Search for a bound state of kaon and pion

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We have searched for a bound state of kaon and pion denoted by $X$. The $X$ was conjectured to explain the so-called $\Theta^+$ resonance as a bound state of kaon, pion and nucleon. This model explains almost all properties of the $\Theta^+$, however, the model works only if the $K\pi$ interaction is strongly attractive. It is so strong that it could make a bound state $X$. Here we report a result of the search for the $X$ by using the $K^+ + N \rightarrow X^+ + N$ reaction at $P_{K} \sim 1.2$ GeV/c. The $X^+ \rightarrow K^+\gamma\gamma$ decay produces $K^+$ in momentum region where other processes cannot fill. We observed signature of the $X^+$ with statistical significance of 2$\sigma$. Production cross section of $X$ with respect to that of $\pi^0$ is $1\pm0.5\%$ if we take it as an evidence and 1.5% if we set an upper limit.

In this paper we present a result of a search for a hypothetical particle as a bound state of kaon and pion which was called $X$. The $X$ was conjectured to explain the $\Theta^+$ as a bound state of kaon, pion and nucleon. The $\Theta^+$ was first observed by the LEPS collaboration at SPring8 as a narrow resonance in the $K^+n$ invariant mass distribution. It should consist of at least 5 quarks thus natural explanation is a penta-quark state. Many following experiments showed positive evidence on the $\Theta^+$ which indicate that its mass is around 1540 MeV and width could be less than 1 MeV. On the other hand, many negative results also appeared. Recently the LEPS group disclosed a new result which further strengthen the positive evidence. They employed the deuterium target where the Fermi momentum correction is much smaller than the carbon target in the first experiment. It is not our intention to review vast amount of studies on the $\Theta^+$ which can be found elsewhere.

There are already number of experiments which gave positive and negative results, therefore a new single experiment can hardly be decisive on the existence of the $\Theta^+$. Situation may be changed if one presents evidence that could consistently explain why certain experiments give positive result and others do not. There is a tendency that positive results are mostly from the low energy experiments and negative ones are from the high energy experiments. In particular, no positive results appeared in the collider experiments. One may restate this observation that reactions with higher momentum transfer have smaller cross sections. This observation contradicts to the model that the $\Theta^+$ is a penta-quark state. Since its size is similar to that of hadrons (baryons and mesons), one expects that the production cross section of the $\Theta^+$ has momentum transfer dependence similar to hadrons.
There are attempts to explain the $\Theta^+$ as a bound state of $K\pi N$\cite{1, 5, 6}. This bound state model gives the spin-parity of $\frac{3}{2}^+$ same as the original theoretical prediction based on chiral soliton model\cite{2}. The chiral soliton model has huge pion component which is similar to the bound state model. Mass of three particles (1570 MeV) and binding energy of 10 MeV/particle gives the observed $\Theta^+$ mass. In particular, the narrow width of 1 MeV or less can be naturally explained in this model.\cite{9} The radius of a bound state, which depends on its binding energy, is generally much larger than that of hadrons. The cross section is thus expected to be small for reactions with high momentum transfer. This model could give consistent description of both positive and negative experimental results. Recent DIANA experiment gave positive result and obtained 0.39 MeV for the width.\cite{8} Such narrow width indicates small production cross section and makes experimental studies difficult. Theoretically, the three body bound state model is almost unique possibility to reproduce such narrow width.

However, currently known two body interactions of $\pi N$, $KN$ and $K\pi$ are not attractive enough to realize the bound state\cite{1, 5, 6}. The $\pi N$\cite{9} and $KN$\cite{10, 11, 12} interactions are based on scattering experiments thus they are rather firm. On the other hand, $K\pi$ interaction is based only on production experiments since both kaon and pion are unstable particles. Kishimoto and Sato conjectured that the $K\pi$ interaction might be attractive more than that has been known\cite{13} to realize $\Theta^+$ as the bound state and it could be strong even to make their bound state $X$\cite{11}. The lowest order decay mode is $X \rightarrow K\gamma\gamma$ since it is a $0^+ \rightarrow 0^-$ transition.\cite{1} This could be a reason why it has not been observed even if it exists. A straightforward experiment to identify the $X$ is to observe invariant mass of a kaon and two $\gamma$'s. The experiment requires dedicated detectors in particular $\gamma$ detector. Since the $X$ is currently speculative to deserve such a sophisticated experiment, we designed an experiment to observe kaon momentum.

