(m_{pK}) = \int \Phi_{D^*} \sigma_{el} M \epsilon_{pK^+} S(E_N, |\vec{p}_F|) \delta(\sqrt{s} - m_{pK}) P \ dE_N \ d^3p_F \ dp_{K^+} \ dR \ d\theta, \ (2)
\]

where \( \Phi_{D^*} \) is the flux of \( K^+ \) originating from the selected \( D^{*-} \) decay, \( \sigma_{el} \) is the cross section for elastic \( K^+p \rightarrow pK^+ \) scattering and \( \epsilon_{pK^+} \) is the efficiency of reconstructing the
secondary $pK^+$ vertex. The nuclear suppression $P$ is assumed to be the same for $pK^+$ pairs and $pK^0$ pairs produced in the charge exchange reaction. We express $N^\text{ch}$ in terms of $N^\text{el}_{D^*}$. The expressions are simplified by the facts that the products $M_{pK^0}$ and $M_{pK^+}$ are approximately independent of $\theta$ for the central part of the detector; the ratio $e_{pK^0}/e_{pK^+}$ is approximately independent of the secondary pair momentum, $|\vec{p}_{pK}|$; and the nuclear suppression $P$ is approximately independent of $|\vec{p}_{pK}|$ (see section V A). We approximate the nuclear spectral function as $S(E_N,|\vec{p}_F|) = W(|\vec{p}_F|) \delta(E_N - f(|\vec{p}_F|))$, where the function $f(|\vec{p}_F|)$ is defined so that $E_N = f(|\vec{p}_F|)$ corresponds to the maximum of $S(E_N,|\vec{p}_F|)$. We obtain

$$N^\text{ch}(m_{pK}) = N^\text{el}_{D^*}(m_{pK}) \frac{\Phi^{K^+}(m_{pK}) \sigma^\text{ch}(m_{pK}) e_{pK^0}(m_{pK}) B}{\Phi^{K^+}_{D^*}(m_{pK}) \sigma^\text{el}(m_{pK}) e_{pK^+}(m_{pK})},$$

where

$$\frac{\Phi^{K^+}(m_{pK})}{\Phi^{K^+}_{D^*}(m_{pK})} = \frac{\int \Phi^{K^+}(|\vec{p}_{K^+}|) W(|\vec{p}_F|) \delta(\sqrt{s} - m_{pK}) e_{pK^+}(m_{pK}, |\vec{p}_{pK}|) d^3p_F dp_{pK^+}}{\int \Phi^{K^+}_{D^*}(|\vec{p}_{K^+}|) W(|\vec{p}_F|) \delta(\sqrt{s} - m_{pK}) e_{pK^+}(m_{pK}, |\vec{p}_{pK}|) d^3p_F dp_{pK^+}}.$$

The p.d.f. of the Fermi momentum distribution $W(|\vec{p}_F|)$ is determined from data in section V A. The form of the $f(|\vec{p}_F|)$ is discussed in the same section. The integrations are described in section V B. Equation (3) provides the basic formula to determine the yield of the charge exchange reaction in our data sample. The formula (3) would be even simpler if we could use $K^+$ projectiles from $D^{*-}$ decays that undergo charge exchange in the detector material. However, the fraction of such events is very low because of the relatively small cross section, and the low $K^0$ reconstruction efficiency and branching fraction.

### A. Determination of $N^\text{el}_{D^*}$

To determine the number of $D^{*-} \to \overline{D}^0 \pi^-$, $\overline{D}^0 \to K^+ \pi^-$ decays for which a $K^+$ interacts elastically in the detector material, the four-momentum of the interacting $K^+$ is reconstructed based on the information available from the produced secondary $pK^+$ pair.

If a secondary $pK$ pair is produced in a quasi-elastic reaction, four-momentum conservation implies

$$E_K + E_N = E_{pK},$$
$$\vec{p}_K + \vec{p}_F = \vec{p}_{pK}.$$  \hspace{1cm} (5)

The nucleon energy, $E_N$ is approximated by [11]

$$E_N = m_N - 2\epsilon - \frac{\vec{p}_F^2}{2m_N},$$  \hspace{1cm} (7)

where $m_N$ is the nucleon mass and $\epsilon \sim 7$ MeV is the nucleon binding energy. This approximation is valid for the high $|\vec{p}_F|$ part of the nuclear spectral function. Another possible approximation is $E_N = m_N - E_R$, where $E_R \sim 26$ MeV is the average removal energy of the bound nucleon. We find that both approximations give a similar resolution in the $\overline{D}^0$ mass (see below) and our result is independent of the choice. The quantities $E_{pK}$ and $\vec{p}_{pK}$ are measured; taking into account the primary and secondary vertex constraints, Eqs (5)–(7) can then be solved iteratively.
The iterative process is started from Eq. (7) where some average value of $|\vec{p}_F|$ is substituted. Then the energy of the projectile $E_K$ is determined from Eq. (5). In the next step the projectile momentum $\vec{p}_K$ is determined from its absolute value $|\vec{p}_K| = \sqrt{E_K^2 - m_K^2}$, and the flight direction obtained from the primary and secondary vertex constraints, taking into account the bending of the track in the magnetic field. The value of $|\vec{p}_F|$ is then determined from Eq. (6) and the iteration loop is closed by substituting the obtained $|\vec{p}_F|$ into Eq. (7).

