Search for Exotic Pentaquark Θ^{++}, Θ^{*++}, Θ^{**++} and Θ^{+} in Hall C

M. Ahmed[1], M. Blackston[1], B. Clasie[2], C. Crawford[2], D. Dutta[1],
H. Gao[1,2] (Spokesperson/Contact Person), C. Howell[1], K. Kramer[1], B. Perdue[1], X. Qian[1],
J. Seely[2], H. Weller[1], W. Xu[1], Q. Ye[1], L.Y. Zhu[2], X. Zong[1]
[1]*Duke University*
[2] *Massachusetts Institute of Technology*

B.Q. Ma, Y.J. Mao
Beijing University, Beijing, China

T. Averett
College of William and Mary

W. Boeglin, L. Kramer, P. Markowitz, J. Reinhold
Florida International University

O.K. Baker, M.E. Christy, W. Hinton, C. Keppel, L. Tang
Hampton University

D.V. Jordan, J.I. McIntyre, D. Milbrath, G.A. Warren
Pacific Northwest National Lab

R. Gilman, C, Glashausser, X.D. Jiang, R. Ransome
Rutgers University

J.P. Chen, R. Ent, D. Gaskell, M. Jones, D. Mack, D. Meekins, S. Wood, C. Yan
Thomas Jefferson National Accelerator Facility

O. Hashimoto, S.N. Nakamura (Spokesperson), Y. Fujii
Tohoku University, Japan

E.J. Beise, J.J. Kelly, P.G. Roos
University of Maryland

J.R. Calarco, F.W. Hersman, M. Holtrop

University of New Hampshire

Y. Oh
Yonsei University, Korea

Abstract

Recent evidence for the existence of pentaquark Θ^+ particle from several experiments at several different laboratories around the world has caused great excitement and raised many unanswered questions. We propose a first magnetic spectrometer experiment searching 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: $\gamma p \rightarrow \Theta^{++}(\Theta^{*++}, \Theta^{**++})K^-$, and $\gamma n \rightarrow \Theta^+ K^-$. The proposed experiment will be carried out in Hall C using the combination of the SOS spectrometer and the HKS spectrometer. In the case of the $\gamma n \rightarrow \Theta^+ K^-$ channel, a neutron counter will be employed in addition. An electron beam having an incident energy of 3.525/3.150 GeV with a beam current of 50 μA will be employed. We request a total number of 19 days for this experiment. The proposed experiment will provide unambiguous evidence for the existence or non-existence of the Θ^{++} (Θ^{*++}, Θ^{**++}) particle, and significantly improve our current knowledge of the mass, the width of the Θ^+ particle, and its production differential cross-section.

I. INTRODUCTION

Quark models [1] have proven to be 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]

In our paper [4] published in 1999, we stated: "The present situation seems to be very promising for the existence of the hybrid states and glueballs. Though much progress has been made and many candidates for the other exotic hadrons have been reported, the existence of the exotic hadrons of multiquark states is still far from being clear, due to the difficulty to clearly distinguish candidates from a large number of various possible meson and baryon resonances."

The following was also stated: "...we notice that the minimal pentaquark states which can be easily measured might be $uuud\bar{s} = p(uud)K^+(u\bar{s})$ and $uudd\bar{s} = n(udd)K^+(u\bar{s})$, which might be produced from physical processes $p(e, e'K^-)Z(uuud\bar{s})$ and $n(e, e'K^-)Z(uudd\bar{s})$ [1] which can be measured at the Thomas Jefferson National Accelerator Facility(JLab)"

What is probably worth quoting most from [4] is the following paragraph: "We can extend the study in this direction by systematic exploration of various minimal pentaquark states with configurations pointed out above, such as to search for $Z(uudd\bar{s})$ from the physical process $D(e, e'K^-p)Z(uudd\bar{s})$ or $D(e, e'\Lambda)Z(uudd\bar{s})$ at JLab. It is interesting to note a recent suggestion [5] on the search for such a $Z(uudd\bar{s})$ particle from the $pp \to n\Sigma^+K^+$ reaction by analyzing the nK^+ invariant mass spectrum. We also point out here that the search of the existence of the exotic new particle $Z(uuud\bar{s})$ can be combined with the planned program of the physical process of $p(e, e'K^-K^+)p$ at JLab. Thus the search for new particles $Z(uuud\bar{s})$ and $Z(uudd\bar{s})$ at JLab is not necessarily in conflict with conventional studies, even though the chance of finding such particles might be small. From another point of view, even the confirmation of the non-existence of $Z(uuud\bar{s})$ and $Z(uudd\bar{s})$ can enrich our understanding of the hadronic structure and the strong interaction."

Obviously, the situation concerning the pentaquark exotic baryon search is completely different FOUR years later, with evidence supporting the existence of the pentaquark Θ^+

[1] Since there is no free neutron target, deuterium targets should be used in this case.

particle coming out from different experiments [6–10] carried out at various laboratories around the world. Recently, the NA49 collaboration at CERN found evidence for the existence of a narrow ($dsds\bar{u}$) pentaquark state with a mass of (1.862 ± 0.002) GeV/c^2 from the proton-proton collision at a center-of-mass energy of 17.2 GeV [11].

II. PHYSICS MOTIVATIONS

The first evidence of the observation of a pentaquark Θ^+ particle came early this year from the LEPS collaboration [6] in which a sharp resonance was reported at a mass of (1.54 ± 0.01) (GeV)/c^2. The experiment was carried out at Spring-8 using a laser backscattered photon beam, a CH target, and K^+ and K^- at forward angles from the $\gamma n \to K^+K^-n$ reaction were detected. The DIANA Collaboration [7] reported evidence for a resonance enhancement at $M = 1539 \pm 2$ MeV/c^2 and $\Gamma \leq 9$ MeV/c^2 in the charge-exchange reaction $K^+Xe \to K^0pXe'$. The CLAS collaboration [8] reported a statistical significance of $(5.3 \pm 0.5)\sigma$ at the K^+n invariant mass of 1542 ± 5 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 [9] collaboration reported a peak at $M_{\Theta^+} = 1540 \pm 4 \pm 2$ MeV (4.8 σ 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 Θ^+ particle is isoscalar. More recently, the HERMES collaboration [10] reported evidence of the Θ^+ 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 [12] also reported evidence on Θ^+ from a hydrogen target by looking at the following two processes: $\gamma p \to \pi^+K^-\Theta^+$ and $\gamma p \to \bar{K}^0\Theta^+$. They found a peak in the invariant mass of nK^+ at 1555 MeV with a width of about 28 MeV from the $\gamma p \to \pi^+K^-\Theta^+$ process and $M = 1571 \pm 4$ MeV with a FWHM of about about 9 MeV from the $\gamma p \to \bar{K}^0K^+n$ channel.

In summary, the experimental situation concerning the Θ^+ and Θ^{++} pentaquark states is the following. There is evidence from different experiments supporting the existence of the pentaquark Θ^+ state, but there is no evidence for the Θ^{++} particle. The mass of the Θ^+ particle is from 1527 MeV to 1571 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 Θ^+ particle is an isoscalar particle.

The CERN NA49 Collaboration [11] reported an exotic $S = -2, Q = -2$ baryon resonance in proton-proton collisions with a mass of 1862 ± 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.

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 Θ^+ pentaquark state. Refs. [13–25] are only a subset of these papers. We do not attempt to review all these theoretical works here, but will discuss in some details the chiral soliton model by Diakonov *et al.* [26] and the diquark model by Jaffe and Wilczek [14]. 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.

