High Resolution Search for Exotic Pentaquark $\Theta^{++}$, and $\Theta^{+}$ at Jefferson Lab

Haiyan Gao and Wang Xu

Department of Physics
Duke University and the Triangle Universities Nuclear Laboratory

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Recent evidence for the existence of pentaquark $\Theta^{+}$ particle from several experiments at different laboratories around the world has caused great excitement and raised many unanswered questions. We discuss a new, high resolution experiment searching for pentaquark states in Hall C at Jefferson Lab using an untagged bremsstrahlung photon beam employing both the hydrogen and the deuterium targets by studying the following processes: $\gamma p \rightarrow \Theta^{++} K^-$, and $\gamma n \rightarrow \Theta^{+} K^-$. This new experiment will significantly improve our current knowledge of the mass, the width of the $\Theta^{+}$ particle if it is confirmed and provide unambiguous evidence for the existence or non-existence of the $\Theta^{++}$ particle from the $\gamma p \rightarrow \Theta^{++} K^-$ process.

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I. INTRODUCTION AND PHYSICS MOTIVATION

The first evidence of the observation of a pentaquark $\Theta^{+}$ particle came in early 2003 from the LEPS collaboration in which a sharp resonance was reported at a mass of $(1.54 \pm 0.01) \text{(GeV)/c}^2$. The DIANA Collaboration reported evidence for a resonance enhancement at $M = 1539 \pm 2 \text{ MeV/c}^2$ and $\Gamma \leq 9 \text{ MeV/c}^2$ in the charge-exchange reaction $K^+ X e \rightarrow K^0 p X e'$. The CLAS collaboration reported a statistical significance of $(5.3 \pm 0.5)\sigma$ at the $K^+n$ invariant mass peak of $1542 \pm 5 \text{ MeV/c}^2$ with a measured width of $21 \text{ MeV}$ for the reaction $\gamma d \rightarrow K^+ K^- p(n)$. The SAPHIR collaboration reported a peak at $M_{\Theta^+} = 1540 \pm 4 \pm 2 \text{ MeV(4.8 } \sigma \text{ confidence level)}$ and an upper limit of $25 \text{ MeV}$ for the width with a $90\%$ confidence level in the $K^+n$ invariant mass distribution from the $\gamma p \rightarrow nK^+ K^0_s$ process. The SAPHIR Collaboration also reported the absence of a signal in the $K^+p$ invariant mass distribution in the $\gamma p \rightarrow pK^+K^-$ reaction. More recently, the HERMES collaboration reported evidence of the $\Theta^{+}$ particle from a deuterium target with the decay mode $\Theta^+ \rightarrow pK^0_s \rightarrow p\pi^+\pi^-$ at $1526 \pm 2 \pm 2 \text{ (MeV)}$ with a width of $7.5 \text{ MeV}$ dominated by detector resolution. The CLAS Collaboration also reported evidence on $\Theta^{+}$ from a hydrogen target from the $\gamma p \rightarrow \pi^+K^-\Theta^+$ process. They found a peak in the invariant mass of $nK^+$ at $1555 \text{ MeV}$ with a width of about $26 \text{ MeV}$.

The CERN NA49 Collaboration reported an exotic $S = -2, Q = -2$ baryon resonance in proton-proton collisions with a mass of $1862 \pm 2 \text{ MeV/c}^2$ and width below the detector resolution of $18 \text{ MeV/c}^2$ in the $\Xi^-\pi^-$, and $\Xi^-\pi^+$ invariant mass spectra. These two states are believed to be candidates for the $ds\bar{s}u$ ($\Xi^{(-)}_{1/2}$), and the $dus\bar{s}$ ($\Xi^{0}_{3/2}$) pentaquark state, respectively. However, there is probably more evidence against the existence of the $ds\bar{s}u$ and $dus\bar{s}$ pentaquark states. Mostly recently, the H1 collaboration reported evidence for a narrow anti-charmed baryon state, interpreting such a state as the pentaquark $ud\bar{d}c\bar{c}$ state.

In summary, the experimental situation concerning the $\Theta^{+}$ and $\Theta^{++}$ pentaquark states is the following. There is evidence from different experiments supporting the existence of the pentaquark $\Theta^{+}$ state, but there is no evidence for the $\Theta^{++}$ particle. The mass of the $\Theta^{+}$ particle is from $1527 \text{ MeV}$ to $1555 \text{ MeV}$, and the width is found to be from $9 \text{ MeV}$ to $26 \text{ MeV}$ limited by detector resolutions. Also, the existing data seem to suggest that the $\Theta^{+}$ particle is an isoscalar particle. However, the existence of $\Theta^{++}$ pentaquark is far from being confirmed experimentally. One also needs to address possible experimental issues such as kinematic reflection due to the decay of higher mass mesons, such as the $f_2(1275)$, the $a_2(1320)$, and the $\rho_3(1690)$.

