IL NUOVO CIMENTO **47 C** (2024) 192
DOI 10.1393/ncc/i2024-24192-x

Colloquia: HADRON2023

J/ψ photoproduction close to threshold at GlueX

E. Chudakov on behalf of the GlueX Collaboration
Thomas Jefferson National Accelerator Facility - Newport News, VA 23606, USA

received 21 December 2023

Summary. — Close to threshold photoproduction $\gamma p \to J/\psi p$ probes small-size gluon configurations in the proton. Under certain assumptions, it allows us to study the proton properties, as gluonic GPDs, anomalous contribution to the mass of the proton, gravitational form factors, and the mass radius of the proton. A careful comparison of the experimental data with the theoretical predictions would help us to verify the validity of those assumptions. The first cross-section measurements of near-threshold reaction $\gamma p \to J/\psi p$ by the GlueX Collaboration (Ali A. *et al.*, *Phys. Rev. Lett.*, **123** (2019) 072001) has attracted a considerable theoretical interest. Along with the relation to the gluonic properties of the proton, the measurement exploited a possibility of the LHCb Pentaquark (P) production in the s-channel of the observed reaction, placing a limit on the decay probability $P \to J/\psi p$. Here we present new GlueX results (Adhikari S. *et al.*, *Phys. Rev. C*, **108** (2023) 025201) based on a four-times larger data set. The higher statistics, along with the full acceptance of the GlueX spectrometer allows us to measure the differential cross-section in several energy ranges and compare the results with several theoretical calculations. The new results have already been used in a number of theoretical papers.

1. – Introduction

The photoproduction $\gamma p \to J/\psi p$ close to threshold ($E_\gamma \approx 8.2$ GeV) has been suggested to probe small-size gluon configurations in the nucleon [1]. Of particular interest is the possible relation of this process to the trace anomaly (see for example ref. [2]) and the problem of the nucleon mass. The 12 GeV operation of the Jefferson Lab electron accelerator gives an opportunity to do detailed and precise measurements very close to threshold. The first such measurement by the GlueX Collaboration [3] has attracted considerable theoretical interest.

For heavy quarkonia the process is expected to be dominated by two-gluon exchange, with the t dependence probing the gluon form factors of the nucleon [4]. Extraction of these form factors from the data requires factorization of the differential cross-section into terms describing the quarkonium wave function and the nucleon vertex. QCD LO calculations confirmed the validity of factorization for heavy quarkonia production at large t, down to threshold energies [5]. Close to threshold, the two gluons are predominantly in a spin-2 state (graviton-like) because of the large skewness([1]), which allowed extracting the gravitational form factors of the nucleon [5] from the data. These form factors have also been extracted using the holographic approach [6-9]. For the first time, the proton mass radius was evaluated [6, 10-12].

The approaches described rely on assumptions that the c-quark is heavy enough and that the $\gamma p \to J/\psi p$ production is dominated by gluon exchange. An alternative production mechanism via open-charm exchange has been proposed [13], predicting cusps at the threshold energies for $\Lambda_c^+\overline{D}$ and $\Lambda_c^+\overline{D}^*$ production. There is no full agreement among theorists on the relationship between the differential cross-section of the reaction and the gravitational form factors. Reference [14], based on calculations of the relevant Feynman diagrams at large t, has not found such a relationship.

More measurements with higher precision and finer granularity would be helpful for studying the production mechanism. Two new measurements were reported recently.

Experiment $J/\psi - 007$ [15] in Hall C at JLab used two high-resolution, small acceptance spectrometers to detect the decay $J/\psi \to e^+e^-$. A high-intensity electron beam passed through a liquid hydrogen target and a thin radiator in front of it. The initial photon energy was reconstructed using kinematic constraints and assuming the exclusive reaction $\gamma p \to J/\psi p$. Measurements were done in a number of kinematic settings.

A new GlueX measurement [16] is based on a 4-times larger data set than the first GlueX measurement [3]. The exclusive reaction $\gamma p \to J/\psi p, J/\psi \to e^+e^-$ was detected. In contrast with the $J/\psi - 007$ experiment, GlueX uses a tagged real photon beam and a nearly 4π-acceptance spectrometer, detecting all secondary particles in the full kinematic range. These new GlueX results are discussed hereafter.

