A Measurement of ^{4}He Coherent J/Ψ Photo-production at threshold in Hall C at Jefferson Lab; Towards a determination of ^{4}He Gluonic Radius

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A Letter of Intent to PAC47

Abstract

In this letter we propose to measure for the first time the matter form factor of ^{4}He at the lowest possible range of t using threshold coherent photo-production of J/ψ on a gaseous ^{4}He target in Hall C at Jefferson Lab. We will attempt for the first time to extract a gluonic matter radius by performing a measurement of this process at the highest possible CEBAF beam energy available in Hall C, and thus the lowest t_{min} values achievable in a fully exclusive measurement. The coherent threshold photo-production of J/ψ on ^{4}He occurs at a photon energy of about 4.5 GeV and large t_{min} of about 4 GeV^2. Therefore, to reach low t_{min} values, we use a bremsstrahlung beam generated from a 11.0 GeV electron beam traversing a 9% copper radiator and striking an existing 20 cm race track ^{4}He gas target with half the liquid He density and half the aluminum wall thickness. The measurement is proposed to be performed in Hall C at Jefferson Lab with a 11.0 GeV incident beam at 50μA current and a 9% radiator. The decay pair from the produced J/ψ will be measured using the HMS and SHMS. The recoiling ^{4}He nucleus will be tagged by a third detector that will cover an angular range between 5° and 30 ° in two settings that match the J/ψ decay acceptance into the spectrometers. At these low t_{min} values the coherent photo-production cross section is proportional to $|AF_T(t)|^2$, which is large enough that, surprisingly, such a measurement is possible with good statistical precision. The results can then be compared to lattice QCD calculations of the matter form factor. The proposed measurements, together with lattice QCD, will allow for the first ever extraction of a gluonic radius. This experiment will be a precursor to the possible complete studies on ^{4}He that can be performed at an EIC.

Contents

Introduction & Motivation

In nuclear physics the description of a nucleus is usually expressed in terms of the hadronic degrees of freedom. Most commonly, it is described using nucleons and their interactions, mediated by light mesons for the long range part of the nucleon-nucleon interaction, multi-pions and heavier mesons for the intermediate region, and a phenomenological repulsive part at short distance. Ab-initio calculations using hadronic degrees of freedom have been very successful in describing the ground state of light nuclei for example. However, at a deeper level it is still puzzling how to relate the success of this nucleon-meson description to the basic degrees of freedom of QCD, quarks and gluons, and their direct role in the emerging properties of a nucleus.

More recently, with the keen desire to understand nuclear physics in terms of QCD, questions about the explicit role of quarks and gluons in nuclei have taken center stage. Ab initio calculations of basic properties of light nuclei using lattice QCD have been initiated, albeit with approximations due to the limited performance of the best available computers. Novel supercomputers such as quantum computers as well as enhanced computing methods are our best future promise to ultimately tackle this problem with the controlled approximations. In the mean time experiments could help provide an answer to some simple but important questions in this regard.

One of the fundamental puzzles in hadronic physics is the origin of the nucleon mass. How does the mass emerge from the relative contributions by the quarks and gluons? An important piece of this puzzle can be gleaned from nature the matter radius of the nucleon, and its relative magnitude compared to the charge radius. The nature of the gluonic radius of a nucleus is a similar puzzling question in nuclear physics. Is the gluonic radius of ^{4}He larger or smaller than the charge radius of ^{4}He? While we understand that the charge radius of a nucleus emanates from the average motion and dynamical properties of the charged quarks it is not obvious what role the gluons play in defining the matter radius of the nucleus. While the charge distribution of many nuclei has been measured through electron scattering, and charge radii have been extracted, one has yet to understand the matter distribution, which must involve the gluons and is therefore not easily accessible by electron scattering.

Similar to the case of the nucleon, the coherent photo-production of J/ψ on ^{4}He offers a unique opportunity to, for the first time, explore the gluonic component of its matter distribution directly. Lattice calculations at the partonic level of the matter form factor in ^{4}He in the measured region will be a powerful benchmark test of QCD in nuclei. With this experiment we will have a sneak preview on the gluonic radius of ^{4}He. We will need first to benckmark first lattice QCD calculations of ^{4}He in the measured range and then extend the calculations to extract the radius from the data and lattice calculations in the unmeasured region. It is also a precursor of the possibilities of similar studies at an EIC.

