# Search for Exotic Pentaquark $\Theta^+$ and $\Theta^{++}$ in Hall C at Jefferson Lab


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# Abstract

Recent evidence for the existence of pentaquark $\Theta^+$ particle from several experiments at several different laboratories around the world has caused great excitement and raised many unanswered questions. We propose a high resolution search for pentaquark states in Hall C using an untagged bremsstrahlung photon beam employing both the hydrogen and the deuterium targets. We propose to study the following processes: (I) $\gamma p \to \Theta^{++}K^-$, and (II) $\gamma n \to \Theta^+ K^-$. The proposed experiment will be carried out in Hall C using the combination of the SOS and the HMS spectrometer for process (I), and the combination of SOS, HKS and a neutron counter for the $\gamma n \to \Theta^+ K^-$ channel. An electron beam having an incident energy of 3.475/3.825 GeV with a maximum beam current of 50 $\mu$A will be employed for the search of the $\Theta^+$ and the $\Theta^{++}$ particle. The $\gamma n \to \Sigma^- K^+$ process will be employed for the absolute mass calibration at an incident electron beam energy of 1.91 GeV. We request a total of 20 days for this experiment. The proposed 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 ($\sigma$). It will also provide unambiguous evidence for the existence or non-existence of the $\Theta^{++}$ particle from the $\gamma p \to \Theta^{++}K^-$ process, important for the determination of the isospin quantum number of the $\Theta^+$ particle.

## I. INTRODUCTION AND PHYSICS MOTIVATION

Quark models [1] are remarkably successful in classifying mesons and baryons as composite systems of quark-antiquark ($q\bar{q}$) states for mesons and three quark ($qqq$) states for baryons. [2] Also, it is well known that the structure of hadrons should be more complicated than the simple lowest valence quark states, and there are additional sea quark-antiquark pairs and gluons inside the hadrons which have been probed by various deep inelastic processes. The situation can be well illustrated by the structure of the nucleon in terms of quark-gluon components as supported by a large amount of phenomenological evidence. The existence of the higher quark-gluon components in the nucleon structure can be described by perturbative quantum chromodynamics (pQCD) for the perturbative aspect and perhaps by the baryon-meson fluctuation configuration [3] for some of the non-perturbative aspects. Therefore a conventional baryon should be composed of various quark-gluon configurations in which the lowest is the three quark ($qqq$) state. From another point of view, there have been various theoretical and experimental investigations on the possibility of the existence of exotic hadrons beyond the conventional quark model spectroscopy, such as multiquark mesons ($qq\bar{q}\bar{q}$) and baryons ($qqqq\bar{q}$), dibaryons ($qqqqqq$), hybrid states ($q\bar{q}g$), and glueballs. [2]

The first evidence of the observation of a pentaquark $\Theta^+$ particle came from the LEPS collaboration [4] in which a sharp resonance was reported at a mass of $(1.54\pm0.01)$ (GeV)/c$^2$. The experiment was carried out at Spring-8 using a laser back-scattered photon beam, a CH target, and the $K^+$ and $K^-$ particles at forward angles from the $\gamma n \to K^+K^-n$ reaction were detected. The DIANA collaboration [5] reported evidence for a resonance enhancement at $M = 1539\pm2$ MeV/c$^2$ and $\Gamma \leq 9$ MeV/c$^2$ in the charge-exchange reaction $K^+Xe \to K^0pXe'$. The CLAS collaboration [6] reported a peak with a statistical significance of $(5.3\pm0.5)\sigma$ at the $K^+n$ invariant mass of $1542\pm5$ MeV/c$^2$ with a measured width of 21 MeV for the reaction $\gamma d \to K^+K^-p(n)$ using a tagged photon beam. The SAPHIR [7] collaboration reported a peak at $M_{\Theta^+} = 1540 \pm 4 \pm 2$ MeV (4.8 $\sigma$ confidence level) and an upper limit of 25 MeV for the width with a 90% confidence level in the $K^+n$ invariant mass distribution from the $\gamma p \to nK^+K^0_s$ process. Furthermore, the SAPHIR Collaboration also reported the absence of a signal in the $K^+p$ invariant mass distribution in the $\gamma p \to pK^+K^-$ reaction and concluded that the $\Theta^+$ particle is isoscalar. The HERMES collaboration [8] reported evidence of the $\Theta^+$ particle from a deuterium target with the decay mode $\Theta^+ \to pK^0_s \to p\pi^+\pi^-$ at $1526 \pm 2 \pm 2$ (MeV) with a width of 7.5 MeV dominated by detector resolution. The CLAS Collaboration [10] also reported evidence on $\Theta^+$ from a hydrogen target by studying the $\gamma p \to \pi^+K^-\Theta^+$ process. They found a peak in the invariant mass of $nK^+$ at 1555 MeV with a width of about 26 MeV.

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 1526 MeV to 1555 MeV, and the width is found to be from 9 MeV to 28 MeV limited by detector resolutions of these experiments. 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 [9]. Here we do not attempt to list all the experiments which report positive evidence for the $\Theta^+$ particle, nor do we attempt to list all the experiments which show negative results.

The CERN NA49 Collaboration [11] reported an exotic $S = -2, Q = -2$ baryon resonance in proton-proton collisions with a mass of $1862 \pm 2$ MeV/c$^2$ and width below the detector resolution of 18 MeV/c$^2$ in the $\Xi^-\pi^-$, and $\Xi^-\pi^+$ invariant mass spectra. These two states are believed to be candidates for the $dsds\bar{u}$ ($\Xi^{--}_{\frac{3}{2}}$) pentaquark state, and the $dsus\bar{d}$ ($\Xi^0_{\frac{3}{2}}$) pentaquark state, respectively. However, there is probably more evidence against the existence of the $dsds\bar{u}$ and $dsus\bar{d}$ pentaquark states [12]. Mostly recently, the H1 collaboration reported [13] evidence for a narrow anti-charmed baryon state, interpreting such a state as the pentaquark $uudd\bar{c}$ state.

What is the theoretical situation regarding the pentaquark state? Many papers have been written since the LEPS collaboration reported the first evidence for the existence of the $\Theta^+$ pentaquark state. Refs. [14–28] are only a subset of these papers. We do not attempt to review all theoretical work here, but will discuss in some details the chiral soliton model by Diakonov *et al.* [14] and the diquark model by Jaffe and Wilczek [16]. The chiral soliton model motivated the original work at LEPS, and the diquark model by Jaffe and Wilczek gives distinctively different predictions from those of the chiral soliton model. For a review of theoretical development on pentaquarks, we refer to reference [29].

The original chiral soliton model prediction by Diakonov, Petrov and Polyakov [14], which largely motivated the LEPS search, gave a mass of 1530 MeV and a total width of less than 15 MeV for the $\Theta^+$ particle. They also predicted that the $\Theta^+$ particle is a spin $\frac{1}{2}$ isoscalar particle. In their chiral soliton model, the lowest multiplets are the octet $(8,\frac{1}{2})$, the decuplet $(10,\frac{3}{2})$, and the antidecuplet $(\bar{10},\frac{1}{2})$. To fix a fundamental quantity in their model, they identified one of the members of the anti-decuplet which has the same nucleon quantum numbers as the well-known N(1710, $\frac{1}{2}^+$) nucleon resonance. The lightest baryon in the antidecuplet is therefore identified as the exotic $\Theta^+$ particle with a predicted mass of 1530 MeV and a predicted width of less than 15 MeV. Another feature of this model is that the equidistant splittings inside the anti-decuplet states are predicted to be $\sim 180$ MeV. In this model the predicted mass for the $\Xi_{3/2}$ state is 2070 MeV.

Jaffe and Wilczek [16] proposed the correlated diquark picture to explain the observed $\Theta^+$ resonance with a narrow width. In their model, 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. In this model, the $\Theta^+$ is predicted to have positive parity and it is the lightest member of the flavor antidecuplet. By identifying the lightest state of the flavor antidecuplet to the observed $\Theta^+$ (1540 MeV) particle, the $M_0 + m_s$ parameter was fixed to be $\sim$ 1540 MeV in the model, where the Hamiltonian including $SU(3)$ violation is $H_s = M_0 + (n_s + n_{\bar{s}})m_s + n_s\alpha$, and $\alpha = \frac{3}{4}(M_\Lambda - M_\Sigma)$. 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 very interesting predictions of this model, which also differs from the chiral soliton model prediction, is the mass of the cascade isospin $\frac{3}{2}$ multiple $\Xi_{3/2}([us]^2\bar{d})$. Jaffe and Wilczek predict that the exotic cascade state mass to be around 1750 MeV with a width about 50% greater than that of the $\Theta^+$ particle, while the chiral soliton model predicts much heavier cascade states. The NA49 Collaboration [11] show evidence for the observation of such isospin-3/2 cascade resonance states, but at a higher mass, 1862 MeV.

Capstick, Page and Roberts [15] hypothesized the $\Theta^+$ particle as an isotensor resonance to explain the observed narrow width of the $\Theta^+$ particle. The decay of the $\Theta^+$ particle to the $K^+n$ state is via isospin-violating strong decays and is estimated to have a decay width of sub-MeV, much smaller than the experimental upper bound of the $\Theta^+$ decay width. The hypothesis that $\Theta^+$ is an isotensor particle implies the existence of $\Theta^{**+++}$, $\Theta^{**++}$, $\Theta^{**0}$, and $\Theta^{**-}$ states. Gerasyuta and Kochkin [30] calculated the mass spectra of the isotensor Theta-pentaquarks with $J^p = \frac{1}{2}^{\pm}, \frac{3}{2}^{\pm}$ in a relativistic quark model. The predicted mass for $\Theta^{**++}$ is 1575 MeV (1761 MeV) for $J^p = \frac{1}{2}^{\pm}$ ($J^p = \frac{3}{2}^{\pm}$). Here we follow 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.

Following the success of the chiral soliton model by Diakonov *et al.* [14] in predicting the $\Theta^+$ particle mass, width and isospin, Walliser and Kopeliovich [31] 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-plet 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 [32] 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 $\Theta^* \to KN$ is less than 44 MeV. Bijker *et al.* [33] constructed a complete classification of $qqqq\bar{q}$ 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 $\Theta^+(1540)$ 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, we believe it is more essential at the present time to confirm the existence of the $\Theta^+$ particle with significantly improved statistics, and to determine the mass and the width of the $\Theta^+$ particle more precisely. Karliner and Lipkin [34] 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[1]. Once the existence of the $\Theta^+$ has been confirmed with high statistics, it is essential to determine the cross-section for producing such an exotic particle, which in turn will help us understand the underlying mechanism for the pentaquark exotics in QCD. So far, there is no reliable experimental information on the production cross-section for the exotic pentaquark $\Theta^+$. The proposed experiment will allow for a determination of the differential cross-section for the $\Theta^+$ particle for the first time. As was mentioned previously the existing data give a rather large range for the mass of the $\Theta^+$ particle, 1526 - 1555 MeV, with a width between 9 - 28 MeV, limited by the detector resolutions. So far, all experiments reporting evidence

[1]Here we drop the notation of $\Theta^{*++}$ and $\Theta^{**++}$ for simplicity.

for the existence of the $\Theta^+$ particle employed large acceptance detection systems, which could be more sensitive to issues such as kinematic reflection raised by Dzierba *et al.* [35]. In their study, Dzierba *et al.* showed that the narrow enhancement in the invariant mass spectrum of the $K^+n$ system around 1540 MeV can be generated as kinematic reflections resulting from the decay of mesons, such as the $f_2(1275)$, the $a_2(1320)$, and the $\rho_3(1690)$. Kinematic reflection is the enhancement in the invariant mass spectrum of the $K^+n$ system when the invariant mass of the photon-nucleon system exceeds the production thresholds for higher mass mesons such as $f_2(1275)$, $a_2(1320)$, $\rho_3(1690)$. This is because several of these mesons are known to have a production cross-section comparable to the total cross-section for the $K^+K^-$ production, and the branching ratio for these mesons decaying into $K^+K^-$ is of several percent. However, the peak position of such an enhancement in the invariant mass spectrum of the $K^+n$ system depends on the incident beam momentum. Therefore, high statistics measurements using high resolution, small-acceptance magnetic spectrometers with different incident beam momenta are very crucial for the confirmation of the $\Theta^+$ particle, and for the more accurate determination of its mass and width. While one may argue about the validity of the quenched Lattice QCD calculations, there is no conclusive evidence for the existence of the $\Theta^+$ particle from lattice calculations [36,37].

So far there has been no evidence for the existence of $\Theta^{++}$ particle from photon induced reactions [6,7]. Chen, Mao and Ma [38] suggested that the observation of null $\Theta^{++}$ peak in photoproduction can exclude $I = 1$ and $I = 2$ for $\Theta$ if the production of $\Theta$ is through the isoscalar component of the photon. On the other hand, if the production of $\Theta$ is through $I = 1$ electromagnetic current dominantly, then the absence of the $\Theta^{++}$ particle in photoproduction can not exclude an isovector $\Theta^+$. Recently, the missing mass technique [39] was employed by the Hall A experiment E04-012 [40] in searching the $\Theta^{++}$ particle. Such a technique is difficult in identifying a small signal from overwhelmingly large backgrounds. This method would be especially challenging if the $\Theta^{++}$ state is not a very narrow state. While there is no evidence on $\Theta^{++}$ from Hall A experiment E04-012 [40], data [43] from RHIC suggest the existence of $\Theta^{++}$ particle. Therefore, a new experiment with much better sensitivity in probing the existence of $\Theta^{++}$ particle from photoproduction is urgently needed. Such an experiment is essential in determining the isospin quantum number of the $\Theta^+$ particle following the confirmation of its existence.

