A Search for Bound Θ^+Nuclei in Hall A

A New Letter of Intent to Jefferson Lab PAC26

Robert J. Feuerbach

Thomas Jefferson National Laboratory

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Abstract

We investigate the feasibility of searching for bound Θ^+-nuclear states in a high-luminosity measurement in Hall A using existing standard equipment. A schematic model for the even-parity Θ^+predicts the pentaquark can be bound in nuclei by several hundreds of MeV. If the $\Theta^+$is observed in a bound state, the binding energy of the pentanuclei could serve as test of the parity of Θ^+particle. A bound pentaquark-nuclear state could also be a cleaner and simpler experiment to perform.

1 Introduction

Recently a discovery[1] and subsequent multiple observations[2, 3, 4, 5, 6, 7] of the manifestly exotic baryon $\Theta^+(1540)$ with five-quark $S = +1$ baryonic state has caused a flury of activity to explain the particle's structure.

The premise of this Letter of Intent is that the Θ^+pentaquark can be observed bound to a nucleus. Support for this premise comes from a recently constructed schematic model[8], where a positive-parity $\Theta^+$is described as the interaction of color-singlet pseudoscaler excitations in a p-wave about a nucleon. One of the conclusions of the calculation is that the pentaquark would be bound to the nucleus with a binding energy on the scale of hundreds of MeV. If the $\Theta^+$is this deeply bound to nuclear states, observing the Θ^+in nuclei might prove simpler and cleaner than a direct observation of the free Θ^+. In addition, the argument for this strongly bound state only holds in the case the Θ^+has even parity, so a measurement would also serve to determine the parity of the pentaquark state.

Different classes of models have different predictions for the quantum numbers and parity of the pentaquark state. In a simple quark model description, with all the quarks in the ground state, the $uudd\bar{s}$ state has a negative parity. The chiral-soliton model[9] that motivated the search for the Θ^+predicts the parity to be positive, as does the diquark model[10] though with very different inputs. A definitive statement about the parity of the Θ^+would have a significant impact.

2 Miller's Schematic model

Here the relevant motivations and results of Miller's schematic model[8] are summarized. In the framework of the quark model, a large residual interaction is required to lower the mass of the $\Theta^+$to the experimentally observed value of 1540 MeV. Since such a large effect cannot be expected to arise from QCD, the additional strength must come from collective effects. By describing the Θ^+as a coherent set of color-single $d\bar{s}$,$u\bar{s}$ pseudoscaler excitations in a p-wave relative to the nucleon, the attraction between the excitations and the nucleon can remain modest, yet the mass, width and K^* interactions of the Θ^+can be accounted for. The overall effect is similar to the mechanism used to describe the nuclear giant dipole resonance.

In a nucleus, the collective action of these excitations result in the pentaquark being bound to the nucleus with a potential proportional to the additional energy due to the two additional quarks, μ. When the quark-quark attractions are taken into account, μ is assigned a minimum value of 250 MeV. The depth of the nuclear binding potential is then found to be

$$V_0 = \mu \left(\frac{M + \mu}{M} \right)^3$$

where M is the mass of the nucleon. For the minimum value of μ comes out to be $V_0 \approx 420$MeV. A mean field calculation then provides a binding energy of 490 MeV. Since the threshold energy of the $\Theta^+$is $M_\Theta^+ - M - M_K = 107$MeV, a bound pentaquark could only decay weakly.

Since the mean field calculation does not take into account the repulsive nucleon core interactions, in this letter we take a more conservative value of a 200 MeV binding potential.