Theory Evaluations

2.1 Theory Model

With the objective to show that in principle the experiment is feasible and determine our beam time request we chose the Pomeron-Exchange model developed in Ref. [1, 2] to evaluate the cross sections. We then merged these cross sections into our simulation to make experimental predictions for the proposed experiment.

Using the factorization approximation within the multiple scattering formulation, the differential cross section of exclusive photo-production of J/ψ on a nuclear target (T) with A nucleons, $\gamma(q) + T(P_i) \longrightarrow J/\psi(k) + T(P_f)$ can be written as

$$\frac{d\sigma}{dt} = \frac{\pi}{|\vec{q}||\vec{k}|}\left(\frac{d\sigma}{d\Omega_{Lab}}\right) \tag{2.1}$$

where the differential cross section in the laboratory frame ($\vec{P}_i = 0$) is

$$\frac{d\sigma}{d\Omega_{Lab}} = \frac{(2\pi)^4|\vec{k}|^2 E_{J/\psi}(\vec{k})E_T(\vec{q}-\vec{k})}{|E_T(\vec{q}-\vec{k})|\vec{k}| + E_{J/\psi}(\vec{k})(|\vec{k}| - |\vec{k}|\cos\theta_{Lab})|} \tag{2.2}$$

$$\times \quad |AF_T(t)|^2 \times \left[\frac{1}{4}\sum_{m_s,\lambda_\gamma}\sum_{m'_s,\lambda_{J/\psi}}\right]|\langle k\lambda_{J/\psi}; p_f m'_s|T_{\mathbb{P}}|q\lambda'_\gamma p_i m_s\rangle|^2 \tag{2.3}$$

where $t = (q-k)^2$, $\cos\theta_{Lab} = \hat{q}\cdot\hat{k}$ and $\langle k\lambda_{J/\psi}; p_f m'_s|T_{\mathbb{P}}|q\lambda'_\gamma p_i m_s\rangle$ is the matrix element of the Pomeron exchange in the nucleon photo-production of J/ψ, $\gamma(q) + N(p_i) \to J/\psi(k) + N(p_f)$.

Here $F_T(t)$, the matter form factor is related to the nuclear charge form factor $F_c(t)$ with no exchange current contributions as

$$F_c(t) = F_N(q^2)F_T(q^2 = t) \tag{2.4}$$

2.2 kinematics

Given that the process is fully exclusive, the largest cross sections will be reached when t is small enough such that the matter form factor of ^{4}He is not too small and thus t is close

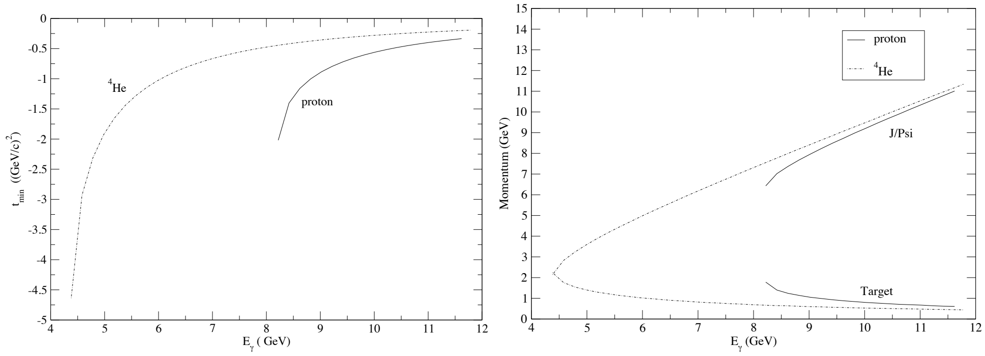

Figure 2.1: Left: Variation of t_{min} for coherent photo-production of J/ψ on a proton and a ^{4}He from threshold to 11.5 GeV photon beam. Right: Momenta of outgoing J/ψ and ^{4}He as a function of photon beam energy.