The original chiral soliton model predicted a mass of $1530 \text{ MeV}$ and a total width of less than $15 \text{ MeV}$ for the $\Theta^{+}$ particle. It also predicted that the $\Theta^{++}$ particle is a spin $\frac{3}{2}$ isoscalar particle and the predicted mass for the $\Xi_{3/2}$ state is $2070 \text{ MeV}$. In the correlated diquark picture by Jaffe and Wilczek, the diquarks QQ are correlated in an antisymmetric color, flavor and spin state. In the case of the $\Theta^{+}$ pentaquark state, it is a bound state of two highly correlated $ud$ pairs and an antiquark. The narrowness of the width of the $\Theta^{+}$ particle can be explained in this model by the weak coupling between the $K^+n$ continuum and the bound state of the two diquark pairs and the antiquark, $[ud]^2\bar{s}$. One of the interesting predictions from this model, which differs from the chiral soliton model prediction, is the mass of the cascade isospin $\frac{3}{2}$ multiple $\Xi_{3/2}((us)^2d)$. It is predicted to be around $1750 \text{ MeV}$ with a width about $50\%$ greater than that of the $\Theta^{+}$ particle.

The $\Theta^{+}$ particle was also hypothesized as an isosensor resonance to explain the observed narrow width of the $\Theta^{+}$ particle via isospin-violating strong decays. The hypothesis that $\Theta^{+}$ is an isosensor particle implies the existence of $\Theta^{++}+, \Theta^{*+}, \Theta^{*0}$, and $\Theta^{*-}$ states. Gerasyuta and Kochkin calculated the mass spectra of the isosensor Theta-pentaquarks with $J^P = \frac{1}{2}^+, \frac{3}{2}^-$ in...
a relativistic quark model. The predicted mass for $\Theta^{+++}$ is 1575 MeV (1761 MeV) for $J^P = \frac{1}{2}^+$ ($J^P = \frac{3}{2}^+$). Here we following the convention in the literature that $\Theta$ represents the I=0 state in anti-decuplet, $\Theta^*$ represents the I=1 state in 27-plet and $\Theta^{**}$ the I=2 state in 35-plet. In the remaining of the paper, we will not explicitly differentiate the $\Theta^{+++}$ and the $\Theta^{++}$ states because the proposed experiment will not be able to determine which multiplet the observed $\Theta^{++}$ particle belongs to.

Walliser and Kopeliovich [14] investigated the implications of the $\Theta^+$ exotic pentaquark for the baryon spectrum in topological soliton models. They estimate the positions of other pentaquark and septuquark states with exotic and with non-exotic quantum numbers, particularly within the 27-plet baryon and the 35-plets multiplets in SU(3) soliton model. In the 27-plet, the $J = \frac{3}{2}, T = 1$ multiple ($\Theta^0, \Theta^+, \Theta^{++}$) are estimated to have a mass of 1.65 to 1.69 GeV. Most recently, Wu and Ma [15] studied the mass and width of the pentaquark $\Theta^*$ states in the 27 baryon multiplet from chiral soliton model. Their calculations show that the mass of $\Theta^*$ is about 1.61 GeV and the width for the process $\Theta^* \rightarrow KN$ is less than 44 MeV. Bijker et al. [18] constructed a complete classification of $qqqq$ states in terms of the flavor-spin SU(6) representation and found that only the anti-decuplet, 27-plets and the 35-plets contain exotic states which can not be constructed by three quarks only. In this model, the ground state pentaquark is identified as the observed $\Theta^0$ (1540) state, and is predicted to be an isosinglet anti-decuplet state. The predicted masses for the excited exotic baryons are 1660 MeV and 1775 MeV.

While it is important to determine the quantum number of the $\Theta^+$ particle, particularly the spin and the parity and to search for other members in the exotic baryon family, it is more essential to confirm the existence of the $\Theta^+$ particle with significantly improved statistics, and to determine its mass and the width more precisely. Karliner and Lipkin [11] derived an upper bound on the mass difference between the $\Xi^*$ and $\Theta^+$ based on simple assumptions about SU(3)$_f$ symmetry breaking and quantum mechanical variational method. The resulting rather robust bound is more than 20 MeV below the experimentally reported $\Xi^*$ - $\Theta^+$ mass difference. It is also very important to verify definitely the non-existence or the existence of the $\Theta^{++}$ particle and to search for the $\Theta^{+++}$ particle.

