Search for Light η-mesic Nuclei via Recoilless $A(e, e'p)_{\eta}B$

(Letter of Intent)

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Abstract

We propose a direct search for light η-mesic nuclei over the missing mass spectrum of the two-body reaction $\gamma^* + A \rightarrow p +_\eta (A-1)$ on ^{4}He and ^{12}C targets. Three key experimental techniques will be applied: (1) a small-forward-angle tagged virtual photon beam to optimize the photon flux; (2) recoilless kinematics to minimize the momentum of produced η's relative to residual nuclei to ensure an attractive ηN interaction; (3) detection of the characteristic $\pi^- p$ pairs decayed from $_\eta(A-1) \rightarrow \pi^- + p + (A-2)$ to reduce the background. We will utilize a high precision spectrometer system (Splitter+HES+HKS) in Hall C. An additional two-arm scintillator telescope located perpendicular to the beam will be used to tag the $\pi^- p$ pairs. We will make a direct search experiment for η-mesic nuclei with high precision and high statistics.

Contents

1 Introduction

1.1 Physics Motivation

It has long been discussed whether the attractive strong interaction among mesons and nucleons may lead to the existence of mesic nuclei—the nuclear bound systems consisting of a meson and a nucleus. Due to the strong cancellation between the isospin 1/2 and 3/2 of πN s-wave scattering lengths, the low-energy s-wave pion-nucleus interaction is repulsive. Consequently, a π^0 bound state does not exist. For charged pions, on the other hand, the electromagnetic interaction provides bound states called pionic atoms. Such deeply bound states were found experimentally in ^{205}Pb at 1s and 2p recently[1]. The K^+ meson is not suitable for bound states because the K^+N interaction is repulsive at low energies. The low-energy K^-N interaction is attractive. The possible existence of deeply bound states of a K^- in light nuclei have been predicted theoretically [2]. A recent result was reported [3] that clear mono-energetic peaks have been found in the proton and neutron energy spectra in the semi-inclusive reaction $^4He(K^-_{stopped}, p/n)$. These states were assigned to the formation of strange tribaryon $S^0(3115)$ and $S^0(3114)$ respectively. In the case of the neutral η meson, an attractive strong ηN interaction was found at low energy. It provides the possibility to form new kinds of short-living nuclei consisting of nucleons and an η bound by the pure nuclear force.

The first prediction for the η mesic nuclei was suggested by Bhalerao and Liu [4] in 1985 through an investigation of the η-nucleon scattering length $a_{\eta N}$. The first-order optical potential of η in nuclear matter can be characterized by:

$$V_\eta(r) = -\frac{4\pi}{2\mu}(1 + \frac{m_\eta}{m_N})\rho(r)a_{\eta N}, \quad (1)$$

where $\rho(r)$ is the nuclear density, and μ is the reduced mass of the η. The real part of the η-nucleon scattering length $a_{\eta N}$ can be interpreted as a measure of the scattering of the initial particles while its imaginary part accounts for losses into other channels. Based on a coupled-channel analysis, Bhalerao and Liu obtained the η-N scattering length of $0.28 + 0.202i$ fm. The positive value of the real part of scattering length indicates that the low-energy ηN interaction is attractive and quasi-bound states of an η and a nucleus should be possible for nuclei with mass number $A > 11$. The widths of these bound states $\Gamma(\eta)$ were estimated at $\sim$10 MeV level. Later on, this conclusion was strengthened by a more sophisticated coupled-channel analysis [8]-[9] which took into account both resonance and non-resonance contribution. The value of $Re(a_{\eta N})$ was found up to 3 times larger than the value from the original article by Bhalerao and Liu [4], indicating that η-meson bound states with atomic number as light as $A = 2$ should be possible [10]. If they exist, one may expect the widths of such states to be relatively narrow in few-nucleon systems.

When the kinetic energy of the η is not zero, the optical potential becomes proportional to the ηN scattering amplitude $f_{\eta N}$. The real part of $f_{\eta N}$, which is just equal to the scattering length $Re(a_{\eta N})$ at threshold, is expected to remain positive up to η kinetic energies of 70 MeV (see Fig. 1). This means that the effective ηA interaction is attractive over a wide energy region near-threshold, $\Delta E_\eta \approx 0{-}70$ MeV [8].

