Near-threshold J/ψ Photoproduction off the Proton and Neutron with CLAS12

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Summary. — Near-threshold J/ψ photoproduction plays a key role in the physics program at the Thomas Jefferson National Accelerator Facility (JLab) 12 GeV upgrade due to the wealth of information it has to offer. J/ψ photoproduction proceeds through the exchange of gluons in the t-channel and is expected to provide unique insight about the nucleon gluonic form factors and the nucleon mass radius.
The JLab based CLAS Collaboration, which uses the CEBAF Large Acceptance Spectrometer (CLAS12), aims to measure the near-threshold J/ψ photoproduction cross section using both a proton and a deuteron target. The latter further offers the possibility of comparing the proton and neutron gluonic form factors and mass radii in a first measurement of the cross sections off a proton or neutron within the deuteron target. These proceedings will describe the aims and experimental design for the measurement of near-threshold J/ψ photoproduction off the proton and neutron with the CLAS12 detector along with the current stage of the data analysis.

1. – Introduction

The mechanical properties of the nucleon describe the internal sheer, pressure, or mass distributions of the quark and gluonic content of the nucleon. These mechanical properties are encoded in Gravitational Form Factors (GFFs) [1] which are defined from the matrix elements of the energy-momentum tensor (EMT). The EMT couples to a spin-2 particle such as the graviton, the assumed force carrier of gravity [2]. However, studying proton-graviton scattering is currently unachievable experimentally and the gravitational field of the proton cannot be measured directly due to its extreme weakness. Instead, one can make use of the fact that any spin-2 field gives rise to a force indistinguishable from gravity [2] to study the nucleon GFFs. The quark sheer and pressure distributions have already been estimated in the context of Deeply Virtual Compton Scattering (DVCS) [3, 4] where the incoming and outgoing spin-1 photons conspire to mimic a spin-2 system.

It has been predicted that J/ψ photoproduction in the near-threshold region can enable access to the gluonic GFFs [5, 6]. In this picture, a two-gluon exchange forms a spin-2 coupling between J/ψ and the nucleon [7, 8, 9]. Two-gluon exchange models were shown to adequately describe near-threshold J/ψ photoproduction total and differential cross sections [7, 8, 9]. Holographic QCD can also be used to model J/ψ photoproduction based on a tensor graviton like exchange (2++) [10, 11, 5]. The D_g GFF which encodes the shear forces and pressure distribution of the gluonic content of the proton, and the A_g GFF which is related to the momentum fraction of gluons in the proton, have already been estimated from near-threshold J/ψ photoproduction on the proton [12].

To highlight the predicted importance of near-threshold J/ψ photoproduction, one can consider the so-called mass puzzle of the nucleon, namely that the sum of the rest masses of the valence quarks of the nucleon does not equal the rest mass of the nucleon itself. In fact, the nucleon derives its mass from the quark-gluon dynamics of its underlying structure and the nucleon mass can be decomposed into the contributions from the quark masses, the energy of quarks and gluons and the contribution from the non-zero trace of the EMT [13, 14]. The EMT contribution to the nucleon mass was previously not well constrained and the nucleon mass could not be calculated from first principles. However, estimates of the magnitude of the trace anomaly contribution were recently obtained from measurements of J/ψ photoproduction on the proton [12, 15, 14].

The validity of relating near-threshold J/ψ photoproduction to the gravitational properties of the nucleon all depends on a two-gluon exchange being the dominant J/ψ production mechanism. However, there are suggestions that near-threshold J/ψ photoproduction could be dominated by the open charm production of $\Lambda^c\overline{D}^{(*)}$ [16, 17]. Furthermore, closer to threshold, the contribution of three-gluon exchange mechanisms to the cross section is expected to dominate that of the two-gluon exchange [18]. The three-gluon mechanism could be responsible for the divergence at low photon energies of the estimates of the magnitude of the trace anomaly contribution to the nucleon mass. An increase in luminosity and an energy upgrade for the experiments that previously measured J/ψ photoproduction on the proton would allow to measure the J/ψ Spin Density Matrix Elements (SDMEs). The three-gluon exchange production mechanism violates charge parity whereas the two-gluon exchange production mechanism does not. This can be used to distinguish between both production mechanisms by using the J/ψ SDMEs to calculate the naturality of J/ψ photoproduction with enough precision to distinguish between two- and three-gluon exchange. At present, the world data on near-threshold J/ψ photoproduction does not have the statistical precision to distinguish between the various proposed production mechanisms and additional data is, therefore, required [17].