The original chiral soliton model prediction by Diakonov, Petrov and Polyakov [26], which largely motivated the LEPS search, gave a mass of 1530 MeV and a total width of less than 15 MeV for the Θ^+ particle. They also predicted that the Θ^+ 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 Θ^+ particle with a predicted mass of 1530 MeV and a predicted with 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 [14] proposed the correlated diquark picture to explain the observed Θ^+ 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 Θ^+ pentaquark state, it is a bound state of two highly correlated ud pairs and an antiquark. In this model, the Θ^+ 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 Θ^+ (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 Θ^+ 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 from 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 Θ^+ 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 [13] hypothesized the Θ^+ particle as an isotensor resonance to explain the observed narrow width of the Θ^+ particle. The decay of the Θ^+ 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 Θ^+ decay width. The hypothesis that Θ^+ is an isotensor particle implies the existence of Θ^{**+++}, Θ^{**++}, Θ^{**0}, and Θ^{**-} states. Gerasyuta and Kochkin [27] 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 Θ^{**++} is 1575 MeV (1761 MeV) for $J^p = \frac{1}{2}^\pm$ ($J^p = \frac{3}{2}^\pm$). Here we following the convention in the literature that Θ represents the I=0 state in anti-decuplet, Θ^* represents the I=1 state in 27-plet and Θ^{**} the I=2 state in 35-plet. Also, in the remaining of the proposal, we will not explicitly differentiate the Θ^{**++} and the Θ^{*++} states because the proposed experiment alone will not be able to determine which multiplet the observed Θ^{++} particle belongs to. Both the chiral soliton model by Diakonov *et al.* [26] and the diquark model by Jaffe and Wilczek [14] predict that the Θ^+ particle is an isosinglet state. The absence of a peak around 1540 MeV in the invariant mass spectrum of the K^+p system from the SAPHIR [9] data suggests that the Θ^+ is an isoscalar particle.

Following the success of the chiral soliton model by Diakonov *et al.* [26] in predicting the Θ^+ particle mass, width and isospin, Walliser and Kopeliovich [28] investigated the implications of the Θ^+ 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 (Θ^{*0}, Θ^{*+}, Θ^{*++}) are estimated to have a mass of 1.65 to 1.69 GeV. Most recently, Wu and Ma [29] studied the mass and width of the pentaquark Θ^* states in the 27 baryon multiplet from chiral soliton model. Their calculations show that the mass of Θ^* is about 1.61 GeV and the width for the process $\Theta^* \rightarrow KN$ is less than 44 MeV. Bijker *et al.* 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 Θ^+ 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 Θ^+ particle with significantly improved statistics, and to determine the mass and the width of the Θ^+ particle more precisely. It is also very important to verify definitely the non-existence or the existence of the Θ^{++} particle and to search for the Θ^{*++} particle. Once the existence of the Θ^+ has been confirmed with high statistics, it is essential to determine the cross-section for producing sucn 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 Θ^+. The proposed magnetic spectrometer experiment will allow for a determination of the differential cross-section for the Θ^+ particle for the first time. As was mentioned previously the existing data give a rather large range for the mass of the Θ^+ particle, 1527 - 1571 MeV, with a width between 9 - 28 MeV, limited by the detector resolutions. So far, all experiments reporting evidence for the existence of the Θ^+ particle employed large acceptance detection systems, which could be more sensitive to issues such as kinematic reflection raised by Dzierba *et al.* [31]. 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 statistic measurements using magnetic spectrometers with different incident beam momenta are very crucial for the confirmation of the Θ^+ 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 seems to be no convincing evidence for the existence of the Θ^+ particle from the lattice [32].

We propose to carry out a systematic search of the Θ^+, Θ^{++}, and Θ^{*++} particle with high statistical accuracy from hydrogen and deuterium targets using magnetic spectrometers in combination with a neutron counter. The pentaquark mass can be determined to better than 1 MeV. The width can be determined to 1.7 MeV and 3.4 MeV for the Θ^{++} (Θ^{*++}) and the Θ^+ particles, respectively, using the Hall C magnetic spectrometers and a neutron counter.

III. THE EXPERIMENT

A. Experimental Overview

We propose to carry out a systematic search for pentaquark states Θ^+, Θ^{++} and Θ^{*++} in Hall C using magnetic spectrometers in combination with a neutron counter by studying two different physical processes. The experiment requires an electron beam at an incident beam energy of 3.525/3.150 GeV with a beam current of 50μA. The experiment will employ both the Hall C 4-cm long cryogenic liquid hydrogen and deuterium targets, and a 6% Cu radiator. The Short Orbit Spectrometer (SOS), the High resolution Kaon Spectrometer (HKS), and a neutron counter will be employed for this experiment. We propose to study the following two processes:

- $\gamma n \rightarrow \Theta^+ K^-$, where Θ^+ decays via $\Theta^+ \rightarrow K^+ n$. 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.

- $\gamma p \rightarrow \Theta^{++}(\Theta^{*++})K^-$, where $\Theta^{++}(\Theta^{*++}) \rightarrow K^+ p$. The K^- particle will be detected in SOS in coincidence with the K^+ particle which will be detected in the HKS spectrometer. By tagging the K^+ particle from Θ^{++} (Θ^{*++}) 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 masse spectra of the K^+K^-, and the KN system. In the search for the Θ^{++} (Θ^{*++}) particle, the situation concerning its mass is different from the case of the Θ^+ particle. Therefore, iterations will be necessary in the data analysis in reconstructing the bremsstrahlung photon energy and the Θ^{++} (Θ^{*++}) particle mass.

B. Proposed Experimental Setup

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

- For the $\gamma p \rightarrow \Theta^{++}(\Theta^{*++})K^-$ and the $\gamma n \rightarrow \Theta^+ K^-$ channels, detection of both the K^+ and K^- particles are needed. The mean life of the kaon in its rest frame is about 1.2×10^{-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 $\gamma n \rightarrow \Theta^+ K^-$ 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 [33] or similar to the proposed neutron counter for the G_E^n experiment (E02-013) in Hall A.

- The maximum central momentum of HKS is 1.2 GeV. This limits HKS to be served as a K^+ detector for most of the proposed kinematics except for one. For the final kinemtics of the Θ^{++} search corresponding to a possible Θ^{*++} mass of 1750 MeV, polarities of HKS and SOS will be switched and SOS will detect K^+ and HKS will detect K^-.

- 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 -9° vertically and Neutron Counter will go up +12° vertically. As such design for new supports for HKS and the Neutron Counter is required.

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 the E01-011 experimental configuration, 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°/-9.0° 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°/-9.0° This experiment will need a smaller platform to hold the HKS detector stack rather than using the T_{20} platform that E01-011 is planning to use.

For the proposed experiment, the HKS spectrometer will be positioned geometrically at $-32.0°/-9.0°$ to the right of the electron beam line facing the beam dump. The corresponding central scattering angle for HKS is -23.0°/$-9.0°$ with the splitter magnet in front.

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

The neutron detector will be positioned on the same side of the HKS, and it is at an angle of -23.0°/+12.0° with respect to the incident electron momentum direction. The SOS spectrometer is positioned at an angle of 20.0° to the left of the incident electron beam momentum direction. Figs. 1 and 2 show two different views of the proposed experimental setup in Hall C.

The detector package in the SOS spectrometer consists of two wire chambers for tracking and position measurements, scintillator hodoscopes for timing, a gas cherenkov 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 1.055, 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 is 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 8 m from the target, covered by a 5 cm Pb plate to suppress the background. It 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 photomultiplier 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. The neutron detection efficiency is about 30%. The maximum rate of each scintillator paddle is around 500 KHz. This requires the up limit of beam current not to exceed 100 μA and the location of the neutron detector not to be close to the beamline. With a beam current of 50 μA, the expected rate of the neutron counter is about 1.4 MHz for a threshold of 30 MeV. The rates of individual PMTs for both veto and neutron counter are listed in Table II.

C. Kinematics

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

- The kinematics chosen for both the $\gamma p \to \Theta^{++}(\Theta^{*++})K^-$ and the $\gamma n \to \Theta^+ K^-$ process correspond to a K^- center-of-mass angle range of $\sim 40^\circ - 70^\circ$.

- 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^-/K^+ particles at a central scattering angle of $+20^\circ$ and the K^+/K^- particle will be detected in the HKS spectrometer at a central scattering angle of -23°/-9° with the splitter magnet in front of the HKS.

- Three different kinematic settings were chosen for the $\gamma p \to \Theta^{++}(\Theta^{*++})K^-$ process corresponding to a possible Θ^{++} (Θ^{*++}) particle mass of 1540 MeV, 1660 MeV and 1750 MeV, respectively. Therefore, the proposed experiment allows a thorough search for the Θ^{++} (Θ^{*++}) particle in the mass range of 1500 MeV to 1800 MeV.

Table III lists the kinematics of the proposed experiment.