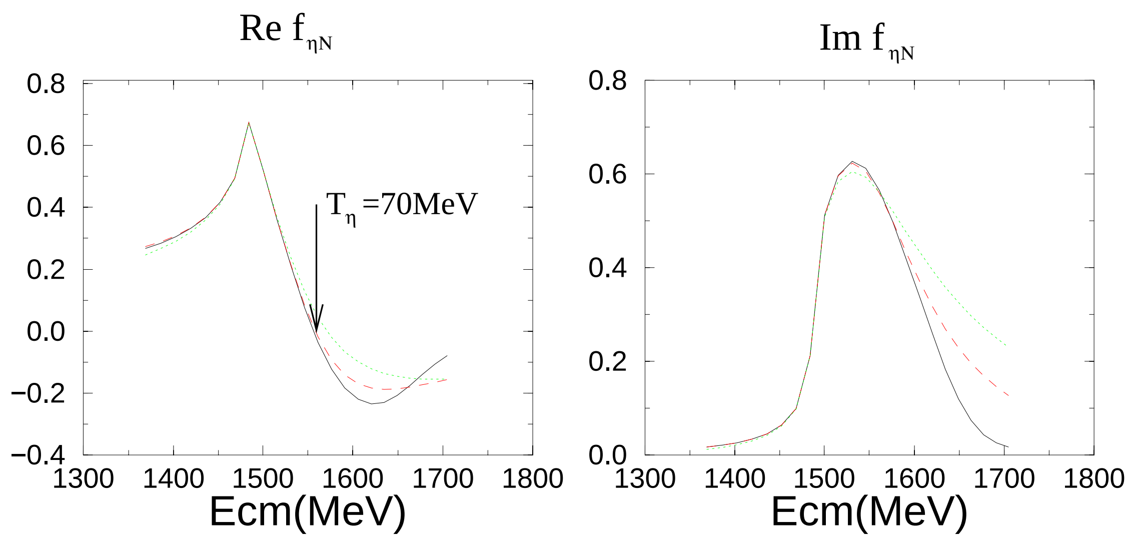

Figure 1: Energy dependence of the ηN scattering amplitude $f_{\eta N}$ (in units of fm) [8].

Investigations of η-nuclei open new possibilities for studying the ηN interaction. All existing data on ηN scattering are indirect and obtained from analysis of reactions in which ηN is produced in the final states. Results of such analysis suffer from large theoretical uncertainties. The average ηA potential in η-nuclei is mainly raised from ηN scattering. Knowing the ηA potential or at least binding energies, may shed light on the underlying ηN interaction. In addition, a study of η-nuclei provides us a natural probe to understand the $S_{11}(1535)$ resonance in the nuclear matter. Since the ηN system dominantly couples to the $S_{11}(1535)$ in the threshold region, analysis of the discrete energy spectrum of an η-mesic nucleus will open a doorway to investigate the in-medium properties of the $S_{11}(1535)$. The isoscalar property of η filters out contaminations of the isospin 3/2 excitations, which allow us to access many new nuclear states that otherwise cannot be easily reached. Due to the s-wave nature of ηNN^* coupling, there is no threshold suppression as in the p-wave πN coupling case. Consequently, a study of η mesic nuclei is particularly suited to investigate the in-medium modification of $S_{11}(1535)$ in a very clear way. Hadron masses are known to be closely related with the chiral condensate $q\bar{q}$. The presence of strange quarks in the η-meson allows one to probe the strange condensate $s\bar{s}$ in addition to non-strange condensates $u\bar{u}$ and $d\bar{d}$. In summary, discovering and learning the properties of η-mesic nuclei are of fundamental significance for understanding the interaction of the η with nucleons and nucleon resonances, and for understanding the behavior of hadrons in nuclear matter.

1.2 Experimental status of η-mesic nuclei searches

The η-nuclei have many resemblances to better known Λ- and Σ- hypernuclei, which consist of nucleons and a Λ or Σ, respectively. A major difference between them is the lifetime. The η-nuclei decay via strong rather than weak interaction as in the hypernuclei case. A typical predicted width of bound-η levels in nuclei is of the order of 10-30 MeV [4][11]-[14] or even 20-50 MeV [15]-[16] compared with typical widths of hypernuclei which are less than a few hundred keV. The largest experimental challenge is how to extract such relatively broad signals from the background. In the past decade, many experimental efforts were devoted to this topic. Several different technical approaches have been applied in η-nuclei research:

1. **The first approach was to study the near threshold total and differential cross sections of real-η production in different reactions**. The $p(d,\ ^3He)\eta$ reaction has been studied close to threshold in several experiments at SATURNE [17]-[18], and very recently at CELSIUS and at COSY [19]-[20]. In this reaction channel, the squared amplitudes show a significant increase when the energy decreases towards threshold. This behavior has been interpreted as a consequence of the existence of a quasi-bound η-^{3}He state [21]-[23]. In the meanwhile, other possible explanations such as final state effects have been discussed as well. A similar result with somewhat smaller near-threshold enhancement has been observed in the $d(d,\ ^4He)\eta$ reaction [22]. The smaller slope of the squared amplitude near threshold in this reaction has been attributed to the larger binding energy of the η in ^4He and thus larger distance of the pole from the physical region as compared to ^{3}He [22][24]. The η-^{3}He and η-^{4}He systems were also studied in η photo-production [25] close to threshold. An attractive force in the final state must lead to a near-threshold enhancement in the cross section of real-η production. Thus these results support the existence of a rather strong ηA attraction even for the lightest nuclei. Independent of the different entrance channels, a common feature of the experiments discussed above involves real-η in the final state. Since the sign of the ηA scattering length $a_{\eta A}$ cannot be determined from those data [18], one cannot distinguish unambiguously whether the observed enhancements are results of η-nucleus bound states or simply virtual states. Consequently, these experiments can only deliver indirect hints for the existence of η-mesic bound states. A conclusive answer can only be elucidated in direct search experiments by studying the properties of η-nuclei systems in the bound region.

