ISSN 0027-1349, Moscow University Physics Bulletin, 2018, Vol. 73, No. 4, pp. 343–350. © Allerton Press, Inc., 2018.
Original Russian Text © V. Burkert, E.N. Golovach, R. Gothe, E.L. Isupov, B.S. Ishkhanov, V.A. Klimenko, V.I. Mokeev, Yu.A. Skorodumina, G.V. Fedotov, 2018, published in Vestnik Moskovskogo Universiteta, Seriya 3: Fizika, Astronomiya, 2018, No. 4, pp. 3–11.

PHYSICS OF ATOMIC NUCLEUS AND ELEMENTARY PARTICLES (REVIEW)

Evaluation of the Integrated Cross Sections of Reactions of Exclusive Pion and Kaon Electroproduction off Protons in the Resonance Region at Photon Virtualities from 5 to 12 GeV^2

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Received July 20, 2017; in final form, August 11, 2017

Abstract—The integrated cross sections of the $ep \to e\pi^+ n$, $ep \to e\pi^0 p$, $ep \to eK^+\Lambda$, and $ep \to eK^+\Sigma^0$ reactions are evaluated in the energy range of nucleon resonance excitation at photon virtualities Q^2 from 5 to 12 GeV^2. These exclusive channels will be explored at photon virtualities $Q^2 > 5$ GeV^2 for the first time in future experiments with the CLAS12 detector. The cross-section evaluation is based on the extrapolation of exclusive contributions to the inclusive structure functions F_1 and F_2 from a region of $Q^2 < 5$ GeV^2, in which the experimental data are available, to the region of higher Q^2. This evaluation of cross sections is of particular importance in the development of the program of experiments with the CLAS12 detector for studying the structure of the ground and excited nucleon states, which may reveal the dynamics of strong interactions in the nonperturbative regime.

Keywords: meson electroproduction.
DOI: 10.3103/S0027134918040057

INTRODUCTION

Experiments with the CLAS detector of the Thomas Jefferson National Accelerator Facility (TJNAF) allowed the nucleon resonance structure to be studied in different reactions of meson electroproduction off protons [1–6] in the resonance region at final hadron energies in the center-of-mass frame (W) less than 2 GeV and at photon virtualities (Q^2) less than 5 GeV^2. The upgrade of the accelerator and CLAS12 detector at the TJNAF is being completed. As a result, the electron-beam energy at Hall-B will increase to 11 GeV, which will make it possible to extend the kinematic region for studying the meson electroproduction off protons up to $W < 4.0$ GeV and $Q^2 < 12$ GeV^2 [7–10].

The first experimental data on reactions of the exclusive meson electroproduction off protons at photon virtualities of 5 GeV$^2 < Q^2 < 12$ GeV^2 are of particular interest. According to recent studies of the hadron structure in the context of the QCD-based method of the Dyson–Schwinger equations [11–13], this Q^2 range corresponds to the distances at which a transition from the quark–gluon confinement regime to the perturbative QCD regime occurs in the strong interaction dynamics. Investigations of reactions of exclusive meson electroproduction off protons with the CLAS12 detector [8, 10] at photon virtualities of $5 < Q^2 < 12$ GeV^2 will provide answers to the key open questions of the Standard Model about the nature of 98% of the hadron mass, the mechanisms of quark–gluon confinement, and their role in he formation of the nucleon structure and spectrum [9].