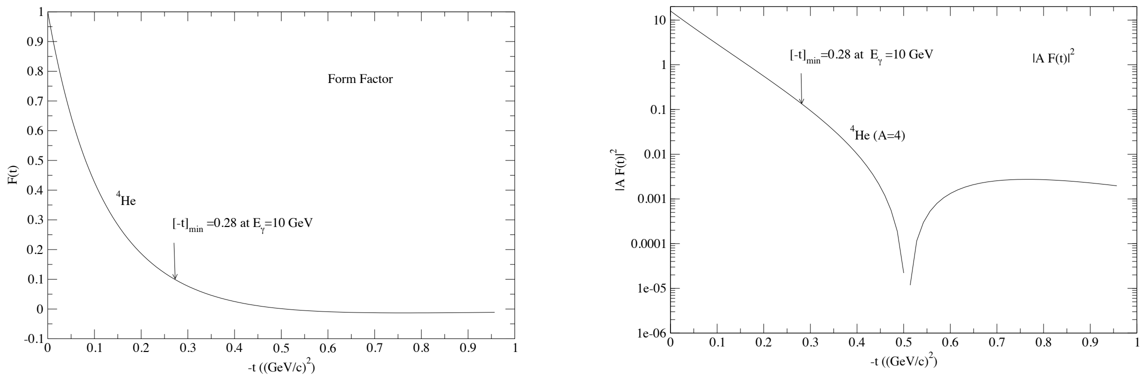

Figure 2.2: Left: Matter form factor as a function of $-t$ of ^{4}He generated in Ref. [3]. Right: $|AF(t)|^2$ using the same form factor.

to t_{min} while t_{min} itself is smallest. To get a sense of the dependence of t_{min} with the photon beam energy and also what momenta of J/ψ and ^{4}He are probed we show this dependence in Fig.2.1

2.3 Theory cross sections estimates

Using the formalism above, with the matter form factor shown in Fig.2.2, the differential cross section was evaluated at different bremsstrahlung beam energies from 8.5 GeV where t is about 0.5 GeV^2 to less then 0.25 GeV^2 at 11 GeV photon beam energy.

It is clear that given the t-dependence of the matter form factor, and the fact that the higher the photon beam energy the lower the accessible t_{min}, we have an opportunity to

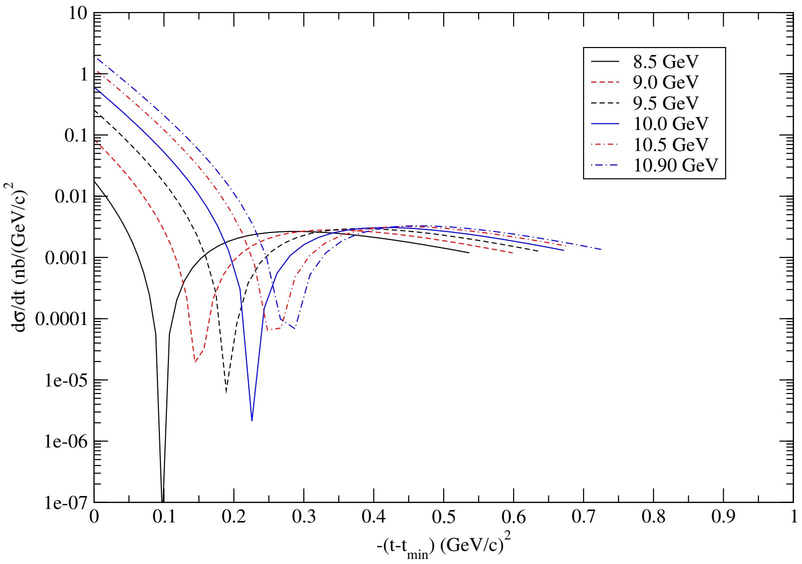

Figure 2.3: Differential cross section $-(t-t_{min})$ dependence for several photon energies well above the coherent threshold production of J/ψ on ^{4}He. Note that the higher the energy the higher the overall differential cross section

measure a differential cross section equivalent to that measured on the proton at photon energies close to the maximum electron beam energy of about 11.0 GeV. An estimation of the differential cross section at different photon beam energies, using the model above, is shown in Fig. 2.3.