D. Simulations

For the two-body process $\gamma p \to \Theta^{++}(\Theta^{*++})K^-$ one can reconstruct the energy of the incident real photon from the measured K^- kinematics provided the undetected particle is the Θ^{++} (Θ^{*++}) exotic baryon with a certain mass value. Once the real photon energy has been reconstructed, the mass of the undetected Θ^{++} (Θ^{*++}) particle can be reconstructed. For the Θ^{++} particle, there is no convincing experimental evidence so far for the existence of such a particle at a mass of 1540 MeV. However, such a particle may exist with a larger mass as suggested by Bijker *et al.* [30] and Gerasyuta and Kochkin [27]. Therefore, an iteration procedure concerning the undetected particle mass is necessary in reconstructing the photon energy from the two-body kinematics, and furthermore in reconstructing the mass of a possible Θ^{++} (Θ^{*++}) particle. In addition to the detection of the K^- particle, the K^+ particle from Θ^{++} (Θ^{*++}) 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 the proposed experiment, three spectrometer settings were chosen corresponding to a possible Θ^{++} (Θ^{*++}) particles with a mass value of 1540 MeV, 1660 MeV and 1750 MeV, respectively. Thus, the proposed experiment allows for the search of the Θ^{++} (Θ^{*++}) particle in the mass range of 1500 MeV to 1800 MeV.

For the $\gamma n \to \Theta^+ K^-$ process, the situation is slightly more complicated because a deuterium target will be employed. The K^+ and the neutron from the Θ^+ decay will be detected, which allows the reconstruction of the Θ^+ mass in a straightforward way. Since the K^- particle will also be detected, the incident real photon energy can be constructed, as well as the initial neutron momentum. Furthermore, the Θ^+ mass can also be reconstructed from the K^- kinematics and the reconstructed real photon energy and the initial neutron momentum.

A Monte Carlo simulation code was written for the purpose of the reconstruction of the Θ^{++} (Θ^{*++}) and Θ^+ exotic baryon masses from all two processes discussed above. In our simulation, we used *rms* momentum resolutions of $\delta p/p = 2 \times 10^{-4}$ for the HKS and 5×10^{-4} for the SOS, and 1.0 mr (7 mr) and 3.0 mr (0.5 mr) for the horizontal and vertical *rms* spectrometer angular resolutions of the HKS (SOS), 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. For the kinematics of our proposed measurements, the reconstructed Θ^{++} (Θ^{*++}) and Θ^{+} mass resolutions are dominated by multiple scatterings of the final state charged particles in the target, and the neutron counter resolutions. The simulated mass spectra for Θ^{+} and Θ^{++} (Θ^{*++}) particles from the proposed measurements are shown in Fig. 5 and Figs. 6, 7, and 8. For example, in Fig. 7 the physical events from the $\gamma p \to \Theta^{++} K^{-}$ process were generated for $M_{\Theta^{++}}$ (Θ^{*++}) =1660 MeV. One can determine the absolute mass of the Θ^{+} particle to better than 1 MeV. The overall experimental resolution in determining the width of the Θ^{+} (Θ^{++}, Θ^{*++}) particle is 1.7 (3.4) MeV.

E. Backgrounds

The primary sources of the physics backgrounds for the proposed $\gamma p \to \Theta^{++}(\Theta^{*++})K^{-}$ process and the $\gamma n(D) \to \Theta^{+} K^{-}$ process are: (i) ϕ meson production, (ii) $\gamma + p \to K^{+} + \Lambda(1520)$ where, $\Lambda(1520) \to p + K^{-}$, and (iii) three-body final state $K^{+}K^{-}$ production [34]. 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. 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 μb and differential cross sections for the ϕ meson photo-production and Λ 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 $\gamma p \to \Theta^{++}(\Theta^{*++})K^{-}$ 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. Figs. 9, 10 and 11 show two-dimensional spectra plotted among various reconstructed quantities: the reconstructed photon energy (E_γ), 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 ϕ production and the $\Lambda(1520)$ channels are suppressed even without a 100 MeV of E_γ 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 a 100 MeV of E_γ cut.

F. Counting Rates

To estimate the coincidence rate for the $\gamma p \to \Theta^{++}(\Theta^{*++})K^{-}$ and the $\gamma n \to \Theta^{+} K^{-}$ measurements, we used the differential cross-section calculated by Oh [18,19,35]. Table IV lists 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 50 μA corresponding to a luminosity of 5.27×10^{37} $(6.36 \times 10^{37})/(\text{cm}^2 \text{ sec})$ for a 4-cm LH2 (LD2) target cell. For the HKS and SOS spectrometers, we used solid angles of 5.8 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 and SOS spectrometers were estimated using the Lightbody and O'Connell code [36]. 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 and SOS spectrometers for this experiment. Both the SOS and HKS total rates for this experiment are dominated by the singles $\pi^+(\pi^-)$ rates. Both HKS 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 and the maximum HKS singles rate is 0.954 MHz.

Since both the SOS and the HKS spectrometers have good particle identification capabilities, the accidental coincidence rate for the coincidence 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. The expected total Θ^{++} (Θ^{*++}) events (1200) and Θ^+ events (1428) are given in Table IV based on the requested running time (see next section). The expected Θ^{++} (Θ^{*++}) events from the $\gamma p \to \Theta^{++}(\Theta^{*++})K^-$ process is based on the differential cross-section calculated by Oh [35]. 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 Θ^{++} (Θ^{*++}) particle to a level of 200 pb/sr with a total number of expected events over 3σ above the background events. Please note the aforementioned 100 MeV E_γ 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_γ cut is not necessary as shown clearly in the simulated results (Figs. 5-8). Therefore, the total projected events for Θ^+ particle $(\Theta^+ +)$ is 8755 (around 8000) based on the input differential cross-section we used in our simulations.

G. Beam Time Estimate

For the search of the Θ^{++} (Θ^{*++}) particle via the $\gamma p \to \Theta^{++}(\Theta^{*++})K^-$ process, we request a total beam time of 150 hours for three different kinematic settings corresponding to a possible Θ^{++} (Θ^{*++}) particle mass of 1540 MeV, 1660 MeV and 1750 MeV, respectively. For the $\gamma n \to \Theta^+ K^-$ process, we request a beam time of 150 hours. We request 300 hours of data taking time with 100 % efficiency and an additional 150 hours for spectrometer and detector checkout, radiator, and spectrometer changes, and background data taking. In total we request 450 hours (19 days) of beam time.

IV. COLLABORATION BACKGROUND AND RESPONSIBILITIES

This experiment requires a bremsstrahlung photon radiator, the standard Hall C liquid hydrogen and deuterium target, the Hall C SOS spectrometer, 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 proposed neutron counter for the Hall A experiment E02-013. The proposed configuration for HKS will be the same as that of the Hall C Hyper-nuclear physics Experiment E01-011. The collaboration overlaps significantly with the E01-011 collaboration. 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.

Configuration	QQD and horizontal bend
Central momentum range	0.97 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: -9.0°
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
Charge Particles	($> 0.5 MeV$)		
$\pi^{\pm}$	160		
$\mu^{\pm}$	40		
$e^{\pm}$	30		
p	10		
Total Charged	240	254,604	one paddle of veto rates
Neutrals	($> 30 MeV$)		
N	400		eff=0.2
Photons	4		eff=0.55
Total Neutrals	404	87,202	one front paddle of NC rates

TABLE II. Estimated rate at 25.8° (-23.0°/+12.0°) in 10cm×160cm veto and neutron counter paddles behind 5cm Pb and 2cm steel from 50μA of 3.5GeV electrons on a 4-cm LD2 target.

E_e (GeV)	$\theta_{\rm SOS}$ (degree)	$P_{\rm SOS}$ (GeV/c)	$\theta_{\rm HKS}/\phi_{HKS}$ (degree)	$p_{\rm HKS}$ (GeV/c)	θ_n/ϕ_n (degree)
3.525 (D)	20.0	1.800	-23.0/-9.0	0.927	-23.0/+12.0
3.525 (H,$M_{\Theta^{++}}(\Theta^{*++}) = 1540$ MeV)	20.0	1.800	-23.0/-9.0	0.927	
3.525 (H,$M_{\Theta^{++}}(\Theta^{*++}) = 1660$ MeV)	20.0	1.625	-23.0/-9.0	1.170	
3.150 (H,$M_{\Theta^{++}}(\Theta^{*++}) = 1750$ MeV)	20.0	1.350	-23.0/-9.0	1.200	

TABLE III. Kinematics for the proposed $\gamma p \to \Theta^{++}K^-$ and the $\gamma n \to \Theta^+ K^-$ reactions. 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.

