DETERMINATION OF THE Θ^+ PARITY IN THE $^9Be(\vec{\gamma}, K^-K^+n)^8Be$ REACTIONS

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Abstract:

We propose to investigate the spin and parity of the exotic Θ^+ baryon in the reaction $^9\mathrm{Be}(\vec{\gamma}, K^-K^+n)^8\mathrm{Be}$ using a beam of linearly polarized photons. The photon asymmetry in $\vec{\gamma}n \to K^-\Theta^+ \to K^-K^+n$ and the decay distribution for $\Theta^+ \to K^+n$ determine uniquely the parity of Θ^+; however, the extraction of its spin content is model dependent. We propose to perform an experiment in Hall B at Jefferson Lab using the coherent bremsstrahlung facility, the CEBAF Large Acceptance Spectrometer (CLAS), and a Low Energy Recoil Detector to be located at the center of CLAS.

1 Motivation

Over the past 15 months several experiments are claiming evidence for a pentaquark state Θ^+ with strangeness S=+1, a mass around M=1.54 GeV, and width less than 25 MeV. The narrow exotic baryon has been observed in the invariant mass of K^+n and pK^0_s (see Table 1 for details).

Experiment	Θ^+Mass (MeV)	Θ^+Width (MeV)	Analyzed reaction	Statistical significance
SPring8 [1]	1540 ± 10	< 25	$\gamma n \to K^-K^+n$	4.6σ
SAPHIR [2]	$1540 \pm 4 \pm 2$	< 25	$\gamma p \to K^0_s K^+ n$	4.8σ
CLAS-d [3]	1542 ± 5	< 21	$\gamma d \to pK^-K^+n$	$(5.2 \pm 0.6)\sigma$
CLAS-p [4]	1555 ± 10	< 26	$\gamma p \to \pi^+K^-K^+n$	$(7.8 \pm 1.0)\sigma$
DIANA [5]	1539 ± 2	< 9	$K^+Xe \to K^0_s pX$	4.4σ
HERMES [6]	$1528 \pm 2.6 \pm 2.1$	$17 \pm 9 \pm 3$	$\gamma^* d \to pK^0_s n$	4–6 σ
SVD [8]	$1526 \pm 3 \pm 3$	< 24	$pA \to pK^0_s X$	5.6σ
BEBC [7]	1533 ± 5	< 20	$\nu A \to K^0_s pX$	6.7σ
ZEUS [9]	$1521.5 \pm 1.5^{+2.8}_{-1.7}$	$6.1 \pm 1.6^{+2.0}_{-1.4}$	$ep \to e'pK^0_s X$ $pe \to e'\bar{p}K^0_s X$	221 ± 48 events
COSY-TOF [10]	1530 ± 5	$< 18 \pm 4$	$pp \to p\Sigma^+K^0_s$	4–6σ

Table 1: Experimental evidence for a narrow S=+1 baryon with mass around 1540 MeV

The pentaquark state was predicted by Diakonov, Petrov, and Polyakov [11] in 1997 in the chiral soliton model as the lowest member of a baryon anti-decuplet. Although the existence of Θ^+ has been observed experimentally, many of its basic properties such as its quantum numbers undetermined. The naive SU(6) quark model and QCD sum rule calculations [12, 13] as well as Lattice QCD calculations [14, 15] predict a spin 1/2 negative parity state. In contrast, the chiral/Skyrme soliton model [11, 16] and correlated quark models [17, 18] predict a spin 1/2 positive parity isoscalar state. Goldstone boson exchange [19, 20] and color magnetic exchange quark models [21] also predict a positive parity for Θ^+.

The measurement of the differential cross section is not sufficient to determine the spin and parity of the narrow pentaquark state. We propose to employ linearly polarized photons to extract the spin and parity of Θ^+. Its parity can be uniquely determined by measuring the photon beam asymmetry Σ. By measuring the spin density matrix elements ρ^1_s and ρ^2_s (s being the spin quantum number of Θ^+), the intrinsic spin of the Θ^+ can be determined, but in a model dependent way [22, 23, 24].

In the following sections, we first outline the method to be employed in order to extract the spin and parity of Θ^+, and then provide a description of the proposed experimental setup.

