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Investigating neutral meson-nuclei bound states with coherent electroproduction of η and ϕ mesons off of ^{4}He in Hall-C

A Letter of Intent to PAC 42

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Abstract

This letter's purpose is to express the collaborations strong interest and intent to investigate the existence of meson-^{4}He bounds states in Hall-C. The existence of bound ϕ-nuclei states has been postulated in light nuclei [1] [2], and explored with the coherent ϕ-D photoproduction in CLAS [3]; however, no conclusive evidence for bound state was found. A similar experiment with coherent η electroproduction off of ^{3}He at MAMI [4] did produce a quantitatively measured resonance state. The theoretical mechanisms for ϕ and η binding to light nuclei are built through two very different processes: nuclear scattering potentials with mesonic degrees of freedom [5] versus a QCD van der Waals type potential with purely gluonic exchanges [1]. In either case, the production of a meson traveling at rest with respect to a dense recoiling nucleus would maximize the interaction potential. The proposed experiment in this letter will be a coincidence experiment withe the SHMS and HMS of Hall-C to investigate the ϕ and η binding in the reactions ^{4}He(e,e' ^{4}He)η and ^{4}He(e,e' ^{4}He)ϕ.

1 Motivation

Recently, there has been increased interest in mesonic bound states in light nuclei. Experiments of coherent ϕ photoproduction off of deuterium at JLAB [6], [3] and coherent η electroproduction off of ^{3}He at MAMI [4] have searched for evidence of quasi-bound states as predicted by a number of different theoretical calculations. One such prediction is a QCD van der Waals interaction mediated by pure pomeron or multi-gluon exchange without pion-exchange. This interaction is expected to dominate between hadrons of exclusively different flavor composition [1]. A study of highly flavor desperate hadrons would be ideal, for instance, an η_c comprised primarily of charm quarks, and a nucleon with no appreciable charm quark contribution as initially proposed by Brodsky *et al* , but with such a study the phase-space is quickly constrained with the maximum energy levels available at the Thomas Jefferson National Accelerator Facility. A much more accessible study is to investigate the primarily-strange ϕ meson interaction with a dense collection of up and down quarks, such as in the ^{4}He nucleus. A ϕ-N bound state has been predicted by Gao, Lee, and Marinov [2], but as of yet there is no experimental data that can conclusively measure the strength, or existence, of a QCD van der Waals potential. The experiment proposed in this document aims to measure the first evidence of this interaction with a ^{4}He nucleus. Previous studies have at Jefferson Lab have investigated ϕ-D coupling, but the results were inconclusive [3]. Unlike the previous coherent-D experiment, the proposed experiment expects the QCD van der Waals interaction potential to be greater with the four-nucleon ^{4}He system, and the kinematics of the experiment are set to maximize this interaction.

Another prediction of bound meson-nuclei states stems from calculations of the meson-nucleon scattering lengths. For bound pionic states, the attractive electromagnetic potential and repulsive strong force potential can balance to form a resonance. While no significant electromagnetic attraction is expected with neutral mesons, like the η or ϕ, an attractive strong interaction is predicted. For the η meson specifically, an attractive-type potential arises from positive-valued phase shift calculations from scattering lengths extracted from data [7]. Many predictions have been made that the η binding to light nuclei is strong enough to observe in medium-energy scattering experiments [5], [8]. Recently, an η-^3He experiment was conducted with the TAPS detector at MAMI, which measured an η-mesic nucleus resonance with binding energy (-4.4 $\pm$ 4.2) MeV and full width (25.6 $\pm$ 6.1) MeV in-line with with theoretical expectations [4]. Scattering lengths for η-^{4}He systems have also been calculated [9], and similar ϕ-mesic systems have been predicted [10] [11].

To investigate mesonic-nuclei binding, this experiment will electro-produce ϕ and η mesons coherently off of a ^{4}He target. The experiment is a coincidence experiment measuring the scattered electron and the recoiling ^{4}He in coincidence. The kinematics of the experiment are set such that, within acceptance, the produced meson and recoiling ^{4}He travel in the same direction and at the same velocity to maximize any potential binding. The correct final state is selected through a missing-mass identification of the meson. The goal of the proposed experiment is to explore light neutral meson coupling to ^{4}He nucleus. Any coupling of this type would result in a deviation in total cross-section near the desired kinematics. The normalized cross-sections, differential in the relative velocity of the meson-^{4}He system, will be extracted and will provide insight into the strength of any interactions.