Finally, the total coherent photo-production cross section on ^{4}He is shown along that on a proton for comparison in Fig. 2.4. The size of this total cross section is dominated by the low t values of the differential cross section. The change in slope as the photon energy becomes larger reflects the relative contribution when t_{min} is above or below the first diffraction minimum in the cross section.

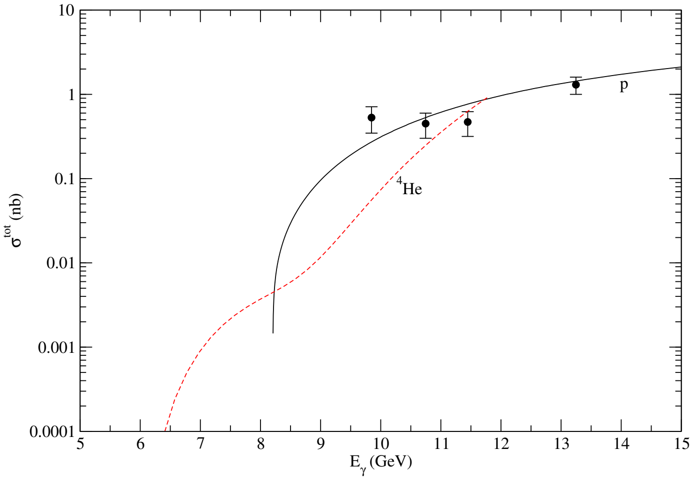

Figure 2.4: Total cross section of coherent J/ψ on ^{4}He (dashed curve). The solid curve is that of the proton for comparison. The data points are part of SLAC and Cornell near threshold proton measurements. GlueX recent data on the proton are not shown here

Proposed Measurement in Hall C

The proposed experiment consists of a fully exclusive measurement of the coherent production of J/ψ on a ^{4}He target using the Hall C spectrometers, HMS and SHMS, to detect the e^+ e^- pair from the J/ψ decay, as well as tagging the recoiling ^{4}He. The recoil ^{4}He detector is yet to be determined, but it will be designed to tag recoils with the lowest possible momentum, a cutoff momentum set by target density, aluminum wall thicknesses, and beam properties.

First, the CEBAF incident electron beam of 11 GeV energy and 50μA current is used on a 9% copper radiator upstream of the target. The generated bremsstrahlung beam will cover the range from threshold to the 11 GeV electron beam energy. The HMS and SHMS angles and momenta are chosen to optimize the low t measurements and thus maximizing the rate while making sure the ^{4}He nuclei can make it out of target with high efficiency and a good momentum. Table 3.1 shows a result of a GEANT simulation where the target density is assumed to be 0.06 g/cm^2 and an aluminum wall thickness of 0.26 mm.

3.1 Target

The target requirements are (i) high luminosity operation and (ii) lowest possible momentum ^{4}He recoil detection. Generally, requirement (i) pushes the target densities higher, however, requirement (ii) favors lower densities to limit the energy loss of recoiling ^{4}He as they exit the target. Balancing these requirements, we assumed a cold gas target with half the density of a helium target previously used for measurements of elastic scattering from ^{4}He at JLab [4]. The previous target system was 20 cm long with 0.5 mm side walls, pressurized to 14 atm at 8 K, and operated with densities of 0.102 g/cm^3 to 0.127 g/cm^3 (just above liquid helium). We also assume that the aluminum walls are half the thickness in the GEANT4 simulation. It appears that with these assumptions ^{4}He nuclei produced at the lowest t values can make it through the target sides assuming they are produced at the center. This will need more design work but is in principle feasible.

Table 3.1: Energy loss of the ^{4}He recoil in the target, assuming a high-density gas target at 50% of the liquid density, and a target wall of 0.26 mm Al. The simulation was performed using GEANT. For momenta larger than 500MeV, more than 99.7% of ^{4}He will make it out of the target with reasonable kinetic energy.