2 Basic concepts

2.1 Measurement of spin and parity

To extract the spin and parity of the exotic Θ^+ baryon, we shall focus on the reaction $\gamma n \to K^-K^+n$, which has been experimentally investigated by the LEPS [1] and CLAS [3] Collaborations. However, since the neutron is bound in CH or ^{2}H, the results suffer from uncertainties in the correction for Fermi motion and, detection and measurement of spectator proton. In our proposed experiment we shall employ a Beryllium target (^{9}Be nucleus) because

of its unique feature, namely that after removing a neutron from its ground state, two α-particles appear from the excited states of a residual ^{8}Be nucleus [25, 26], i.e.

$$^9Be \longrightarrow \; n + \; ^8Be^* \; \longrightarrow n + \alpha + \alpha \tag{1}$$

The measurement of energy and direction of both recoil αs provides an effectively free neutron target, since its Fermi motion is known.

Additionally, we will use a beam of linearly polarized photons, which will allow for extracting the spin and parity of the Θ^+ pentaquark by measuring the photon asymmetry and decay distribution of $\Theta^+ \to K^+ n$ as function of the K^- production angle. The photon asymmetry, Σ, is given by [27, 28]

$$\Sigma = \frac{d\sigma_\perp - d\sigma_{||}}{d\sigma_\perp + d\sigma_{||}} \tag{2}$$

where $d\sigma_\perp (d\sigma_{||})$ is the differential cross section for Θ^+ for the incoming photon polarization perpendicular (parallel) to the production plane.

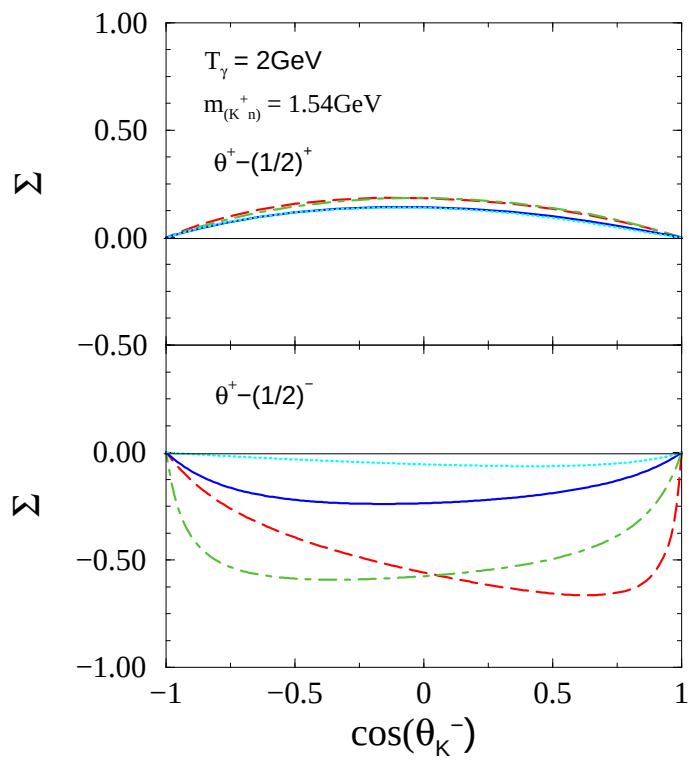

Figure 1: Photon asymmetry in the (γn) center-of-mass frame for both positive and negative parity cases of Θ^+. Different curves correspond to different choices of the pseudoscalar–pseudovector admixture for the $KN\Theta^+$ coupling and the anomalous magnetic moment κ_{Θ^+} (from Ref. [23]).

As an example, Fig. 1 shows the photon asymmetry Σ as function of the K^- production angle, for positive (*top*) and negative (*bottom*) parity of Θ^+ as predicted by Nakayama *et al.* [23]. Theoretical predictions confirm that

- the photon asymmetry is slightly [22, 24] or significantly [23] positive if the parity of Θ^+ is positive;
- the photon asymmetry is significantly negative [22, 23, 24] if the parity of Θ^+ is negative.

The angular distribution of the decay particles, K^+ and n, in the Θ^+ rest frame depends directly on J^π of Θ^+; however, without beam polarization the distributions are expected to be ambiguous. See Ref. [22, 23] for details.