2. – GlueX experiment

2·1. *Apparatus.* – The GlueX experiment is running in the Hall D complex at JLab. A detailed description of the apparatus is given in ref. [17]. The electron beam passes through a $\approx 0.04\%$ R.L. diamond radiator, producing coherent Bremsstrahlung photons, that peak at about 9 GeV. The energy of each photon is measured with the help of a tagging system, with a resolution of 0.1–0.2%. The energy spectrum and the flux of the tagged photons are measured with the help of the pair spectrometer in front of a 30 cm-long liquid hydrogen target. The calculated integrated luminosity (fig. 1(a)) shows the coherent peaks and reflects the segmentation and efficiency of the tagger detectors.

The photon beam interacts with the liquid hydrogen target located in the upstream part of the GlueX spectrometer in Hall D, shown in fig. 1(b). The magnetic spectrometer is based on a $\sim$2 T superconducting solenoid. The tracks of charged particles are detected with a set of drift chambers inside the bore, and photons are detected with two electromagnetic calorimeters: one inside the bore (BCAL) and one at the exit of the magnet (FCAL). Scintillating hodoscopes around the target and in front of the FCAL are used for timing measurements. The spectrometer has a nearly uniform acceptance for charged particles and photons in a range of $0 < \varphi < 360°$, $1° < \theta < 120°$. For particle identification, time-of-flight, $\mathrm{d}E/\mathrm{d}x$, and electromagnetic calorimeter techniques are used.

([1]) The skewness parameter ξ represents the longitudinal momentum transfer.

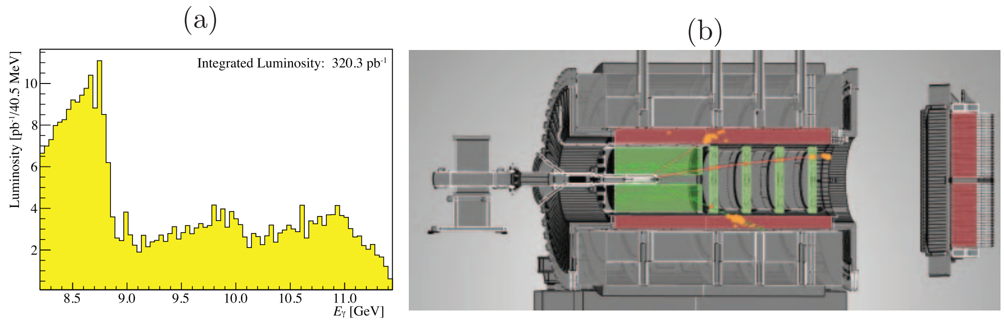

Fig. 1. – (a) The energy spectrum of the integrated luminosity [16]. (b) The GlueX spectrometer.

The trigger logic selected events with full energy in the electromagnetic calorimeters above a certain value and had a high detection efficiency for the decay $J/\psi \to e^+e^-$.

2·2. *Data analysis*. – The final states pe^+e^- were sought. Protons were identified using $\mathrm{d}E/\mathrm{d}x$ in the drift chambers and the TOF measurements. Electrons and positrons were identified against a large pion background by comparing their energy release in the electromagnetic calorimeters to the measured momentum. The candidates for the exclusive reaction $\gamma p \to pe^+e^-$ were selected using the full kinematic fit of the final state particles with the measured 4-momentum of the beam photon. The fit also helped to significantly improve the mass resolution of $M(e^+e^-)$ thanks to the high energy resolution of the beam photons. The mass spectrum of e^+e^- candidates in fig. 2(a) shows the J/ψ and ϕ signals. The continuum consists of the Bethe-Heitler pairs and a $\pi^+\pi^-$ background. The normalized to the beam flux $E_\gamma - t$ distribution of the $J\psi$ candidates is shown in fig. 2(b).

