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

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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 $K^+n \to pK^0_S$. We set an upper limit of $\Gamma_{\Theta^+} < 0.64\,\mathrm{MeV}$ at the 90% C.L. for $m_{\Theta^+} = 1.539\,\mathrm{MeV}/c^2$. These results are obtained from a $397\,\mathrm{fb}^{-1}$ data sample collected with the Belle detector near the $\Upsilon(4S)$ resonance, at the KEKB asymmetric energy e^+e^- collider.

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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). Belle utilises the small fraction of tracks that interact with the material of the inner part of the detector to search for pentaquarks. Particles produced in e^+e^- annihilation at Belle have quite low momenta; the most probable kaon momentum is only $0.6\,\mathrm{GeV}/c$. This allows to access the low energy domain where most of the pentaquark evidences were found. We used a $357\,\mathrm{fb}^{-1}$ data sample collected at the $\Upsilon(4S)$ resonance and $40\,\mathrm{fb}^{-1}$ at an energy 60 MeV below the resonance. Details of the analysis can be found in [2].

The distributions of the reconstructed secondary pK^0_S vertices in the plane transverse to the beam direction are shown in Fig. 1, for the two configurations of the inner detectors [3, 4]. The detector structures are clearly visible. The mass spectra for pK^- and pK^0_S secondary vertices are shown in Fig. 2. No significant structures are observed in the $m_{pK^0_S}$ spectrum, while in the m_{pK^-} spectrum a $\Lambda(1520)$ signal with the yield of $(4.02 \pm 0.08) \times 10^4$ events is clearly visible.

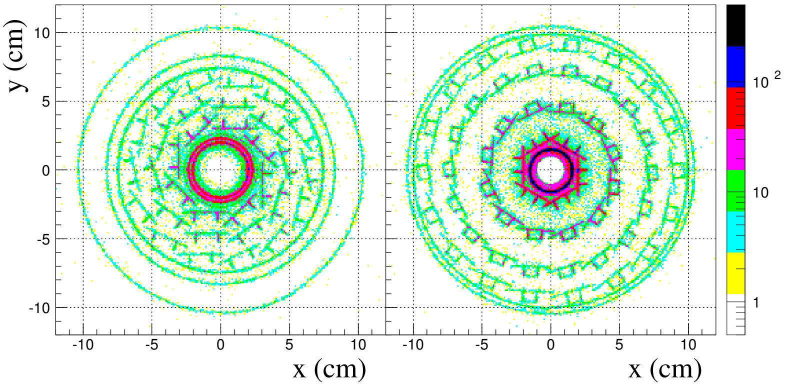

Figure 1: Distribution of reconstructed secondary pK^0_S vertices in the plane transverse to the beam direction, for the two configurations of the inner detectors.

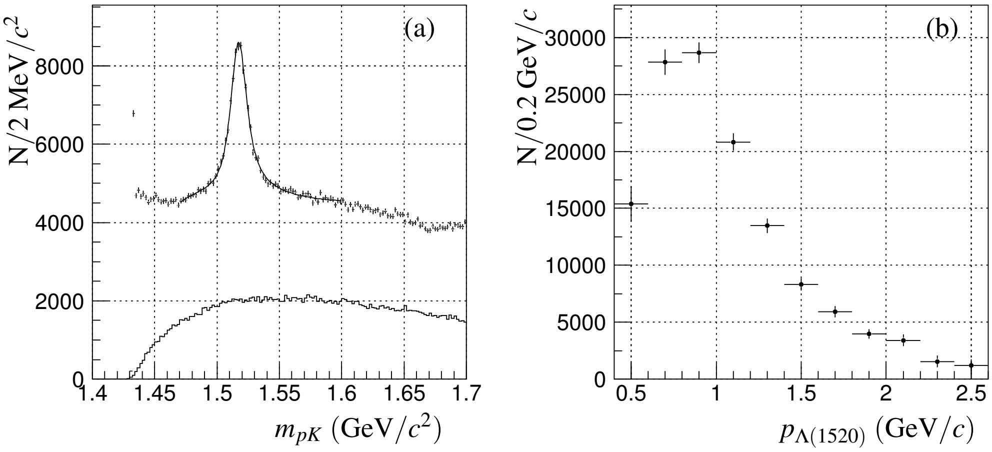

Figure 2: (a) Mass spectra of pK^- (points with error bars) and pK^0_S (histogram) secondary pairs. (b) Efficiency corrected momentum spectrum of the $\Lambda(1520)$.