2. **The second approach was to search for η bound states in the missing mass spectrum in inclusive reactions**. This method is a classic approach in hypernuclear experiments and has been proven to be successful. Two of such attempts were performed at Brookhaven [26] and LAMPF [27] through the $\pi^+ + A \rightarrow p + X$ reaction soon after the first theoretical suggestion [4]. The signature of the η-mesic bound state in the BNL experiment was a peak with width of $\Gamma_p \sim 9$ MeV predicted by Liu [28] in the kinetic energy spectrum of knockout protons from the two-body reaction $\pi^+ + A \rightarrow p +_\eta (A-1)$. The π^+ beam momentum was 800 MeV/c and the trigger was detection of only one proton at fixed scattering angle $\theta_p = 15^o$. No clean peak was observed. The LAMPF experiment was carried out with a lower momentum (640 MeV/c) π^+ beam, and a tighter trigger requiring the detection of a proton in coincidence with a pion from the decay of the η-nucleus through the $S_{11}(1535)$ resonance. As noted in the report [27], an excess of counts was observed in the expected area of proton kinetic energy spectrum. Unfortunately, this experiment was not completed and no final result was obtained. For this type of experiment, the binding energy and

width of a possible η-nucleus bound state are determined by the excitation energy spectrum of the residual system (or missing mass spectrum) at the presence of an inclusive background, which may not be related to η production. The combinations of different η bound states and nucleon-hole excited states may contribute to the observed excitation energy spectrum as well. Two negative results discussed above do not necessarily demonstrate nonexistence of such physical objects, since the inclusive method is less sensitive for searching for broad peaks, even though it has been successful in hypernuclear experiments searching for narrow peaks (a few times 100 keV). Further improvement would at least require tagging the η decay products.

3. **The third method is to detect the decay products of the η-nucleus**. The first such experiment was performed at the photon beam of the LPI electron synchrotron [29]-[30] on a ^{12}C target through the following reaction:

$$\gamma +^{12} C \rightarrow N_1 +_\eta (A-1) \rightarrow N_1 + (\pi^+ n) + (A-2) \tag{2}$$

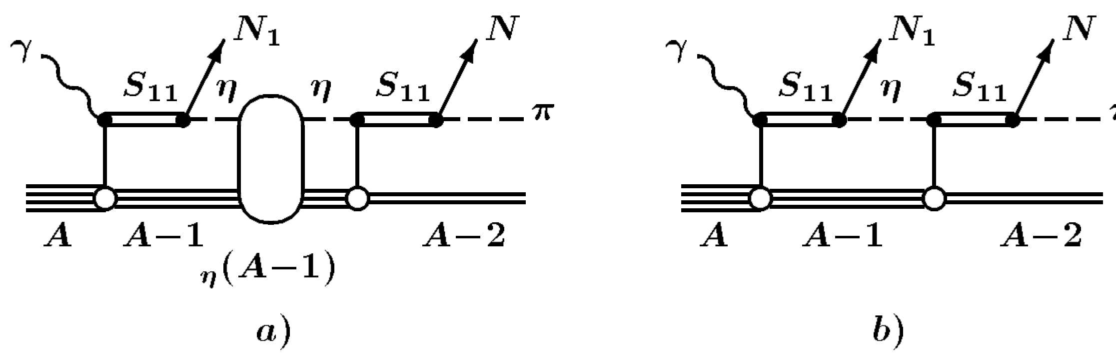

Figure 2: (a) Mechanism of formation and decay of η-nucleus through S_{11} in a photoproduction; (b) Background production without formation of intermediate η-nucleus.

The formation of the η-nucleus followed by decay is pictured in Fig.2(a). Both production of η by the photon and annihilation of η into πN pairs proceeds through S_{11} resonance. The knockout nucleon N_1 from the η-production vertex carries away most of the incident photon momentum so that the produced η's will have low momentum, and hence the ηA interaction will remain attractive to have a high probability to form the ηA bound state [31]. The πN pairs from η-nucleus decays have very characteristic kinematics. They share the total kinetic energy of about $m_\eta - m_\pi \sim 400$ MeV ($T_\pi \simeq 310$ MeV for π and $T_N \simeq 90$ MeV for nucleon) and with an opening angle of $\theta_{\pi N} \sim 180^o$. Without the formation of an η-nucleus, the background process as shown in Fig.2(b), the produced η's have relatively higher momentum and propagate freely. In this case final πN pairs will also carry higher center-of-mass momentum and their kinematic characteristics, such as opening angles, will be different from those of pairs produced through the stage of the η-nucleus. The detection of such characteristic πN pairs in the bound region can be a signature of η-nucleus formation. A bound state of η is expected to be seen as a peak in the total energy spectrum of these pairs. Indeed, a broad peak with a width of ~ 100 MeV (including the experimental resolution) and centered by $\Delta E \sim 40 \pm 15$ MeV lower than the ηN threshold was found over πN total energy spectrum at LPI, as shown in Fig 3. It was interpreted as the first direct signal of bound η-nucleus formation[29]-[30].

