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Determining the nature of the theta^+ using polarization asymmetries

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E03-113

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(A Letter-of-Intent to Jefferson Lab PAC25)

Determining the nature of the θ^+ using polarization asymmetries

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1 Motivation

A new baryon resonance (Θ^+) in K^+n and $K^o_s p$ systems has been observed by several independent experiments[1]. Because of its positive strangeness, the Θ^+ is explicitly exotic and its minimal quark content is $uudd\bar{s}$. Such a state was predicted as a member of an antidecuplet of the flavor group $SU(3)_F$ [2]. This unitary identification assumes zero isospin of Θ^+, and continues to be favored [3, 4, 5]. However, other identifications with higher isospin have also been suggested in the literature [6, 7]. The mass of the Θ^+ was predicted to be 1530 MeV [2]. Several of the present experiments give the nearby value 1540 MeV, with a range of 1526-1555 MeV. The determination of the mass and the width is subject of new proposal to PAC25 [8].

Making a convincing case that a "bump" is indeed a new particle is difficult. The strongest evidence for a resonance is the observation of a rapid change in the strong phase of the relevant amplitude as a function of the energy of the K^+n system. A prerequisite for such a demonstration is an apparatus with resolution better than the width of the resonance. In addition, an observable with phase sensitivity must be found. It is likely that the proposal of ref [8] will meet the requirements on resolution unless the resonance is less than roughly 5 MeV in width. In this letter of intent we show how a polarized ^{3}He target can be used to gain sensitivity to a rapidly changing phase associated with the new resonance. By flipping the spin of a polarized ^{3}He target in a direction normal to the scattering plane, we can measure an asymmetry that results from an interference between the θ^+ production and the non-resonant background. The background should have a phase (or phases) that are roughly constant over the energy scale of the width of the θ^+. Any rapid variation of the asymmetry as a function of the energy of the K^+n system would provide convincing evidence of a rapidly varying phase characteristic of a true resonance. We will show below that this is possible with the apparatus of ref [8] under reasonable assumptions about the properties of the resonance and background.

We note that the quantum numbers of the Θ^+ are are as yet unknown, though there is weak evidence that $J = 1/2$ is preferred, as was predicted [2]. Many models predicted a positive parity, but lattice gauge calculations [9] and constituent quark models predict a negative one. The parity puzzle has sparked lively discussion in the literature, since a $uudd\bar{s}$ positive parity state requires at least one unit of orbital angular momentum in the quark configuration. It is possible that our asymmetry data might shed light on this important issue. Even if we do not establish the parity, however, our experiment would provide an important first step in that direction.

In summary, we propose a study of the polarization asymmetry in the photoproduction of the exotic baryon using a transversely polarized He-3 target. Under favorable conditions, a rapid variation of the asymmetry will be observed, providing convincing evidence that the θ^+ is indeed a new particle.

2 The Θ^+ state production and decay

The production of a θ^+ using a polarized neutron target is illustrated in fig. 1. An incident photon splits into a K^- and a K^+, and the K^+ scatters from a polarized neutron. Fig. 1 specifically depicts resonant scattering, but in what follows, we recognize that there will be non-resonant $K^+ n$ scattering as well. The polarization of the target neutron is assumed to be normal to the plane defined by the initial and final momentum of the K^+. With this configuration, it is expected that spin-orbit coupling will cause the distribution of the final states to be polarization sensitive. Without even knowing the strength of the interaction (which is expected to be strong) we can, in principle, learn about the spin and parity of the resonance by determining which partial wave is associated with the resonance. More importantly, we will show that we can expect a polarization asymmetry that will change rapidly at the location of the θ^+ if it is truly a new particle.

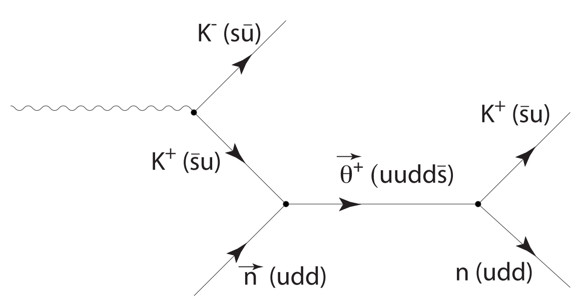

Figure 1: Diagram illustrating the production of a θ^+ from a polarized neutron target.