We propose to carry out a systematic, high resolution search of the $\Theta^+$, and the $\Theta^{++}$ particle with high statistical accuracy from hydrogen and deuterium targets using magnetic spectrometers in combination with a neutron counter (in the case of $\Theta^+$). The pentaquark mass can be determined to better than 0.5 MeV. The width ($\sigma$) can be determined to 2.8 MeV and 1.3 MeV for the $\Theta^{++}$ and the $\Theta^+$ particles, respectively, using the Hall C magnetic spectrometers and a neutron counter.

## II. THE EXPERIMENT

### A. Experimental Overview

We propose to carry out a systematic search for pentaquark states $\Theta^+$, and $\Theta^{++}$ particle in Hall C using magnetic spectrometers in combination with a neutron counter ($\Theta^+$) by studying two different physical processes. The experiment requires an electron beam at an incident beam energy of 3.475/3.825 GeV with a maximum beam current of 50$\mu$A. The experiment will employ both the Hall C 4-cm long cryogenic liquid hydrogen and deuterium targets, and a 6% Cu radiator. For the $\Theta^{++}$ search, the Short Orbit Spectrometer (SOS) and the High Momentum Spectrometer (HMS) will be employed. For the $\Theta^+$ search, the SOS, the High resolution Kaon Spectrometer (HKS), and a neutron counter will be used. We propose to study the following two processes:

- $\gamma n \to \Theta^+ K^-$, where $\Theta^+$ decays via $\Theta^+ \to K^+ n$. Due to the lack of a free neutron target, a liquid deuterium target will be used. The $K^-$ particle will be detected in the SOS spectrometer in coincidence with the $K^+$ and the neutron which will be detected in the HKS spectrometer, and the neutron counter, respectively. By detecting all three particles, the untagged bremsstrahlung photon energy, and the initial neutron momentum inside the deuteron can be reconstructed completely. Furthermore, the $\Theta^+$ mass can be reconstructed directly from the detected $K^+$ and the neutron.

- $\gamma p \to \Theta^{++} K^-$, where $\Theta^{++} \to K^+ p$. The $K^-$ particle will be detected in SOS in coincidence with the proton which will be detected in the HMS spectrometer. One can also detect the decay $K^+$ particle in HMS in coincidence with the $K^-$ particle. The coincidence rate will be significantly lower than that with detecting the proton because of the rather low $K^+$ momentum and the 25-meter HMS flight path. Therefore, we propose to carry out the search of the $\Theta^{++}$ particle as a function of the reconstructed invariant mass of the $K^+ p$ by detecting the proton from the $\Theta^{++}$ decay. Once the existence of the $\Theta^{++}$ particle is demonstrated, a dedicated measurement will be carried out by detecting the $K^-$ and $K^+$ in coincidence to provide additional confirmation. The reconstructed mass resolution by detecting the $K^+$ particle is 2.8 MeV ($\sigma$), while the mass resolution is 3.85 MeV ($\sigma$) when detecting the proton. By tagging the proton or the $K^+$ particle from the $\Theta^{++}$ decay, backgrounds from other physical processes having a final state different from the $K^+ K^- p$ final state will be suppressed. Backgrounds from physical processes which have the same $K^+ K^- p$ final state are suppressed by cuts in the reconstructed photon energy spectrum, in the reconstructed invariant mass spectra of the $K^+ K^-$, and the $K^- p$ system.

### B. Proposed Experimental Setup

In designing the experiment, the following factors need to be considered:

- For the $\gamma n \to \Theta^+ K^-$ channels, detection of both the $K^+$ and $K^-$ particles are needed. The mean life of the kaon in its rest frame is about $1.2 \times 10^{-8}$ second. Therefore, spectrometers with short flight path are very crucial for such an experiment. The Short-Orbit Spectrometer (SOS) and the High Resolution Kaon (HKS) spectrometer in Hall C serve these purposes well.

- For the $\gamma n \to \Theta^+ K^-$ process, neutron detection is required in addition to the detection of the $K^+$ and the $K^-$ particles. We propose to use a neutron detector similar to what was employed by the JLab Hall C experiment E93-026 [41] or similar to the neutron counter for the upcoming $G_E^n$ experiment (E02-013) in Hall A.

- For the $\gamma p \to \Theta^{++} K^-$ process, the majority of the proposed measurements require the detection of the proton and the $K^-$ particle. Therefore, the combination of the existing SOS/HMS spectrometer is sufficient for these measurements. A radiator system was used successfully in Hall C deuteron photodisintegration experiments E89012 and E96003. Therefore, the proposed program on $\Theta^{++}$ search can be carried out right away.

- The maximum central momentum of HKS is 1.2 GeV. This limits HKS to be served as a $K^+$ detector for the $\gamma n \to \Theta^+ K^-$ process.

- The two spectrometers with reversed polarities will be used for the calibration of the mass determination using the $\gamma n \to \Sigma^- \pi^+$ process (see Section F).

- In the dispersion plane of the HKS spectrometer, the most forward angle the neutron counter can be positioned is 59° with respect to the electron beam line at a distance of 4.2 meters from the target. However, the neutron counter is required to be at 39° kinematically. The solution we proposed is to position both HKS spectrometer and Neutron Counter at -23 ° with respect to the electron beam line [2] in the horizontal plane. HKS will go down -11° vertically and Neutron Counter will go up +14° vertically. Design for new supports for HKS and the Neutron Counter is required.

We propose to carry out the proposed experiment in two phases: phase A and phase B. Phase A can be carried out right away on the $\Theta^{++}$ search using the combination of the SOS and the HMS spectrometers. The phase B on the $\Theta^+$ search requires major installation and a detailed discussion concerning phase B is described below.

Given the fact that we are proposing to use the SOS, the target will be a 4 cm LH2 (LD2) target, the maximum target length seen by the SOS at 90°. Since the LH2 (LD2) target is at the SOS pivot and the distance from the SOS-HMS pivot to the E01-011 target position (downstream) is about 4.6 meters, we tried to position the HKS such that the flight path for the $K^+$ is as short as possible. This is achieved by moving the HKS upstream towards the SOS pivot from the position used in the Hypernuclear experiment, E01-011. Since beamline will be blocked by HKS if HKS is at-23 °, we also plan to use the splitter magnet to bend the $K^+$ events outward to a larger angle. The minimum distance that the splitter magnet could be positioned due to the size of the scattering chamber is 1.25 m from the target. Keeping the splitter plus HKS system identical to that of experiment E01-011, we thus need to move the splitter to a 1.25 m from the SOS pivot. By rotating the splitter plus HKS system -12.1°/-11.0° away from the beam line from the E01-011 configuration, we can achieve the necessary configuration. The HKS will be physically at an angle of -32.0°/-11.0° to the right of the electron beam line facing the beam dump. The corresponding central scattering angle for HKS is -23.0°/$-11.0$° with the splitter magnet in front. The neutron detector will be positioned on the same side of the HKS, and it is at an angle of -23.0°/+14.0° with respect to the incident electron momentum direction. The SOS spectrometer is positioned at an angle of 20.0° (or 48.0°) to the left of the incident electron beam momentum direction. Figs.

[2]negative sign here refers beam right when facing the beam dump

1 and 2 show two different views of the proposed experimental setup in Hall C for Phase B. This experiment will need a smaller platform to hold the HKS detector stack rather than using the $T_{20}$ platform that E01-011 will use.

The detector package in the SOS spectrometer consists of two wire chambers for tracking and position measurements, scintillator hodoscopes for timing, a gas Cerenkov counter, an aerogel counter and a segmented Pb glass shower counter for particle identification. The momentum resolution of SOS is better than 0.1%. General characteristics of the HKS spectrometer are listed in Table I and the momentum resolution is $10^{-4}$. The HKS detector configuration is similar to that of the SOS spectrometer. As in Experiment E01-011, the singles rate in HKS is dominated by the singles pion rate. Two layers of aerogel Cerenkov counter with index of refraction of 1.05, which will be installed for Experiment E01-011 to achieve efficient rejection of pions, will be beneficial to the proposed experiment. A lucite Cerenkov counter with wavelength shifter will be employed for proton rejection. The timing resolution of 80 ps aimed for the time-of-flight scintillators of HKS will help further for particle identification. The tracking chambers of HKS are capable of accepting rates as high as a few MHz.

The neutron detector shown in Fig. 3 is 10 m from the target, covered by a 12 cm Pb plate to suppress the background from the target area. The background from the radiator stacked around by more than 12 inches of lead with water cooling is negligible. The neutron detector consists of multiple vertical layers of segmented plastic scintillators. Two thin layers of scintillator paddles sandwiched by three 2 cm steel plates are used as veto detectors to distinguish charged particles. The front steel plate can suppress low energy particles generated from target, beamline and the Pb plate; The back steel plate is used mainly to reduce low energy particles generated within the thin layer of scintillator paddles of the veto detector. Behind the veto detectors, three layers of thick scintillator paddles are used for detecting the neutrons. The surface area of each scintillator paddle is 160 cm $\times$ 10 cm. The thickness of a thin scintillator paddle is less than 1 cm and the thickness of a thick scintillator paddle is 10 cm. All scintillators are equipped with photo-multiplier tubes on both ends to provide spatial and timing information for the detected particles.

The entire volume for neutron detection is 160 cm wide, 160 cm tall and 30 cm deep. The timing resolution is expected to be about 300 ps which determines the momentum resolution for the neutron detection from the Time-of-Flight information. The neutron momentum range for the proposed experiment is between 500 MeV to 880 MeV. The spatial resolution for the neutron counter is 5-10 cm. We used the detector development tool GEANT in combination with the FLUKA and MICAP packages for the design of this neutron detector. The background fluxes from target were obtained by Gdinr M. C [42]. calculation. The neutron detection efficiency shown in Fig 4 is a ratio of detected neutron events, in which neutron signals are above a threshold of 30 MeV to the total incident neutron events. The average neutron detection efficiency in the neutron momentum range for the proposed experiment is about 30%[3]. The rates of individual PMTs from Gdinr M. C. calculation and GEANT simulation for both veto and neutron counter are listed in Table II. The maximum

[3]The more realistic value for the neutron efficiency is assumed to be 20% in projecting the proposed measurements

rate of each scintillator paddle is around 500 KHz. This requires the upper limit of beam current not to exceed 100 $\mu$A and the location of the neutron detector not to be close to the beamline. With a beam current of 50 $\mu$A, the expected rate of the neutron counter is less than 0.5 MHz for a threshold of 30 MeV.

### C. Kinematics

The kinematics for the proposed measurements were chosen based on the following considerations:

- The kinematics chosen for the $\gamma p \to \Theta^{++}K^-$ process and the $\gamma n \to \Theta^+K^-$ process correspond to a $K^-$ center-of-mass angle range of $\sim 35^\circ - 55^\circ$, and $\sim 40^\circ - 70^\circ$, respectively.
- The HKS spectrometer can handle higher overall singles rates (a few MHz) than the SOS spectrometer (1 MHz). The SOS spectrometer will be used for detecting $K^-$ particles at a central scattering angle of $+20^\circ$ and the $K^+$ particle will be detected in the HKS spectrometer at a central scattering angle of -23°/-11° with the splitter magnet in front of the HKS for the $\Theta^+$ kinematics.
- Three different kinematic settings were chosen for the $\gamma p \to \Theta^{++}K^-$ process corresponding to a possible $\Theta^{++}$ particle mass of 1540 MeV, 1660 MeV and 1750 MeV, respectively. Therefore, the proposed experiment allows a thorough search for the $\Theta^{++}$ particle in the mass range of 1500 MeV to 1800 MeV.

Table III and Table IV list the kinematics of the proposed experiment. Fig. 5 contains various kinematics plots for the proposed $\Theta^+$ measurement. Fig. 6 and Fig. 7 are kinematics plots for the $\Theta^{++}$ search by detecting the coincidence $K^-p$ and $K^-K^+$, respectively.

### D. Simulations

For the two-body process $\gamma p \to \Theta^{++}K^-$ ($\Theta^{++} \to K^+p$), one can reconstruct the energy of the incident real photon and the undetected $\Theta^{++}$ particle mass from the coincidence measurement of the $K^-$ momentum and angle, and the proton or $K^+$ momentum and angle from the $\Theta^{++} \to K^+p$ decay. For the $\Theta^{++}$ particle, there is no evidence so far for the existence of such a particle with a mass of 1540 MeV from photoproduction $\gamma p \to \Theta^{++}K^-$ process. However, there is evidence [43] suggesting the existence of such a state around 1530 MeV from RHIC. Furthermore, such a particle may exist with a larger mass as suggested by Bijker *et al.* [33] and Gerasyuta and Kochkin [30]. In addition to the detection of the $K^-$ particle, the proton or the $K^+$ particle from $\Theta^{++}$ decay will be detected in coincidence with the $K^-$ particle to suppress backgrounds from other physical processes which have final states different from $K^+K^-p$ final state. In this proposal, three spectrometer settings for SOS and HMS are proposed corresponding to a reconstructed central $K^+p$ invariant mass of 1540, 1670 and 1750 MeV, respectively. Thus, the proposed experiment allows for the search of the $\Theta^{++}$ particle in the mass range of 1500 MeV to 1800 MeV.