If evidence for a ϕ bound state is seen from this experiment, it would provide strong motivation to explore binding with heavier charmed mesons, like the η_c or J/ψ. At Jefferson Lab, strong experiments with η_C or J/ψ bound states could be run, but not without moderate adjustments to the Hall-A or Hall-C instrumentation and more beam-time than proposed here. If evidence for an η bound state is seen, this would confirm the existence of binding beyond the η-^{3}He state seen recently at MAMI. In any result, this experiment would be the first ever exploration of ϕ or η binding with a ^{4}He nucleus.

2 Kinematics

The experiment will be run with three primary kinematic settings; ^{4}He(e,e' ^{4}He), ^{4}He(e,e' ^{4}He)η, and ^{4}He(e,e' ^{4}He)ϕ. The initial setting will be to detect exclusive elastic ^{4}He events as a baseline measurement with well known cross-section measurements at SLAC [12] and JLab [13]. A study of this reaction will allow us to understand and control our systematic uncertainties. Following those settings, the majority of the production running will be done on the inclusive coherent ϕ and η electroproduction. A summary of the settings is provided in Tab. 1.

Reaction	e' Mom. (GeV/c)	e' Angle (deg)	^{4}He Mom. (GeV/c)	^{4}He Angle (deg)
^{4}He(e,e' ^{4}He)	10.75	7.2	1.40	76.0
^{4}He(e,e' ^{4}He)η	10.15	7.6	1.43	55.0
^{4}He(e,e' ^{4}He)ϕ	9.7	5.7	1.30	35.5

Table 1: Proposed central kinematic settings for the SHMS and HMS.

If one constrains the ^{4}He and meson to be bound, with a fixed beam energy, the kinematics are constrained to a single variable. In Fig. 1, various kinematic quantities have been calculated versus the scattered electron energy. The constraints on what electron energy to choose for the experiment come in a few ways. First, the minimum angle of the SHMS is 5.5 degrees. Next, one wants a small $|t|$ to maximize the meson production cross-section, and also a small Q^2 to maximize the virtual photon flux.

3 Coherent ϕ and η electroproduction off of ^{4}He cross-section determination

There is no existing measurements or cross-section data of coherent ϕ electroproduction off of ^{4}He, and no published theoretical calculations. The method employed here to calculate the cross-section starts with published data on coherent photoproduction of ϕ and η off of deuterium. These cross-sections can be found in an energy range close to that of the proposed kinematic settings for the ϕ differential in t [6]. To extrapolate to the ^{4}He coherent cross-section, one can assume that, to fist order, the ϕ-^{4}He cross-section can be represented as follows:

$$\left(\frac{d\sigma}{dt}\right)_{He4} = \left(\frac{d\sigma}{dt}\right)_{D} \frac{F_C^2(t)_{He4}}{F_C^2(t)_D} \tag{1}$$

Where $F_C(t)$ is the charge form factor. The charge form factor has been explored extensively in electron elastic scattering experiments for both the D and the ^{4}He nuclei. The functional form used for calculations in this proposal is calculated from Brodsky's dimensional-scaling quark model [14] for light nuclei F_C plus a small empirically motivated correction for the lowest Q^2 values. The results of this calculation, and the resulting