We employed the $N(K^+, X^+)N$ reaction for the production of the $X$\cite{11}. Its momentum transfer could be even lower than 100 MeV/c for the $X$ ejected at forward angles for $P_K \sim 1$ GeV/c.\cite{1} We can expect appreciable cross section for the reaction with such small momentum transfer. A $K^+$ momentum spectrum can give signature since the $K^+$ from the decay of the $X^+$ could have higher momentum than that of $K^+$ induced by $\pi^0$ production reaction.

The experiment (PS-E548) was carried out at the K2 beam line of the 12 GeV proton synchrotron of KEK (KEK-PS).\cite{14} The primarily purpose of the E548 experiment is a study of kaonic nuclei by the $(K^-, N)$ reaction where 1 GeV/c $K^-$ beam was employed. Since details of the experiment have been described in ref\cite{15} we present here what is relevant to the present experiment. The $X$ is quadruplet due to its strangeness ($s = 1$ and $s = -1$) and isospin 1/2. We could choose either $K^-$ or $K^+$ beam to produce $X^-$ or $X^+$, respectively. We employed 1.2 GeV/c $K^+$ beam for the present search due to reasons in the following. The beam intensity of $K^+$ is higher than that of $K^-$ and higher beam momentum gives higher beam intensity. The $K^+$ beam gives less background than that of $K^-$ which accompanies hyperon production.
The beam intensity was typically $4 \times 10^4/\text{spill}$ for the primary proton beam intensity of $2 \times 10^{12}/\text{spill}$. A spill consisted of 1.7 second of continuous beam in every 4 second. The momentum bite of the incident $K^+$ beam was 17 MeV/c ($\sigma$). The momentum of the outgoing $K^+$ was measured by the KURAMA spectrometer whose momentum resolution was $\sim 6.4$ MeV/c. Polyethylene ($\text{CH}_2$) was used as a target which had dimensions of $10 \times 4.5 \times 20.5 \text{ cm}^3$. Overall momentum resolution is found to be 24 MeV/c which includes the energy loss struggling of $K^+$ in the target. The target was sandwiched by six 1 cm thick plastic scintillator hodoscopes with 5 cm granularity in the $z$ (beam) direction. $\gamma$ rays from the $X$ decay were measured by a decay counter surrounding the target. The decay counter consists of two sets of 25 NaI arrays. Each NaI has dimensions of $6.5 \times 6.5 \times 30 \text{ cm}^3$. The array was set at 15 cm above and below the target. In front of the NaI detectors, 1 cm thick plastic scintillators were placed to identify charged particles. Additional 12 NaI counters were placed to cover forward angles which gave supplemental information. Scattered $K^+$’s at forward angles hardly distinguished from beam through events. We set the trigger condition that the NaI arrays have energy deposit more than 4 MeV. This reduces trigger rate tolerable to data acquisition system. Energy calibration of NaI counters were made by punch through muon beam and cosmic ray muons. In order to obtain $\gamma$ ray energy, we first select a NaI which has the maximum energy and summed energy of adjacent NaI’s. The NaI arrays cover $\sim 30\%$ of solid angle which is insufficient to construct invariant mass of $X$ or $\pi^0$. However, it is enough to tag events that accompany $\gamma$ rays for the present experiment.

Figure [1] shows the $K^+$ momentum spectrum. Here scattering angles of $K^+$’s are from 2 to 12 degrees and accompanying $\gamma$ ray energy is more than 10 MeV where no nuclear $\gamma$ rays are expected effectively. We took 5 ns for the “true+accidental” coincidence and adjacent 2.5 ns for both sides for “accidental” coincidence. In order to obtain “true” events, “accidental” events were subtracted from the “true+accidental” events. The $K^+$ momentum spectrum of the beam through events has a peak at 1.17 GeV/c. The large fluctuation of events at around 1.17 GeV/c is due to accidental coincidence of vast amount of beam through events. We see a bump that starts at around 1000 MeV/c toward low momentum region. This corresponds to $\pi^0$ production. We have events in a 1000$\sim$1100 MeV/c region which cannot be due to either accidental coincidence nor $\pi^0$ production. Figure [1] shows the simulated spectra of $\pi^0$ events and $X$ particle events plotted together with the true events. The events in 1000-1100 MeV/c region (REGION-X here after) indicates production of the X if we can confirm that no background processes can fill the REGION-X. We considered the following processes.