To extract cross sections of different exclusive channels of reactions of meson electroproduction off protons, the Monte Carlo simulation of events of these reactions is required, which is performed by event generators (EGs). To develop these EGs, the information on differential cross sections of the investigated exclusive channels is needed. In this case the differential of cross sections should correspond to the unambiguously defined kinematics of the final state. For reactions with two hadrons in the final state, the information on two-fold differential cross sections is required; for reactions with three final hadrons, the data on five-fold differential cross sections are needed, etc. The experiments with the CLAS detector [1–3, 9] allowed detailed information on differential cross sections and polarization asymmetries to be obtained for the majority of exclusive channels of meson electropro-

duction off protons in the resonance region for the first time. The analysis of these data allowed the development of reaction models that realistically describe differential cross sections of exclusive channels of meson electroproduction off protons at photon virtualities of $Q^2 < 5$ GeV^2 [1, 5, 6, 9, 13]. However, there is no information about these reactions at $Q^2 > 5$ GeV^2 at present. The development of EGs for describing exclusive reactions of the meson electroproduction off protons in the resonance region at $Q^2 > 5$ GeV^2 will be performed at the initial stage within the following approach:

—the form of differential cross sections in the phase space of reactions is assumed to be the same as was obtained from the available experimental data at maximum photon virtualities;

—the dependences of integrated cross sections on W and Q^2 are evaluated by extrapolation of the available experimental results to the range of $Q^2 > 5$ GeV^2.

The extrapolation of the integrated cross sections of two-charged-pion electroproduction off protons was performed in [14] for the first time. In this work extrapolation is conducted for the $ep \to e\pi^+n$, $ep \to e\pi^0p$, $ep \to eK^+\Lambda$, and $ep \to eK^+\Sigma^0$ channels.

1. EVALUATION OF INTEGRATED CROSS SECTIONS OF π^+n AND π^0p, $K^+\Lambda$ AND $K^+\Sigma^0$ ELECTROPRODUCTION OFF PROTONS AT $Q^2 > 5$ GeV^2

Differential cross sections of the π^+n and π^0p, $K^+\Lambda$ and $K^+\Sigma^0$ reactions at photon virtualities of $Q^2 < 5$ GeV^2 have been measured with the CLAS detector [1]. The mentioned cross sections are stored in the CLAS Physics Database [21]. The integrals of these cross sections with respect to all kinematic variables of the final state, so-called fully integrated cross sections, are the initial data for evaluating the integrated cross sections of these channels in a range of $Q^2 > 5$ GeV^2. The differential and fully integrated cross sections of the exclusive meson electroproduction off protons are defined by a sum of the contributions of the longitudinal and transverse parts (see Eq. (1) in 1.1); in this case, the longitudinal part contribution is multiplied by a value of the transverse polarization of the virtual photon ε. The parameter ε is determined by the incident electron-beam energy. To make the procedure for extrapolating the fully integrated cross sections to a range of $Q^2 > 5$ GeV^2 independent of the parameter ε (or the incident electron-beam energy), the fully integrated cross sections of exclusive channels are recalculated into their contributions to inclusive structure functions $F_1(W, Q^2)$ and $F_2(W, Q^2)$. Then, these contributions are extrapolated to a range of $Q^2 > 5$ GeV^2 in the context of the procedure described in section 1.1. During the extrapolation, the constraints are taken into account that are imposed by the Q^2-evolution of the inclusive structure functions $F_1(W, Q^2)$ and $F_2(W, Q^2)$. Data on these functions are available in the entire range of $Q^2 < 12$ GeV^2 [25]. From the evaluated contributions of exclusive channels to the inclusive structure functions at $Q^2 > 5$ GeV^2, the fully integrated cross sections of reactions in the range of $Q^2 > 5$ GeV^2 are calculated at the given energy of incident electrons (or at the value of the parameter ε).