The following reaction will be investigated to extract the parity of Θ^+:

$$\vec{\gamma} +^9 Be \longrightarrow K^- + K^+ + n + \alpha + \alpha \tag{3}$$

where two α particles will be detected in a Low Energy Recoil Detector (LERD), K^- and K^+ will be detected in CLAS. Since the polarized photon is tagged, the neutron can be identified by missing mass. We can unambigiously reconstruct the reaction (3). The photon asymmetry can be determined for background subtracted event samples where K^+n are the decay products of Θ^+.

2.2 Beryllium target

We propose to use a ^{9}Be nucleus and investigate the reaction (3). The probabilities of α feeding is governed by spectroscopic factors, which are the most important nuclear structure ingredients in transition amplitudes for direct nuclear reactions [29]. The spectroscopic factors are extracted from the ^{9}Be(p,d)^{8}Be reaction.[30] In Table 2, energy levels of the excited nucleus $^8Be^*$ and the coefficients of fractional parentage g_i^2 [32] are presented.

Table 2: **Energy levels of ^{8}Be and fractional parentage coefficients.** (The normalization used: Σg_i^2=1)

Experiment					Model			
Ajzenberg-Selove [25]					Barker [33]		Cohen-Kurath [34]	
E_i (MeV)	J_i^π	T_i	Γ (keV)	decay	E_i (MeV)	g_i^2	E_i (MeV)	g_i^2
0.00	0^+	0	6.8 (eV)	α	0.00	0.110	0.00	0.112
3.04	2^+	0	1500	α	3.09	0.151	3.41	0.144
11.4	4^+	0	$\approx$ 3500	α	10.3	$\sim$	11.29	$\sim$
16.63	2^+	1(+0)	108	γ, α	16.76	0.303	15.81	0.308
16.92	2^+	0(+1)	74	γ, α	16.89	0.086	14.44	0.095

Due to the binary and symmetric division of the excited nucleus ^{8}Be*, the α particles separate axially with equal momentum in the rest frame of ^{8}Be* (which we further call the center-of-mass system). Thus, in analogy of fission fragment angular correlation technique [26, 31], the measurement of the $\alpha\alpha$ folding angle, $\theta_{\alpha\alpha}$, translates into a determination of the ^{8}Be* momentum. The angles of α particles in the laboratory frame, ψ_i, are related to the angles in the center-of-mass system θ_{cm} as

$$\begin{aligned} \tan\psi_1 &= \sin\theta_{cm}/(x_1 + \cos\theta_{cm}) \\ \tan\psi_2 &= \sin\theta_{cm}/(x_2 - \cos\theta_{cm}) \end{aligned} \tag{4}$$

where $x_i^2 = (v/v_i')^2$ and v, v_i' stand for the velocities of the ^{8}Be* and α_i in the center-of-mass system, respectively.

3 Experimental setup

The Hall-B Tagger System [36] and CLAS detector [37] equipped with the Low Energy Recoil Detector (LERD) [38, 39] will be used as for this experiment. The LERD will be based on a Low Pressure Multiwire Proportional Chamber (LPMWPC) [38] and will be located in the center of CLAS (see Fig. 2). Linearly polarized photons will be produced via coherent bremsstrahlung, as successfully employed in CLAS-g8a [40, 41].

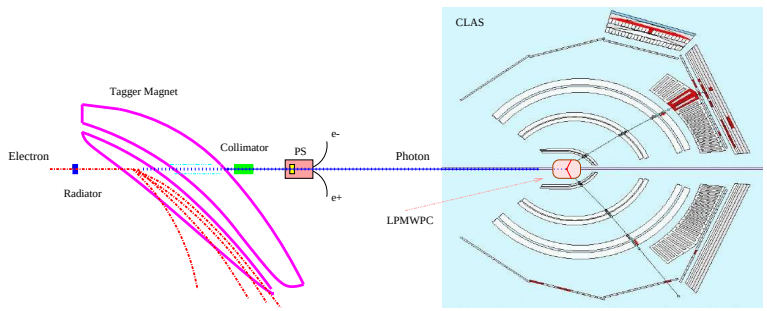

Figure 2: Experimental setup for the Θ^+ spin and parity determination.