The projectile four-momentum is determined for all secondary $pK^+$ pairs. The resulting $K^+$ projectile candidates are then combined with all the $\pi^-$ candidates in the event to form $D^0$ candidates; the $\bar{D}^0$ candidates are combined with all the remaining $\pi^-$ candidates to form $D^{*-}$ candidates. The $\pi^-$ candidates are required to be positively identified based on the CDC ($dE/dx$), TOF and ACC information and to originate from the vicinity of the IP. We reject vertices with additional tracks and require $50 < |\vec{p}_F| < 300\text{ MeV}/c$. The lower bound on $|\vec{p}_F|$ is used to reject interactions on hydrogen (see below). Events in a $\pm 2\text{ MeV}/c^2$ ($3\sigma$) window in $\Delta m_{D^*} = m_{D^*} - m_{D^0}$ are selected and the mass of the daughter $\bar{D}^0$ candidates is plotted (see Fig. 3 (a)). A signal of $470 \pm 26\bar{D}^0$ events with the mass consistent with the PDG value and a mass resolution of $16\text{ MeV}/c^2$ is observed. The $\bar{D}^0$ signal and sideband regions are selected as $|m_{K^+\pi^-} - m_{\bar{D}^0}| < 50\text{ MeV}/c^2$ and $60 < |m_{K^+\pi^-} - m_{\bar{D}^0}| < 110\text{ MeV}/c^2$, respectively. The sideband subtracted distribution of $|\vec{p}_F|$ is shown in Fig. 3 (b). The peak near zero is attributed to interactions on hydrogen, which is present in the detector material. If $E_N = m_N$ is used instead of Eq. (7), this peak is found at zero, as expected for interactions with a free proton. The $|\vec{p}_F|$ spectrum is fitted to the parametrization, expected in the oscillator model [12]: $|\vec{p}_F|^2\left[1 + 4/3(|\vec{p}_F|/p_0)^2\right] \exp\left(-|\vec{p}_F|^2/p_0^2\right)$. The value for the model parameter returned by the fit, $p_0 = 115 \pm 4\text{ MeV}/c$, is comparable to those obtained from other measurements of $|\vec{p}_F|$ distributions [12].

We find that the fraction of $D^{*-}$ events in the hydrogen peak is roughly independent of pair momentum. Since this fraction is inversely proportional to $P$ (there can be no rescattering in hydrogen), we conclude that $P$ is also roughly independent of pair momentum, which is important to perform the integration in Eq. (4).
The $m_{p\bar{K}}$ spectra are fitted in $m_{pK}$ bins to determine the $D^*$ yield. The fit function is comprised of the sum of a Gaussian and a first order polynomial. The Gaussian mean and width and the polynomial parameters are all floated in the fit. The number of $D^*$ mesons in the $\Theta(1540)^+$ region is $24 \pm 7$ per 50 MeV/$c^2$ bin.

**B. Determination of $\Phi^{K^+}/\Phi_{D^*}$**

The fluxes of primary $K^+$'s and $K^+$'s from $D^{*-}$ are determined from data. Primary $K^+$ candidates are required to originate from the vicinity of the IP and to be positively identified based on the CDC ($dE/dx$), TOF and ACC information. $D^{*-}$ candidates are selected by combining the kaon candidate with pion candidates, in the same way as described above. Correction for reconstruction efficiency and contamination from other particle species is performed using MC that is calibrated from data. The integration in Eq. 4 is performed using a Monte Carlo technique. The nucleon Fermi momentum $\vec{p}_F$ is assumed to be isotropic relative to the projectile momentum $\vec{p}_K$. The fact that the secondary $pK$ pair efficiency depends on the momentum results in a correction of about 3% in the ratio. The flux ratio at $m_{pK} = 1.539$ GeV/$c^2$ is equal to $850 \pm 20$; the uncertainty is dominated by the assumption concerning the relation between $E_N$ and $|\vec{p}_F|$. For this measurement we use about 20% of the data sample distributed uniformly over the running period.

**C. Determination of $\sigma^{\text{ch}}/\sigma^{\text{el}}$**

The cross sections $\sigma^{\text{ch}}$ and $\sigma^{\text{el}}$ are obtained from published data [7, 13]. The data are fitted with polynomials in $m_{pK}$, and the ratio of the fitted functions is used to obtain $\sigma^{\text{ch}}/\sigma^{\text{el}}$. The value of the ratio is $0.35 \pm 0.02$ at $m_{pK} = 1.539$ GeV/$c^2$ and rises with $m_{pK}$. Errors are assigned based on the typical experimental errors in the region of interest.