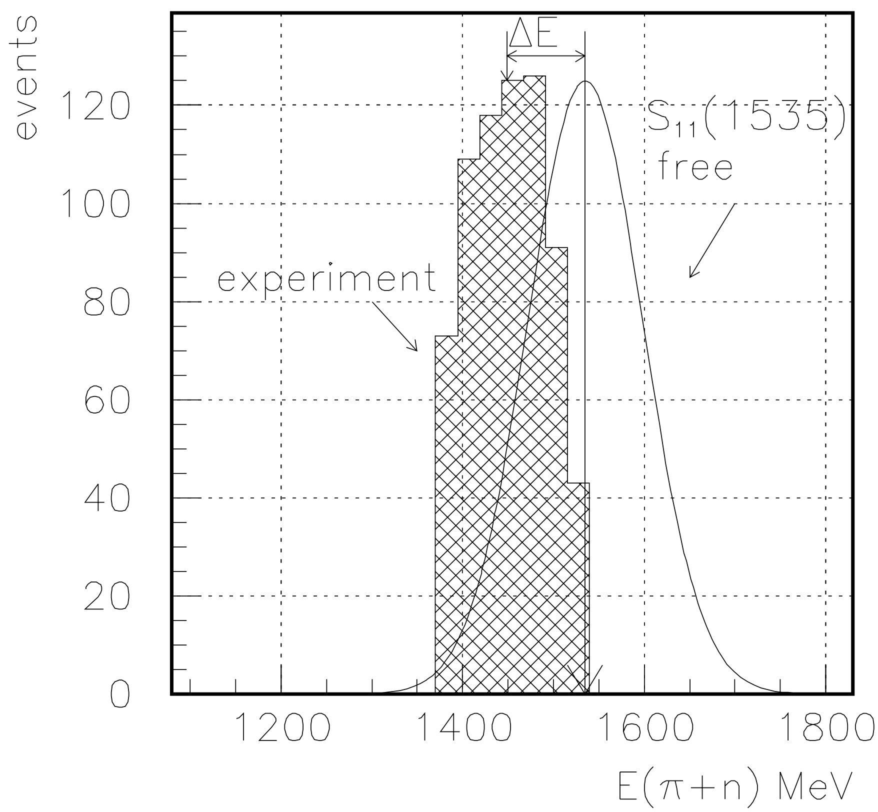

Figure 3: Result from LPI[29]-[30]. Distribution over the total energy of the $\pi^+ n$ pair after a subtraction of the background.

Another result was reported recently by the TAPS collaboration [32]. They investigated the photoproduction of η-mesic ^{3}He by studying two possible decay channels - the coherent η production and the decay into π^0p, as shown in Fig 4. In the channel $\gamma + {}^3He \rightarrow \eta + {}^3He$, a resonance-like behavior of the coherent cross section associated with an isotropic angular distribution in the threshold regime is observed (see the right plot in Fig 4). In contrast, a strong forward peak is expected for coherent η production from form factor considerations. In the channel $\gamma + {}^3He \rightarrow \pi^0 + p + X$, correlated π^0-proton pairs with relative angles near 180° in the CM system have been observed that give rise to a peak-like structure at energies slightly below the η pro-

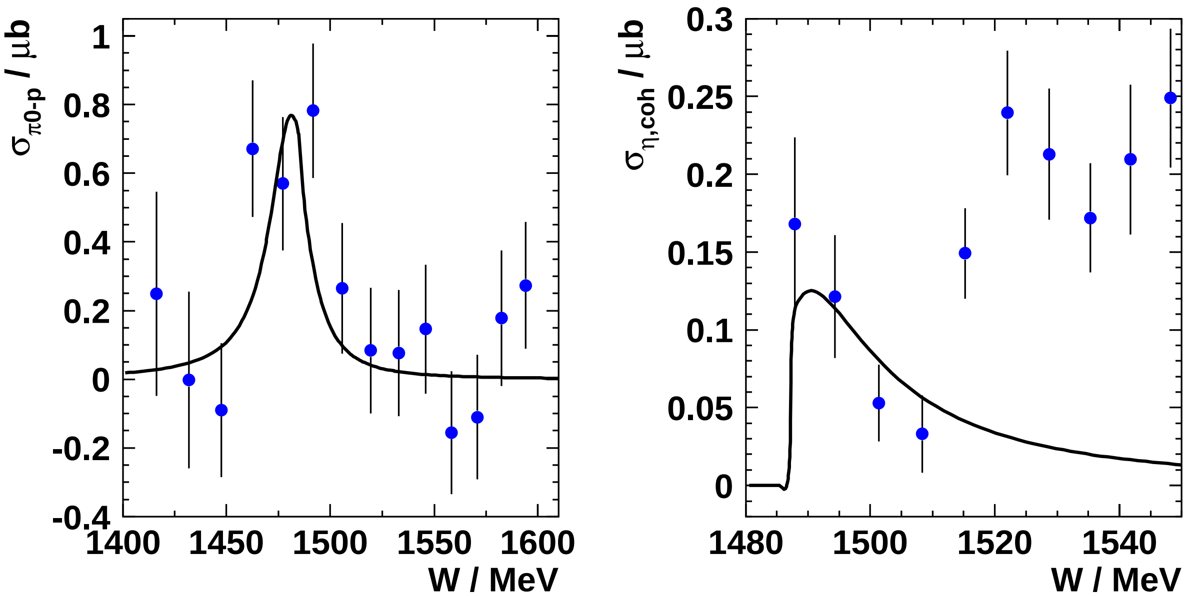

Figure 4: Result from TAPS collaboration [32]. Comparison of the decay channels of an η-mesic nucleus together with a simultaneous fit. The resonance position is at 1481.2 MeV $\pm$ 4.2 MeV with a full width of (25.3 $\pm$ 6.1) MeV.

duction threshold (see the left plot in Fig 4). A Breit-Wigner distribution was applied to extract resonance parameters (binding energy=(-4.4 $\pm$ 4.2) MeV, full width=(25.6 $\pm$ 6.1) MeV). These signatures were taken as evidence for the existence of ${}^{3}_{\eta}He$ bound state.