In order to evaluate the J/ψ photoproduction cross-section, the detected Bethe-Heitler process was used for normalization in the $1.2 < M_{e^+e^-} < 2.5$ GeV/c^2 interval (see fig. 2(a)), thus avoiding uncertainties coming from the flux measurements and efficiencies

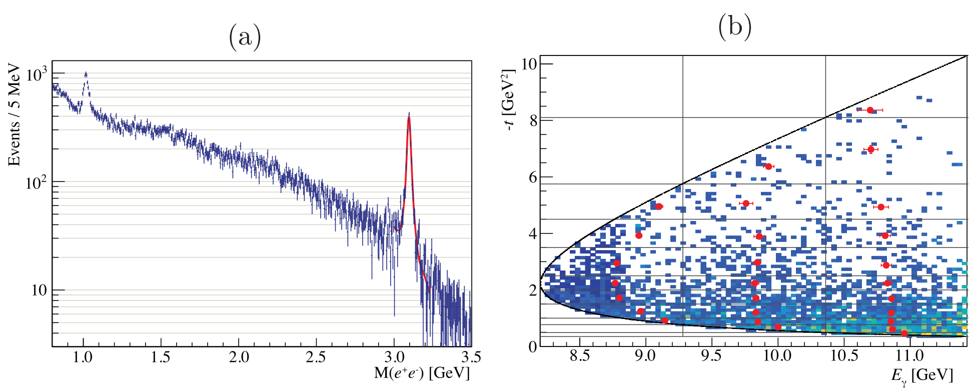

Fig. 2. – (a) The mass spectrum of e^+e^- candidates (ref. [16]). (b) The flux-weighted $E_\gamma - t$ distribution of the J/ψ candidates (ref. [16]). For evaluation of the differential cross-section the area was split into 3 bins in E_γ and 11 bins in t. The solid red dots show the average E_γ, t values per bin.

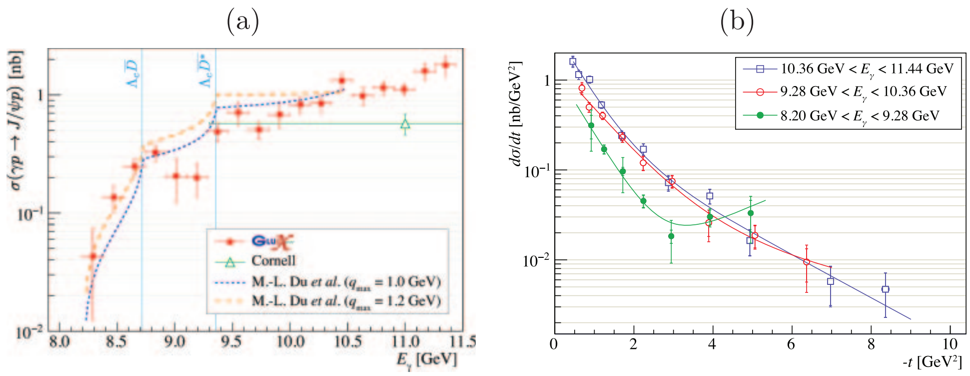

Fig. 3. – (a) The measured full J/ψ cross-section (ref. [16]), compared with the calculations of open charm exchange [13]. The vertical lines indicate the energy thresholds for $\Lambda_c\overline{D}$ and $\Lambda_c\overline{D}^*$ production. (b) The measured J/ψ differential cross-section (ref. [16]) in three beam energy intervals. The data are fitted with a sum of two exponential functions. At the lowest energy the second exponential contribution is significant.

common for both BH and J/ψ event reconstruction. The background under the J/ψ peak consists of BH events, misidentified $\pi^+\pi^-$ pairs and misreconstructed combinations. Its contribution has been evaluated based on the shape of the mass spectrum. The background in the BH sample, dominated by $\pi^+\pi^-$ pairs, has been evaluated by analyzing signals in the electromagnetic calorimeters. This procedure, along with the evaluation of the relevant systematic uncertainties, is discussed is detail in ref. [16]. The results are presented in fig. 3.

There is an indication of a dip at about 9.1 GeV in the full cross section fig. 3(a). The location of the dip matches the coherent edge in the photon beam spectrum (fig. 1(a)). It has been demonstrated that the dip comes from the J/ψ yield, while the measured cross sections of other reactions, including BH show no dip around that location. It is intriguing that the dip happens to occur between the energy thresholds for $\Lambda_c\overline{D}$ and $\Lambda_c\overline{D}^*$ production. The open-charm production model [13] predicts a similar structure. However, the statistical significance of the dip is only 2.6σ.

The differential cross-section for three beam energy intervals is shown in fig. 3(b). At the lowest energy, we observe an enhancement of $\mathrm{d}\sigma/\mathrm{d}t$ at large values of t, indicating a deviation from the t-channel production mechanism. The statistical significance of this deviation from the dipole model [4] is about 2.3σ.