		SOS			HKS					
E_γ (GeV)	Beam (μA)	π^- (kHz)	e^- (kHz)	K^- (Hz)	π^+ (kHz)	p (kHz)	K^+ (Hz)	neutron (kHz)	Beam time (hours)	Expected Events
3.450(D)	50	336	133	2320	535	419	992	1400.0	150	1428(8755)
3.450(H,1)	50	92.7	39.8	1170	166	118	505	-	50	1259(7690)
3.450(H,2)	50	153	34.1	1170	89.7	75.3	505	-	50	1315(8453)
			HKS			SOS				
3.075(H,3)	50	66	6.2	707	294	204	836	-	50	930(2095)

TABLE IV. Singles rate estimate and coincidence signal rate for the proposed $\gamma p \to \Theta^{++}K^-$ and the $\gamma n \to \Theta^+ K^-$ measurements. The expected Θ^{++} (Θ^{*++}) events for 50 hours of beam time at 100% efficiency is a few thousand total and is about 1000 with a 100 MeV E_γ cut(see text for details), and the expected Θ^+ events for 150 hours of beam time at 100% efficiency is 8755 total and 1428 with a 100 MeV E_γ cut.

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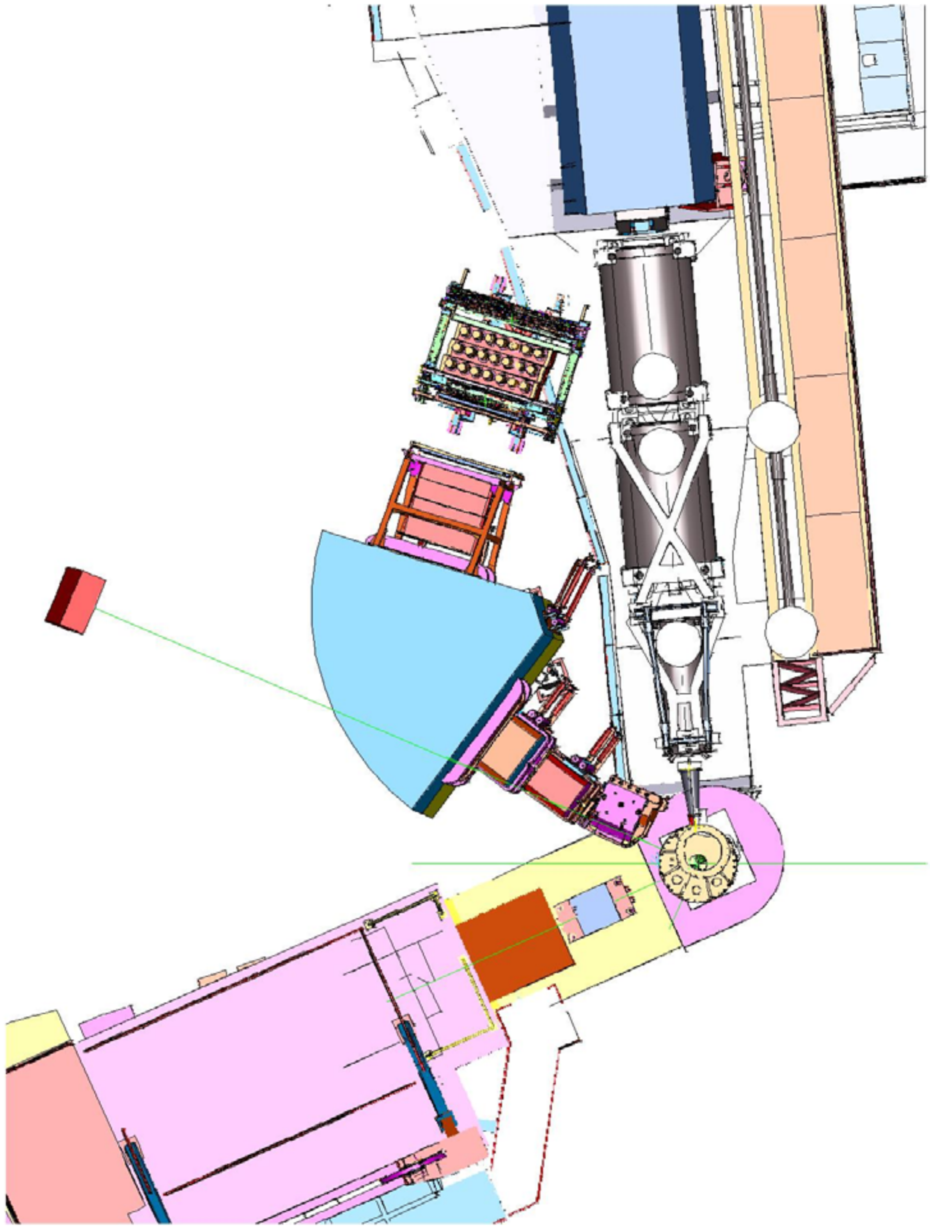

FIG. 1. Top view of the experimental setup for the proposed experiment.

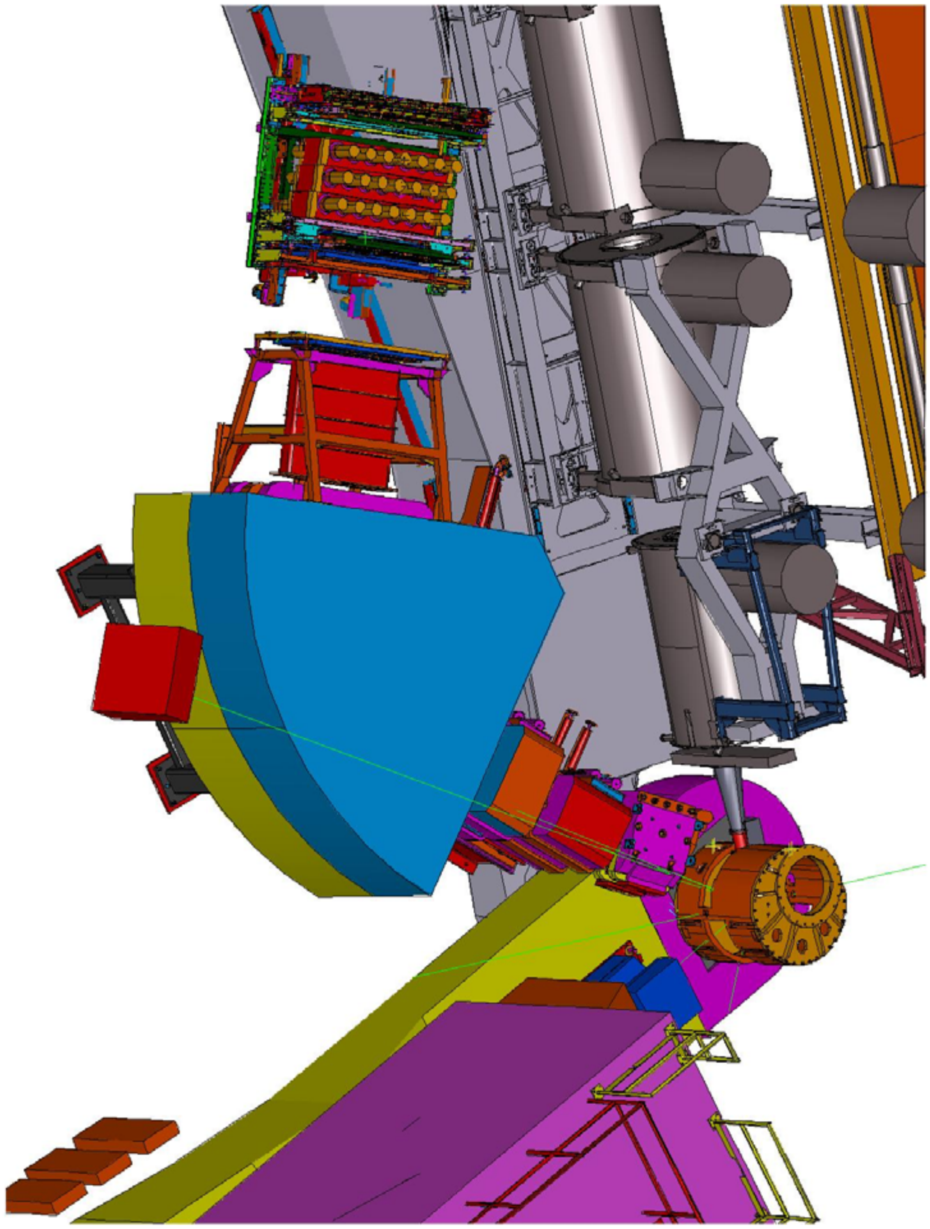

FIG. 2. Isometric view of the experimental setup for the proposed experiment.