3.1 Low Energy Recoil Detector

Since our experiment requires recoil detection, a thin target is desireable. In order to achieve reasonable count rate, intense beam have to be employed. Therefore, any recoil detectors should withstand a high radiation environment. The properties of the Low Energy Recoil Detectors, namely the Low-Pressure Multiwire Proportional Chambers (LPMWPCs) [38] and Low-Pressure Multi-Step Chambers (LPMSCs) [39] are very suitable for these goals.

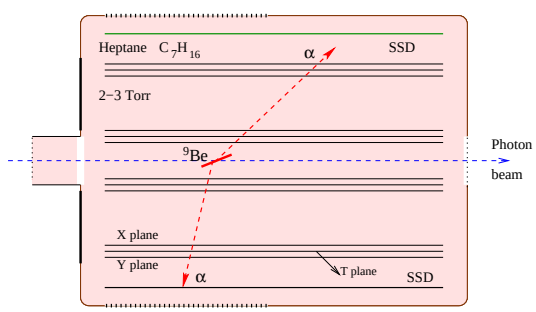

Figure 3: A schematic sketch of the Low Pressure Multiwire Proportional Chamber proposed for the detection of recoil αs in the reaction $^9Be(\vec{\gamma}, K^-K^+n)^8Be$.

Among the qualities are the following:

- High rate capability;
- An extreme insensitivity to gamma and relativistic particles;
- Capability to operate with external gate, which minimizes space charge effects;
- Negligible radiation damage;

- High efficiency ($\sim 100\%$) for detecting low energy recoils;
- Negligible influence on the energy of recoils (the recoils move through the detectors with practically constant velocity)

By means of this low-pressure technique it is possible to detect:

a) Protons with energy 0.1 – 5 MeV;

b) Deuterons with energy 0.2 – 10 MeV;

c) Alpha particles with energy 0.4 – 100 MeV;

as well as more heavy particles.

A Low Pressure Multiwire Proportional Chamber filled with a Heptane (C_7H_{16}) gas at a pressure of 3 Torr will be used in our proposed experiment. This detector is insensitive to electromagnetically interacting and minimum ionizing particles. The LPMWPC will be cylindrical shaped, having a diameter of 12 cm and a length of 22 cm. Surrounding the ^{9}Be target will be two cylindrical MWPCs (cf Fig. 3, diagonal cut view). The position and timing of the measured αs will be resolved to an uncertainty (FWHM) of 1 mm and 0.5 ns, respectively. The two outgoing αs will generate around 20 signals. Each detector provides 5 signals, four ADC-signals for a coordinate and one TDC-signal for time information. The MWPC detectors have no window and particles go through the detectors without distortion. The first cylindrical detector has a radius of 1.5 cm – the axis of the cylinder coincides with the beam direction – and the second one a radius of 3.5 cm. Just outside of the second detector there will be a Cylindrical Solid State Silicon Detector (CSSSD or just SSD) with a thickness of 0.3 mm to measure the energy of α particles with a 0.1 MeV resolution. LERD will have circular up- and downstream windows of 1.5 cm diameter, covered by a mylar foil of 0.012 mm thickness.

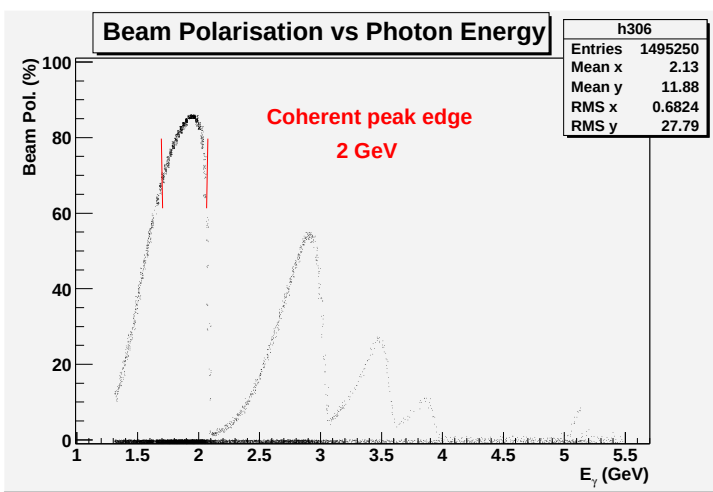

Figure 4: Beam polarization versus photon energy (CLAS-g8a data).