1.1. Extrapolation of Fully Integrated Exclusive Cross Sections to the Range of $Q^2 > 5$ GeV^2

The experimental data on reactions of the exclusive π^+n, π^0p, $K^+\Lambda$, and $K^+\Sigma^0$ electroproduction off protons [1, 15–20], contained in the CLAS Physics Database [21], were used to determine contributions of these channels to the inclusive structure functions $F_1(W, Q^2)$ and $F_2(W, Q^2)$ at $Q^2 < 5$ GeV^2. In studying the N^* structure and spectrum, all observables are expressed through the variables W and Q^2. Therefore, the inclusive structure functions were recalculated from the set of variables (x_B, Q^2), most widely used in physics of deep inelastic scattering, to the set of variables (W, Q^2). The experimental data on inclusive structure functions $F_1(W, Q^2)$ and $F_2(W, Q^2)$ are available now in the entire kinematic range of photon virtualities $Q^2 < 12$ GeV^2, which is investigated in this work. Constraints imposed by the inclusive structure functions $F_1(W, Q^2)$ and $F_2(W, Q^2)$ on the extrapolated exclusive contributions of π^+n and π^0p, $K^+\Lambda$ and $K^+\Sigma^0$ channels provide the reliability of their extrapolation to the range of photon virtualities of $5 < Q^2 < 12$ GeV^2.

A fully integrated cross section of reactions of meson electroproduction off protons can be presented in the form [22]

$$\sigma(W,Q^2) = \sigma_T(W,Q^2) + \varepsilon\sigma_L(W,Q^2), \qquad (1)$$

where $\sigma_T(W, Q^2)$ and $\sigma_L(W, Q^2)$ are the components of the cross section of the reaction under exposure to the transversely and longitudinally polarized virtual photons. The polarization parameter ε is defined by the expression

$$\varepsilon = \left(1 + 2\left(1 + \frac{\nu^2}{Q^2}\right)\tan\left(\frac{\theta}{2}\right)\right)^{-1}, \qquad (2)$$

where ν is the energy transferred by an electron, while θ is the angle of electron scattering in the laboratory frame.

In the CLAS-detector experiments, only unpolarized integrated cross sections of the exclusive meson electroproduction off protons, determined by the sum in the right-hand side of (1), are obtained. In this work a separation of the transverse and longitudinal components of the exclusive cross sections $\sigma_T^i(W, Q^2)$ and $\sigma_L^i(W, Q^2)$ is performed based on the assumption

$$\sigma_L^i(W,Q^2) \approx 0.2\sigma_T^i(W,Q^2), \quad i = \pi^+n, \pi^0p, K^+\Lambda, K^+\Sigma^0. \qquad (3)$$