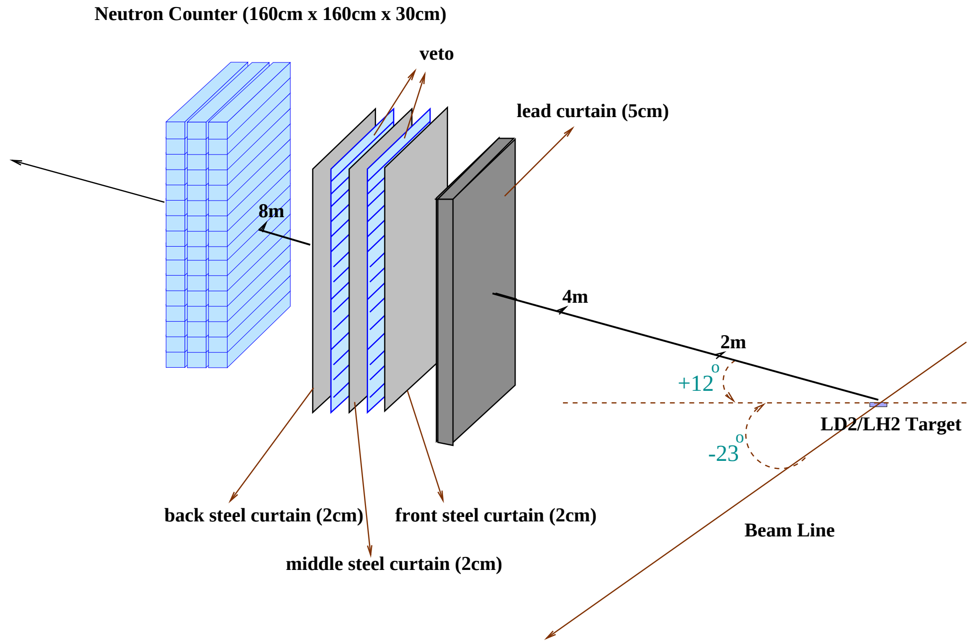

FIG. 3. A schematics diagram of neutron detector setup.

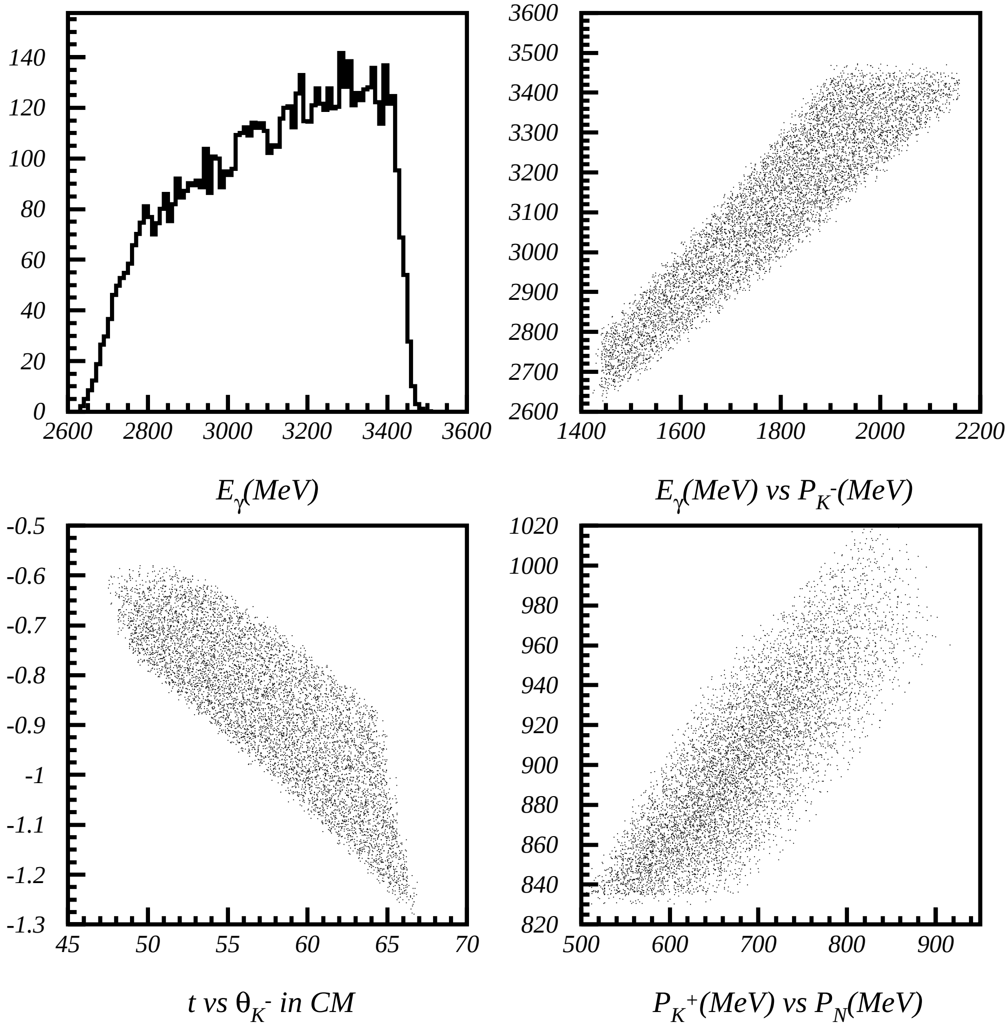

FIG. 4. The distributions with a Θ^+ or Θ^{++} (Θ^{*++}) mass of 1540 MeV a) the reconstructed E$_\gamma$; b)E$_\gamma$ versus momentum of K^-; c) the correlation between t (GeV/c)^2 and scattering angle of K^- in CM; d)the correlation between Nucleon and K$^+$ momenta.