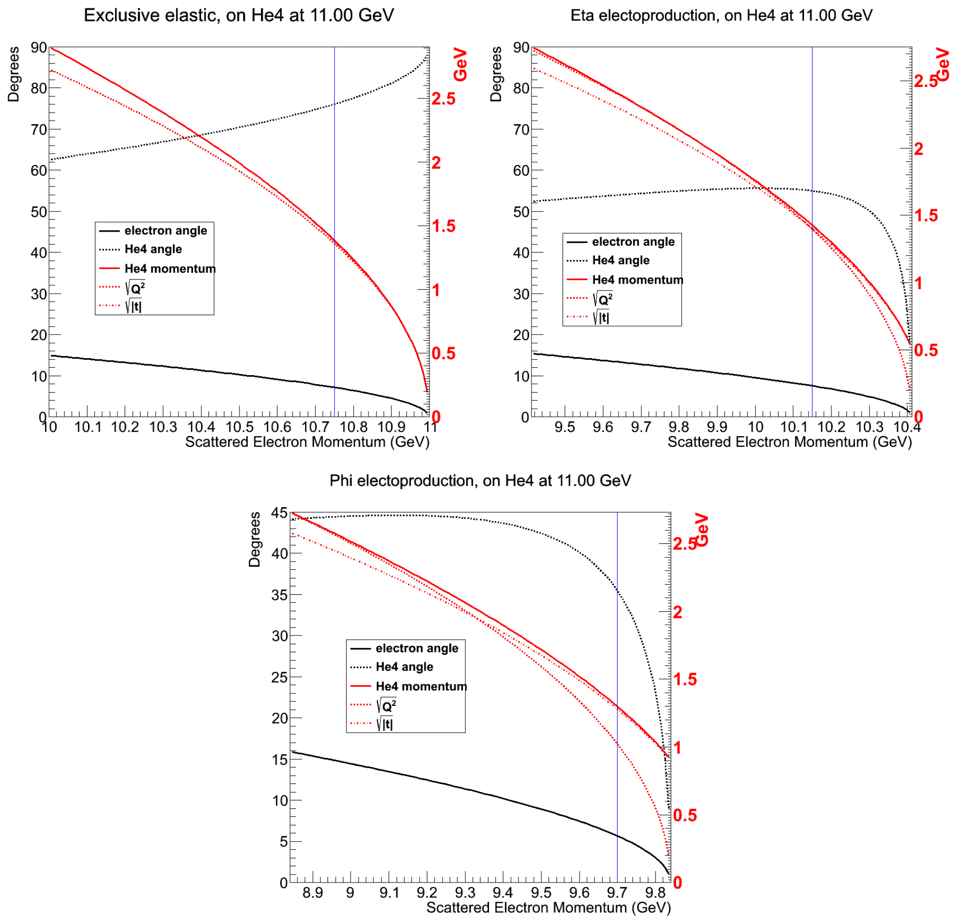

Figure 1: Calculations of the 3 proposed kinematics for the elastic (top left), η (top right), and ϕ production (bottom). The plots show all kinematics calculated as a function of the scattered electron momentum. The black curves show the scattered electron (solid) and scattered ^{4}He angle (dashed) corresponding to the left axis. The red curves show the scattered ^{4}He momentum (solid) root-Q^2 (dashed) and root-t (dot-dashed) corresponding to the right axis. The vertical blue line is the proposed kinematic setting for the experiment.

$[F_C]_{He4}/[F_C]_D$ function is shown in Fig. 2. Note that the region of interest is in values of t from -1 to -2 GeV^2, and that no diffractive region structure is expected in the differential cross-section, and hence diffractive regions are not represented in the curves. A similar extrapolation is made using the charge form-factor ratio above, only using the $d\sigma/d\Omega$ differential cross-section on deuterium calculated by Ritz and Arenhoval [15] to extrapolate an η-^{4}He coherent cross-section.

4 Detector Hardware Requirements

The proposed experiment will use the SHMS and HMS detectors in Hall-C. The SHMS detector will be used to detect the scattered electrons at the angles shown in Tab. 1. For the SHMS, the standard Hall-C configuration for this detector is more than adequate for this experiment. One possible upgrade that would help control tracking inefficiencies is re-