For the $\gamma n \to \Theta^+ K^-$ process, a deuterium target will be employed. The $K^+$ and the neutron from the $\Theta^+$ decay will be detected, which allows the reconstruction of the $\Theta^+$ mass in a straightforward way, achieving a mass resolution better than 1.3 MeV ($\sigma$). Since the $K^-$ particle will also be detected, the incident real photon energy as well as the initial neutron momentum inside the deuteron can be reconstructed. This technique was used successfully in a recent Hall A experiment [44] on photopion production $\gamma n \to \pi^- p$ process.

A Monte Carlo simulation code was written for the purpose of the reconstruction of the $\Theta^{++}$ and the $\Theta^+$ exotic baryon masses from the two processes discussed above. In our simulation, we used *rms* momentum resolutions of $\delta p/p = 2 \times 10^{-4}$ for the HKS, $1 \times 10^{-3}$ for the SOS and the HMS spectrometer. We used 1.0 *mr* (5.5/0.8 *mr*) and 3.0 *mr* (0.5/1.2 *mr*) for the horizontal and vertical *rms* spectrometer angular resolutions of the HKS (SOS/HMS), respectively. We used 300 ps for the neutron counter timing resolution and 5 cm for its spatial resolution in the simulation. Multiple scattering in the target, windows, and air gaps were included in the simulation, along with straggling and energy loss for the outgoing particles. The simulated mass spectra for the $\Theta^+$ particle from the proposed measurement is shown in Fig. 8. The simulated mass spectra for the $\Theta^{++}$ particle for the three proposed coincidence measurements of $K^-$ and proton are shown in Figs. 9, 10, and 11. For the proposed $\Theta^{++}$ search by detecting the $K^- K^+$ in coincidence, the simulated spectrum is shown in Fig. 12, which gives a significantly smaller width than that by detecting the proton. The overall experimental resolution in determining the width ($\sigma$) of the $\Theta^+$ ($\Theta^{++}$) particle is 1.3 (2.8) MeV[4].

### E. Backgrounds

The primary sources of the physics background for the proposed $\gamma p \to \Theta^{++} K^-$ process and the $\gamma n(D) \to \Theta^+ K^-$ process are: (i) $\phi$ meson production, (ii) $\gamma + p \to K^+ + \Lambda(1520)$ where, $\Lambda(1520) \to p + K^-$, and (iii) three-body final state $K^+ K^-$ production [45]. Monte Carlo simulations have been carried out to study these backgrounds, taking into account the momentum and angular resolutions of the two hadron spectrometers (SOS and HKS) and the full momentum and angular acceptances of SOS and HKS for the $\Theta^+$ case, and the combination of the SOS and HMS spectrometers for the $\Theta^{++}$ particle search. As mentioned before, multiple scattering in the target, windows and air gaps were also included. The total resonant and non-resonant $K^+ K^-$ photo-production cross section is estimated to be about 1.5 $\mu$b and differential cross sections for the $\phi$ meson photo-production and $\Lambda$ production at a photon energy of around 3 GeV are known from existing data. The spectrometer momentum and angle settings based on the two-body kinematics of the $\gamma p \to \Theta^{++} K^-$ and the $\gamma n \to \Theta^+ K^-$ 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. Fig. 13 shows two-dimensional spectra plotted among various reconstructed quantities for

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[4]From coincidence measurement of $K^- K^+$

the $\Theta^+$ kinematics: the reconstructed photon energy ($E_\gamma$), the invariant mass of the $K^+K^-$ pair, the invariant mass of the $K^-p$ system, and the invariant mass of the $K^+N$ system for any event which is in the acceptance of the spectrometers. Therefore, it is clear that both the $\phi$ production and the $\Lambda(1520)$ channels are suppressed even without a 100 MeV of $E_\gamma$ cut. Furthermore, backgrounds due to kinematic reflections discussed previously from the $f_2(1275)$, the $a_2(1320)$, and the $\rho_3(1690)$ channels are shown to be suppressed as well without a 100 MeV of $E_\gamma$ cut. Fig. 14 show similar two-dimensional spectra for the $\Theta^{++}$ kinematics by detecting the the $K^-$ and the proton in coincidence.

A preliminary GEANT3 monte carlo simulation [46] has been carried out for the proposed experimental configuration with a 6% copper radiator in front of the LD2 target to address the potential background issue in the neutron counter and the HKS spectrometer raised by PAC 26. For a total of $1 \times 10^7$ electrons simulated, there is no hit recorded in either the neutron counter or the HKS. Simulations with improved statistics is ongoing.

### F. Calibration

In order to determine the absolute mass of the $\Theta^+$ particle to better than 0.5 MeV, calibration of the proposed method of mass determination is essential. We propose to use the following reaction to carry out the mass calibration: $\gamma n \to \Sigma^- K^+$. The particle data book value for the mass of the $\Sigma^-$ is $1197.436 \pm 0.033$ MeV. The $\Sigma^-$ particle will be reconstructed by its decay to a neutron and a $\pi^-$ 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 the mass of the $\Theta^+$, which is reconstructed by detecting the neutron and the $K^+$ particle in coincidence. In addition, the $K^+$ particle will be detected in the SOS spectrometer at an angle of $+48°$ with the reversed polarity in coincidence with the neutron and the $\pi^-$ particle. The HKS spectrometer polarity will also be reversed in order to detect the $\pi^-$ particle from the $\Sigma^-$ decay, but the spectrometer physical configuration and location will be identical to those for the pentaquark $\Theta^+$ kinematics. The neutron counter orientation will need to be rotated from $-23°/+14°$ down to $-23°/+7°$ in order to carry out the proposed mass calibration measurements. For the calibration measurement, we propose an incident electron beam energy of 1.910 GeV corresponding to a $W$ value of 2.11 GeV. The kinematics for the calibration reaction is listed in Table III. For the proposed kinematics, the corresponding central $K^+$ center-of-mass angle is 102° for the $\gamma n \to \Sigma^- K^+$ reaction. For an incident electron beam current of 50$\mu$A, the total $\Sigma^-$ events are $10^4$, and $3.5 \times 10^3$ with a 100 MeV cut in the reconstructed photon beam energy for a total beam time of 50 hours based on the known $\Sigma^-$ photoproduction cross section. Fig. 15 shows the simulated calibration measurement for the $\Sigma^-$ particle mass determination and the its mass can be calibrated to better than 0.3 MeV. The upper panel shows the simulation result for the $\gamma n \to \Sigma^- K^+$, $\Sigma^- \to \pi^- n$ reaction only, while the lower panel result included accidental and other possible physical backgrounds. One can see clearly that the measurement is very clean by detecting all three final state particles.

For the case of the $\Theta^{++}$ particle search, the combination of the SOS and HMS spectrometer was well calibrated in previous Hall C measurements on kaon electroproduction [47]. The absolute mass of the $\Theta^{++}$ particle can be determined to better than 1.0 MeV.

### G. Counting Rates

To estimate the coincidence rate for the $\gamma p \to \Theta^{++}K^-$ and the $\gamma n \to \Theta^+K^-$ measurements, we used the differential cross-section calculated by Oh *et al.* [20,21,48] shown in Fig. 16 for $\Theta^+$ for an incident photon beam energy of 3.5 GeV. The black solid curve is the result without the $K^*$ contribution. The green and the red curves correspond to the $g_{K^*N\Theta} = -0.7g_{KN\Theta}$, and $g_{K^*N\Theta} = 0.7g_{KN\Theta}$, respectively. Fig. 17 shows the calculated differential cross section by Close and Zhao [50] as a function of $K^-$ center-of-mass angle for the $\gamma n \to \Theta^+K^-$ reaction for two different incident photon beam energies. The so-called "fall-apart" mechanism is adopted which leads to a larger $K^*N\Theta$ coupling constant than that of $KN\Theta$ coupling by a factor of $\sqrt{3}$. A 1 MeV width for the $\Theta^+$ particle is used in this calculation, and a larger width will correspond to a larger cross section by simple scaling. The solid line is the result in the Born limit without $K^*$ exchanges, while the dashed and dotted curves are results including $K^*$ exchanges of different signs. In the $K^-$ angular coverage of the proposed kinematics, both calculations give very similar angular dependence.

Table V and Table VI list the calculated coincidence rates together with the singles rates (see discussion below) at the proposed kinematics with the spectrometer acceptances taken into account. In estimating the rates, we used a beam current of 25 (50) $\mu$A corresponding to a luminosity of $2.63 \times 10^{37}$ $(6.36 \times 10^{37})/(\text{cm}^2 \text{ sec})$ for a 4-cm LH2 (LD2) target cell. For the HKS (HMS) and SOS spectrometers, we used solid angles of 5.8 (6.0) $msr$ and 9.0 $msr$ for the extended target and 0.9 for the detection efficiency. In addition, we used a photon energy bin of 100 MeV near the end point, giving a centroid of the photon energy bin around 75 MeV below the end point.

Singles hadron rates in the HKS (HMS) and SOS spectrometers were estimated using the Lightbody and O'Connell code [49]. Quasifree kaon production was assumed to scale as $A^{0.8}$ and normalized to the data from Hall C experiment E89-009, giving an upper limit of 2320 Hz for the HKS for this experiment. The singles electron rates were estimated from the code QFS. Table IV shows the expected singles rates for the HKS (HMS) and SOS spectrometers for this experiment. Both the SOS and HKS total rates for this experiment are dominated by the singles $\pi^+(\pi^-)$ rates. All three spectrometers (HKS, HMS and SOS) can handle a total rate up to a few MHz. The maximum total singles rates estimated for SOS from this experiment is 0.5 MHz, 0.4 MHz for HMS and the maximum HKS singles rate is 0.954 MHz.

Since both the SOS and the HKS (HMS) spectrometers have good particle identification capabilities, the accidental coincidence rate for the coincidence $K^-p$, $K^+K^-$, and the coincidence $K^+K^-n$ measurements are negligible compared with the coincidence signal rate for a coincidence timing window of 2 ns with particle identification cuts taking into account detector ineffciencies in particle identification. Fig. 18 and Fig. 19 show the accidental and the corrected coincidence timing spectrum for the coincidence $K^-p$ and $K^-K^+$ measurement, respectively. The expected total $\Theta^{++}$ events and $\Theta^+$ events are given in Table IV based on the requested running time (see next section). The expected $\Theta^{++}$ events from the $\gamma p \to \Theta^{++}K^-$ process is based on the differential cross-section calculated by Oh [48]. For the kinematics of the proposed experiment, the differential cross-section $\frac{d\sigma}{d\Omega}_{cm}$ is around 2.0 nb/sr. Therefore, the proposed experiment will have a sensitivity to the existence or non-existence of $\Theta^{++}$ particle to a level of 100 pb/sr with a total number of expected events over $3\sigma$ above the background events. Please note the aforementioned 100 MeV $E_\gamma$ cut is only important for the determination of the production differential cross-section once the existence of the particle has been established. In order to establish the existence of such exotic particles, this $E_\gamma$ cut is not necessary as shown clearly in the simulated results (Figs. 8-12). Therefore, the total projected events for $\Theta^+$ particle ($\Theta^{++}$) is 5837 (around 15K to 23 K) based on the input differential cross-section we used in our simulations.

### H. Beam Time Estimate

For the proposed Phase A on the search of the $\Theta^{++}$ particle via the $\gamma p \to \Theta^{++} K^-$ process, we request a beam time of 75 hours by detecting the $K^-$ and the proton in coincidence for three different kinematic settings corresponding to a possible $\Theta^{++}$ particle mass of 1540 MeV, 1660 MeV and 1750 MeV, respectively. In addition, we request a beam time of 50 hours for the coincidence $K^+K^-$ detection for one of the three aforementioned kinematic settings. In addition, we request 50 hours for background data taking and target/radiator/spectrometer changes. So the total beam time request for the $\Theta^{++}$ search (Phase A) is 175 hours. Here we emphasize again that the proposed Phase A measurements can be carried out right away with the existing Hall C SOS and the HMS spectrometers.

For Phase B, the $\gamma n \to \Theta^+ K^-$ process, we request a beam time of 150 hours for production data taking with 100 % efficiency and an additional 150 hours for spectrometer and detector checkout, calibration measurements, target/radiator/spectrometer changes, and for background data taking. The total request for Phase B is 300 hours.

In total we request 475 hours (20 days) of beam time.

## III. COLLABORATION BACKGROUND AND RESPONSIBILITIES

This experiment requires a bremsstrahlung photon radiator, the standard Hall C liquid hydrogen and deuterium target, the Hall C SOS and HMS spectrometers, the new High resolution Kaon Spectrometer (HKS), and a neutron counter similar to that which was used for the Hall C experiment E93-026 or the neutron counter for the Hall A experiment E02-013. For the Phase A part of the proposal, the proposed measurements can be carried out right away using the existing Hall C SOS and the HMS spectrometers. The collaboration overlaps significantly with the E01-011 collaboration. The Caltech group and the Duke group will take on the major responsibility of assembling a neutron counter for this experiment. The experiment requires engineering and technical support from the Jefferson Lab in configuring a new platform for the HKS for the running configuration of this experiment, and for the installation of a neutron counter in Hall C. Many members in our collaboration have extensive experience in experiments with bremsstrahlung photon beams both in Hall C and in Hall A. The expertise and manpower of this collaboration is adequate to carry out the proposed experiment. This collaboration also has strong theoretical support.