In this type of approach, the binding energy and width of the ηA bound states are determined by fitting the excitation function of correlated πN pairs with a Breit-Wigner distribution [32] near η-production threshold. As pointed out by a recent paper [33], if a structure is predominantly inelastic, a Breit-Wigner fit might be a good approximation; however, if a structure is predominantly elastic, using a Breit-Wigner is not justified in the near threshold region. In addition, current existing data described above suffer from low statistics or poor energy resolution. Higher statistics and improved energy resolution data are needed in order to have conclusive evidence of ηA bound states. There are several experiments already are on their way – at GSI [34] with a ion beam, at COSY [35]-[37] and JINR NUCLOTRON [38] with a proton beam, and at ESRF [39] with a photon beam.

In summary, despite several decades of progress, there is still no solid evidence for the existence of η-mesic bound states.

Reaction	Threshold
$p + p \to \eta + p + p$	1982 MeV/c
$\pi^- + p \to \eta + n$	686 MeV/c
$K^- + p \to \eta + \Lambda$	719 MeV/c
$\gamma + p \to \eta + p$	707 MeV/c

Table 1: Elementary η-production on proton

2 A proposed new experiment at Jlab

We propose to perform a direct search experiment in Hall C using the Splitter-HES-HKS experimental setup with an additional two-arm scintillator telescope. This will include: (1) using small-forward-angle tagged virtual photon beam on the light targets (^4He and ^{12}C) with a recoilless kinematics $\gamma^* + A \to p +_\eta (A-1)$; (2) the forward scattering electron and knockout proton will be measured by high resolution spectrometer HES and HKS respectively, and the missing mass spectrum will be reconstructed to search for possible formation of $_\eta(A-1)$ bound states; (3) correlated $\pi^- p$ pairs from the reaction $_\eta(A-1) \to \pi^- + p + (A-2)$ will be detected by a two-arm scintillator telescope located at the target area perpendicular to the beam, in order to cut down the background. This setup will combine, for the first time, the advantages of both the second and third methods described in the previous section.

- **The use of a tagged virtual photon beam to produce η on light nuclei has certain advantages**. Table 1 lists various elementary processes to produce η mesons on a proton. The proton-induced η-production involves three-body final states making it not as desirable experimentally. The kaon-induced reaction suffers from the low beam intensity and a small cross section. Comparing with hadron-induced reactions, the photon(electron) beam interacts weakly with nuclear matter, providing a low distortion probe to investigate interactions between nucleon and η mesons. Using a virtual photon beam tagged by the HES spectrometer in small forward angles, the high photon flux will compensate for a smaller η production cross section compared to hadron-induced processes.

  On the other hand, if η-mesic bound states exist, both binding energy and widths increase with A. For a heavy nucleus, the increase in predicted width will make it difficult to see possible bound states over the continuum background. Very light nuclei such as ^3T or ^3He which allow for a small binding energy with a single bound state therefore seem to be the most promising candidates. According to the predictions [13][40], a photon beam energy in 760–840 MeV region is optimal to form η-mesic bound state on ^4He and ^{12}C via $A(\gamma, p)_\eta B$ reaction. At this energy, the momentum transfer is favorable to the formation of a s-wave η. Particularly, recent reports from TAPS collaboration [32] on ^3He and from LPI electron synchrotron [29]-[30] on ^{12}C have shown the indications of possible η-nuclei in the bound region. Therefore, we will focus on searching for $^3_\eta T$ and $^{11}_\eta B$ bound states using ^4He and ^{12}C targets. In addition, we also consider the possibility to use a ^{10}B target depending on the availability of the ^{10}B isotope of a few mg/cm^2 thickness. One advantage of using ^{10}B is that we will be able to measure all final state particles exclusively: $\gamma^* +^{10} B \rightarrow p + \ {}^9_\eta Be$, then ${}^9_\eta Be \rightarrow p + \pi^- + \ {}^8Be$. The residual ^8Be will decay immediately into two-alpha through $^8Be \rightarrow \alpha + \alpha$. These two correlated α's can be detected by a low pressure multiwire chamber.

- **Search for η-nuclei over the missing mass spectrum of** $\gamma^* + A \rightarrow p +_\eta (A - 1)$. The virtual photon will be tagged by using the HES spectrometer to detect the electrons scattered in small angles, and knockout forward protons will be measured by high resolution HKS spectrometer. This setup was designed for the hypernuclear spectroscopic experimental program in Hall C to provide a missing-mass resolution of $\sim$ 300 keV[41], which is negligible compared with predicted η-nuclei widths ($\sim$ 10 MeV). Therefore, both width and binding energy of possible $_\eta(A-1)$ bound state will be directly determined by the width and position of the peak observed over the missing mass spectrum with high precision.

  In addition, the reaction $\gamma^* + A \rightarrow p +_\eta (A - 1)$ will allow us to use recoilless kinematics. The forward proton carries away most of the incident beam momentum so that produced η will have small kinetic energy relative to the residual nucleus where the ηN interaction remains attractive, in order to optimize the probability to form $_\eta(A - 1)$. The recoilless kinematics was proven to be a powerful experimental tool by the discovery of deeply bound pionic atom[42][43] and to be very useful to extract the meson properties at finite density [44][45].