The observed hard momentum spectrum of the $\Lambda(1520)$ (see Fig. 2 (b)) implies that they are produced in inelastic interactions. We find that non-strange projectiles do not produce $\Lambda(1520)$ since the secondary pK^- pairs are accompanied by an additional K^+ from the same vertex in only $\sim 0.5\%$ of events. The observed $\Lambda(1520)$ yield cannot be produced by Λ projectiles even if the inelastic ΛN cross section is assumed to be saturated by inclusive $\Lambda(1520)$ production. We therefore conclude that our $\Lambda(1520)$ signal is due to inelastic interactions of kaons, with a contribution of Λ interactions no larger than a few percent.

The $\Theta(1540)^+$ is assumed to be narrow and its shape is determined by the detector resolution function ($\sim 2\,\mathrm{MeV}/c^2$). For $m = 1540\,\mathrm{MeV}/c^2$ the $\Theta(1540)^+$ yield is $N < 270$ 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 of 2.5% at the 90% C.L. It is assumed that $\mathscr{B}(\Theta(1540)^+ \to pK^0_S) = 25\%$. Our limit is much more restrictive than the results reported by many experiments that observe the $\Theta(1540)^+$ [1].

Possible exclusive pentaquark production is studied using the $K^+n \to pK^0_S$ reaction, searching for the $\Theta(1540)^+$ as an intermediate resonance. The reaction $K^+n \to pK^0_S$ contributes only 2.5% to the sample of secondary pK^0_S pairs at low masses. The main background from inelastic interactions can be suppressed by only a factor of four, since the projectile is not reconstructed. Thus the $\Theta(1540)^+$ signal is searched for in the conditions with signal-to-noise ratio of one tenth. We conservatively assume that all the inelastic interactions do not produce the $\Theta(1540)^+$ signal. We also neglect the contributions of the $K^0_S p \to \Theta(1540)^+ \to pK^0_S$ and $K^0_L p \to \Theta(1540)^+ \to pK^0_S$ reactions.

The contribution of charge exchange reaction is determined indirectly using the known flux of primary K^+, Φ^{K^+}, the reaction cross section, σ^{ch}, the amount of material, M, and the reconstruction efficiency for the secondary pK^0_S pair, $\varepsilon_{pK^0_S}$, and taking into account nuclear effects:

$$N^{\mathrm{ch}}(m_{pK}) = \int \Phi^{K^+}\, \sigma^{\mathrm{ch}} M\, \varepsilon_{pK^0_S}\, \mathscr{B}\, S(E_N, |\vec{p}_F|)\; \delta(\sqrt{s} - m_{pK})\, P\, dE_N\, d^3p_F\, dp_{K^+}\, dR\, d\theta, \qquad (1)$$

where $\mathscr{B}$ is the product of K^0 branching fractions $\mathscr{B} = \mathscr{B}(K^0 \to K^0_S)\,\mathscr{B}(K^0_S \to \pi^+\pi^-)$, $S(E_N, |\vec{p}_F|)$ 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 θ 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 $\varepsilon_{pK^0_S}$ 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 $D^{*-} \to \overline{D}^0\pi^-$, $\overline{D}^0 \to K^+\pi^-$ for events where a K^+ interacts elastically in the detector material. The number of such events, $N^{\mathrm{el}}_{D^*}$, can be expressed as an integral, similar to (1). On the other hand, $N^{\mathrm{el}}_{D^*}$ can be determined from the data. Thus N^{ch} is expressed as a product of $N^{\mathrm{el}}_{D^*}$ and the ratio of two integrals, where most of the systematic uncertainties cancel.