## TABLES

| | |
|---|---|
| Configuration | QQD and horizontal bend |
| Central momentum range | 0.42 GeV/c - 1.20 GeV/c |
| Momentum acceptance | ±10% |
| Momentum resolution ($\Delta p/p$) | 2 $\times 10^{-4}$ |
| Solid angle | 5.8 msr with splitter |
| Angular acceptance-scattering angle | ± 49.5 mrad |
| Angular acceptance-out of plane | ± 29.6 mrad |
| Angular resolution-scattering angle | 1 mrad |
| Angular resolution-out of plane | 3 mrad |
| Kaon detection angle | Horizontal: 23.0° |
| | Vertical: -11.0° |
| Particle flight path | 10.0 m |

TABLE I. HKS spectrometer specifications specific to the proposed experimental geometry.

| | Flux Density ($\#/cm^2 - sec$) | Detected Rate (Hz) | Notes |
|---|---|---|---|
| Particles | ($> 0.5 MeV$) | | |
| $\pi^{\pm}$ | 240.0 | | |
| $\mu^{\pm}$ | 4.2 | | |
| $e^{\pm}$ | 3.2 | | |
| p | 168.0 | | |
| n | 55.2 | | |
| Photons | 40.0 | | |
| Total | 510.6 | 408,480 | one paddle of veto rates |
| Neutrals | ($> 30 MeV$) | | |
| N | 50 | | eff=0.2 |
| Photons | 20 | | eff=0.55 |
| Total Neutrals | 21 | 33,808 | one front paddle of NC rates |

TABLE II. Estimated rate at 26.7° (-23.0°/+14.0°) in 10cm×160cm veto and neutron counter paddles behind 12cm Pb and 2cm steel from 50$\mu$A of 3.5GeV electrons on a 4-cm LD2 target.

| $E_e$ (GeV) | $\theta_{\rm SOS}$ (degree) | $P_{\rm SOS}$ (GeV/c) | $\theta_{\rm HMS}$ (degree) | $p_{\rm HMS}$ (GeV/c) |
|---|---|---|---|---|
| 3.825 (H,p,$M_{\Theta^{++}}$ = 1540 MeV) | 16.0 | 1.708 | -20.0 | 1.180 |
| 3.825 (H,p,$M_{\Theta^{++}}$ = 1660 MeV) | 15.0 | 1.708 | -20.0 | 1.455 |
| 3.825 (H,p,$M_{\Theta^{++}}$ = 1750 MeV) | 15.0 | 1.708 | -20.0 | 1.670 |
| 3.825 (H,$K^+$,$M_{\Theta^{++}}$ = 1540 MeV) | 16.0 | 1.708 | -20.0 | 0.841 |

TABLE III. Kinematics for the proposed $\gamma p \to \Theta^{++}K^- \to K^+pK^-$, where $p$ indicates that the $K^-$ and p will be detected by SOS and HMS, respectively, while $K^+$ represents the measurement in which the $K^-$ and $K^+$ will be detected in coincidence. The negative sign indicates that the HMS spectrometer is on the right hand side of the beam line facing the beam dump. The centroid of the photon energy is 75 MeV below the incident electron beam energy.

| $E_e$ (GeV) | $\theta_{\rm SOS}$ (degree) | $P_{\rm SOS}$ (GeV/c) | $\theta_{\rm HKS}/\phi_{HKS}$ (degree) | $p_{\rm HKS}$ (GeV/c) | $\theta_n/\phi_n$ (degree) |
|---|---|---|---|---|---|
| 3.475 (D, $\Theta^+$) | 20.0 | 1.800 | -23.0/-11.0 | 0.880 | -23.0/+14.0 |
| 1.910 (D, $\Sigma^-$) | 48.0 | 0.700 | -23.0/-11.0 | 0.540 | -23.0/+7 |

TABLE IV. Kinematics for the proposed $\gamma n \to \Theta^+ K^-$ reactions, and the calibration reaction $\gamma n \to \Sigma^- K^+$. The negative sign indicates that the HKS spectrometer and the neutron counter are on the right hand side of the beam line facing the beam dump. The centroid of the photon energy is 75 MeV below the incident electron beam energy. The negative momentum settings for the SOS and the HKS spectrometers indicate that both spectrometer polarities will be reversed for the calibration reaction.

|  |  | SOS |  |  | HMS(p) |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
| $E_\gamma$ (GeV) | Beam ($\mu$A) | $\pi^-$ (kHz) | $e^-$ (kHz) | $K^-$ (Hz) | $\pi^+$ (kHz) | p (kHz) | $K^+$ (Hz) | Beam time (hours) | Expected events |
| 3.750(H,p,1540 MeV) | 25 | 136.7 | 53.8 | ~1170 | 77.0 | 121.4 | ~1430 | 25 | 23360 |
| 3.750(H,p,1660 MeV) | 25 | 189.2 | 51.9 | ~1170 | 55.2 | 76.1 | ~1430 | 25 | 16555 |
| 3.750(H,p,1750 MeV) | 25 | 208.7 | 44.9 | ~1170 | 45.5 | 36.1 | ~1430 | 25 | 15100 |
| 3.750(H,$K^+$,1540 MeV) | 25 | 136.7 | 53.8 | ~1170 | 268.5.0 | 134.2 | ~1430 | 50 | 781 |

TABLE V. Singles rate estimate and the coincidence signal rate for the proposed $\gamma p \to \Theta^{++}K^-$. The expected $\Theta^{++}$ events for 25 hours of beam time at 100% efficiency is 15-23 K total for the $\gamma p \to \Theta^{++}K^- \to K^+pK^-$, where $K^-$ and p will be detected by SOS and HMS, respectively; $\Theta^{++}$ events for 50 hours of beam time at 100% efficiency is about 800 total for the $\gamma p \to \Theta^{++}K^- \to K^+pK^-$ process, where $K^-$ and $K^+$ will be detected by SOS and HMS, respectively.

|  |  | SOS |  |  | HKS |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
| $E_\gamma$ (GeV) | Beam ($\mu$A) | $\pi^-$ (kHz) | $e^-$ (kHz) | $K^-$ (Hz) | $\pi^+$ (kHz) | p (kHz) | $K^+$ (Hz) | neutron (kHz) | Beam time (hours) | Expected Events |
| 3.400(D) | 50 | 336 | 133 | 2320 | 535 | 419 | 992 | 338 | 150 | 952(5837) |
|  |  | HKS |  |  | SOS |  |  |  |  |  |
| 1.910(D) | 50 | 26.0 | 54.6 | - | 7.6 | 7.6 | 1700 | - | 50 | 2328(7246) |

TABLE VI. Singles rate estimate and the coincidence signal rate for the proposed $\gamma n \to \Theta^+K^-$ measurements, and the calibration reaction $\gamma n \to \Sigma^-K^+$. The expected $\Theta^+$ events for 150 hours of beam time at 100% efficiency is 5837 total and 952 with a 100 MeV $E_\gamma$ cut.

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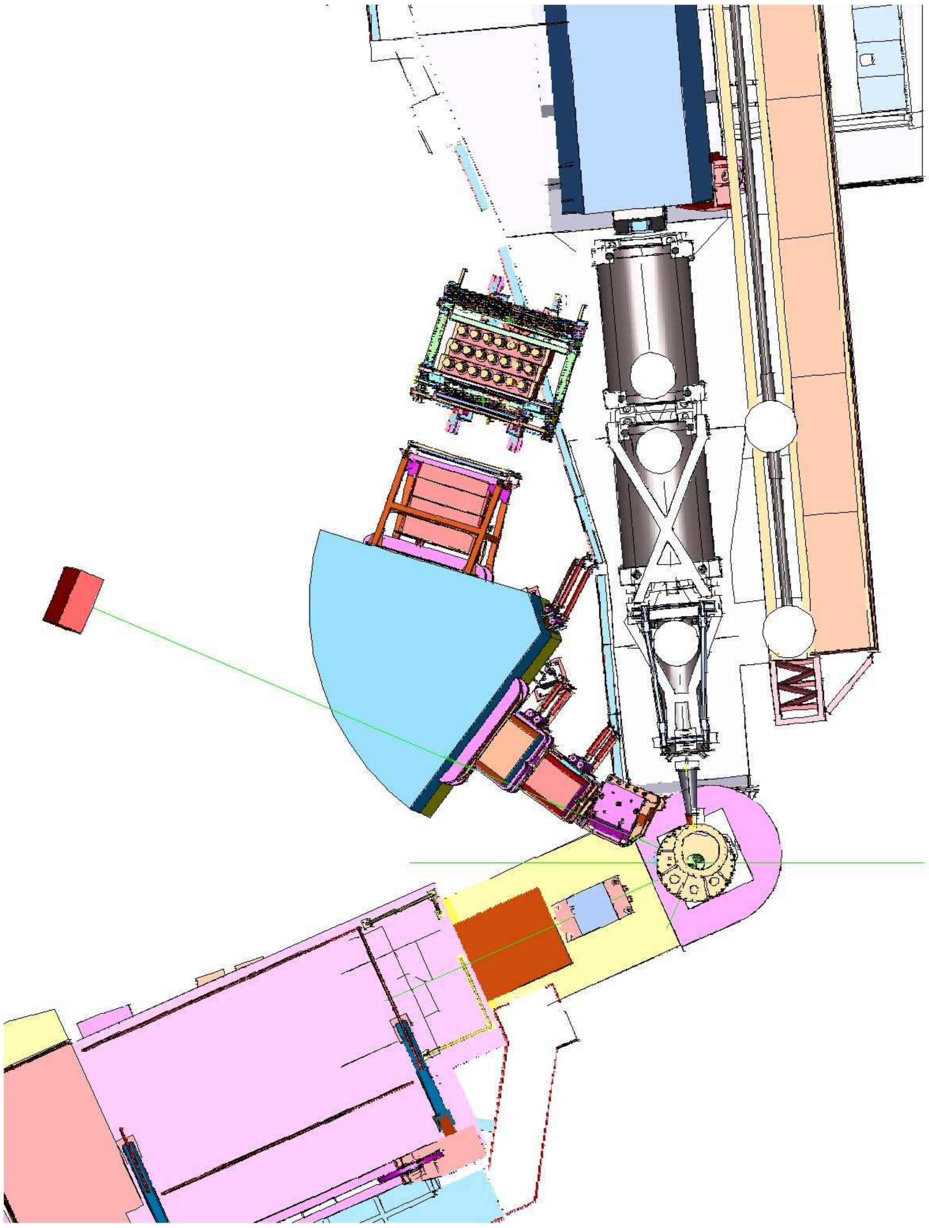

FIG. 1. Top view of the experimental setup for the proposed experiment (Phase B)

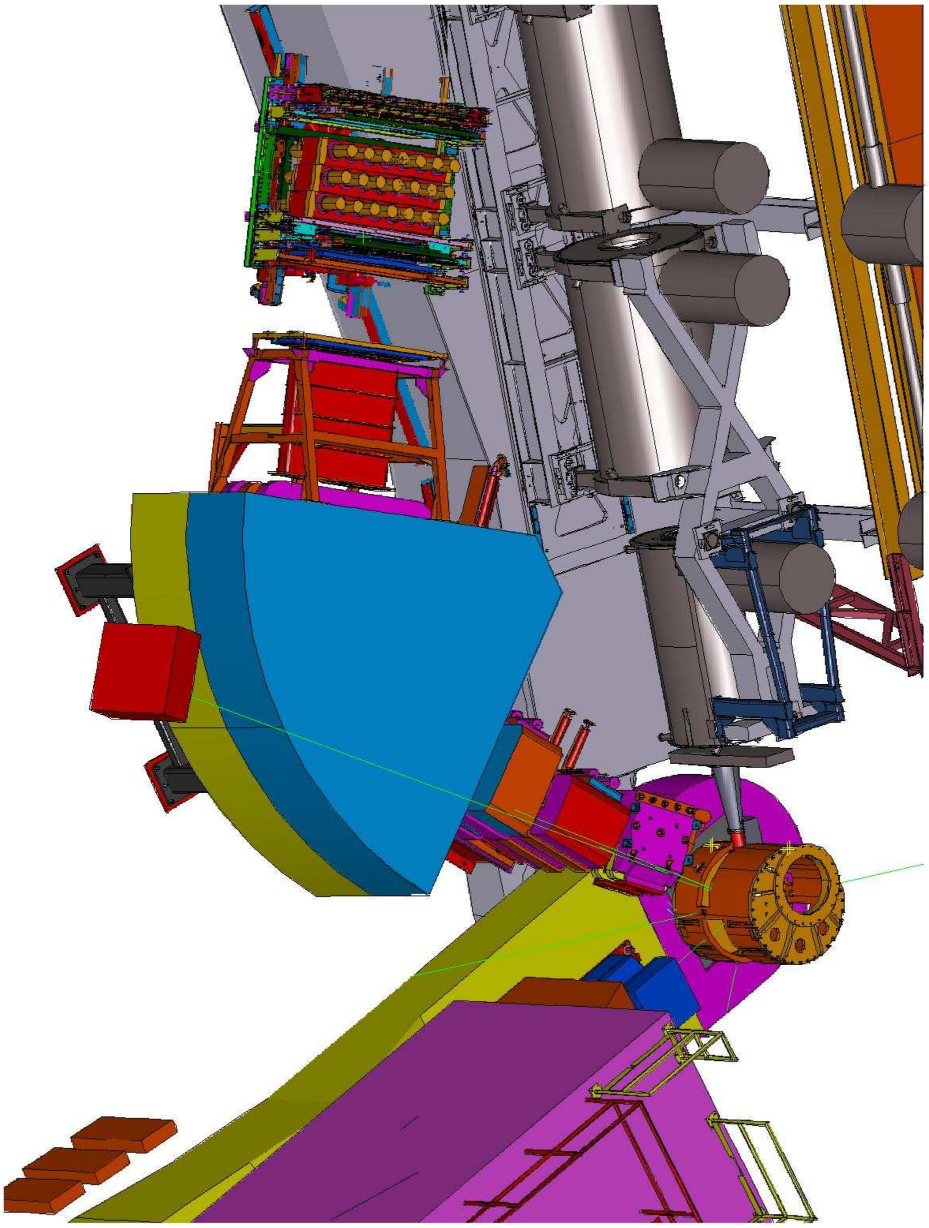

FIG. 2. Isometric view of the experimental setup for the proposed experiment (Phase B).