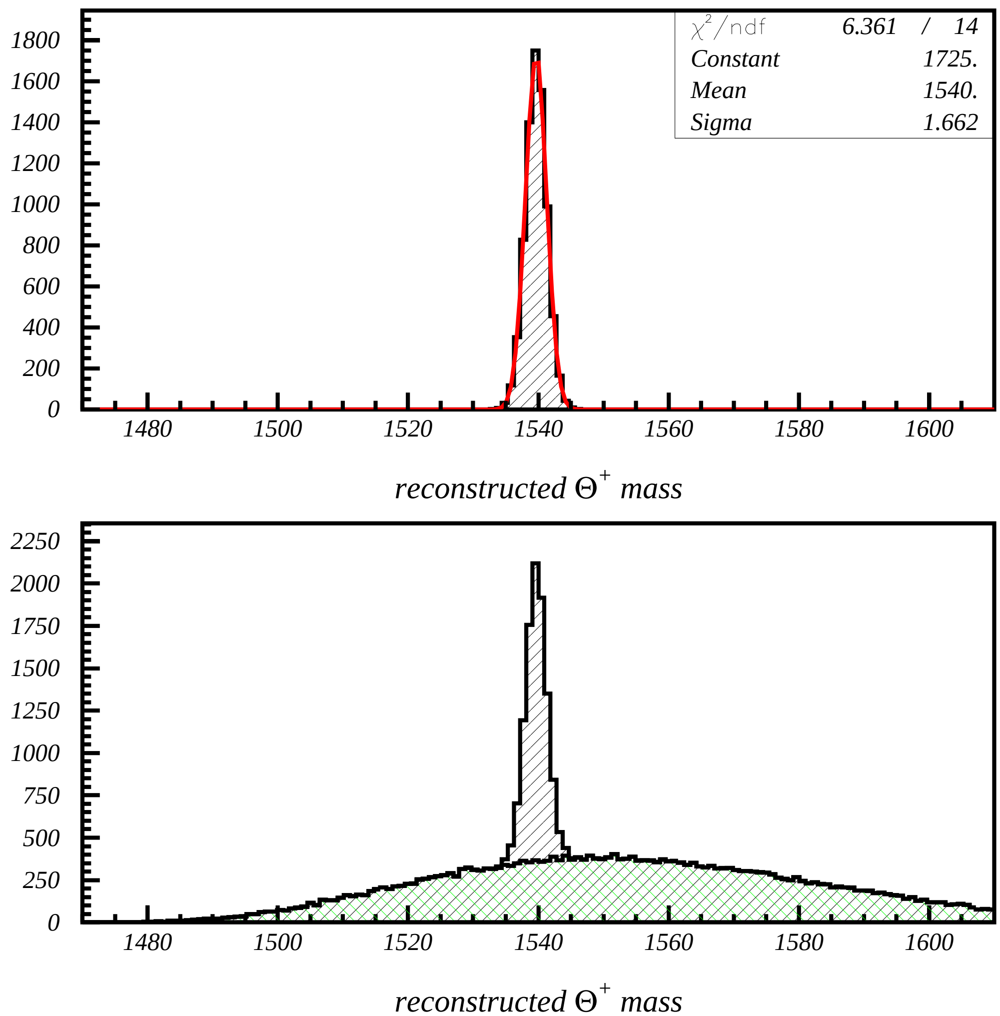

FIG. 5. Reconstructed Θ^+ mass spectra for the proposed experiment. In this simulation, physical events were generated from the $\gamma n \to \Theta^+ K^-$ process with a Θ^+ mass of 1540 MeV; The background is from K^+K^- pairs and an accidental coincidental rate(which is negligible.).

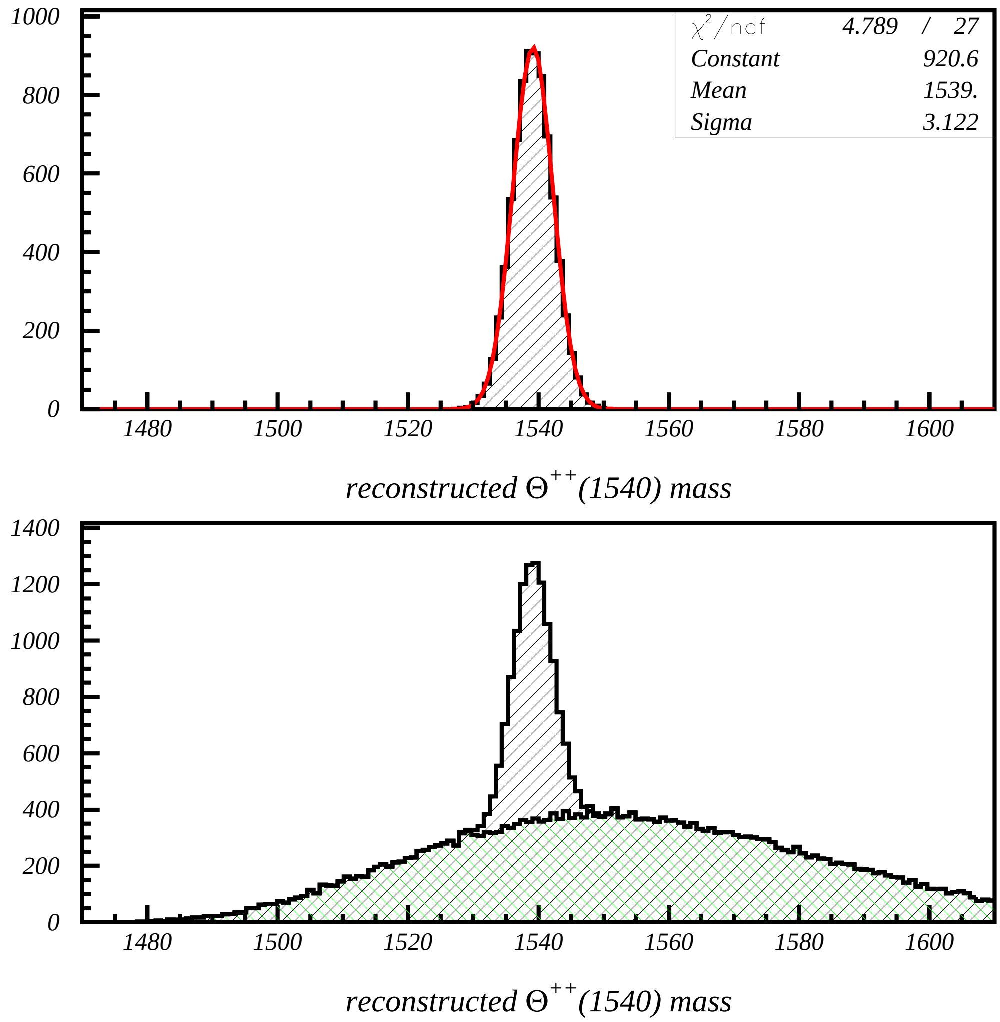

FIG. 6. Reconstructed Θ^{++} (Θ^{*++}) mass spectra for the proposed experiment. In this simulation, physical events were generated from the $\gamma p \to \Theta^{++}(\Theta^{*++})K^-$ process with a Θ^{++} (Θ^{*++}) mass of 1540 MeV; The background is from K^+K^- pairs and an accidental coincidental rate(which is negligible.).

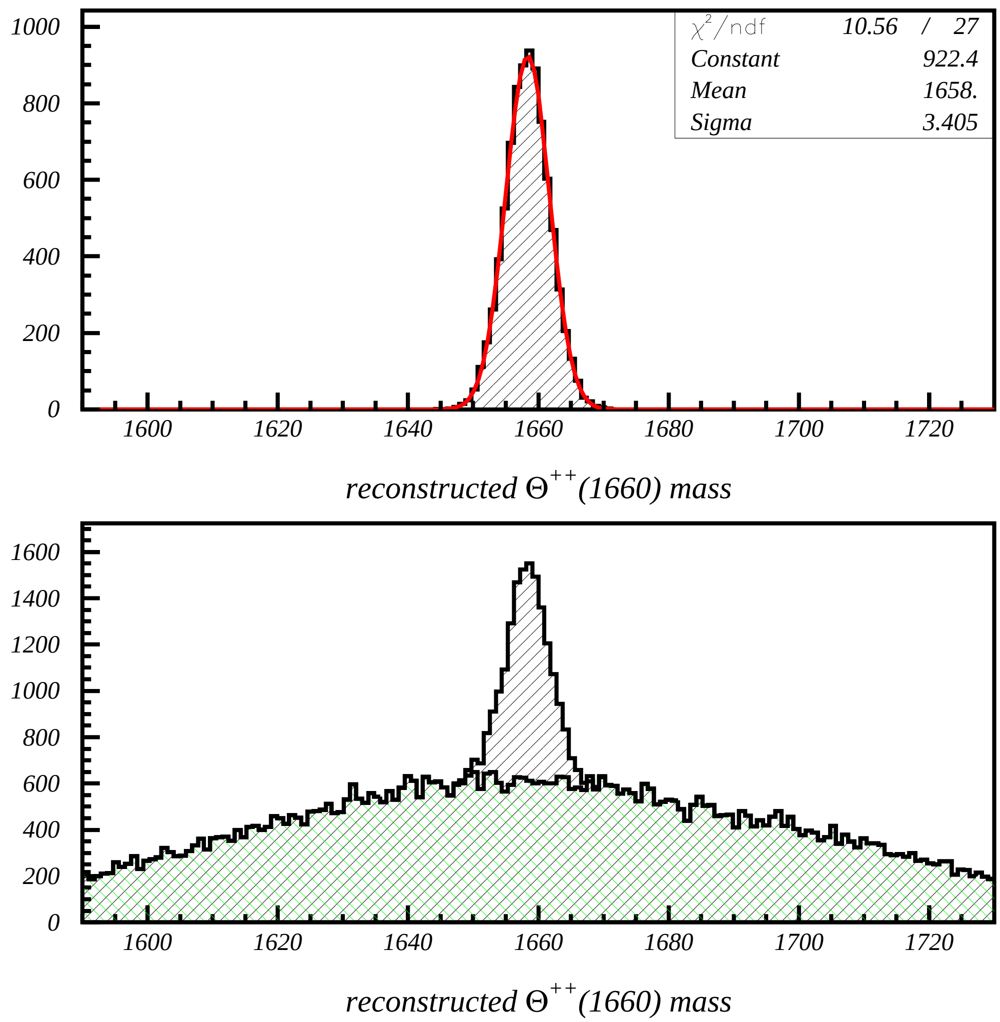

FIG. 7. Reconstructed Θ^{++} (Θ^{*++}) mass spectra for the proposed experiment. In this simulation, physical events were generated from the $\gamma p \rightarrow \Theta^{++}(\Theta^{*++})K^-$ process with a Θ^{++} (Θ^{*++}) mass of 1660 MeV; The background is from K^+K^- pairs and an accidental coincidental rate(which is negligible.).