3.2 Beam and Target

Polarized tagged photon beam in the energy region of 2.0-4.0 GeV will be used (see Fig. 4). For the beam collimation we propose to use the active collimator [42] with the diameter of

2 mm, which collimates to a spot size of about 0.5 cm at the center of CLAS when the collimator is located at the distance of 21.58 m from the radiator. It secures a good fraction of the collimated tagged photons at the center of the CLAS.

In Fig. 5 the collimated spectrum of the liniarly polarized photon beam is presented, obtained from g8a data.

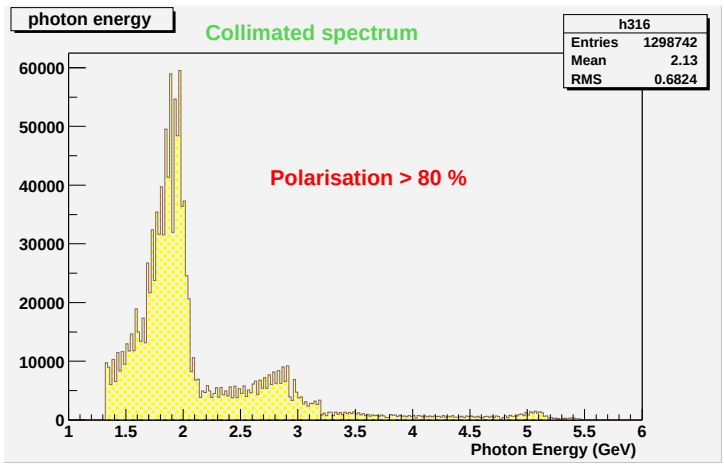

Figure 5: Collimated spectrum of linearly polarized photon beam (CLAS-g8a data).

As target we propose to use a thin tilted ^{9}Be foil with a thickness of 3 mg/cm^2 located inside the Low Energy Recoil Detector (LERD). The tilted target increases the effective target length for incident photons, e.g. a tilt of 6° increases the effective target length by a factor of 10.

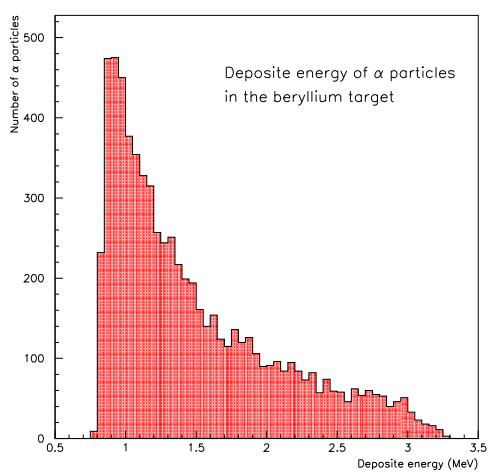

Figure 6: Deposited energy of α particles inside the proposed Beryllium target. The αs are produced from ^{8}Be decay (see Table 2).

Additionally, the tilted target allows for recoil αs to escape the ^{9}Be target. GEANT simulation results as well as nuclear data tables [35] show that α-particles with an energy of

at least 8 MeV are capable to leave a ^{9}Be target of 3 mg/cm^2 thickness. Table 2 shows that α-particles coming from the quantum levels 2^+ are capable to escape the target. According to our Monte-Carlo simulations, such αs account for about 40 % of all α products escaping the target. In Fig. 6 GEANT simulated results are presented for the deposited energy that α particles lose in the proposed ^{9}Be target. α particles lose in average 16 % of their energy inside the Beryllium target. The lowest energetic α particles have at least 4.5 MeV kinetic energy just after getting out from the target, which is sufficient to reach the Solid State Detector. The direction of these αs is being reconstructed by two MWPC on their path.