All the previous measurements of near-threshold J/ψ photoproduction have been made on the free proton using stationary liquid hydrogen targets [15, 12]. These proceedings will present preliminary results of the first measurement of the near-threshold cross section on the bound neutron and bound proton in a liquid deuteron target. Measuring photoproduction on both proton and neutron will bring new constraints on open-charm contributions to the cross section. Comparing the cross section on proton and neutron also allows to test the isospin invariance of the production mechanism. Finally, additional data of near-threshold J/ψ photoproduction, whether on the free or bound proton, will be required to distinguish between the proposed J/ψ production mechanisms.

2. – Methodology

All previous measurements of near-threshold J/ψ photoproduction have been made at the Thomas Jefferson National Accelerator Facility (JLab) which is located in Newport News, Virginia. The Continuous Electron Beam Accelerator Facility (CEBAF) [19] produces a 12 GeV electron beam and delivers it to the four experimental halls located at JLab. Hall D houses the GlueX experiment and Hall C houses the J/ψ-007 experiment, both of which measured J/ψ photoproduction on the proton [15, 12]. The work presented here uses data taken with the CLAS12 detector, which is housed in Hall B. CLAS12 consists of three detectors, the Forward Tagger (FT) covering polar angles of 2.5 to 5 degrees, the Forward Detector (FD) covering polar angles of 5 to 35 degrees, and the Central Detector (CD) covering polar angles of 35 to 125 degrees. Both the FD and CD have full azimuthal coverage [20].

For the analysis of J/ψ photoproduction, all final state particles are detected in the FD. The High Threshold Cherenkov Counter (HTCC) was built to identify electrons [21]. The Drift Chambers (DC) measure the charge and momentum of charged particles [22]. The Forward Time Of Flight (FTOF) counters were designed to identify charged hadrons [23]. The Electromagnetic Calorimeters (PCAL and EC) are used to detect neutrals and identify electrons and muons [24].

CLAS12 aims to make measurements of J/ψ photoproduction on both liquid hydrogen and liquid deuterium targets, enabling the measurement of J/ψ photoproduction on the free and bound proton and the bound neutron. In the experiments, an electron beam is incident on the stationary target. Since, the aim is to extract the J/ψ photoproduction cross section, we are interested in events where the four-momentum transfer, Q^2, to the virtual photon is close to zero, i.e. where the photon is quasi-real. The four-momentum transfer to the recoil nucleon is measured by the Mandelstam variable t. The J/ψ meson is very shortly lived and is reconstructed by means of its di-lepton decay, either e^+e^- or $\mu^+\mu^-$. The decay leptons along with the recoil nucleon are all detected in the Forward Detector, while the scattered electron is undetected.

The first step of the analysis of J/ψ photoproduction is to identify the final state particles. Electrons and positrons are required to produce a signal in the HTCC and have a ratio of their energy deposition to momentum around 0.25. Muons are minimum ionising particles which are selected with cuts on their energy deposition in the calorimeters. Muons are required to have a low energy deposition whilst electrons are required to have a high energy deposition. This allows to unambiguously separate muons and electrons. The lepton particle identification is refined by training a boosted decision tree classifier [25] on variables from several CLAS12 detector subsystems, such as energy deposition, cluster information in the calorimeters, and the number of photoelectrons produced in the HTCC. Refs. [26, 27] demonstrate in detail how a cleaner positron and muon identification can be achieved by using such machine learning classifiers. To identify protons, and charged hadrons in general, the time-of-flight technique is used by means of a cut on the event distribution over speed versus momentum. Only a neutral charge is required to identify neutrons. No further identification procedures were applied for neutrons as there is not any strong evidence of photon contamination.