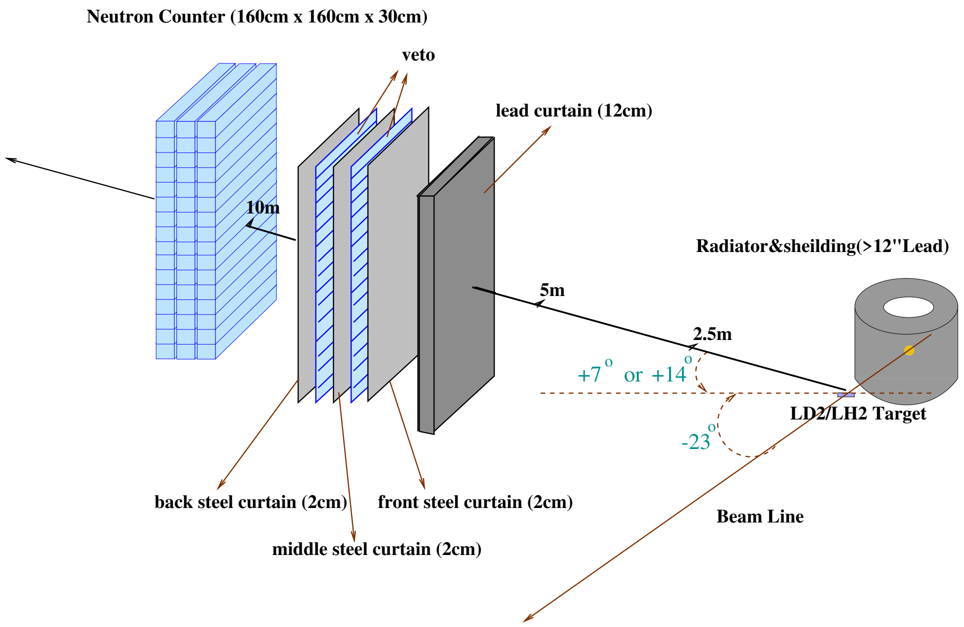


FIG. 3. A schematics diagram of the neutron detector setup.

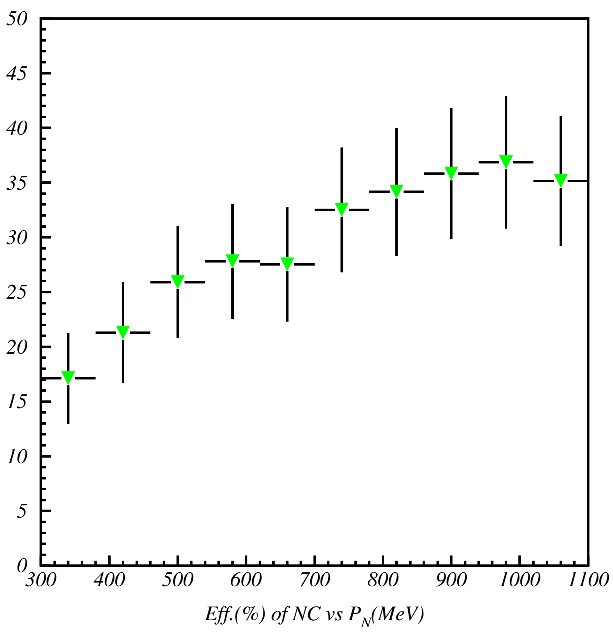


FIG. 4. The neutron detection efficiency as a function of neutron momentum (see text).

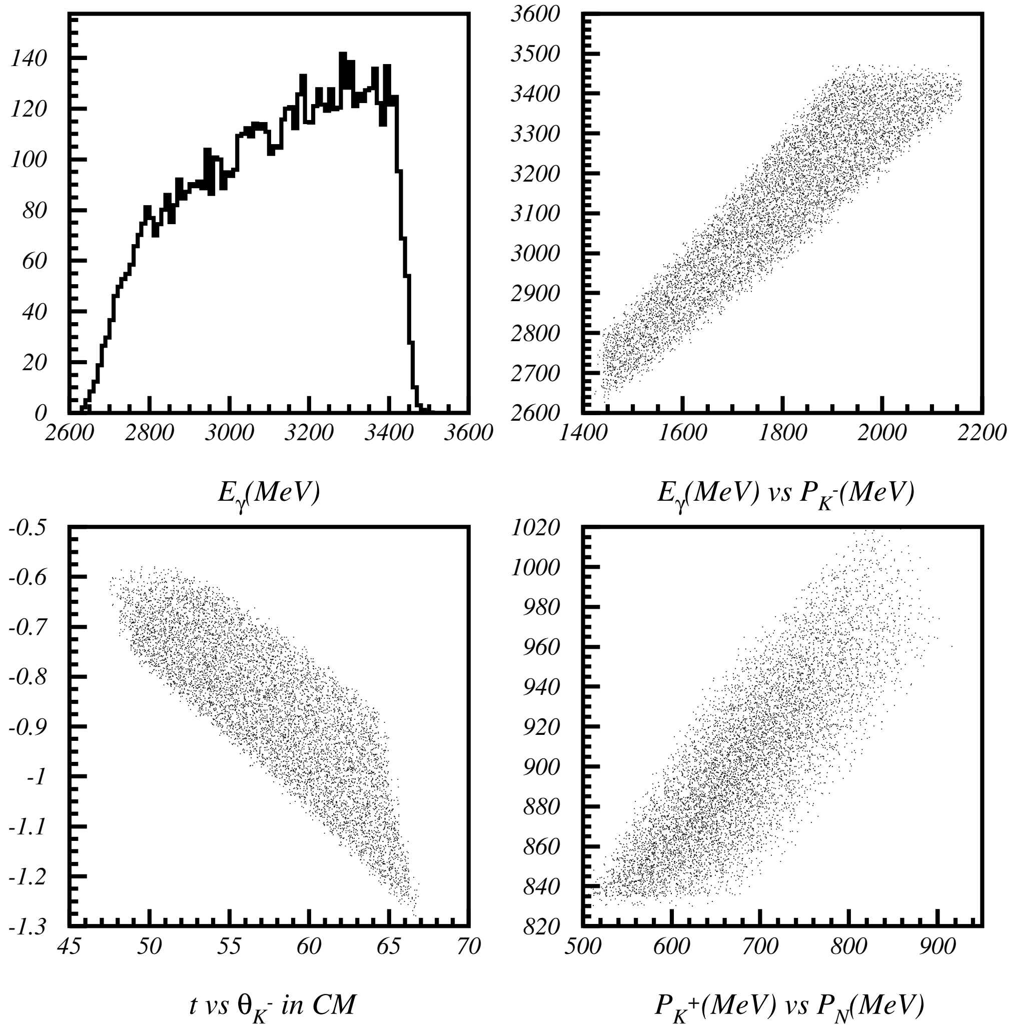


FIG. 5. The kinematics plots for the proposed $\Theta^+$ search corresponding to a mass of 1540 MeV. a) the reconstructed $E_\gamma$; b) $E_\gamma$ versus momentum of $K^-$; c) scattering angle of $K^-$ in c.m. versus $t$; d) the correlation between the $K^+$ and the neutron momentum.

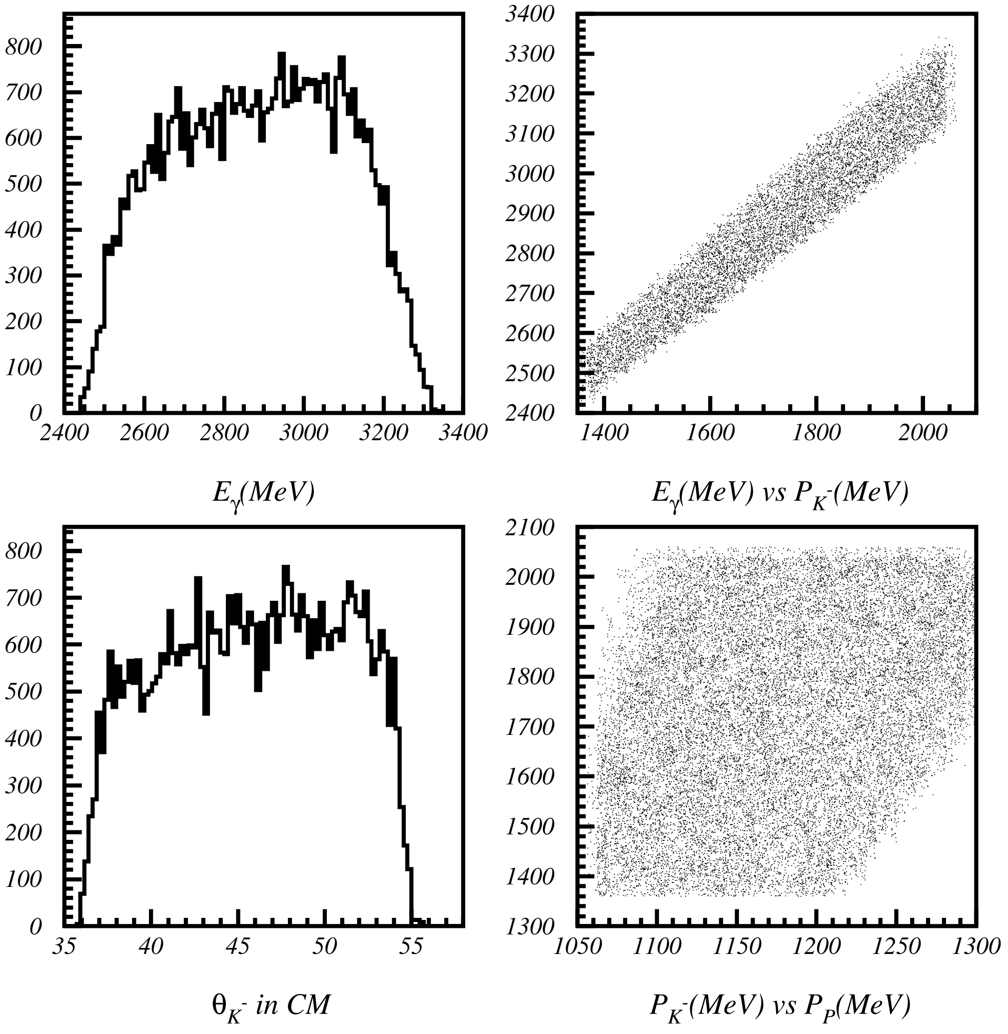


FIG. 6. The kinematics plots for the proposed $\Theta^{++}$ search corresponding to a mass of 1540 MeV for the coincidence $K^-p$ measurement. a) the reconstructed $E_\gamma$; b) $E_\gamma$ versus momentum of $K^-$; c) scattering angle of $K^-$ in c.m.; d) the correlation between the $K^-$ and the proton momenta in the $\gamma(p, K^-p)$ process.