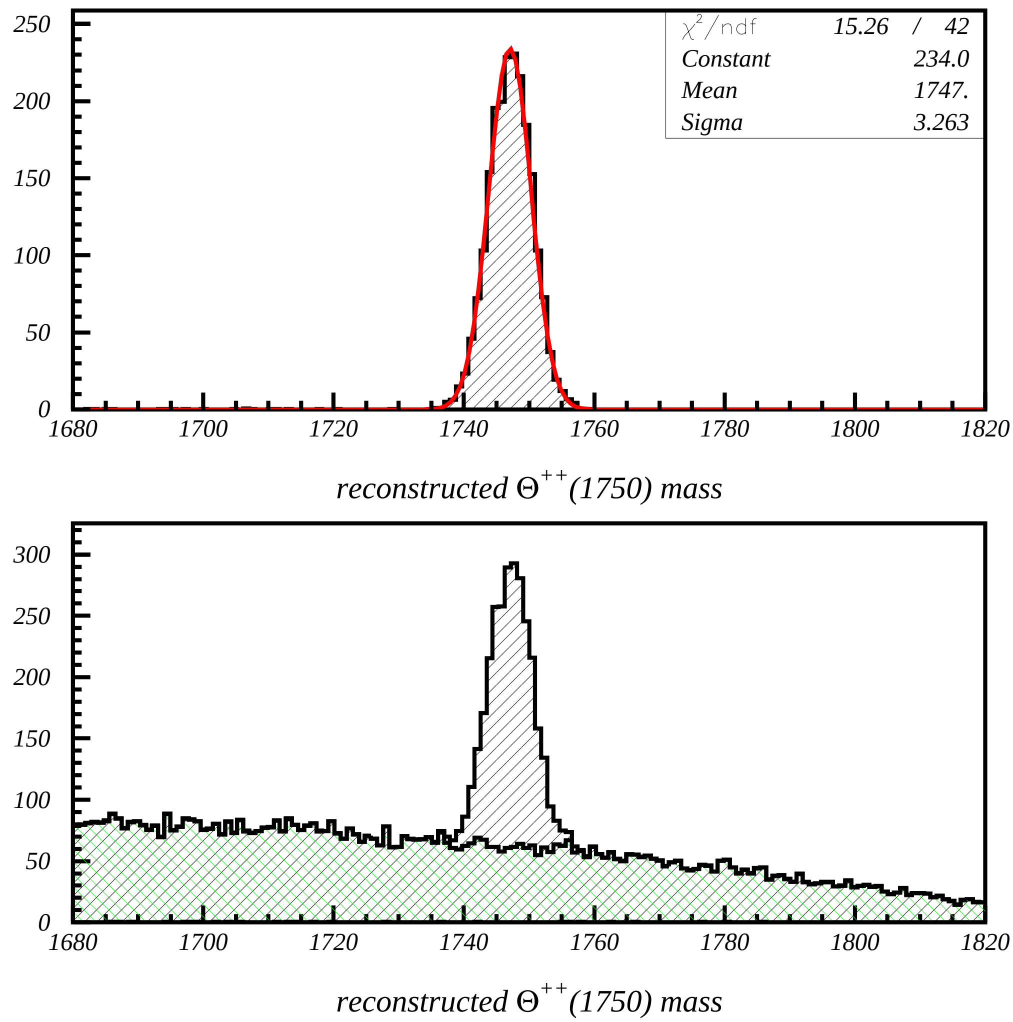

FIG. 8. Reconstructed Θ^{++} (Θ^{*++}) mass spectra for the proposed experiment. In this simulation, physical events were generated from the $\gamma p \to \Theta^{++}(\Theta^{*++})K^-$ process with a Θ^{++} (Θ^{*++}) mass of 1750 MeV; The background is from K^+K^- pairs and accidental coincidental rate(which is negligible.).

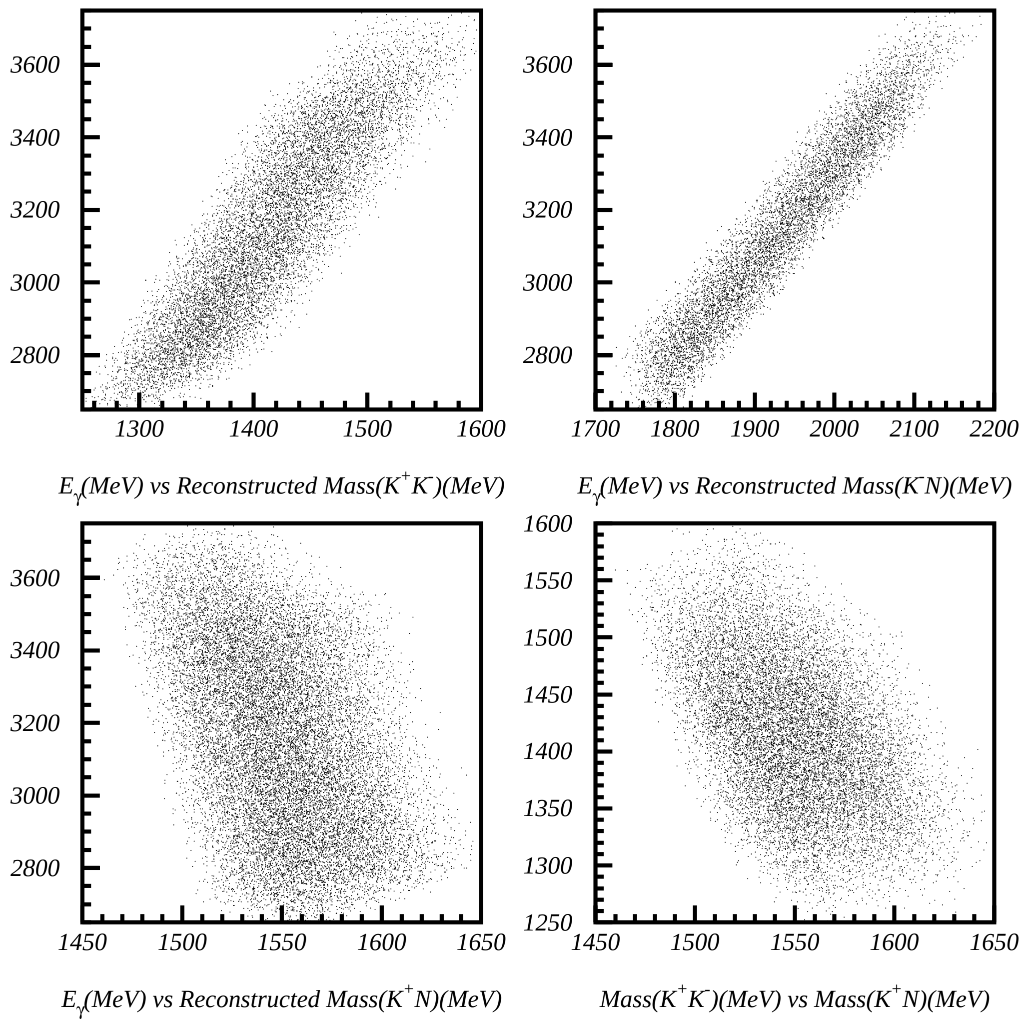

FIG. 9. Two-dimensional spectra for a Θ^+ or Θ^{++} (Θ^{*++}) of mass of 1540 MeV among various reconstructed quantities: the reconstructed photon energy (E_γ, in MeV), the invariant mass of the K^-K^+ pair (in MeV), the invariant mass of the $K^-Nucleon$ pair (in MeV) and the invariant mass of the $K^+Nucleon$ pair (in MeV) for any event inside the acceptance of the spectrometers.