- **Detect the characteristic $\pi^- p$ pairs from $_\eta(A - 1)$ decay to filter out the background**. According to Monte Carlo simulation, the major background in the missing mass spectrum within our spectrometer acceptance is quasifree η-production, however, single and double pion photo-production, single $f_0(600)$ and lower tail of ρ production, and other two-, three- and four- body photo-disintegration processes also contribute to the absolute background. We will tag the slow η's production by measuring the back-to-back $\pi^- p$ pairs from $_\eta(A - 1) \rightarrow \pi^- + p + (A - 2)$ decay with a two-arm scintillator telescope transverse to the beam. Expected kinetic energies are $T_\pi \simeq 310$ MeV for π^- and $T_p \simeq 90$ MeV for proton respectively, with a opening angle $\theta_{\pi p} \sim 180^o$. Such $\pi^- p$ pairs can not be produced easily in any background processes at energies as high as $E_\gamma \sim 700$ MeV, whereas they naturally appear due to η's captured (or stopped) in the nucleus[29][30]. After applying such filter, the expected bound/QF ratio should be larger than a factor of 2 on ^4He target [13] (see Fig 5).

We realize that there was a Letter of Intent proposed in 2001 (LOI-01-001) at Jlab to search for light η-mesic nuclei in photoproduction by G. A. Shkol et al. The major difference is that we suggest to search for light η-mesic nuclei directly from high resolution missing mass spectrum while measuring the correlated $\pi^- p$ pairs as a filter to reduce the background. It is not possible to obtain a missing mass spectrum with the setup proposed in LOI-01-001 by using an untagged real photon beam.

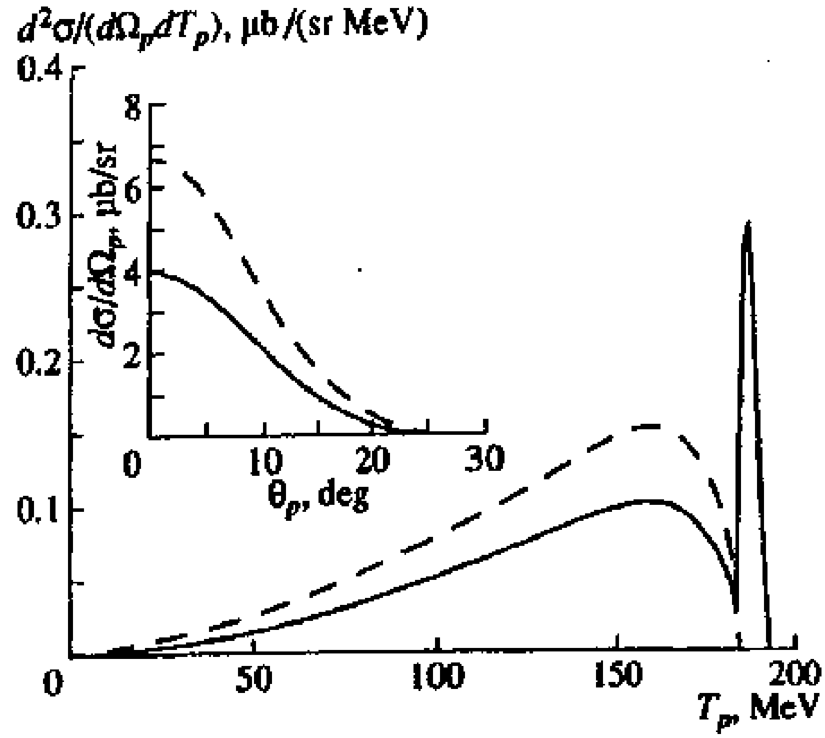

Figure 5: Predicted double-differential cross section of the η-mesic nucleus formation $^4He(\gamma,p)^3_\eta T$ (the peak on the right end) as a function of the knockout proton kinetic energy in the lab frame on the top of the quasifree $^4He(\gamma,\eta p)^3T$ background. The photon energy is $E_\gamma = 760$ MeV and the proton emission angle is $\theta_p = 10^o$. The insert displays the differential cross section of the reaction $^4He(\gamma,p)^3_\eta T$ as a function of the proton emmision angle at the same photon energy. The solid curves are with proton final-state interaction correction, and the dashed curves are without. Figure is from [13].

2.1 Experimental setup

We will use splitter+HES+HKS spectrometer configuration (see Fig 6) which is very similar as the one currently used by hypernuclear spectroscopics experiment E-01-011 [41]. The only difference is that the Enge spectrometer will be replaced with a new High resolution Electron Spectrometer (HES) to tag the scattering electrons. The HES is developed by Japanes collaborators for future hypernuclear spectroscopic experimental program in Hall C. It will be constructed and shipped to Jefferson lab in the end of 2006. The HKS spectrometer will be used to detect protons. As the virtual photon flux and possible η-nuclei formation cross section are maximum at small angle, both HES and HKS are positioned as far forward in angle as possible without accepting 0-degree electrons or positrons. The splitter magnet after the target will deliver the scattering electrons and protons into the physical acceptances of the HES and HKS respectively. A new two-arm scintillator telescope will be located in