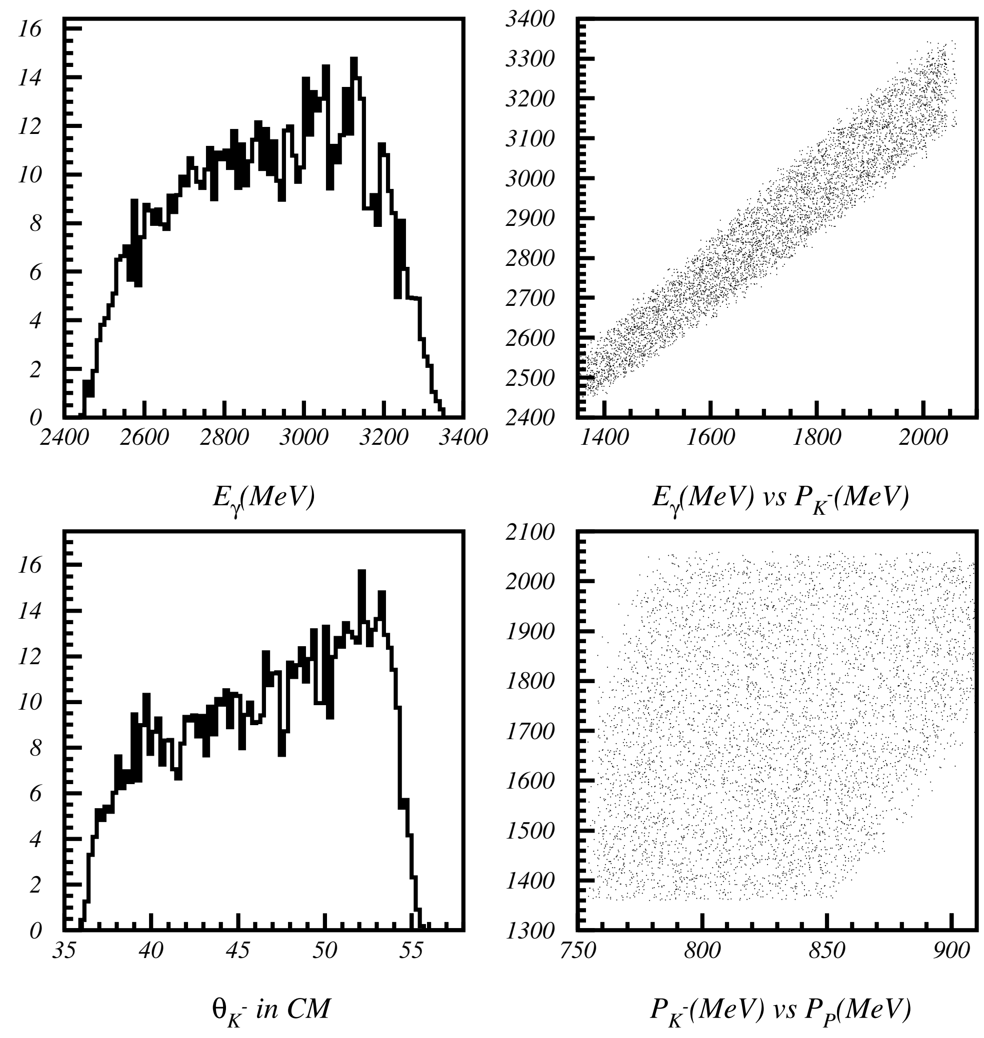


FIG. 7. The kinematics plots for the proposed $\Theta^{++}$ search corresponding to a mass of 1540 MeV for the coincidence $K^-K^+$ measurement. a) the reconstructed $E_\gamma$; b) $E_\gamma$ versus momentum of $K^-$; c) scattering angle of $K^-$ in c.m.; d) the correlation between the $K^-$ and the proton momenta in the $\gamma(p, K^-K^+)$ process.

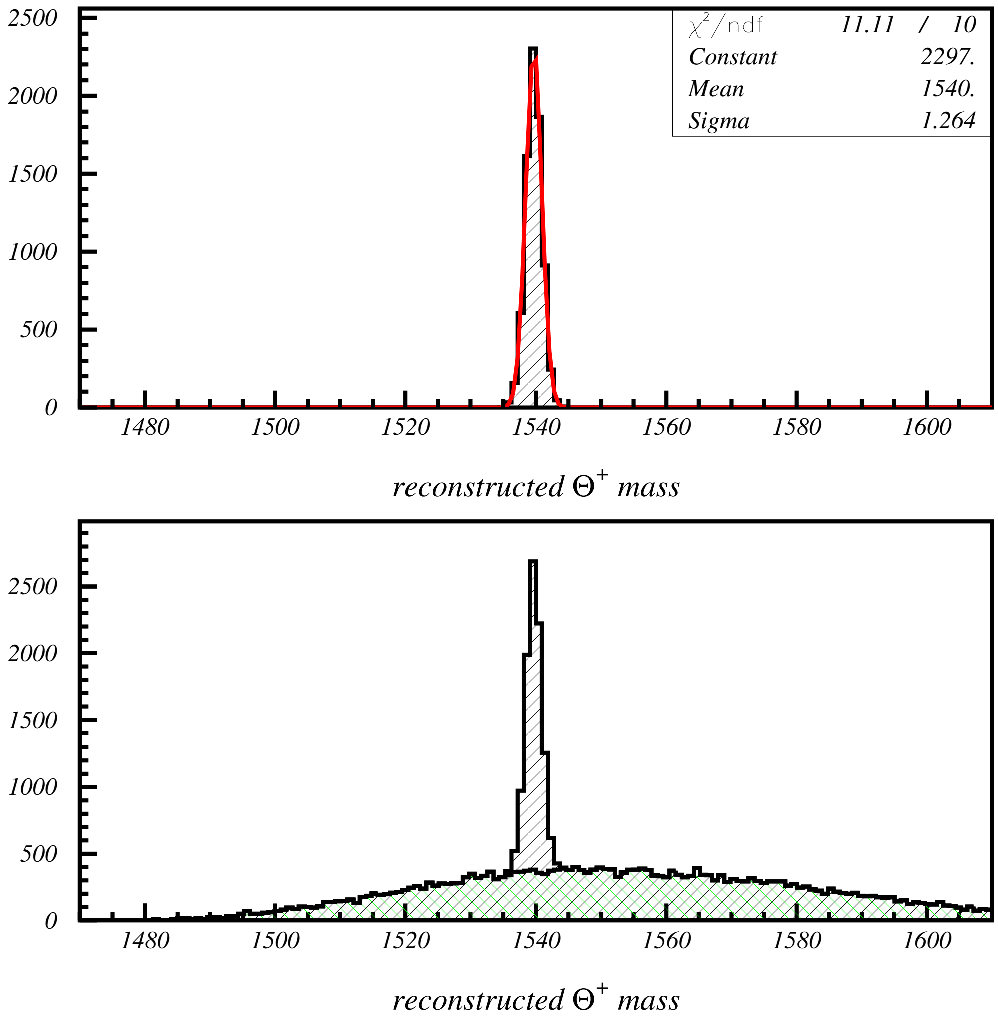


FIG. 8. Reconstructed $\Theta^+$ mass spectra for the proposed experiment. In this simulation, physics events were generated from the $\gamma n \to \Theta^+ K^-$ process with a $\Theta^+$ mass of 1540 MeV; The background is from the $\gamma n \to K^+ K^- n$ three-body final state, and the accidental background coincidence rate (which is negligible.).

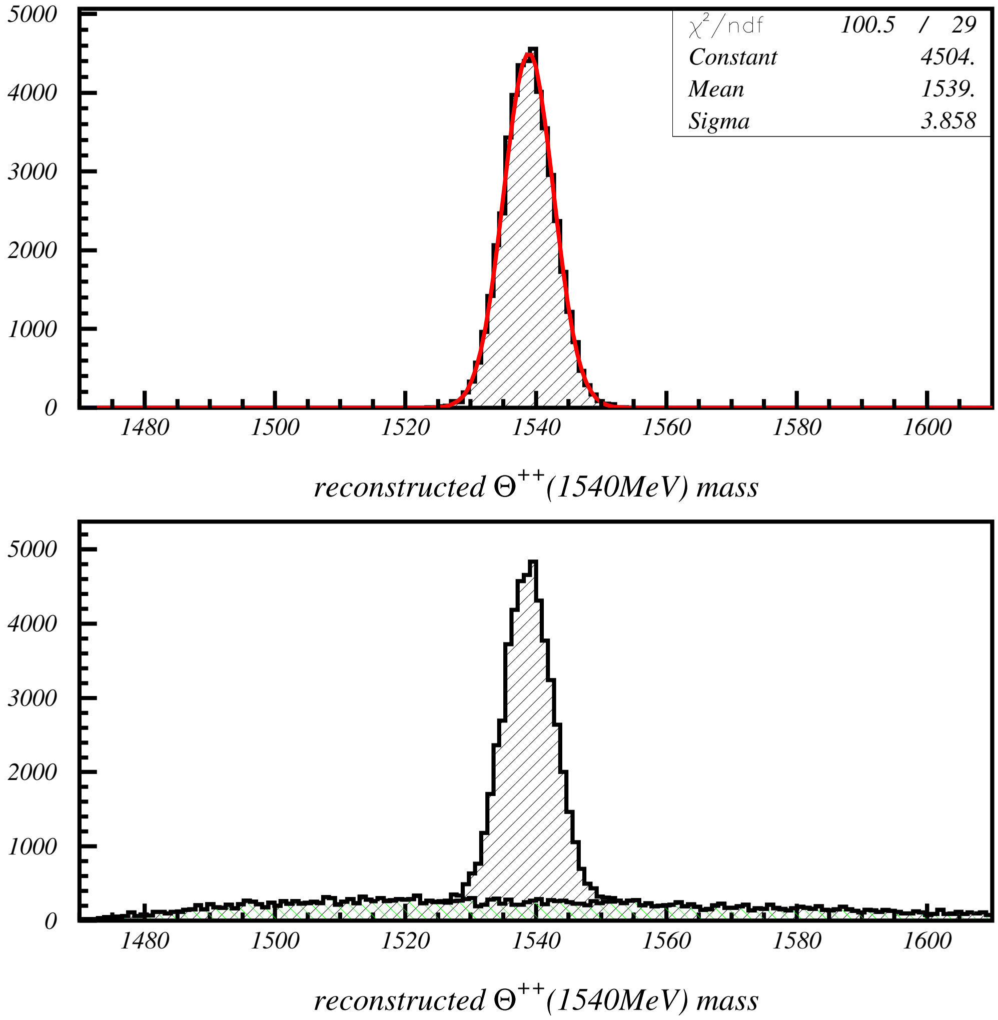


FIG. 9. Reconstructed $\Theta^{++}$ mass spectra from the $\gamma(p, K^-p)$ process for the proposed experiment. In this simulation, physics events of interest were generated from the $\gamma p \to \Theta^{++}K^-$ process with a $\Theta^{++}$ mass of 1540 MeV; The background is The background is from the $\gamma p \to K^+K^-p$ three-body final state, and the accidental background coincidence rate (which is negligible).

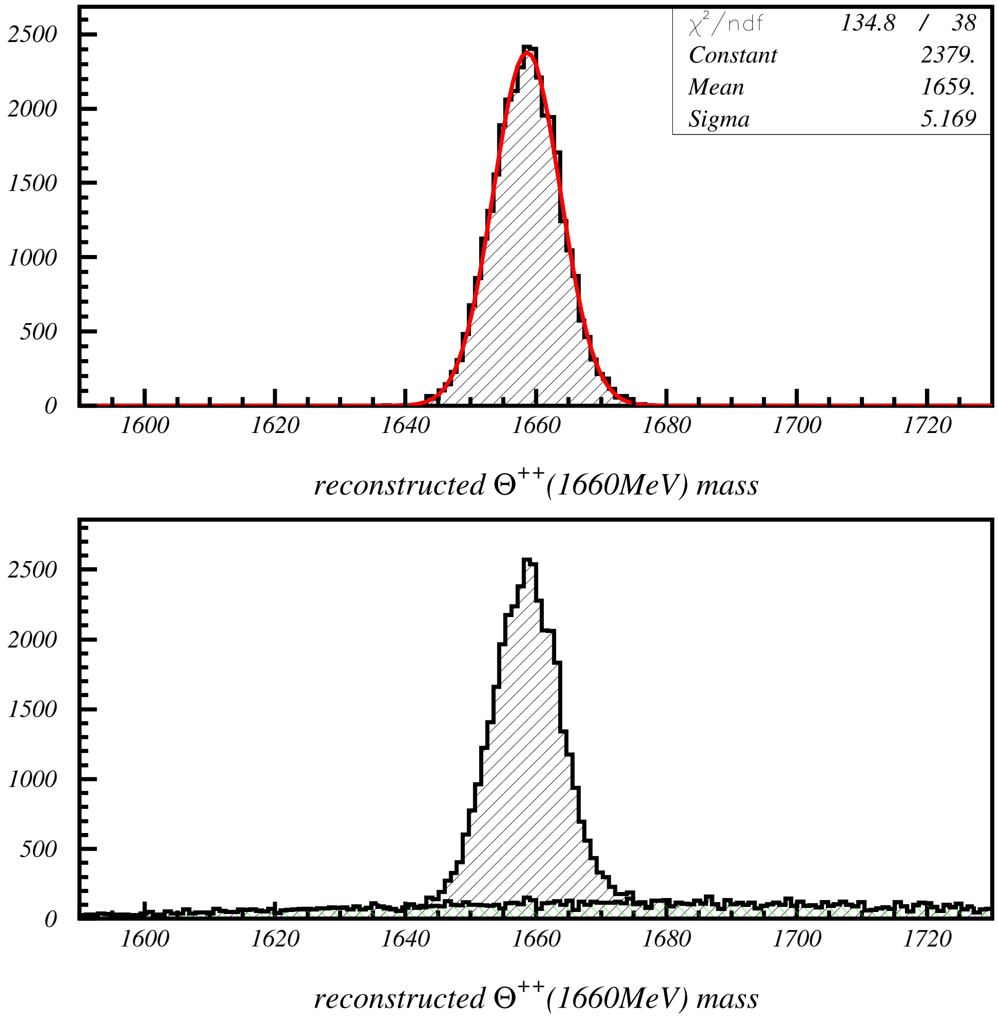


FIG. 10. Reconstructed $\Theta^{++}$ mass spectra in $\gamma(p, K^-p)$ process for the proposed experiment. In this simulation, physics events of interest were generated from the $\gamma p \to \Theta^{++}K^-$ process with a $\Theta^{++}$ mass of 1660 MeV; The background is from the $\gamma p \to K^+K^-p$ three-body final state, and the accidental background coincidence events (which are negligible).