2.1 Formalism for phase shift analysis with spin-orbital interaction

The scattering of the K^+ can be analyzed using partial wave analysis, a subject that can be found in many textbooks. In what we present we follow closely the notation of Landau and Lifshitz from section 140[10]. The case considered here is the scattering of a projectile with spin $s = 1/2$ from a target with spin $s = 0$. The system has total angular momentum $j = l \pm 1/2$. Due to conservation of parity and total momentum the orbital moment l is also conserved in the scattering process. The most general operator with action on the initial wave function which produces the final wave function has a form

$$\hat{f} \;=\; \hat{a} \;+\; \hat{b}\,\hat{\mathbf{l}} \cdot \hat{\mathbf{s}},$$

where $\hat{a}$ and $\hat{b}$ are operators that depend only on $\mathbf{l^2}$, and $\hat{\mathbf{s}}$ is a spin operator. The operator $\hat{f}$ can be expanded as

$$\hat{f} \;=\; \sum_{l=0}^{\infty}(2l+1)(a_l + b_l\,\hat{\mathbf{l}} \cdot \hat{\mathbf{s}})\,P_l(cos\theta)$$

which can be shown to have the form

$$\hat{f} \;=\; A \;+\; 2B\,\hat{\nu} \cdot \hat{\mathbf{s}},$$

where the A and B are given by

$$A \;=\; \frac{1}{2ik}\sum_{l=0}^{\infty}\Big[(l+1)(e^{2i\delta_l^+} - 1) + l(e^{2i\delta_l^-} - 1)\Big]\,P_l(cos\theta), \;\text{ and}$$

$$B \;=\; \frac{1}{2k}\sum_{l=0}^{\infty}(e^{2i\delta_l^+} - e^{2i\delta_l^-})P_l^1(cos\theta),$$

and $\hat{\nu}$ is a unit vector directed normal to the scattering plane. Here the superscripts + and − refer to whether $j = l + \frac{1}{2}$ or $j = l - \frac{1}{2}$. The cross section of the process is

$$\frac{d\sigma}{d\Omega} = |A|^2 + |B|^2 + 2Re(AB^*)\,\nu \cdot \mathbf{P}, \tag{1}$$

where $\mathbf{P} = 2\mathbf{s}$ is the initial polarization of the projectile.

The final term of eqn. 1 can result in a polarization asymmetry if both A and B are non-zero. Furthermore, if the polarization asymmetry changes as we move across the θ^+ resonance, we will have seen strong evidence of a phase change due to resonant scattering, a phenomena that would be hard to explain if the θ^+ were not a true resonance. In certain situations, it may even be possible to determine the parity of the resonance. All this becomes clearer by examining some simplified situations.

2.2 Scattering assuming truncation at p-wave scattering

The form of A and B is particularly simple if we truncate our sums at $l = 1$. We then have

$$A = \frac{1}{2ik}\left\{(e^{2i\delta_0^+} - 1) + \Big[2(e^{2i\delta_1^+} - 1) + (e^{2i\delta_1^-} - 1)\Big]\cos\theta\right\} \tag{2}$$

and

$$B = \frac{1}{2ik}\left(e^{2i\delta_1^+} - e^{2i\delta_1^-}\right)\sin\theta \tag{3}$$

If the scattering were purely resonant, only one of the three phases δ_0^+, δ_1^-, and δ_1^+ would be non-zero. The physical relevance of the three phases is summarized as follows:

δ_0^+	$j = l + \frac{1}{2}$	$l = 0$	$\frac{1}{2}^-$
δ_1^-	$j = l - \frac{1}{2}$	$l = 1$	$\frac{1}{2}^+$
δ_1^+	$j = l + \frac{1}{2}$	$l = 1$	$\frac{3}{2}^+$

When only one of these phases is non-zero, the quantity $A\,B^*$ is purely imaginary, and the last term in eqn. 1 is zero. There is thus no polarization asymmetry. It is also seen that with either δ_0^+ or δ_1^- being non-zero, corresponding to the θ^+ being either a $\frac{1}{2}^-$ or $\frac{1}{2}^+$ resonance, the angular distribution is isotropic. Only in the case where δ_1^+ is non-zero, corresponding to the θ^+ being a $\frac{3}{2}^+$ resonance is there a non-trivial angular distribution.

The scattering will not be purely resonant, however. We expect there to be a strong background from $K^+ n$ scattering, although it is not obvious *a priori* which partial waves will dominate the non-resonant background. We consider briefly a simple example.