**D. Determination of $\epsilon_{pK^0_S}/\epsilon_{pK^+}$**

Monte Carlo simulations are used to estimate the ratio $\epsilon_{pK^0_S}/\epsilon_{pK^+}$. The angular distribution in the reaction c.m. frame is assumed to be uniform as expected for low energy elastic $K^+p$ scattering and for $\Theta(1540)^+ \rightarrow pK^0_S$ decay. We consider the following sources of systematic uncertainty: $K^0_S$, $K^+$ and secondary $pK$ reconstruction efficiency (7%), uncertainty in material description (5%), uncertainty in the description of the reaction kinematics (5%), and the MC statistical uncertainty (5%). The ratio of efficiencies at $m_{pK} = 1.539$ GeV/$c^2$ is $(43 \pm 5\%)$. Here all the uncertainties are added in quadrature.

**E. Upper limit on $\Theta(1540)^+$ yield in exclusive reaction**

To suppress the contribution of inelastic reactions in the sample of secondary $pK^0_S$ pairs we reject vertices with additional tracks and require $50 < |\vec{p}_F| < 300$ MeV/$c$. The lower bound on $|\vec{p}_F|$ is used to reject interactions on hydrogen, which do not contribute to the charge exchange reaction. The effect of angular cuts used by DIANA to suppress rescattering is checked, and found not to suppress background significantly when the $|\vec{p}_F|$ cut is applied, and not to improve the sensitivity. The $pK^0_S$ mass spectrum and the expected yield from the
charge exchange reaction is shown in Fig. 4 (a). The statistical and systematic uncertainties

\[ \frac{N}{2 \text{MeV/c}^2} \]

on \( N^{\text{ch}} \) are added in quadrature. In the \( \Theta(1540)^+ \) region we expect \( (1.03 \pm 0.36) \cdot 10^3 \) charge exchange events per 50 MeV/c\(^2\) bin. The \( m_{pK^0_S} \) distribution is fitted to a third order polynomial and a signal p.d.f. positioned at various values of \( m_{pK^0_S} \). The fit finds \( N_{\Theta^+} = -11 \pm 59 \) candidates at \( m_{pK} = 1.539 \text{GeV/c}^2 \). The ratio of the \( \Theta(1540)^+ \) yield to the charge exchange reaction yield can be expressed in terms of the \( \Theta(1540)^+ \) width (see for example [14]):

\[ \Gamma_{\Theta^+} = \frac{N_{\Theta^+}}{N^{\text{ch}}} \frac{\sigma^{\text{ch}}}{107 \text{mb}} \frac{B_i}{B_f} \Delta m, \]

where \( B_i \) and \( B_f \) are \( \Theta(1540)^+ \) branching fractions into initial and final states, \( B_i = B_f = 0.5 \), and \( \Delta m \) is the mass interval of \( pK^0_S \) pairs used to determine \( N^{\text{ch}} \). The resulting values of \( \Gamma_{\Theta^+} \) are shown as a function of \( m_{pK} \) in Fig. 4 (b). Also shown in Fig. 4 (b) are the 90% C.L. upper limits, obtained with the Feldman-Cousins method [8], and the current PDG value for the \( \Theta(1540)^+ \) width [7], which is based on the DIANA result. A similar width has been inferred from a reanalysis of \( K^+d \) scattering [15]. It is assumed that nuclear suppression for the \( \Theta(1540)^+ \) is the same as for nonresonant \( pK^0_S \) pairs.

**VI. CONCLUSIONS**

Using kaon interactions in the material of the Belle detector, we searched for both inclusive and exclusive production of the \( \Theta(1540)^+ \). No \( \Theta(1540)^+ \) signal was found in the sample of
secondary \( pK_S^0 \) pairs. For inclusive production we set the following upper limit:

\[
\frac{\sigma(KN \rightarrow \Theta(1540)^+X)}{\sigma(KN \rightarrow \Lambda(1520)X)} < 2.5\% \text{ at the 90\% C.L.}
\]

For exclusive production we find

\[
\Gamma(K^+n \rightarrow \Theta(1540)^+ \rightarrow pK_S^0) < 0.64 \text{ MeV at the 90\% C.L.}
\]

at \( m_{\Theta^+} = 1.539 \text{ MeV}/c^2 \). This upper limit is below the current PDG value of \( \Gamma = 0.9 \pm 0.3 \text{ MeV} \), and below 1.0 MeV for a wide interval of possible \( \Theta(1540)^+ \) masses. This measurement uses a sample of low energy kaon interactions and allows for a direct comparison with the DIANA result. With similar sensitivity, our results do not support their evidence for the \( \Theta(1540)^+ \).

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