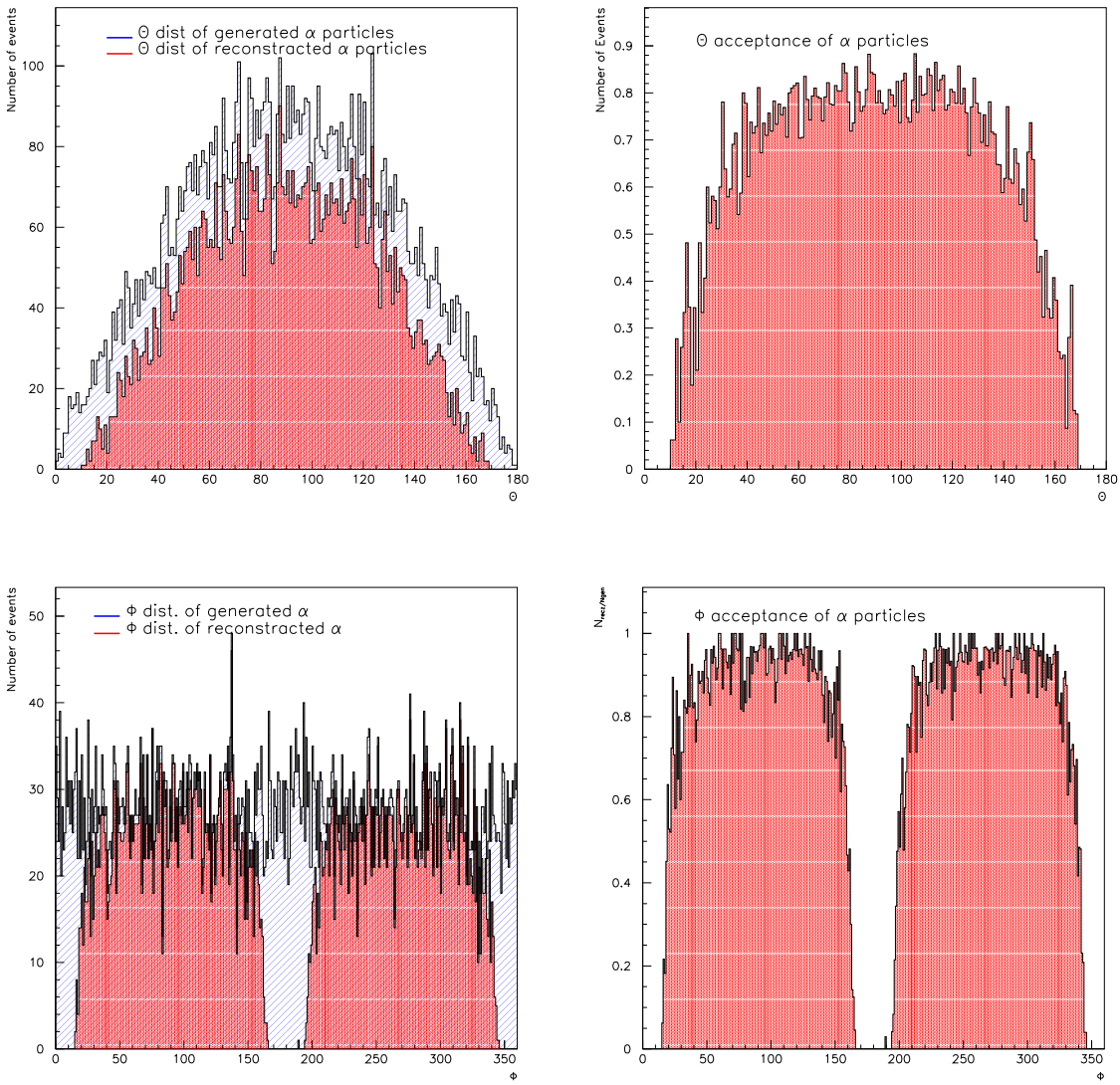

Figure 7: Acceptance of the LERD for α particles. *Top*: θ acceptance; *bottom:* ϕ acceptance. The blue (dark) distribution shows the MC-generated events, the red (light) distribution those α particles that were reconstructed in MWPCs and SSD.

3.3 LERD acceptance

Figure 7 shows the polar and azimuth angle distributions for generated α particles (blue histogram) and for reconstructed αs in MWPCs and SSD (red histogram). Only α particles in the very forward or backward directions (at $0 \leq \theta \leq 10°$ or $170° \leq \theta \leq 180°$) will not be detectable.