KE MeV	P_{recoil} GeV/c	Exit eff. %	KE (peak) MeV
30.5	0.480	85.4	1-2
33.0	0.499	99.7	10.2
36.0	0.521	99.8	16.5
39.0	0.543	99.6	21.5
42.0	0.563	99.6	26.2
45.0	0.583	99.6	30.4
50.0	0.615	99.6	36.9
55.0	0.645	99.9	43.2
60.0	0.674	99.6	49.2
70.0	0.729	99.6	60.6

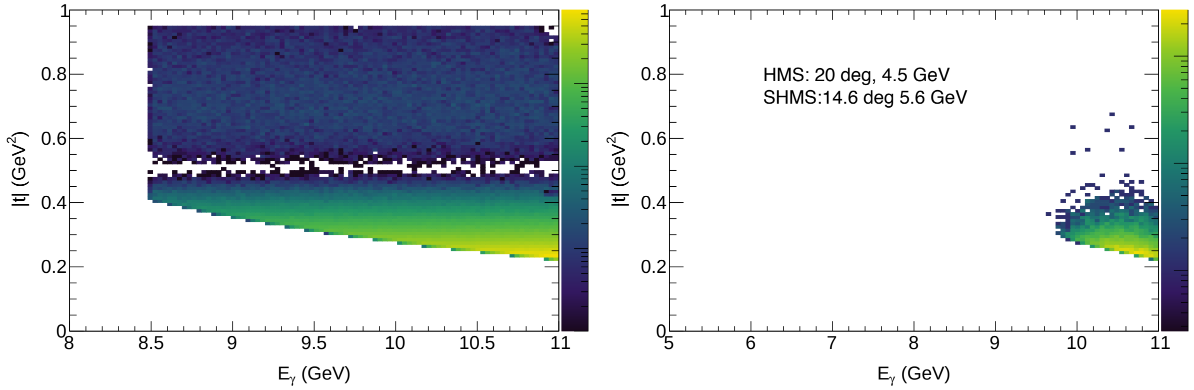

Figure 3.5: Left: Phase space for the process of photo-production weighted by the cross section model described earlier. The white band correspond to the diffraction minimum. Right: Accepted phase space due to the spectrometers angular and momentum settings. Note: a t closest to t_{min} is selected to maximize the measured rate.

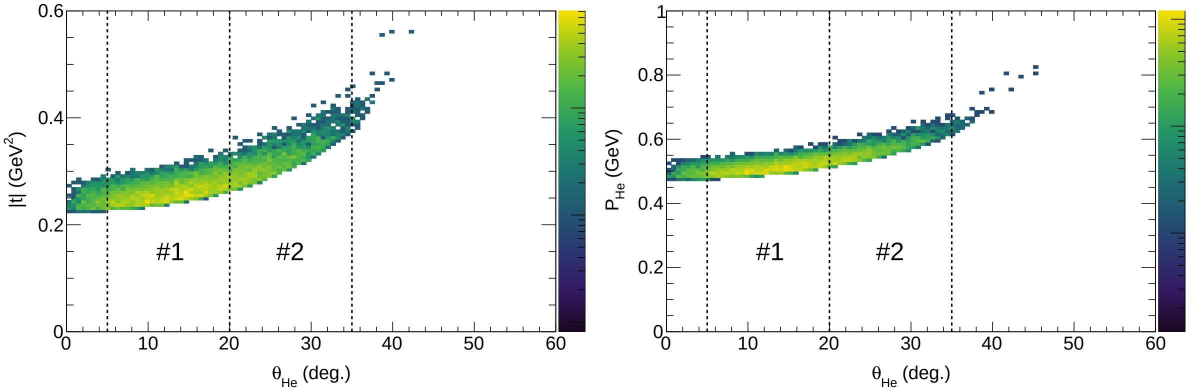

Figure 3.6: Left: Relation between t and the recoil ^{4}He angle for the spectrometer setting of Fig. 3.5. A lever arm in t can be obtained by going from smaller to larger angles. The dashed regions #1 and #2 correspond to the low-angle and high-angle recoil setup proposed for this experiment. Right: ^{4}He momentum vs angle for the chosen setting.