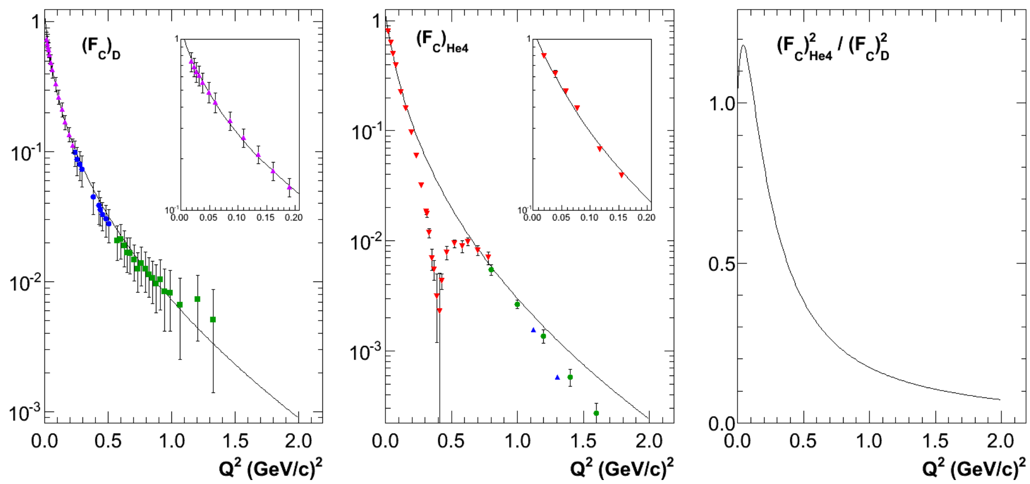

Figure 2: Plots show the charge form-factor vs Q^2 for deuterium (left), ^{4}He (center), and the ratio of ^{4}He to deuterium squared. The curves shown are calculations from Brodsky's dimensional-scaling quark model with empirical corrections to better represent data at low Q^2. The data for deuterium was collected by DESY (blue circles) [16], Cambridge (violet triangles) [17], and Saclay (green boxes) [18]. The data for ^{4}He was collected by Stanford (red down-triangles) [19], SLAC (green circles) [12], and JLab (blue triangles) [13].

placement of the SHMS drift chambers with GEM tracking planes. The advantage of such an upgrade is discussed briefly in the following section. The ^{4}He will be detected in the HMS at momentums and angles shown in Tab. 1. One thing to note here, is that the central momentum setting corresponds to the double charge Helium atom. The equivalent momentum setting for protons or pions would be one-half the number listed in the table. The recent elastic coherent ^{4}He scattering experiment E04-018 [13] detected ^{4}He at momentums close to this experiment's proposed central momentum setting. Very clean and efficient triggering was accomplished by setting a minimum ADC signal threshold in the first scintillator plane. The ^{4}He will produce a very large ADC signal as it leaves all of its energy in the standard 2 cm thick scintillator plane.

In addition to a scintillator ADC trigger, a true single-arm coincidence would help to control backgrounds. To best accomplish this, a very thin scintillator plane (< 0.5 cm thick) followed by a standard Hall-C scintillator plane with separation of $\sim 2\ m$ would be used. With this separation between planes, the flight times for the pion, proton, and ^{4}He are $\sim$ 8ns, 13ns, and 18ns respectively. The combination of a scintillator energy deposit and a time-of-flight measurement will give very clean particle-type discrimination. In order to use this TOF cut effectively, all other sub-detectors in between scintillator planes would have to be pushed aside to minimize energy loss or multiple scattering.

The target cell specifications will be identical to those used for the Happex ^{4}He target [20], [21], [22]. This cell puts compressed ^{4}He gas at $\sim$13 atm and $\sim$7 K over a 20 cm target to give an areal density of 2.56 g/cm^2. The target cell is designed to have very thin walls to minimize absorption and radiative effects as the recoiling ^{4}He leaves the cell. The walls are: entrance (0.178 ± 0.02)mm, exit (0.213 ± 0.02)mm, side (0.290 ± 0.02)mm. The gas ^{4}He target can handle a relatively large amount of current, and this experiment is designed to run entirely with 80 μA of current.

5 Simulations and background rates

The above versions of the target and cross-sectional formula have been implemented in SIMC. SIMC is then run under typical conditions, with the standard energy loss, electron radiative effects, and multiple scattering options implemented. For final state identification, the largest affect on the reconstructed ϕ-meson width comes from multiple scattering. A simulated yield spectra of the missing mass is shown in Fig. 3.

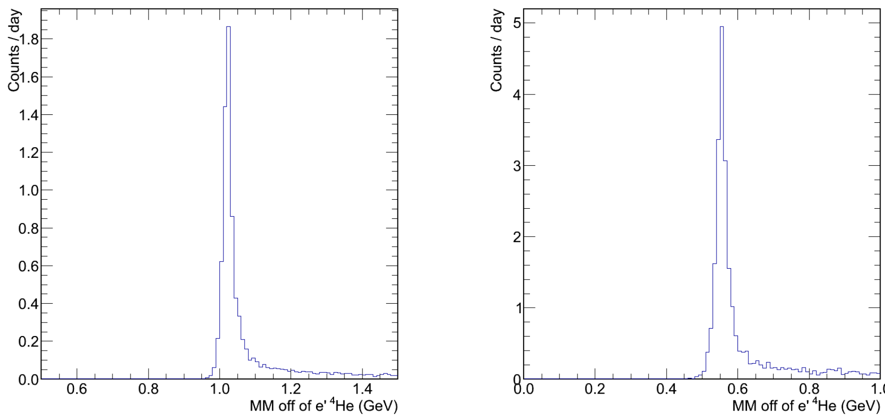

Figure 3: The missing mass for 1 day of beam-time as simulated with SIMC introducing the cross section calculated above for coherent ϕ production (left) and η production (right). The simulation accounts for radiative corrections on the electron, energy-loss, and multiple scattering for both particles. Basic acceptance cuts have been applied to the simulation.