To determine $N^{\mathrm{el}}_{D^*}$ from data, the four-momentum of the projectile K^+ is reconstructed based on the four-momentum of the secondary pK^+ pair and the initial and final vertex constraints. For the energy of the bound nucleon we use a deuteron approximation: $E_N = m_N - 2\varepsilon - \frac{\vec{p}_F^{\,2}}{2m_N}$, where m_N is the nucleon mass, $\varepsilon \sim 7\,\mathrm{MeV}$ is the nucleon binding energy and $|\vec{p}_F|$ is the Fermi momentum.

To suppress the contribution of inelastic reactions in the sample of secondary pK^0_S pairs we reject vertices with additional tracks and require $50 < |\vec{p}_F| < 300\,\mathrm{MeV}/c$. The lower bound on $|\vec{p}_F|$ is used to reject interactions on hydrogen, which do not contribute to the charge exchange reaction. The pK^0_S mass spectrum and the expected yield from the charge exchange reaction is shown in Fig. 3 (a). The statistical and systematic uncertainties on N^{ch} are added in quadrature.

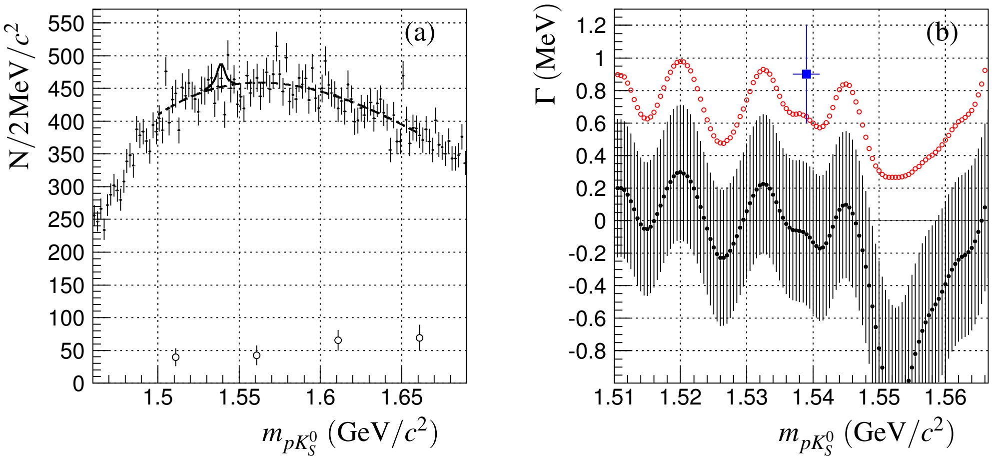

Figure 3: (a) Invariant mass spectrum for secondary pK^0_S pairs (points with error bars) and expected yield of the charge exchange reaction per $2\,\mathrm{MeV}/c^2$ (open circles with error bars). A fit to a third order polynomial is shown with a dashed curve. The $\Theta(1540)^+$ contribution expected from the DIANA result is shown with solid line. (b) The yield of $\Theta(1540)^+$ from the fit, expressed in terms of the resonance width (black dots). The open dots correspond to the upper limit at the 90% C.L. The square with error bars indicates the current PDG value for the $\Theta(1540)^+$ width.

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 [5]). The resulting values of Γ_{Θ^+} and the 90% C.L. upper limits are shown as a function of m_{pK} in Fig. 3 (b). It is assumed that nuclear suppression for the $\Theta(1540)^+$ is the same as for nonresonant pK^0_S pairs. For exclusive production we find $\Gamma_{\Theta^+} < 0.64\,\mathrm{MeV}$ at $m_{\Theta^+} = 1.539\,\mathrm{MeV}/c^2$. This upper limit is below the current PDG value of $\Gamma = 0.9 \pm 0.3\,\mathrm{MeV}$, and below $1.0\,\mathrm{MeV}$ 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 [6]. With similar sensitivity, our results do not support their evidence for the $\Theta(1540)^+$.

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