Firstly, effect of the momentum resolution and momentum spread of the beam are evaluated. It might leak the $K^+$ from the $\pi^0$ production into the REGION-X. The effect is evaluated by the momentum spread of beam through events measured simultaneously. It represents overall effect of momentum resolution of the system, momentum spread of the beam, energy struggling of the beam in the target and all other relevant effects. We include the measured beam momentum distribution in our simulation and then calculated $K^+$ momentum spectrum from the $p + K^+ \rightarrow p + K^+ \pi^0$ reaction. In the simulation we assumed that the momentum distribution
Fig. 1. Momentum spectrum of the \((K^+, K^+)\) reaction on the \(\text{CH}_2\) target gated by \(\gamma\) rays is shown. Filled boxes with error bars represent “true = (true+ accidental) - accidental” events, solid line represents “accidental” events which is plotted in the negative Y-direction. The “true” events together with the simulated events of \(\pi^0\) (thick solid line) and \(X\) (dashed line) are plotted, where both the simulated histograms are normalized to the “true” data points. The factor 2 is multiplied to the vertical scale above 1100 MeV/c. The incident beam from the beam through events are also shown in the figure which is normalized arbitrary to fit within the vertical scale. The highest number of events is around 2200 at the peak in the incident beam histogram.

of three particles in the final state follows the three body phase space volume. We included the angular coverage of the NaI detector in the simulation to reproduce the effect of \(\pi^0\) momentum direction on the spectrum although its effect is small. The simulation reproduces well the spectrum below \(P_K = 1\) GeV/c and negligible events are seen above that as shown in figure 1. The simulated histogram of \(\pi^0\) production in figure 1 is normalized to the “true” histogram. The integrated number of events of the “true” histogram are taken as the normalization parameter to which each simulated histogram is normalized.

Secondly, the reaction takes place not only on a free proton but also on nucleons bound in \(^{12}\text{C}\). We included Fermi motion of a target nucleon to calculate \(K^+\) momentum spectrum. We used 250 MeV/c for the Fermi momentum. Here energy momentum of a nucleon is taken as \((E_N, p_F)\) where \(p_F\) is three momentum vector of Fermi motion and \(E_N\) is an energy of bound nucleon given by,

\[
E_N = m_N - BE - \frac{P_F^2}{2M_R},
\]
Fig. 2. Momentum spectrum of the \((K^+, K^+)\) reaction on the CH\(_2\) target gated by the charged particles is shown. Data points were shown by filled boxes with error bars. They are results of “true = (true+accidental) - accidental”. The spectrum in the negative Y-direction represents “accidental” events. The “true” events and simulated events of charged pions (thick line) are plotted together, where the simulation is normalized to the “true” data points. The incident beam from the beam through events are also shown in the figure.

where \(BE\) stands for binding energy of a nucleon in a specific state and \(\frac{P^2}{2M_R}\) is a recoil energy of a residual nucleus. It makes the slope at the threshold region (\(\sim 1000\) MeV/c) gentler than that on a nucleon target a little bit. It slightly reduces events in REGION-X but no distinguishable change is seen thus cannot explain the events in the REGION-X.