3.2 Simulation of rates for the measurement

The simulation used is similar to that of the proton experiment E12-16-007 performed in Hall C Ref. [5] except that the target is ^{4}He and the cross section model is that described above in this letter. In this experiment, because the form factor of ^{4}He drops dramatically, it is important to optimize the setup to measure a t distribution in a range close to the lowest value of t_{min} that is accessible. Shown in Fig. 3.5 is the full phase space available for the coherent photo-production reaction weighted by the model cross section (left) and the selected region of measurement that would allow to get a reasonable rate for a 5% statistical uncertainty at low t in 2 weeks of a 50μA electron beam on 20 cm high pressure race track ^{4}He target. The recoil kinematics corresponding to this phase space are shown in Fig. 3.6.

The measurement must be fully exclusive as the incoherent channel, where the J/ψ is produced off a single nucleon in the nucleus, can easily overwhelm the desired coherent signal. This experiment will need the design of a ^{4}He tagging system with a coverage of about 10 degrees. Provided the PAC finds the physics case compelling we intend to design such a system for a future proposal. Many possibilities are under consideration but we are not in a position to offer a serious design at this time. As shown in Fig. 3.6, we intend to split the data taking in two angular settings of the ^{4}He tagging system to maximize the available lever-arm in t. In each setting the measurement would take 7 days.

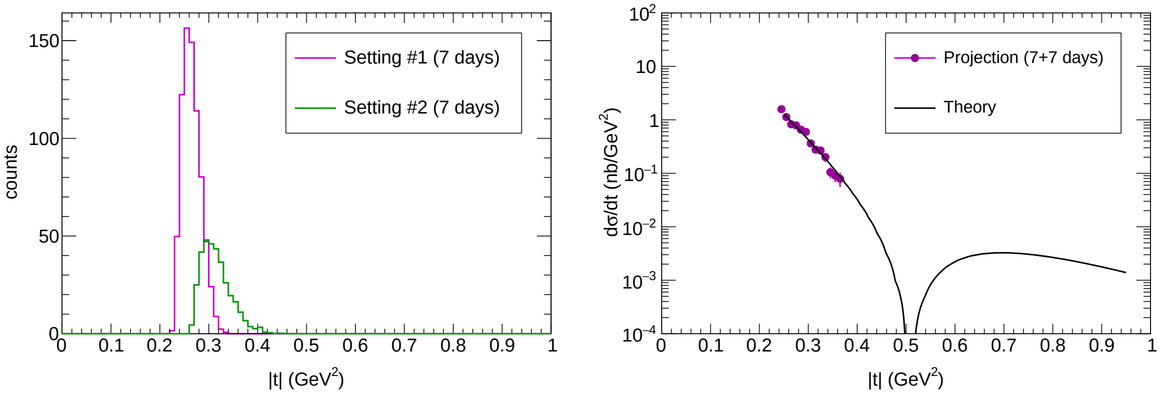

Figure 3.7: Left: Measured t dependence results folded with the bremsstrahlung photon beam and experimental acceptance after 14 days of beam on target (7 days per setting). Right: unfolded t dependence of the differential cross section after combining both data sets. The solid curve is given by the model described earlier.

3.3 Projected Results

We show in Fig. 3.7 the projected results in the two settings of the ^{4}He tagger with no changes in the spectrometers settings. Each of the settings will require 7 days of beam on target. The experiment will be able to measure with good precision the cross section in the low t-region, which is crucial to constrain the gluonic radius.

Summary

We presented in this letter of intent a motivation and possible feasibility of measuring the coherent photo-production cross section of ^{4}He in a range of low t_{min} with the goal of comparing the matter form factor with lattice calculations and attempting for the first time to extract the gluonic radius of ^{4}He. The experiment requires 14 days of a 50μA electron beam impinging on 9% radiator and striking a 20 cm ^{4}He long gas target. The HMS and SHMS in combination with a ^{4}He nucleus tagger are needed for afully exclusive coherent photoproduction measurement. We know very little about the gluonic form factor of ^{4}He in a partonic picture of its description. This experiment will be a first in this regard and a stepping stone towards future studies at an EIC. The determination of the slope of this gluonic form factor, even at low t, might reveal an unexpected behavior from what we understand of ^{4}He in a nucleonic picture, used as an approximation in our model to estimate the rates. This proposed measurement in combination with modern lattice calculations predictions of the ^{4}He nucleus matter form factor will be critical for a deeper understanding of of the partonic view of this tightly bound nuclear system.

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