3.4 Trigger and event reconstruction

In order to measure the reaction (3), we propose to trigger on the coincidence of Tagger-Master OR (to be configured to expand over the coherent peak), 2 signals from the Low Energy Recoil Detector, and the Time of Flight (TOF) counters in CLAS. For the second level trigger (readout trigger) we require to have hit patterns of two tracks detected in the CLAS Drift chamber system. Directions and energies of the two α particles will be measured by LERD, while the two charged particles (K^-, K^+) will be identified using the CLAS detector.
Events with two αs and two Kaons will be at the center of our scientific interest. The missing neutron will be identified via missing mass and missing momentum. Tagging information (E_γ) and reconstructed 4-momenta of the recoil αs allow us to specify the center-of-mass frame of $\gamma n \rightarrow K^- K^+ n$, and thus the emission angle of K^-. The Θ^+ baryon is then identified via sideband subtraction (and/or signal+background fit) in the invariant mass spectrum of $(K^+ n)$ or the missing mass distribution of $\gamma n \rightarrow K^- X$. Finally, beam asymmetry and decay angular distribution are being extracted as function of the K^- emission angle. We will require 2 different orientations of the photon polarization (crystal orientation in coherent bremsstrahlung).

4 Count rate estimate

The yield of the events with Θ^+ and 2α particles as a decay products of an excited ^{8}Be nucleus caused by tagged photon beam [36] in the energy region of 3 GeV can be estimated by the relation

$$N_{\Theta^+} = \sigma_{tot} N_\gamma N_{nuc.}^{^9Be} f_{2\alpha} f_{LERD} f_{CLAS} f_{br} T_{day} \tag{5}$$

where the total cross section of Θ^+ production according to many theoretical predictions is to be from 15-200 nb, and for a count rate estimate we will take 100nb, i.e. $\sigma_{tot} = 10^{-31} cm^2$. We plan to make use of five targets, which will effectively increase the count rate by a factor of five. The thin-foil targets will be spaced 3 cm apart and sandwiched between each target will be a thin sheet of paper-like material to prevent forward-going alphas from interacting with its neighbor target. The exact details are to be worked out. We can further increase this count rate by increasing the flux by a factor of two to three. We will, however, need to install a finer segmented T-Counter array in the coherent peak to afford for this increase, since the T-Counters cannot sustain a rate exceeding 6 MHz. The number of photons in 3 GeV energy region is $N_\gamma = 10^7 \gamma/sec$, and the number of nucleus in ^{9}Be per cm^2 is $N_{nuc.}^{^9Be} = 10^{22} nuc./cm^2$. The $f_{2\alpha}$ factor is introduced to account for the Monte-Carlo calculations that only 40 % of all α particles can get out from the ^{9}Be target, hence $f_{2\alpha} = 0.4$ (see Table 2). The f_{LERD} factor accounts for the $0.8 \times 4\pi$ acceptance of α particle detection in the Low Energy Recoil Detector, hence $f_{LERD} = 0.8$. f_{CLAS} is the factor to account for a CLAS acceptance for K^- and K^+, which is about $(0.3 \times 4\pi)$, hence f_{CLAS}=0.3. f_{br} stands to account for a number of neutrons in the Beryllium nucleus $f_{br} = 5/9 = 0.56$, and T_{day} is the data taking time per day,

hence $T_{day} = 8.64 \times 10^4$ sec. Taking into account all this, the estimated number of events with Θ^+ per day is $N_{\Theta^+} = 46$.

5 Summary

We propose to measure the spin and parity of the recently discovered exotic baryon Θ^+. A ^{9}Be target will be used since it provides an effectively free neutron target – by measuring energy and direction of the two recoil αs in a Low Energy Recoil Detector. The photon asymmetry and decay distribution for $\vec{\gamma}n \to K^-\Theta^+ \to K^-K^+n$ will be measured, which are directely related to the spin and parity of Θ^+. The coherent bremsstrahlung facility and the CLAS detector in Hall B at Jefferson Lab along with the proposed Low Energy Recoil Detector based on Low Pressure MWPC technique, are the ideal facilities for performing this experiment.

References

[1] T. Nakano *et al.* (LEPS Collaboration), Phys. Rev. Lett. **91**, 012002 (2003).

[2] J. Barth *et al.* (SAPHIR Collaboration), Phys. Lett.**B 572**, 127 (2003).

[3] S. Stepanyan *et al.* (CLAS Collaboration), Phys. Rev. Lett. **91**, 252001 (2003).