3. – Discussion

The new results from both the GlueX and $J/\psi - 007$ experiments have been used in a new round of theoretical calculations related to the gluonic properties of the nucleon.

The JPAC group in ref. [18] analyzed the latest data by fitting the differential and total cross sections using a model that assumed the most generic properties of the reaction amplitudes. The goal was to separate possible contributions from the gluon exchange and the open charm exchange. It has been demonstrated that close to threshold, the data can be described only by a few partial waves, simplifying the model. The authors concluded that the existing data do not exclude a strong violation of factorization and of the vector meson dominance assumed in several papers on the subject. Resolving the ambiguity would require higher statistical accuracy and would also be helped by measurements of the open charm production, as $\gamma p \to \Lambda_c^+ \overline{D}^{\circ}$. On the experimental side, one may note that, although the production cross-section for open charm is expected to be an order of magnitude higher than for J/ψ, the background will also be much higher, making signal extraction difficult in the fixed target experiment with an extended liquid hydrogen target. Such a measurement should be possible at EIC with the help of the vertex detector.

The analysis [5] was updated [19, 20] using the new data. In this approach, the photoproduction of heavy quarkonium is based on the LO PQCD calculation and is expressed in terms of gluon GPDs. In the heavy quark limit the large momentum transfer leads to a large skewness ξ of the GPD. In the limit $\xi \to 12$ the amplitude is related to the gravitational form factors. It is concluded that the existing data allows extracting a general t dependence of the form factors but are not precise enough for separating two different form factors. More accurate data at larger t (and, consequently, larger ξ) are needed to resolve the ambiguities.

More measurements of the J/ψ photoproduction at JLab are foreseen. The earliest may come from the GlueX-II experiment, which is scheduled to finish data collection by mid-2025, and is expected to quadruple the existing GlueX statistics.

* * *

Notice: authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes.

REFERENCES

[1] Kharzeev D., Satz H., Syamtomov A. and Zinovjev G., *Eur. Phys. J. C*, **9** (1999) 459.
[2] Hatta Y. and Yang D.-L., *Phys. Rev. D*, **98** (2018) 074003.
[3] Ali A. *et al.*, *Phys. Rev. Lett.*, **123** (2019) 072001.
[4] Frankfurt L. and Strikman M., *Phys. Rev. D*, **66** (2002) 031502.
[5] Guo Y., Ji X. and Liu Y., *Phys. Rev. D*, **103** (2021) 096010.
[6] Mamo K. A. and Zahed I., *Phys. Rev. D*, **103** (2021) 094010.
[7] Hatta Y., Rajan A. and Yang D.-L., *Phys. Rev. D*, **100** (2019) 014032.
[8] Mamo K. A. and Zahed I., *Phys. Rev. D*, **101** (2020) 086003.
[9] Mamo K. A. and Zahed I., *Phys. Rev. D*, **104** (2021) 066023.
[10] Kharzeev D. E., *Phys. Rev. D*, **104** (2021) 054015.
[11] Ji X., Liu Y. and Zahed I., *Phys. Rev. D*, **103** (2021) 074002.
[12] Wang R., Kou W., Xie Y.-P. and Chen X., *Phys. Rev. D*, **103** (2021) L091501.
[13] Du M.-L., Baru V., Guo F.-K., Hanhart C., Meissner U.-G., Nefediev A. and Strakovsky I., *Eur. Phys. J. C*, **80** (2020) 1053.
[14] Sun P., Tong X.-B. and Yuan F., *Phys. Rev. D*, **105** (2022) 054032.
[15] Duran B. *et al.*, *Nature*, **615** (2023) 813.
[16] Adhikari S. *et al.*, *Phys. Rev. C*, **108** (2023) 025201.
[17] Adhikari S. *et al.*, *Nucl. Instrum. Methods A*, **987** (2021) 164807.
[18] Winney D. *et al.*, *Phys. Rev. D*, **108** (2023) 054018.
[19] Guo Y., Ji X., Liu Y. and Yang J., *Phys. Rev. D*, **108** (2023) 034003.
[20] Guo Y., Ji X. and Yuan F., *Phys. Rev. D*, **109** (2024) 014014, arXiv:2308.13006 [hep-ph].