3 Analogy to Hypernuclear Electroproduction

In the electroproduction of Λ-hypernuclei, the reaction is

$$e\_A \to e' K^+ B_\Lambda$$

where one of the protons in A has been exchanged for a Λ. The cross-section is calculated similarly as for photoproduction as [11]:

$$\sum_f \frac{d\sigma^f}{d\Omega}(\gamma A \to K^+ B) = \mathrm{Z}\frac{d\sigma}{d\Omega}(\gamma p \to K^+ \Lambda) \tag{1}$$

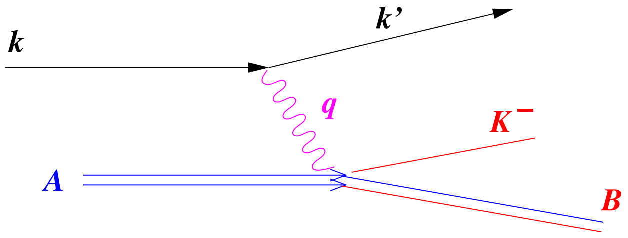

Figure 1: Kinematic variables for describing exclusive electron-nucleus scattering to a bound state: k and k' are the four momenta of the incoming and outgoing electrons, A and B are the four momentum of the target and bound final-state nuclei, and $q = k - k'$ is the four momentum of the exchanged photon.

$$\sum_g \frac{d\sigma^g}{d\Omega}(\gamma A \to K^+ B_\Lambda) = \lambda \mathrm{Z} \frac{d\sigma}{d\Omega}(\gamma p \to K^+ \Lambda) \tag{2}$$

where f denotes all final hypernuclear states (both bound and in the continuum), g only the bound final states, and Z the atomic number of the nucleus. However, generally the Λ is produced into the continuum; the probability for it to be bound to the nucleus is the "sticking probability", denoted here by λ. Typical values for λ for Λ hypernuclei are around 5%, where the depth of the binding potential for the hyperon is 30 MeV, as compared to that for a proton of 60 MeV[11]. As the momentum transfer to the nucleus increases, the sticking probability falls of rapidly.

For the case of $\Theta^+ K^-$ production, a similar relationship is assumed to hold, where the $\Theta^+$is produced off a neutron in the nucleus. Using the same form as (2), the photo-production cross-section for the $\Theta^+$is then:

$$\sigma_{B_{\Theta^+}} \equiv \sum_g \frac{d\sigma_{\Theta^+}}{d\Omega_K}(\gamma A \to K^- B^+_\Theta) = (\mathrm{A} - \mathrm{Z})\lambda_{\Theta^+} \frac{d\sigma_{\Theta^+}}{d\Omega_K}(\gamma n \to K^- \Theta^+) \tag{3}$$

However, we expect λ to be larger for Θ^+production than for Λ production due to the larger binding potential (200 MeV versus 30 MeV); this is currently being investigated.

4 Kinematic definitions

The reaction taking place involves six four-momenta:

$$k = (E, \vec{k}), \text{for the incident electron}$$

$$k' = (E', \vec{k}'), \text{for the scattered electron}$$

$$N = (M, \vec{P}), \text{for the target nucleon in the nucleus}$$

$$A = (M_A, \vec{P_A}), \text{for the target nucleus}$$

$$K = (E_K, \vec{p_K}), \text{for the final state kaon}$$

$$B = (M_B, \vec{P_B}), \text{for the final state nucleus.}$$

In addition, it is useful to use

$$q = (k - k') = (\nu, \vec{q}), \text{for the virtual photon.}$$

Under the assumption of the exchange of a single virtual photon, the electro-production cross-section can be expressed as:

$$\frac{d\sigma^3_{\Theta^+}}{dE' d\Omega_e d\Omega_K} = \Gamma \frac{d\sigma_{\Theta^+}}{d\Omega_K}$$

where

$$\Gamma = \frac{\alpha}{2\pi^2} \frac{E'}{E} \frac{s - M^2}{MQ^2} \frac{1}{1-\epsilon}, \epsilon = \left(1 + 2\frac{|\vec{q}|^2}{Q^2} \tan^2 \frac{\theta_e}{2}\right)^{-1},$$

Γ is the virtual photon flux, ϵ specifies the polarization of the virtual photon, $d\Omega_e$ and θ_e is the solid angle and scattering angle subtended by the scattered electron, and the Mandelstam variable $s = (q + N)^2$ is the invariant sum of the photon-nucleon four momentum. We will also use the Mandelstam variable $t = (q - K)^2$, the momentum transfer to the nucleus.