We proposed [20] a new, high resolution search for pentaquark $\Theta^+$, $\Theta^{++}$ and $\Theta^{+++}$ in Hall C at Jefferson Lab using high resolution magnetic spectrometers in combination with a neutron counter by studying two different physical processes: the $\gamma n \rightarrow \Theta^+ K^-$, where $\Theta^+$ decays via $\Theta^+ \rightarrow K^+ n$, and the $\gamma p \rightarrow \Theta^{++}(\Theta^{+++}) K^-$, where $\Theta^{++} \rightarrow K^+ p$. Due to the lack of a free neutron target, a liquid deuterium target will be used for the $\gamma n \rightarrow \Theta^+ K^-$ process. The $K^-$ particle will be detected in the Short Orbit Spectrometer (SOS) in coincidence with the $K^+$ and the neutron which will be detected in the High resolution Kaon Spectrometer (HKS), and the neutron counter, respectively. By detecting all three particles, the un-tagged bremsstrahlung photon energy, the mass of the $\Theta^+$ particle, and the initial neutron momentum inside the deuteron can be reconstructed completely.

For the two-body process $\gamma p \rightarrow \Theta^{+++}(\Theta^{+++}) K^-$ process one can not reconstruct the mass of the undetected $\Theta^{+++}(\Theta^{+++})$ particle from detecting $K^-$ particle only unless the energy of the incident real photon is known. Assuming the $\Theta^{+++}(\Theta^{+++})$ particle decays into $K^+$ and $P$, the incident real photon energy can be reconstructed by detecting $K^+$ in coincidence with the $K^-$ particle. Such coincidence detection also suppresses backgrounds from other physical processes which have final states different from the $K^+ K^- p$ final state. The proposed experiment allows for the search of the $\Theta^{+++}(\Theta^{+++})$ particle in the mass range of 1500 MeV to 1800 MeV.

The primary sources of the physics backgrounds for the proposed $\gamma p \rightarrow \Theta^{+++}(\Theta^{+++}) K^-$ process and the $\gamma n(D) \rightarrow \Theta^+ K^-$ process are: (i) $\phi$ meson production, (ii) $\gamma + p \rightarrow K^+ \Lambda(1520)$ where, $\Lambda(1520) \rightarrow p + K^-$, and

![FIG. 1: Reconstructed $\Theta^+$ mass spectra for the proposed experiment. In this simulation, physical events were generated from the $\gamma n \rightarrow \Theta^+ K^-$ process with a $\Theta^+$ mass of 1540 MeV; The background is from $K^+ K^-$ pairs and an accidental coincidental rate.](image)
FIG. 2: The reconstructed $\Sigma^{-}$ mass from the $\gamma n \rightarrow \Sigma^{-}K^{+}, \Sigma^{-} \rightarrow \pi^{-}n$ reaction (see text).

(iii) three-body final state $K^{+}K^{-}$ production. Monte Carlo simulations have been carried out to study these backgrounds, taking into account the momentum and angular resolutions of the two hadron spectrometers and their full momentum and angular acceptances. The spectrometer momentum and angle settings based on the two-body kinematics of the $\gamma p \rightarrow \Theta^{++}(\Theta^{*+})K^{-}$ and the $\gamma n \rightarrow \Theta^{+}K^{-}$ processes together with the reconstructed photon energy cut ($E_{0} - 125 \leq E_{\gamma} \leq E_{0} - 25$ MeV), where $E_{0}$ is the incident electron beam energy, effectively suppress the background contributions from the aforementioned physical processes. Cuts can be applied in the invariant mass of the $K^{+}p$ ($K^{+}n$) system in order to suppress these backgrounds further. Simulations show that both the $\phi$ production and the $\Lambda(1520)$ channels are suppressed even without a 100 MeV of $E_{\gamma}$ cut and kinematic reflections are not issues for the proposed experiment. Fig. 2 shows the projected result on the $\Theta^{+}$ particle search.

The $\gamma n \rightarrow \Sigma^{-}K^{+}$ reaction will be used for the mass calibration. The $\Sigma^{-}$ particle will be reconstructed by its decay into neutron and $\pi^{-}$ particle. The neutron will be detected in the neutron counter in coincidence with the $\pi^{-}$, and the mass of the $\Sigma^{-}$ particle will be reconstructed in a similar way as that of the $\Theta^{+}$ particle. To suppress the background the $K^{+}$ particle will be detected in the SOS spectrometer in coincidence with the neutron and the $\pi^{-}$ particle. Fig. 2 shows the simulated $\Sigma^{-}$ particle mass determination, which is better than 0.3 MeV. The upper panel shows the simulation result for the $\gamma n \rightarrow \Sigma^{-}K^{+}, \Sigma^{-} \rightarrow \pi^{-}n$ reaction only, while the lower panel result includes accidental and other possible physical backgrounds. This new experiment will determine the absolute mass of the $\Theta^{+}$ particle to better than 0.5 MeV and determine the $\Theta^{+}$ particle width to better than 1.3 MeV ($\sigma$).

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