Background proton and pion rates were calculated with the well established Wiser code [23] for all three proposed kinematics. All Wiser rates are only calculations of the electron-proton interaction in the ^{4}He nucleus. While this likely underestimates the pion rate, with a time of flight and energy deposit trigger, all π^+ singles are expected to be rejected. The contribution of proton rate from electron-neutron interactions is expected to be much smaller than from the electron-proton interaction and hence providing a reasonable estimate for the proton rates at the proposed kinematics. For the electron arm, π^- rates are much smaller than the singles electron rates. For all settings, the π^+ and proton rates are calculated using one-half the central momentum setting of the ^{4}He to account for only half the charge. These rates are shown in Tab. 2. Elimination of the pion and proton rate in the HMS can be done with high precision on the trigger level, using ADC signal discrimination as described in the previous section.

The highest level of background comes from electrons in the SHMS. The rates were calculated with QFS [24] and CTEQ6 [25] and found to rise quickly at lower angles and higher momentums. Fig. 5 shows the expected rate over the SHMS acceptance for the ^{4}He(e,e' ^{4}He)ϕ kinematic setting. The $>$ 5 MHz singles rate in the SHMS for the 9.7 GeV/c and 5.7 deg setting would lead to a cripplingly high tracking inefficiency without some adjustment to the experiment settings or the spectrometer hardware. Additionally, this rate is expected to spike over 25 MHz in regions at the lowest theta within acceptance (around 4.7 degs). This singles rate could be cut by roughly a factor of two by offsetting the central spectrometer angle to 6.7 degs, but would place the desired ^{4}He(e,e' ^{4}He)ϕ electron signal off-center in the acceptance. Such a change would leave the overall signal

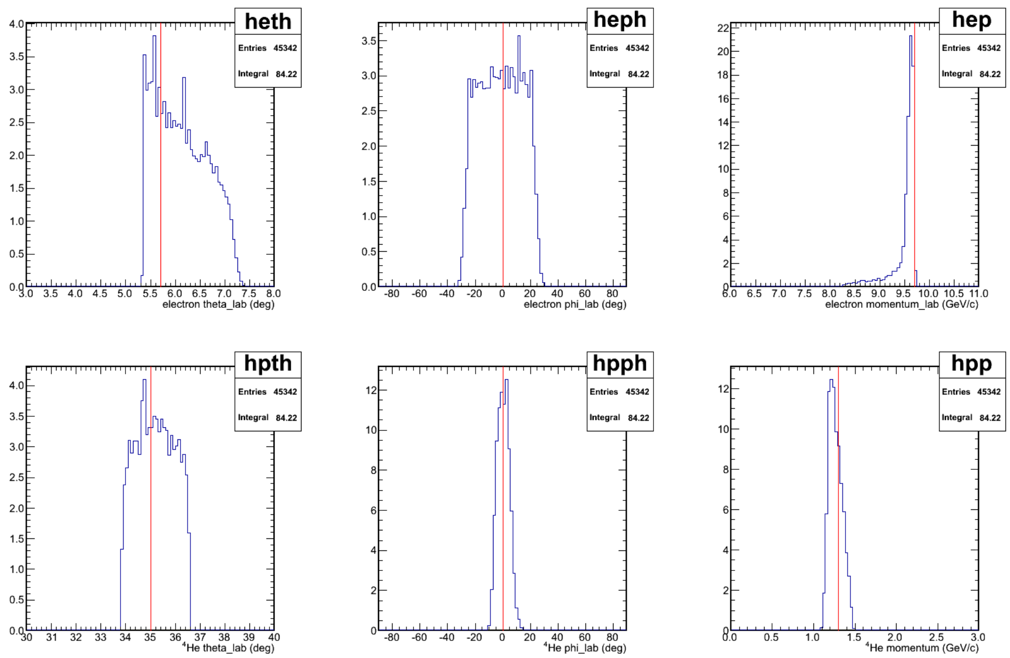

Figure 4: The SIMC yield calculations for coherent ϕ production at the proposed kinematic settings. The yields are scaled to 10 days of beam-time. The simulation accounts for radiative corrections on the electron, energy-loss, and multiple scattering for both particles. Basic acceptance cuts have been applied to the simulation.