[4] V. Kubarovsky *et al.* (CLAS Collaboration), Phys. Rev. Lett. **92**, 032001 (2004) [Erratum-ibid. **92**, 049902 (2004)].

[5] V. Barmin *et al.* (DIANA Collaboration), Phys. Atom. Nucl. **66**, 1715 (2003) [Yad. Fiz. **66**, 1763 (2003)].

[6] A. Airapetian *et al.* (HERMES Collaboration), Phys. Lett. **B 585**, 213 (2004).

[7] A.E. Asratyan, A.G. Dolgolenko, and M.A. Kubantsev, Phys. At. Nucl. **67**, 682 (2004) [Yad. Fiz. **67**, 704 (2004)].

[8] A. Aleev *et al.* (SVD Collaboration), hep-ex/0401024.

[9] S. Chekanov (ZEUS Collaboration), hep-ex/0403051, Phys. Lett. B (in print); hep-ex/0405013.

[10] M. Abdel-Bary *et al.* (COSY-TOF Collaboration), hep-ex/0403011.

[11] D. Diakonov, V. Petrov, M. Polyakov, Z. Phys. **A 359**, 305 (1997).

[12] Shi-Lin Zhu, hep-ph/0307345.

[13] J. Sugiyama, T. Doi, M. Oka, hep-ph/0309271.

[14] F. Csikor et. al hep-lat/0309090.

[15] S. Sasaki, hep-lat/0310014.

[16] H. Weigel, Eur. Phys. J. **A 2**, 391 (1998).

[17] R.L. Jaffe, F. Wilczek, hep-ph/0307341.

[18] D. Borisyuk, M. Faber, A. Kobushkin, hep-ph/0307370.

[19] F. Stancu, D.O. Riska, hep-ph/0307010.

[20] A. Hosaka, hep-ph/0307232.

[21] B.K. Jennings, K.Maltman, hep-ph/0308286.

[22] Qiang Zhao, hep-ph/0310350.

[23] K. Nakayama, K.Tsushima, Phys. Lett. **B 583**, 269 (2004).

[24] M. Guidal, M.Y. Polyakov, M. Vanderhaeghen, presented in the workshop

[25] F. Ajzenberg-Selove; Nucl. Phys. **A 490**, 1 (1988).

[26] L. Majling *et al.*, Czech. J. Phys. **51**,1 (2001).

[27] R.L. Walker, Phys. Rev. **182**, 1729 (1969).

[28] K. Schilling, P. Seyboth, and G. Wolf, Nucl. Phys. **B 15**, 397 (1970).

[29] J. Bang *et al.*, Phys. Rept. 125 (1985).

[30] J.L.Schoonover, T.Y. Li and S.K. Mark, Nucl. Phys. **A 176**, 567 (1971).

[31] P. Bartsch *et. al.*, Eur. Phys. J. **A 4**, 209 (1999).

[32] R. Bertini *et al.*, Phys. Lett. **B 90**, 375 (1980); Phys. Lett. **B 136**, 29 (1984).

[33] F.C. Barker, Nucl. Phys. **83**, 418 (1966).

[34] S. Cohen and D. Kurath, Nucl. Phys. **A 101**, 1 (1967).

[35] L.C. Northcliffe and R.F. Schilling; Nuclear Data Tables **A 7**, 233-463 (1970).

[36] D.I. Sober *et al.*, Nucl. Inst. Meth. **A 440**, 263 (2000).

[37] B.A. Mecking *et. al.*, Nucl. Instr. Meth. **A 503**, 513 (2003).

[38] K. Assamagan *et al.*, Nucl. Instr. Meth. **A 426**, 405 (1999).

[39] A. Breskin, G. Charpak, S. Majewski, Nucl. Instr. Meth. **220**, 349 (1984).

[40] P.L. Cole *et al.*, Proceedings of EMI2001, Osaka, Japan, World Scientific, 2002.

[41] C. Gordon, J. Melone *et al.*, Proceedings of 2nd Intl. Conf. on Nucl. and Part. Physics with CEBAF, Dubrovnik, Croatia (2003), World Scientific, 2004.

[42] P.L.Cole; "The IPN-Orsay/UTEP Instrumented Collimator", August 1999, unpublished