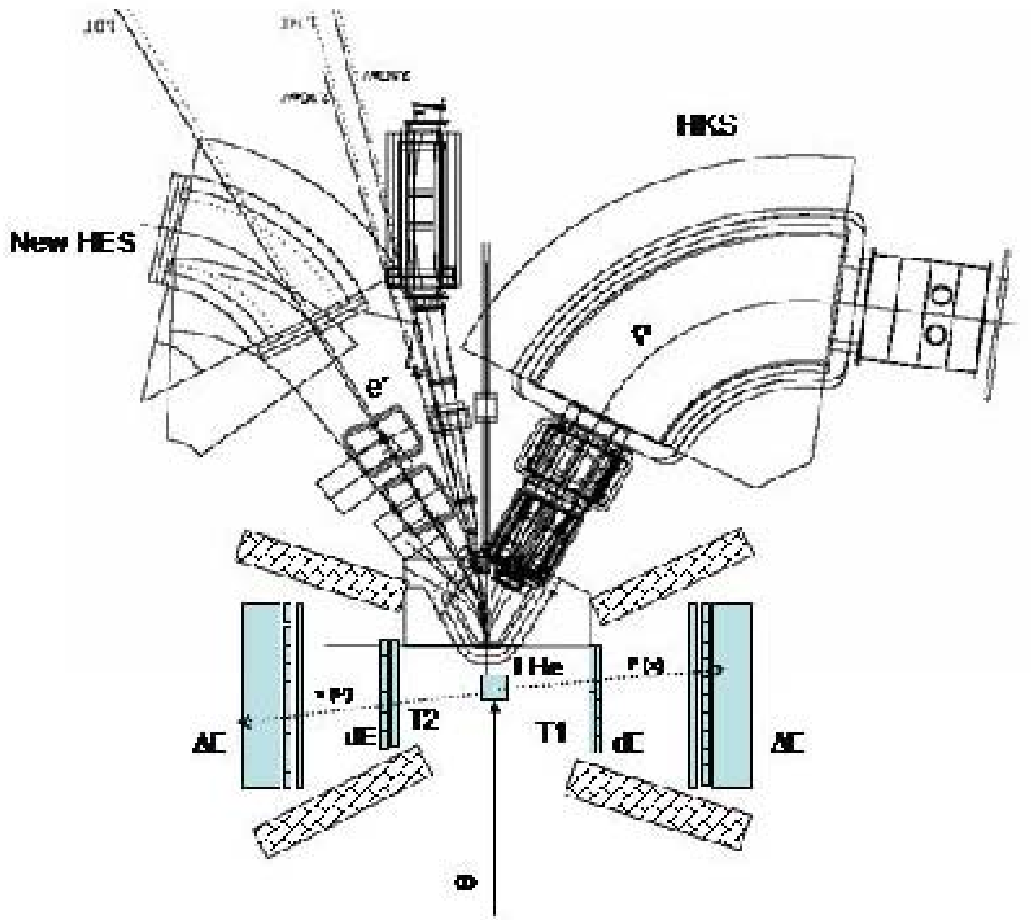

Figure 6: Schematic layout for experimental setup (not in scale).

target area transverse to the beam to detect the $\pi^- p$ pairs. The details of the experimental setup are summarized in Table 2.

We plan to use 1.4 GeV electron beam. The HES spectrometer central momentum will be set at 600 MeV/c to tag electrons at $\sim$ 5 degree. With its $\pm 10\%$ momentum acceptance, it will provide a tagged virtual photon beam at energy from 740 to 860 MeV, which will cover the optimized energy region recommended by the theoretical predictions [13][14]. The HKS spectrometer central momentum will be set at 700 MeV/c to detect protons at 7 degree. The hardware trigger will be formed by (e',p) coincidence. A two-arm scintillator telescope will be optimized to measure the $\pi^- p$ pairs ($T_\pi \simeq 310$ MeV and $T_p \simeq 90$ MeV with opening angle $\simeq 180^o$) from $_\eta(A-1)$ decay, in order to tag slow η's in off-line analysis. A schematic view of a possible telescope layout is shown in Fig

Beam condition	
Electron beam energy	1400 MeV
Beam momentum stability	1×10^{-4}
HES spectrometer (virtual photon tagger)	
Central momentum	600 MeV/c
Momentum scceptance	±10%
Momentum resolution($\delta p/p$)	2×10^{-4}
Tilt angle	Vertical: 5 degree;
	Horizontal: 0 degree
Solid angle acceptance	10 msr
HKS spectrometer (forward proton detector)	
Central momentum	700 MeV/c
Momentum scceptance	±10%
Momentum resolution($\delta p/p$)	2×10^{-4}
Proton detection angle	Horizontal: 7 degree
Solid angle acceptance	20 msr
Horizontal angular acceptance	±100 mr
Vertical angular acceptance	±75 mr

Table 2: Experimental specification

6. We will detect a $\sim$ 90 MeV proton in coincidence with a relativistic charged particle in the posite direction. In order to maximize the geometrical acceptance, we consider to use two identical time-of-flight scintillator telescopes. Each telescope will consist of: (1) a timing-start counter; (2) three layers of dE/dx thin scintillators; (3) a thick scintillator block to stop the protons. The distance between two timing counters ($\sim$ 0.8 m) will provide identification of the characteristic protons ($T_p \sim 90$ MeV, $\beta_p \sim 0.43$) from the background of the relativistic particles (π, e). The front face of each telescope will be 6 scintillator counters of size of 60×10 cm^2 and 100 cm distance from the target. We are going to investigate the backgound around the target. A plastic counter or a fiber scintillator is planned to be installed near target area during E01-011/E02-017 experiment in order to check the background rate. We will look into all possible options in the next a few months in order to optimize the detector design and off-line trigger logic.