Once the final state particles are identified, events consistent with the quasi-real photoproduction of a di-lepton pair are selected by removing high Q^2 events. The aim is to study the reaction $eN_{bound} \to (e')l^+l^-N$ where J/ψ is incoherently produced on one of the bound nucleon, N_{bound}, of the deuteron, a di-lepton pair l^+l^- is produced in the J/ψ decay and detected along with the recoil nucleon, whereas the scattered electron e'

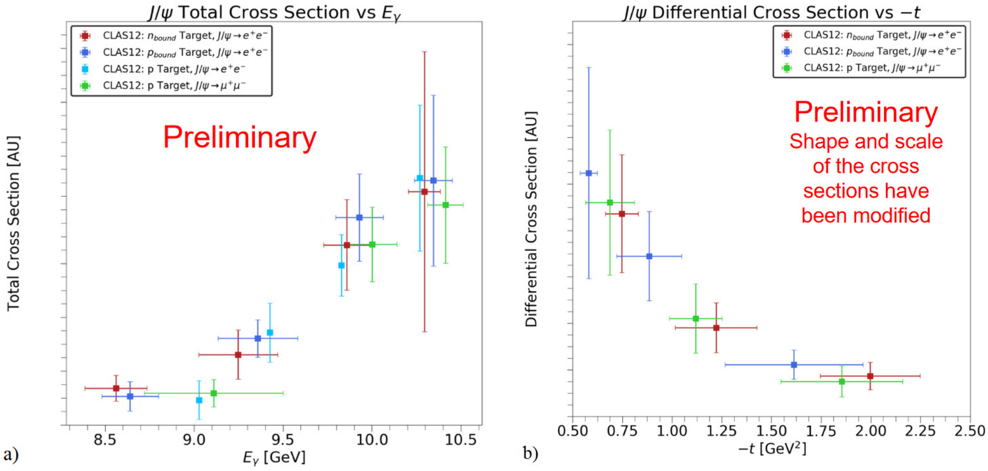

Fig. 1. – The total (a) and differential (b) J/ψ photoproduction cross sections produced on the free proton with J/ψ decaying to e^+e^- (cyan) and $\mu^+\mu^-$ (green) and produced on the bound proton (blue) and neutron (red) with J/ψ decaying to e^+e^-. The results are preliminary and shown in arbitrary units. The shape of the differential cross section has also been re-scaled so that the reader would not attempt to fit it as the results are still preliminary.

goes undetected. These events are identified by requiring the invariant mass of missing particles to be consistent with that of the undetected scattered electron. The di-lepton invariant mass is then fitted with a third order polynomial and a gaussian in the region of the J/ψ mass. A parameter of the fit returns the number of detected J/ψs in bins of the energy E_γ of the incident photon and $-t$. This allows to determine the total cross section in bins of E_γ and the differential cross section as a function of $-t$.

3. – Results and Outlook

Figure 1 shows the total and differential J/ψ photoproduction cross sections produced on the free proton with J/ψ decaying to e^+e^- and $\mu^+\mu^-$ and produced on the bound proton and neutron with J/ψ decaying to e^+e^-, as determined from CLAS12 data. The results are preliminary and shown in arbitrary units. The shape of the differential cross section has also been modified so that the reader should not attempt to fit it. The good agreement within the statistical uncertainty between the total cross sections of J/ψ photoproduction on the bound and free proton indicates that final-state interaction contributions to the total cross section are smaller than the statistical uncertainties of the data. The good agreement within the statistical uncertainty of the total and differential cross sections produced on the bound proton and bound neutron suggests that whatever production mechanism is at play must be isospin invariant, or if isospin invariance is broken, the effect is smaller than the reported statistical uncertainty.

A two-gluon exchange, as the dominant near-threshold J/ψ production mechanism, means the mechanical properties of the nucleon can be probed with J/ψ photoproduction. CLAS12 is aiming towards a first measurement directly comparing the near-threshold J/ψ photoproduction cross sections on the bound proton and bound neutron. The mechanical properties of the nucleon can be extracted from the differential cross section and both the total and differential cross sections are useful to study the production mechanism of J/ψ [17]. Measuring the cross section on the neutron allows to place further constraints on the near-threshold J/ψ production mechanism. Some work remains on the absolute normalization of the CLAS12 measurements. The statistical precision of the measurements is also set to be improved. AI based improvements in the tracking reconstruction at CLAS12 show an average 50% increase in the reconstruction efficiency for events with three charged particles in the final state. The data already taken at CLAS12 is being reprocessed with the new tracking improvements. The experiment aiming for the measurements of J/ψ photoproduction on deuterium still has roughly 60% left to run. Future luminosity upgrades at JLab and CLAS12 will enable high statistics measurements of J/ψ photoproduction and a better understanding of the production mechanism of J/ψ near-threshold.

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This work has been funded by the U.K. Science and Technology Facilities Council under grants ST/P004458/1 and ST/V00106X/1.

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