5 Experimental Conditions

To maximize the production rate and the sticking probability λ, we need to maximize the virtual photon flux Γ and minimize the momentum transfer to the nucleus, t. For this purpose, we plan to use the Hall A HRS with the two septum magnets in the 6 degree configuration. This provides an angular acceptance of 4.5 msr and momentum acceptance of ±4.5% for observing both the electron and kaon. For the calculations in this letter, we are using a ^{12}C target and a luminosity of $\mathcal{L}_{eN} = 10^{38}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

Due to the extreme forward positioning of the spectrometers, the angular coverage in the out-of-plane angle ϕ would be large. For the M2 measurement in the proposal for E04-012[12], a simulation was performed at similar kinematics to those studied below. The simulation found the acceptance in ϕ to span up to 80 degrees. This experiment could then be sensitive to the Σ polarization observable for the pentanucleus in the very forward direction.

The identification of the kaon in the HRS can be performed with two detectors in the standard HRS configuration. First, a pre-existing aerogel detector (n=1.015) can be used to separate the K^- from pions and electrons up to a momentum of 2.6 GeV/c. Above this, the standard gas cerenkov (n=1.0042) can serve to reject the lighter particles. In additional the time-of-flight along the 27m pathlength through the spectrometer and detector stack, with a timing resolution of 200ps or better, can identify coincident events.

6 Rate Estimate

A conservative value for $\frac{d\sigma_{\Theta+}}{d\Omega_K}(0^\circ, \gamma n \to K^- \Theta^+)$, the photoproduction cross-section, was chosen of 25nb based upon prior experimental estimates of the cross-section.

The observed rate of the produced bound Θ^+-nuclear state can be expressed as:

$$\nu_{B_{\Theta+}} = \sigma_{B_{\Theta+}} \dot{\mathcal{L}}_{\gamma^* N} \dot{f}_K^{HRS} \dot{f}_K^{decay}$$

with

$$\mathcal{L}_{\gamma^* N} = \frac{\mathrm{A} - \mathrm{Z}}{\mathrm{A}} \Gamma \dot{\Delta} \Omega_e \Delta E' \dot{\mathcal{L}}_{eN}$$

where f_K^{HRS} is the fraction of K^- associated with Θ^+production within the HRS acceptance, f_K^{decay} is the fraction of kaons decaying along the 27m through the HRS, A is the atomic weight and Z the atomic number of the target, $\Delta\Omega_e$ is the angular acceptance of the HRS (4.5msr), $\Delta E'$ is the momentum acceptance (±4.5%).

For an incident beam energy of 5 GeV, and a momentum settings of 2.3 GeV/c to detect the electron,

$$\mathcal{L}_{\gamma^* N} = 0.7\dot{1}0^{-6} \dot{\mathcal{L}}_{eN} = 7.2\dot{1}0^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}.$$

The resultant observed production rate, for a central momentum setting for the kaon-arm of 2.2 GeV/c, taking λ to be 0.05, is then:

$$\nu_{B^+_\Theta} = \lambda 520 \text{ per hour} \approx 26 \text{ per hour}$$

where f_K^{HRS} is estimated to be 0.04 from previous studies for the proposal E04-012, and $f_K^{decay} = 0.2$. This rate is very large, and even if λ is lowered by a factor of 100, it is still appreciable and very competitive with what can be achieved in approved experiments.

7 Outlook

Prior to submitting this experiment to the PAC as a full proposal, there are a couple of items we wish to understand more fully. First is the background rates. As previously mentioned, due to the the production of the K^- "below threshold" the physics background should be minimal. During the currently running Hall A Pentaquark experiment (E04-012) we will have the opportunity to collect data at very similar kinematics. We also intend to have a better understanding of the probablity the $\Theta^+$is produced bound within a nucleus. Data taken recently during the HyperNuclear experiment E94-107 should prove useful as a testing ground for this calculation.

We welcome suggestions and feedback from the PAC.

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