SHMS cent. mom. (GeV/c)	SHMS Angle (deg)	QFS e (kHz)	Wiser π^- (kHz)
9.7	5.7	5491.0 (2793.5)	2.5
10.15	7.6	978.6	1.1
10.75	7.2	629.3	< 0.1
HMS cent. mom. (GeV/c)	HMS Angle (deg)	Wiser proton (kHz)	Wiser π^+ (kHz)
1.3 (0.65)	35.5	414.3	1554.0
1.43 (0.715)	55.0	118.9	208.2
1.4 (0.700)	76.0	< 0.1	36.9

Table 2: Singles rates for both spectrometer arms at all proposed settings. For the SHMS, the number in parentheses indicates the rate over the wider angle half of the spectrometer acceptance (from 5.7 to 6.7 degs in theta). For the HMS central momentums, the number in parentheses is the single charge momentum setting equivalent to the ^{4}He double charge setting. See text for discussion.

rate mostly unchanged. Another option would be to replace the SHMS drift chambers with GEM planes. Such an enhancement of the SHMS to handle high rates would be greatly beneficial to future experiments, although the finer points of that discussion is beyond the scope of this proposal.

Nucleon-resonance backgrounds are predicted to be negligible, as excited states would be expected to break up the ^{4}He. Hadronic backgrounds are excluded by a tight cut at the ϕ or η mass in the missing mass spectrum. The expected singles rates for electrons, protons, and pions for all settings are shown in Tab. 2.

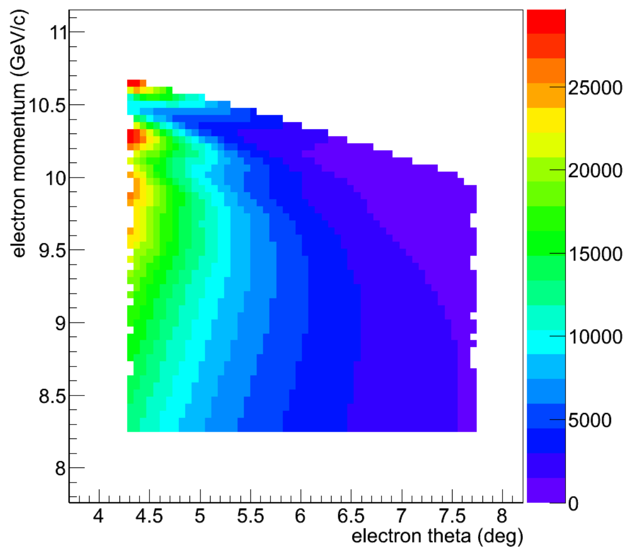

Figure 5: The simulated electron rate over the SHMS acceptance for a central angle of 5.7 deg and a central momentum of 9.7 GeV/c, the z-axis scale is average rate over the bin in kHz. The majority of the electron singles rate comes at high momentum and low angle. See text for a discussion of how to mitigate the high rate regions.

6 Run Plan and Projected Results

The proposed experiment will start with the exclusive elastic scattering setting ^{4}He(e, e' ^{4}He) with 12 hours of beam-time. This will provide a basis of $\sim$ 2000 elastic ^{4}He counts. The η production setting will run for 4 days, providing an estimated 100 counts, followed by the ϕ production setting which will then run for 10 days of beam-time, providing an estimated total of 80 counts after all acceptance and analysis cuts.

The primary goal of the experiment is to measure the deviation in cross-section over the meson-^{4}He relative velocity. If a real potential between the meson and ^{4}He exists, then a deviation of the cross-section would be strongest where the relative velocity between the meson and nuclei is zero. For this study, a explicit cross-section determination is not necessary. only the relative variation in cross-section needed. Shown in Fig. 6 are the expected raw and normalized yields versus the difference in beta. These plots are produced from the simulation results of SIMC. Error bars on the plots come from statistical uncertainties alone, which are expected to dominate over the systematics with the proposed beam-time request.