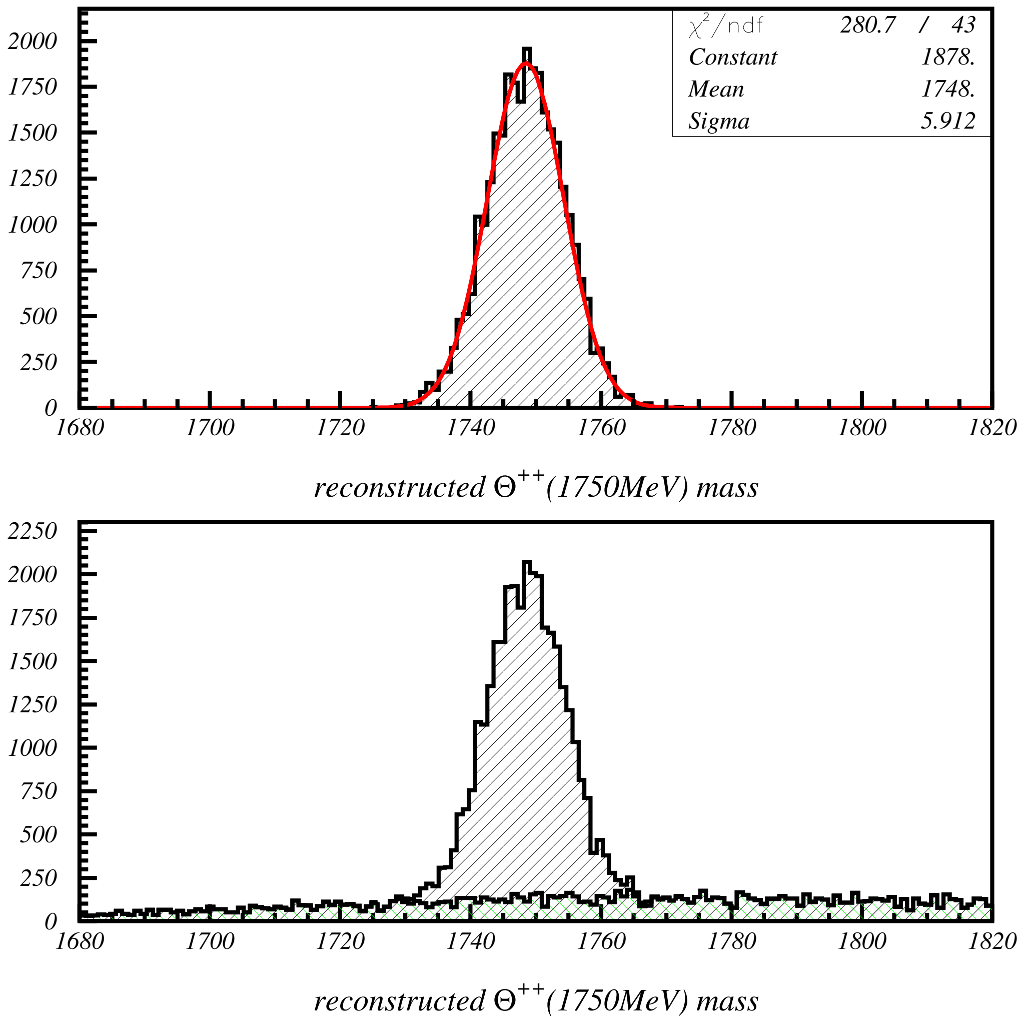


FIG. 11. Reconstructed $\Theta^{++}$ mass spectra in $\gamma(p, K^-p)$ process for the proposed experiment. In this simulation, physics events of interest were generated from the $\gamma p \to \Theta^{++}K^-$ process with a $\Theta^{++}$ mass of 1660 MeV; The background is from the $\gamma p \to K^+K^-p$ three-body final state, and the accidental background coincidence events (which are negligible).

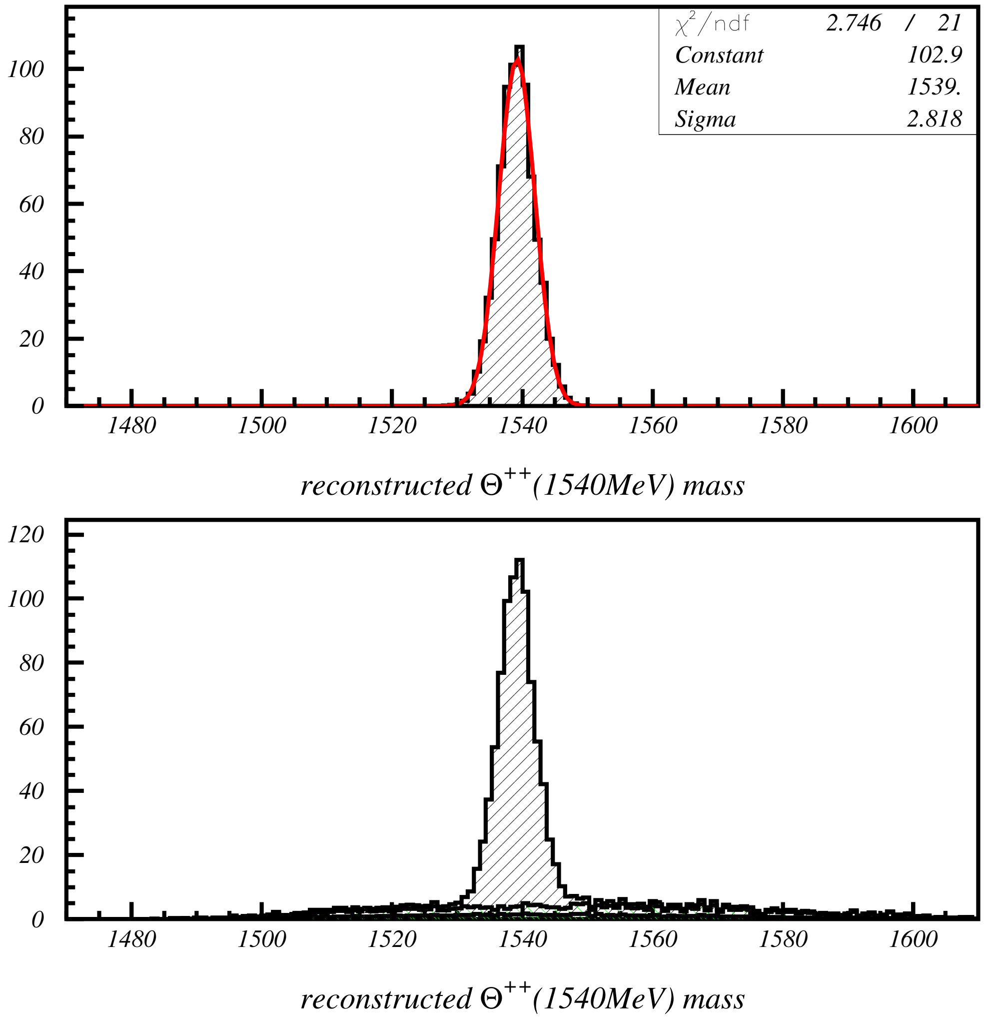


FIG. 12. Reconstructed $\Theta^{++}$ mass spectra from the $\gamma(p, K^- K^+)$ process for the proposed experiment. In this simulation, physics events of interest were generated from the $\gamma p \to \Theta^{++} K^-$ process with a $\Theta^{++}$ mass of 1540 MeV; The background is from the $\gamma p \to K^+ K^- p$ three-body final state, and the accidental background coincidence events (which are negligible).

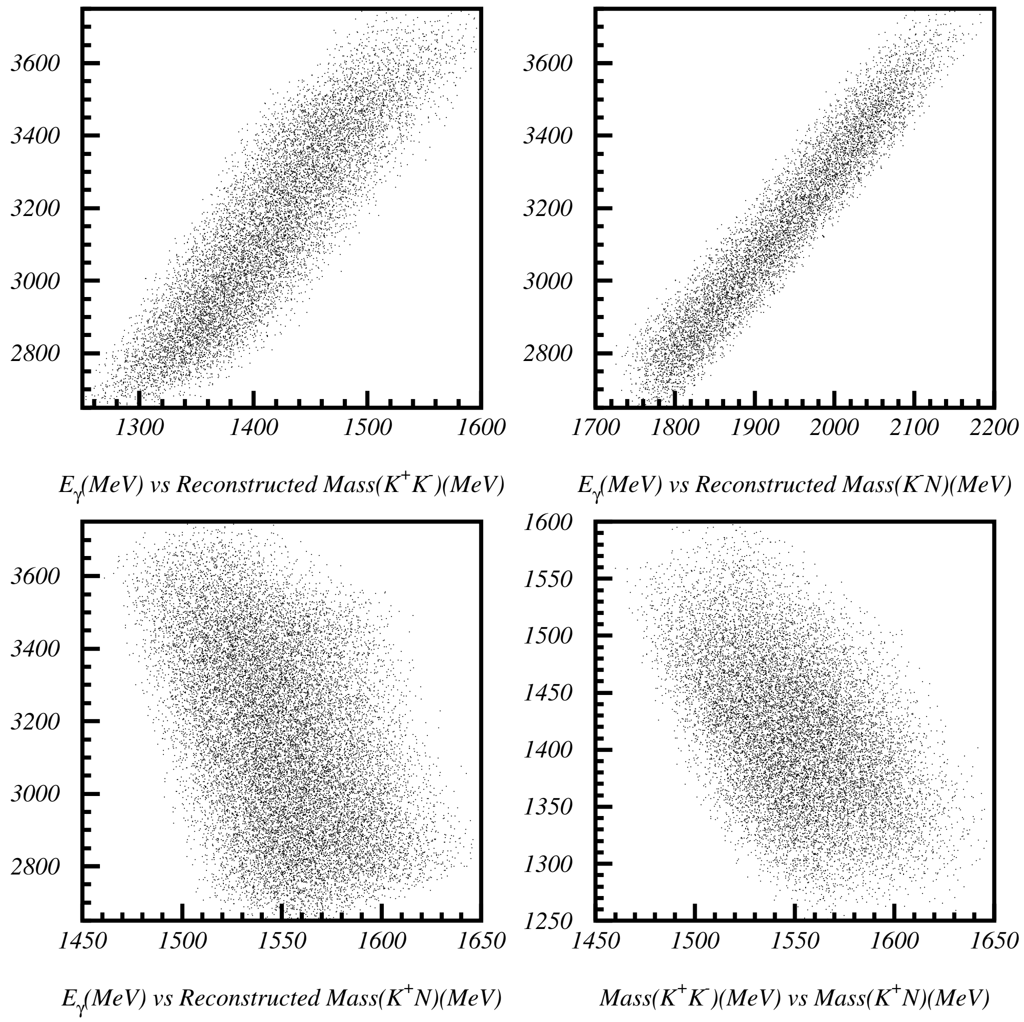


FIG. 13. Two-dimensional spectra for a $\Theta^+$ of mass of 1540 MeV among various reconstructed quantities: the reconstructed photon energy ($E_\gamma$, in MeV), the invariant mass of the $K^-K^+$ pair (in MeV), the invariant mass of the $K^-Nucleon$ pair (in MeV) and the invariant mass of the $K^+Nucleon$ pair (in MeV) for any event inside the acceptance of the spectrometers.

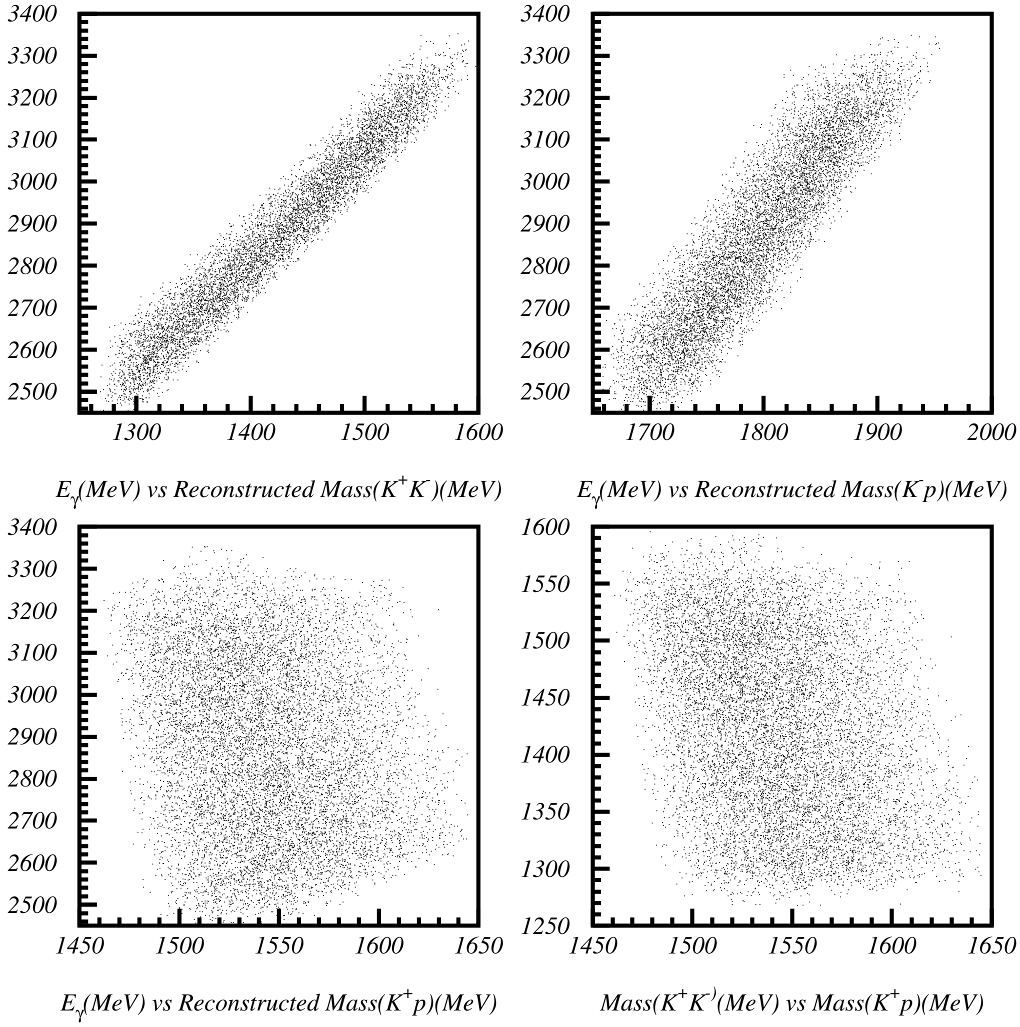


FIG. 14. Two-dimensional spectra for a $\Theta^{++}$ of mass of 1540 MeV among various reconstructed quantities: the reconstructed photon energy ($E_\gamma$, in MeV), the invariant mass of the $K^-K^+$ pair (in MeV), the invariant mass of the $K^-p$ pair (in MeV) and the invariant mass of the $K^+p$ pair (in MeV) for any event inside the acceptance of the spectrometers for the coincidence measurement of $K^-$ and the proton.