Thirdly, we considered \(K^+\) inelastic scattering which may accompany \(\gamma\) rays from nuclear excited states. The REGION-X corresponds excitation energy of 60 \(\sim\) 150 MeV in \(^{12}\text{C}\). It is unlikely that inelastic scattering excite such region since quasifree scattering at forward angles can excite up to a few ten’s MeV region. Even if the REGION-X is excited, one expects almost no accompanying nuclear \(\gamma\) rays over 10 MeV. Contrary, emission of particles (protons and neutrons) are expected. We used the NaI detector to tag charged particles by taking coincidence with plastic scintillators in front of the NaI. Figure 2 shows a spectrum gated by charged particles. The spectrum shows extra events in beam through region with a few ten’s MeV/c lower momentum region which corresponds excitation of \(^{12}\text{C}\) by a few ten’s MeV. We see negligible events in the REGION-X. Since the \(X\) has no charged particle decay mode, the fact that REGION-X has almost no events in figure 2 and some events in figure 1 is consistent with the existence of \(X\). The spectrum below 1000 MeV/c
corresponds reaction with $\pi^+$ production. The simulated histogram normalized to the “true” data points is shown in figure 2. Good agreement of the simulation with the data indicates that we reasonably include relevant processes in the simulation.

![Image](image_url)

(a) Mass spectra of the scattered particles. (b) Scattered $K^+$ mass spectra of true and accidental events of REGION-X.

Fig. 3. (a) Scattered particles mass spectra of the ($K^+, K^+$) reaction on the CH$_2$ target gated by the $\gamma$ rays. Contribution from the accidental coincidence is subtracted. (b) The mass spectrum in $K^+$ region for events in REGION-X. The true events are plotted in the positive Y-direction and accidental events are in the negative Y-direction. The number of events are used in the equation.

So far, no process can explain extra events in the REGION-X in the $\gamma$ gated spectrum. We further looked at the mass spectrum of scattered particles gated by $\gamma$ rays shown in figure 3(a). Since we can see the distinct $K^+$ peak, $M_s=300-600$ MeV/c$^2$ region was selected to obtain momentum spectra in figure 1 and 2. Mass spectrum of events in the REGION-X is also plotted in figure 3(b). The $K^+$ peak is less distinct thus we conclude that events in the REGION-X include backgrounds.

In order to extract number of candidate events corresponding to the production of the $X$, we take the following procedure. We define true and side band for both time spectrum and mass spectrum for events in the REGION-X. $T_T$ for true coincidence has 5 nsec width and $T_S$ for side band has 2.5 nsec width for both side of true coincidence. $M_T$ for true kaon corresponds to 400-550 MeV/c$^2$ and $M_S$ for side band corresponds to 300-400 MeV/c$^2$ and 550-600 MeV/c$^2$. Here we assume that $T_T$ and $M_T$ include background events that can be estimated by $T_S$ and $M_S$, respectively. Then the number of true event corresponding to $X$ production ($N_X$) can be estimated by the following equation,

$$N_X = N(T_T \cap M_T) - N(T_T \cap M_S) - N(T_S \cap M_T) + N(T_S \cap M_S)$$

$$= 26 - 13 - 1 + 2 \pm \sqrt{26 + 13 + 1 + 2} = 14 \pm 6.48$$

Here $N()$ stands for number of events for condition represented in parenthesis. There are two ways to show this result. If $X$ is produced, we observed 2 $\sigma$ effect. If it is taken to be an upper limit, number of events corresponding to $X$ production is less than 20.5 events ($1 \sigma$).
We convert this number of events into $R_X$ which is a ratio of $X$ production cross section to that of $\pi^0$. We made the following assumption to estimate it. Since small momentum transfer is essential, we assume that all $K^+$ produced from $X^+$ is within angular acceptance of the spectrometer ($2 \sim 12$ degrees) which corresponds momentum transfer of less than 0.1 GeV/c where $X^+$ is scattered less than 5 degrees. On the other hand $\pi^0$ production follows phase space distribution. Production of the $X$ gives events not only in the REGION-X but also below 1000 MeV/c as shown by a dashed line in figure 1. The number of $\pi^0$ events below 1000 MeV/c after subtraction of $X$ contribution and the number of $X$ events in the REGION-X were compared with the simulation. We found that the $R_X = 1.0 \pm 0.5\%$. We can also give $R_X \leq 1.5\%$ as an upper limit. The overlap of $X$ and kaon gives $\sim 1/100$ which indicates that the $X$ is an extended object or equivalently loosely bound system. The result suggests existence of the $X$. Although the statistical significance is not enough to draw definite conclusion, it deserves further study.

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