Motivation for this experiment is a first ever exploration of η or ϕ binding to a ^{4}He nuclei. The proposed beam-time is 15 days of beam-time for exploring both the η and ϕ states, but increased beam-time or focused time on only one channel would increase precision. To illustrate this, Fig. 7 shows the normalized yield for 20 total days on η alone. Increased statistics would require a more careful study of the systematic uncertainties, but conservative estimates put them at most at the 10% level, dominated in the ϕ kinematic setting by tracking efficiency with a $\sim$2 MHz background singles rate.

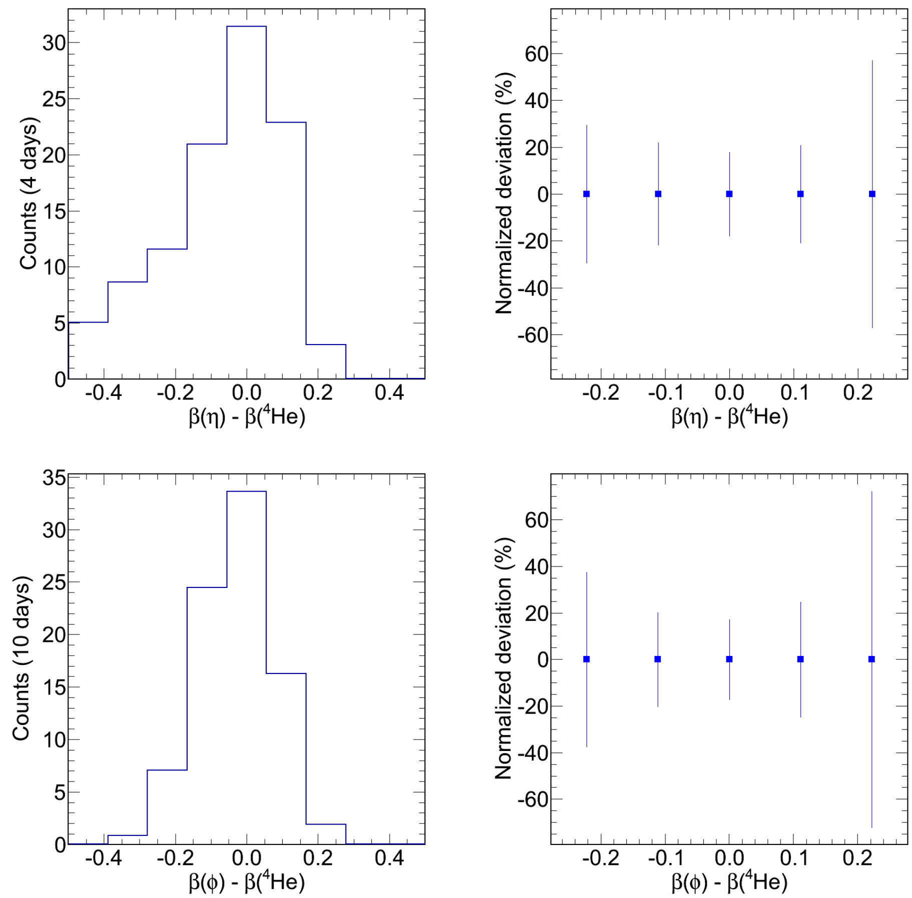

Figure 6: The simulated counts and normalized yield deviation for η (top) and ϕ (bottom) versus the difference in velocity of the meson with respect to the recoiling ^{4}He over the proposed run time. The normalized yield shows the resolving power of a deviation over the difference in velocity. A deviation away from zero could be an indication of a bound-state.

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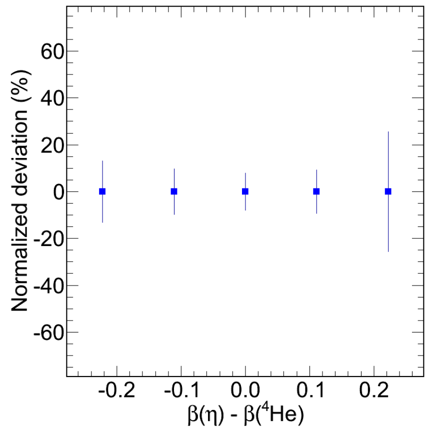

Figure 7: Equivalent plot to the top right plot of Fig. 6, only with 20 total days of beam-time on the ^{4}He(e,e' ^{4}He)η reaction alone.

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