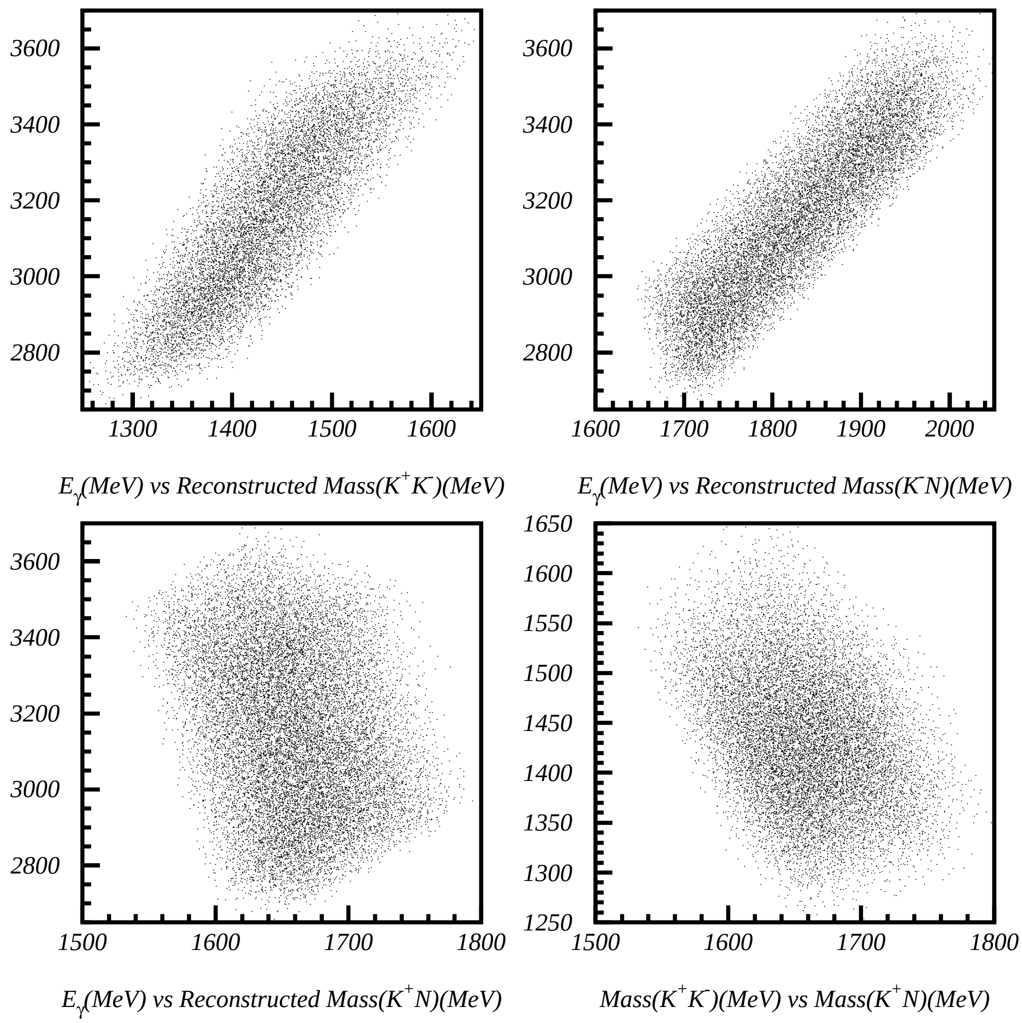

FIG. 10. Two-dimensional spectra for a Θ^+ or Θ^{++} (Θ^{*++}) of mass of 1660 MeV among various reconstructed quantities: the reconstructed photon energy (E_γ, in MeV), the invariant mass of the K^-K^+ pair (in MeV), the invariant mass of the $K^-Nucleon$ pair (in MeV) and the invariant mass of the $K^+Nucleon$ pair (in MeV) for any event inside the acceptance of the spectrometers.

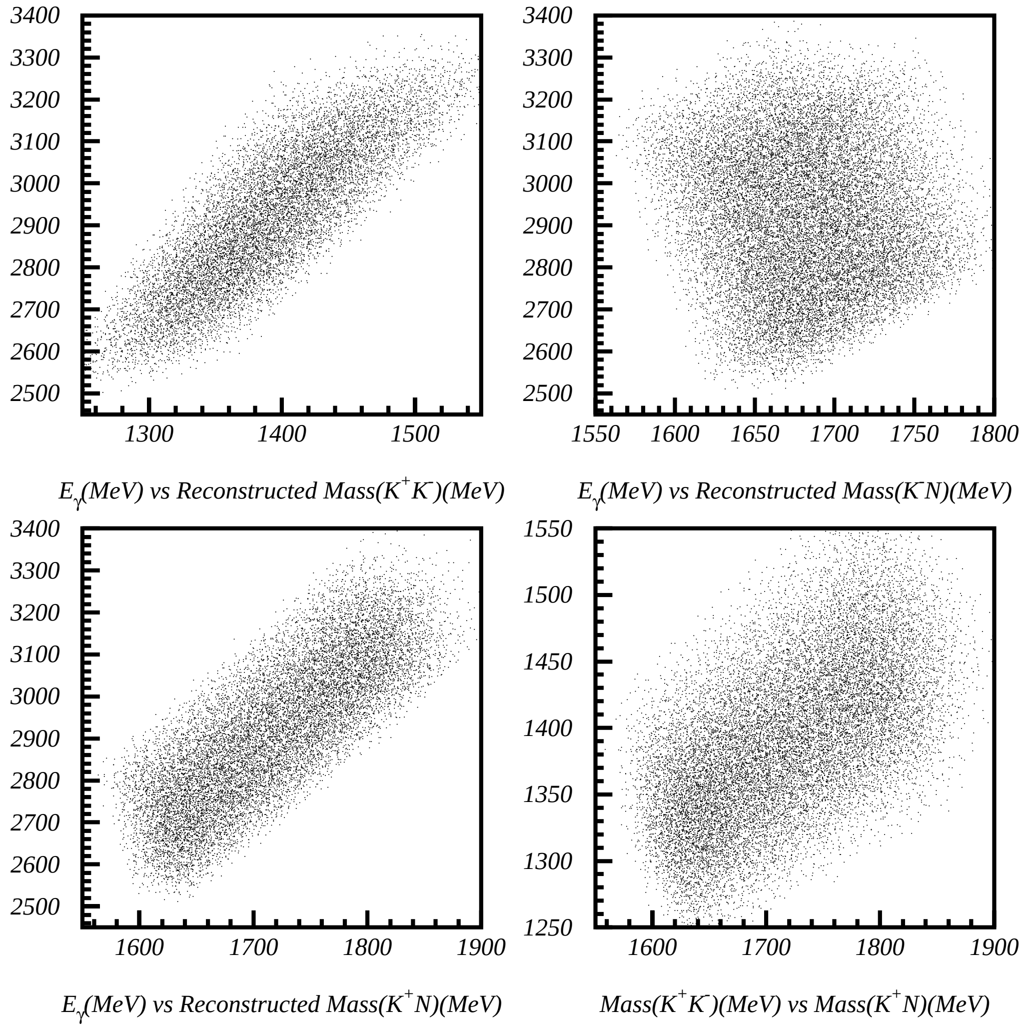

FIG. 11. Two-dimensional spectra for a Θ^+ or Θ^{++} (Θ^{*++}) of mass of 1750 MeV among various reconstructed quantities: the reconstructed photon energy (E_γ, in MeV), the invariant mass of the K^-K^+ pair (in MeV), the invariant mass of the $K^-Nucleon$ pair (in MeV) and the invariant mass of the $K^+Nucleon$ pair (in MeV) for any event inside the acceptance of the spectrometers.