2.2 Yield estimation

The yield of η-mesic nuclei can be estimated as following:

$$R = N_\gamma \cdot N_n \cdot \frac{d\sigma}{d\Omega} \cdot \Omega_p \cdot Br(\pi^- p) \cdot \Delta\Omega_{p/\pi^-} \cdot f(\pi^- p) \qquad (3)$$

- The N_γ is the virtual photon rate. Assume the electron beam current is $I_e = 5\ \mu$A, the virtual photon flux factor $\Gamma_\gamma \sim 0.07\ \gamma$'s/GeV/sr, and HES spectrometer acceptance is

$\Delta E = 0.12$ GeV in energy and $\Delta\Omega_e \sim 10$ msr in solid angle, the expected photon rate would be:

$$
\begin{aligned}
N_\gamma &= \Gamma_\gamma \cdot \Delta E \cdot \Delta\Omega_e \cdot I_e \\
&\simeq 0.07 \cdot 0.12 \cdot 10 \times 10^{-3} \cdot 3 \times 10^{13} \\
&\simeq 2.5 \times 10^9 \quad (\gamma/\mathrm{s})
\end{aligned}
$$

- N_n is the area density of the target nuclei. Assume a 4 cm ^4He high pressure target with density of $\rho \sim 0.134$ g/cm^3, then

$$
\begin{aligned}
N_n &= \frac{\rho t}{A} \cdot N_A \\
&\simeq \frac{0.134 \cdot 4}{4} \cdot 6 \times 10^{23} \\
&\simeq 8.0 \times 10^{22} \quad (^4\mathrm{He/cm}^2)
\end{aligned}
$$

- The $\frac{d\sigma}{d\Omega}$ is the differential cross section for the reaction $\gamma^* +^4 He \rightarrow p +^3_\eta T$. It is ~ 1 μb/sr according to [13].
- $\Delta\Omega_p$ is the solid angle acceptance for forward knockout proton detection. It is ~ 20 msr for HKS spectrometer.
- $Br(\pi^- p) \sim 0.15$ is the branching ratio of $^3_\eta T \rightarrow \pi^- + p + d$.
- $\Delta\Omega_{p/\pi^-} \sim 0.06$ is the geometrical acceptance of the two-arm telescope for p or π^-.
- $f(\pi p) \sim 0.4$ is a correlation function which gives a probability that the p hits the first arm while correlated π^- hits the second arm.

Consequently, the yield for ^4He target would be:

$$
\begin{aligned}
R &\simeq 2.5 \times 10^9 \cdot 8.0 \times 10^{22} \cdot 1 \times 10^{-30} \cdot 20 \times 10^{-3} \cdot 0.15 \cdot 0.06 \cdot 0.4 \\
&\simeq 1.44 \times 10^{-2} \quad (\mathrm{Hz}) \\
&\simeq 50 \quad (\mathrm{events/h})
\end{aligned}
$$

For 10 days running period, we will have about 12,000 events on ^4He target. The yield for more heavier targets should be higher because the cross section increase with A.

2.3 Trigger rate

We will use (e′, p) coincidence as a hardware trigger. Based on our spectrometer setting, estimated single rates (scaled from current E-01-011 on-line data) are listed in Table 3. With two layers of aerogel Cerenkov counters in HKS, the pion rejection rate is $\sim 4 \times 10^{-4}$ [41] in our momentum region. For a 4 cm ^{4}He high pressure gas target, estimated trigger rate is:

$$\text{trigger rate} \sim 1.6 \times 10^4 \cdot 3.9 \times 10^5 \cdot 20 \times 10^{-9} \sim 125 \quad \text{(Hz for } 1\mu\text{A electron beam).} \tag{4}$$

Target	Beam intensity (μA)	p rate (Hz)	π^+ rate (Hz)	e′ rate (Hz)
4cm ^{4}He	1	1.6×10^4	6.5×10^4	3.9×10^5

Table 3: Estimated single rates

3 Summary

We propose to directly search for light η-mesic nuclei over the missing mass spectrum of the two-body reaction $\gamma^* + A \rightarrow p +_\eta (A-1)$ on ^{4}He and ^{12}C targets. Three key experimental techniques will be applied: (1) small-angle tagged virtual photon beam to optimize the photon flux; (2) the recoilless kinematics to minimize the momentum of produced η's relative to residual nuclei to maximize the probability of the $_\eta(A-1)$ formation; (3) detection of the characteristic $\pi^- p$ pairs from $_\eta(A-1)$ decay to reduce the background. We will utilize the high precision spectrometer system (Splitter+HES+HKS) in Hall C. An additional two-arm scintillator telescope will greatly improve the signal-to-noise ratio. With about 10 days beam time, we will have enough statistics to determine both width and binding energy of possible η-mesic bound state with high precision.

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