2.2.1 Interfering with s-wave background

Here we consider the case where the non-resonant background is purely s-wave. In this case the non-resonant background will contribute to δ_0^+. If the θ^+ is a $\frac{1}{2}^-$ resonance, δ_0^+ will be the only non-zero phase shift, and there would be no polarization asymmetry. In contrast, if the θ^+ is a $\frac{1}{2}^+$ resonance, there will be a non-zero δ_1^- phase shift, and we would expect a polarization asymmetry when sitting on the resonance. Given the simple case we are considering, it is not hard to estimate the size of the effect.

When we restrict ourselves to an *s*-wave non-resonant background and a *p*-wave resonance with $J^\pi = \frac{1}{2}^+$ there are only two non-zero phases: δ_0^+ and δ_1^-. To compute the polarization asymmetry we need to evaluate the last term of eqn. 1. We find that

$$Re(k^2 AB^*) = \sin\theta\,\sin\delta_0^+\,\sin\delta_1^-\,\sin(\delta_0^+ + \delta_1^-) \tag{4}$$

Because the non-resonance cross section σ_0 is proportional to the $\sin^2\delta_0^+$ and the cross section on the resonance σ_1 is proportional to the $\sin^2\delta_1^-$, it is easy to show that the polarization asymmetry $A_{\text{polarization}}$ has the form (at the resonance peak $\delta_1^- = \pi/2$)

$$A_{\text{polarization}} = \frac{\sin\theta\,\sqrt{\sigma_0\,\sigma_1}\,\sin(\delta_0^+ + \delta_1^-)}{\sigma_0 + \sigma_1 + 2\,\cos\theta\sqrt{\sigma_0\,\sigma_1}\,\cos(\delta_0^+ - \delta_1^-)} \quad . \tag{5}$$

The value of δ_0^+ we estimated from the KN total cross section as 23°. By using $\theta = 45°$ and the cross sections ratio of 4 (see [8]) the asymmetry was found to be 0.24.

2.2.2 Interfering with a more complicated background

Given the momentum of the K^+ in the center-of-mass frame when on resonance, which is roughly 270 MeV/c, we can reasonably expect contributions from partial waves with $l = 1$ if not even higher. This would result in a polarization asymmetry even when off resonance. On resonance, there will be a contribution from one of the three phases δ_0^+, δ_1^-, or δ_1^+ (depending on the J^π of the θ^+) that is not present when off resonance. Thus, if the θ^+ is truly a particle, we would expect the polarization asymmetry to change as we pass over the resonance. Deducing the parity of the state from the polarization asymmetry will be non-trivial, but the observation of an effect would be a powerful confirmation that the θ^+ is indeed a new particle.

2.2.3 Summary of what can be learned from polarization asymmetries

- In the absence of a non-resonant background, no polarization asymmetry is expected.
- If the θ^+ has $J^\pi = \frac{1}{2}^-$, and the non-resonant background is purely s-wave, we would still not expect a polarization asymmetry.
- If the non-resonant background contains partial waves that correspond to $l = 1$ or higher, we would in general expect a polarization asymmetry for any value of J^π.
- The observation of a polarization asymmetry that changes at the resonance is convincing evidence that the θ^+ is indeed a new particle.

3 Measurement

The measurement will allow the observation of a narrow Θ^+ state in an invariant mass spectrum and the collection of an angular distribution of the decay products for different transverse polarization states of He-3. The measurements will use a 40 cm polarized He-3 target with a bremsstrahlung radiator located 70 cm upstream of the target center.

3.1 The setup

We are going to study the reaction n$(\gamma, K^- n K^+)$. The concept of the measurement is shown in Fig. 2. An electron beam with a current of 5 μA at an energy of 4.5 GeV will be used. The negative kaon will be detected in the magnetic spectrometer HRS-left at a central angle 6° with a septum magnet. The positive kaon will be detected in the BigBite spectrometer at horizontal/vertical angles 18°/15° and the neutron will be detected in the large neutron detector at horizontal/vertical angles 18°/22°. The invariant mass resolution (FWHM) is about 2.9 MeV. For more information see the proposal [8].