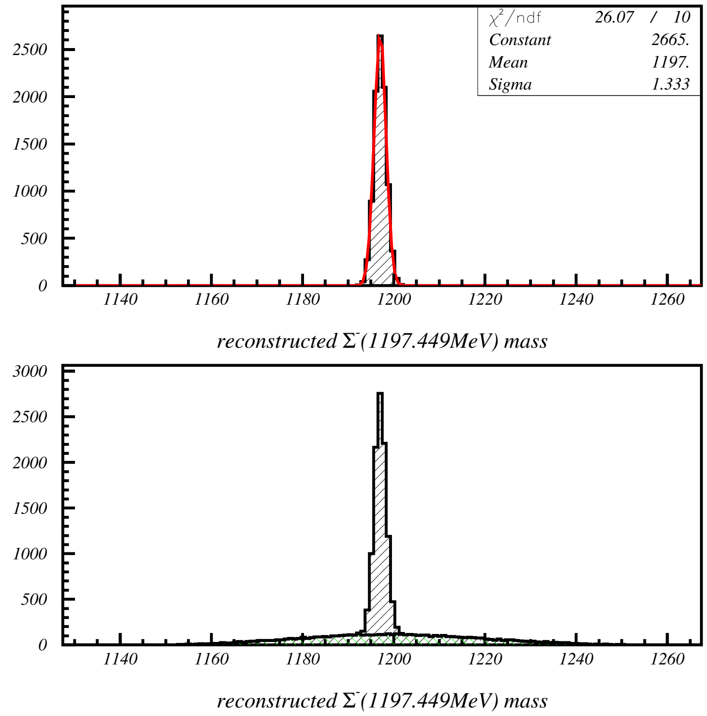


FIG. 15. The reconstructed $\Sigma^-$ mass from the $\gamma n \to \Sigma^- K^+$, $\Sigma^- \to \pi^- n$ reaction (see text).

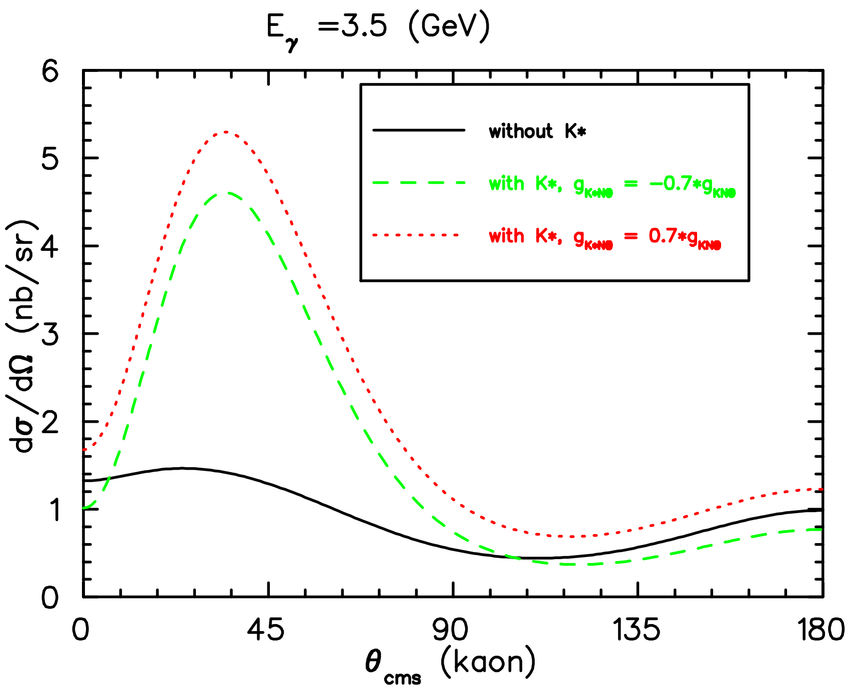


FIG. 16. The calculated differential cross section by Oh *et al.* [20,21,48]. See text for details.

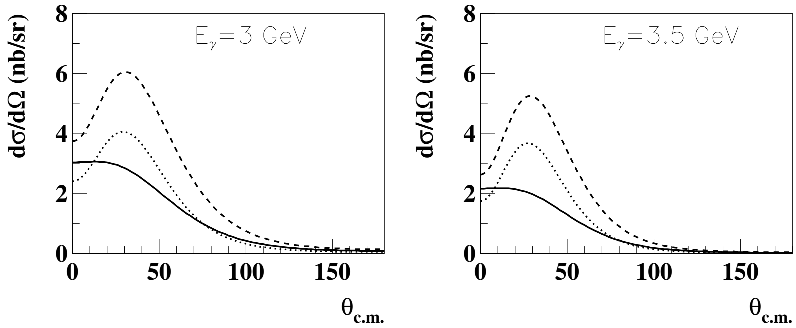


FIG. 17. The calculated differential cross section by Close and Zhao [50]. See text for details.

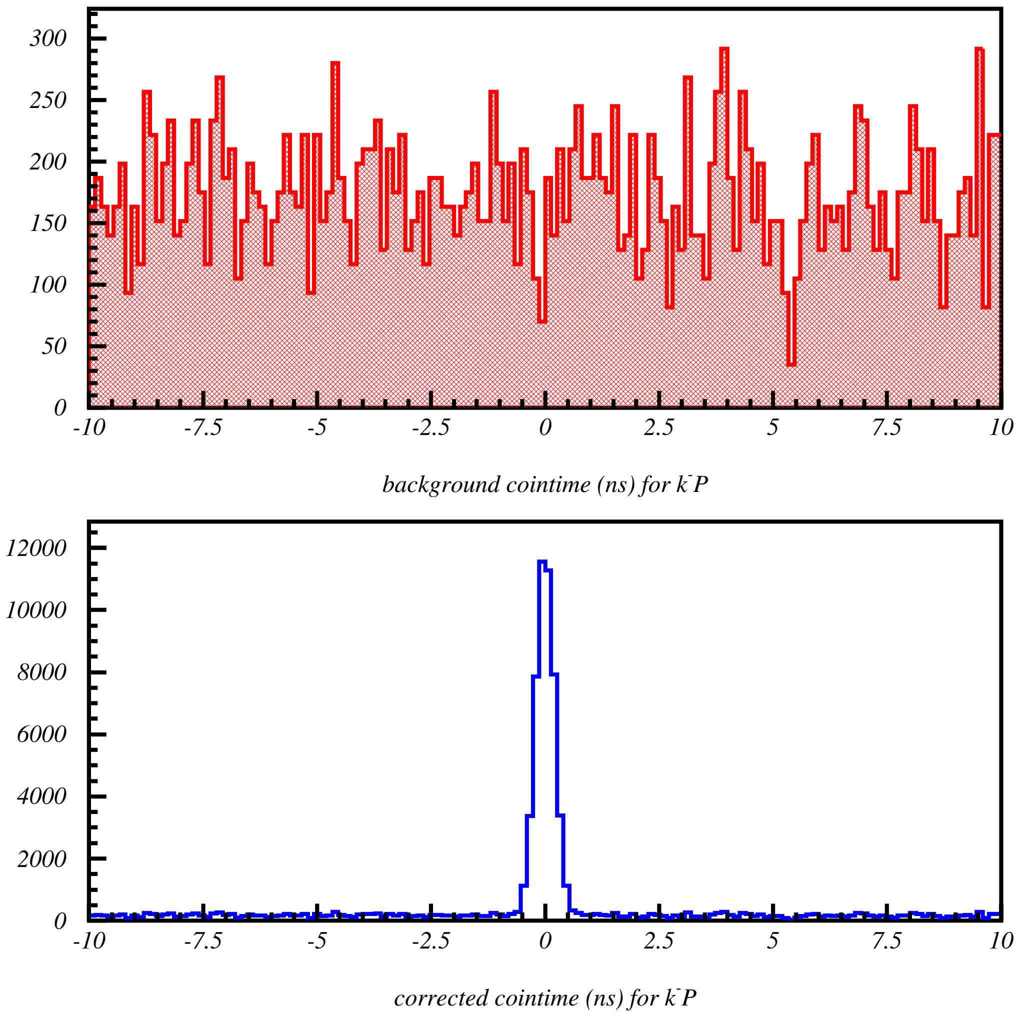


FIG. 18. The coincidence timing spectrum for the $\gamma(p, K^- p)$ process.

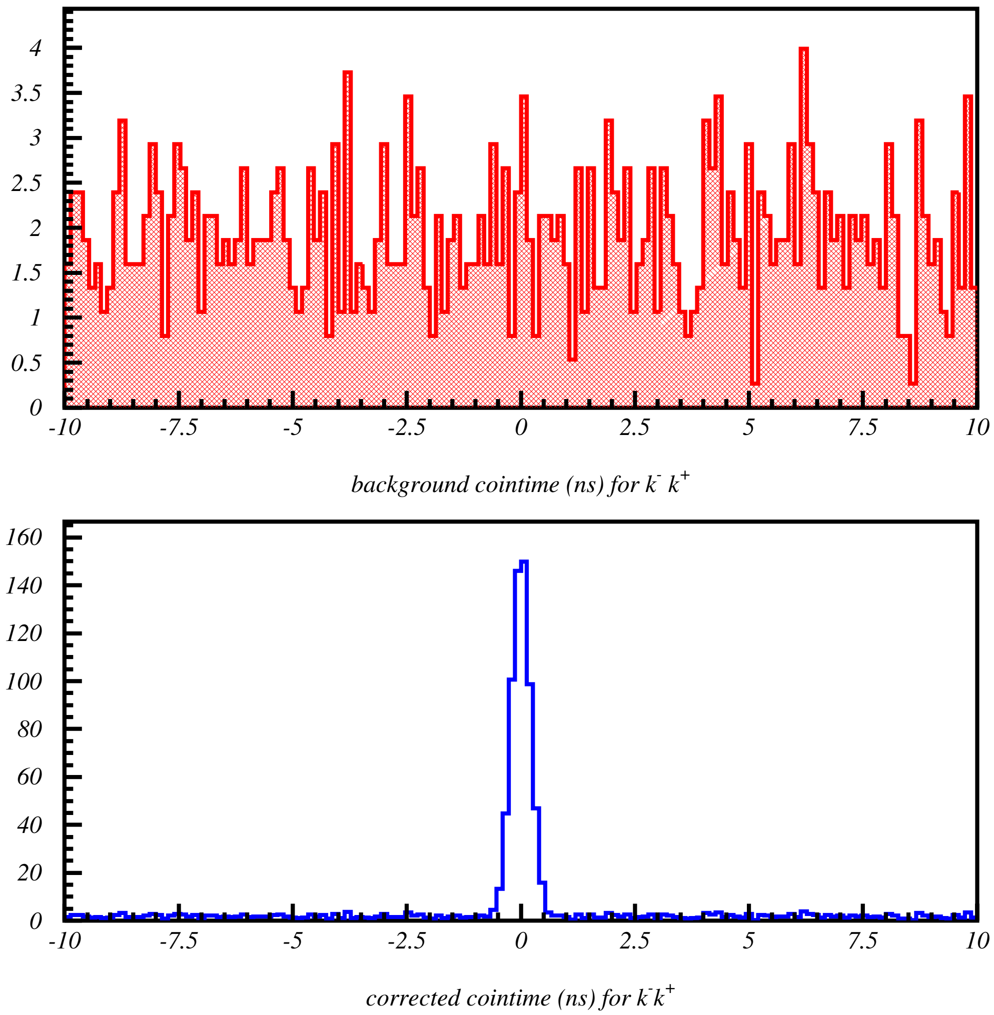


FIG. 19. The coincidence timing spectrum for the $\gamma(p, K^- K^+)$ process.