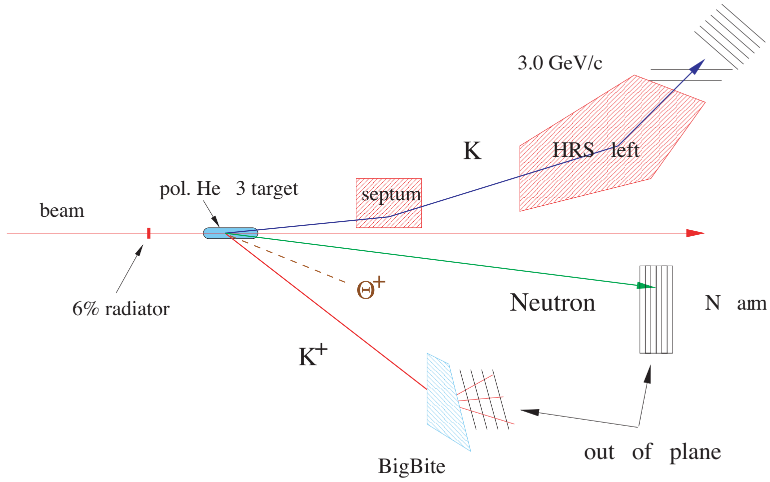

Figure 2: The experimental setup for the first part of the experiment.

3.2 The Θ^+ production rate

The photon-neutron luminosity $\mathcal{L}_{\gamma n}$ can be calculated as

$$\mathcal{L}_{\gamma n} = \frac{N}{A} \cdot (0.015 + 0.06) \cdot \frac{\Delta E_\gamma}{E_\gamma} \cdot \mathcal{L}_{eN} \sim 5.25 \times 10^{-4} \cdot \mathcal{L}_{eN} = 5.25 \times 10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1}. \quad (6)$$

Here E_γ and ΔE_γ are defined by the kaon momentum range accepted in HRS-left with $\langle E_\gamma \rangle =$ 4.0 GeV and $\Delta E_\gamma = 0.28$ GeV. The electron-nucleon luminosity $\mathcal{L}_{eN} = 3 \times 10^{36}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The factor 0.06 reflects a contribution from the real photon flux produced in the radiator. This leads to the production rate

$$\nu^{\Theta^+}_{\gamma, K^- nK^+} = \mathcal{L}_{\gamma n} \cdot \sigma^{\Theta^+}_{\gamma n} \cdot f^{HRS}_{\gamma, K^-} \cdot f_{nK^+} \cdot f^{decay}_{K^-} \cdot \eta_n \cdot f^{decay}_{K^+} \cdot b_{nK^+} = 55 \text{ events per day},$$

where $\sigma^{\Theta^+}_{\gamma n}$ is the θ^+ production cross section estimated at 50 nb, f^{HRS}_{γ,K^-} is the fraction of K^- associated with Θ^+ production within HRS angular and momentum acceptances ($\approx$0.034), f_{nK^+} is the fraction of Θ^+ events when both decay products are in the angular acceptance of the BigBite and N-arm detector (f_{nK^+} is $\approx$0.005), $f^{decay}_{K^-} = 0.33$ is the survival probability of a K^- after a 25 meter path in the HRS, $\eta_n = 0.24$ is the detection efficiency of the neutron, $f^{decay}_{K^+} = 0.36$ is the average survival probability of K^+ after a flight of 5 meters from the target to the BigBite trigger detector, and $b_{nK^+} = 0.5$ is the branching ratio for Θ^+ decay to nK^+. The actual rate $\nu^{\Theta^+}_{\gamma,K^- nK^+}$ may be larger or smaller depending upon the cross section.

With three weeks of running we estimated that 1200 events will be collected. For the simplified case of an s-wave background and a $\frac{1}{2}^-$ resonance, we would expect a raw asymmetry of 0.10 assuming a physics asymmetry of 0.24 and a target polarization of 40%. This represents a 3.4 sigma determination of the polarization asymmetry on resonance.

4 Discussion

As we write this letter-of-intent we face many unanswered questions. We do not know whether the neutron in the initial state will retain its polarization. We do not know well the production cross section for the θ^+. We do not know well which l states will contribute to our non-resonant background. It seems clear, however, that if the θ^+ is truly a new particle, there will very likely be a polarization asymmetry associated with that resonance that is distinct from that of the non-resonant background. The observation of that polarization asymmetry and the fact that it is different from that of the non-resonant background would provide compelling evidence that the θ^+ is not just some sort of artifact or bump. We anticipate that some of the outstanding questions which at present prevent us from finalizing a proposal will become clarified in the near future, allowing us to propose a full experiment.

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