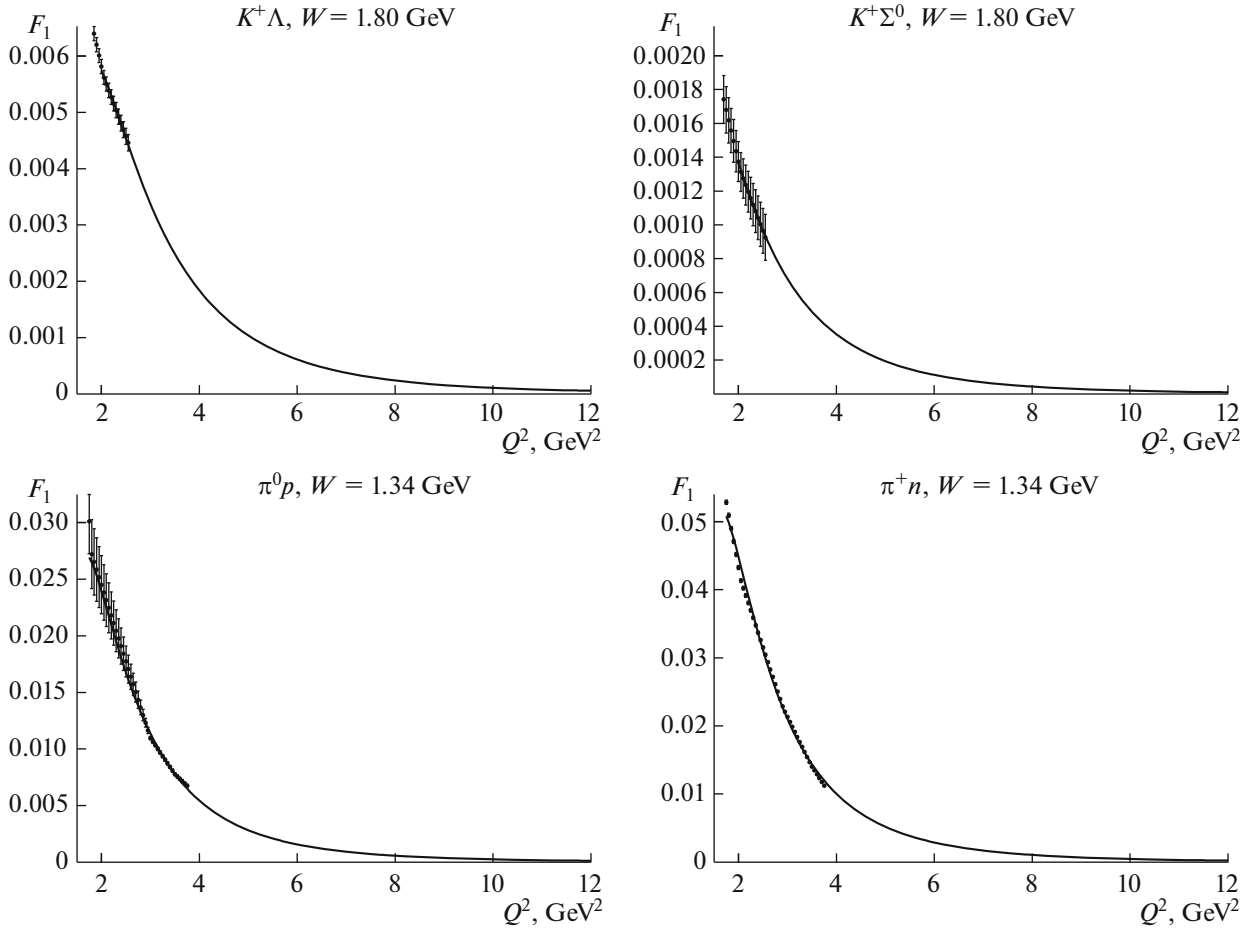

Fig. 1. Interpolation and extrapolation of the contributions of exclusive electroproduction channels $ep \to e\pi^+ n$, $ep \to e\pi^0 p$, $ep \to eK^+\Lambda$, and $ep \to eK^+\Sigma^0$ to the structure function $F_1(W, Q^2)$ in a range of photon virtualities of $Q^2 < 12$ GeV^2. Points with error bars are the result of interpolation of experimental data from CLAS Physics Database [17]. Results of parameterization of Q^2 dependences of experimental data by formula (6) are shown with solid lines.

The evaluation is based on experimental data on the longitudinally-polarized photon contributions to inclusive cross sections of electron scattering on protons [23] on the assumption that these contributions to the exclusive channels are the same as those in the inclusive cross sections. The contributions of exclusive channels of the $\pi^+ n$ and $\pi^0 p$, $K^+\Lambda$ and $K^+\Sigma^0$ electroproduction are calculated from the longitudinal and transverse components of integrated cross sections of these channels $\sigma_T^i\ (W, Q^2)$ and $\sigma_L^i\ (W, Q^2)$ in the following way [22]:

$$F_1^i = M_p \frac{K}{4\pi^2\alpha}\sigma_T(W,Q^2), \tag{4}$$

$$F_2^i = \nu\frac{\sigma_T(W,Q^2)+\sigma_L(W,Q^2)}{4\pi^2\alpha}\frac{(2\nu M_p - Q^2)Q^2}{2M_p(Q^2+\nu^2)}, \tag{5}$$

where M_p is the proton mass, while $K = \dfrac{2\nu M_p - Q^2}{2M_p}$.

The operator product expansion [24] describes the Q^2-evolution of momenta of the inclusive structure functions $F_1(W, Q^2)$ and $F_2(W, Q^2)$ at $Q^2 \gg \Lambda^2_{QCD}$, where $\Lambda_{QCD} \approx 0.2$ GeV is the QCD scale parameter. During the extrapolation of exclusive channel contributions to inclusive structure functions it was assumed that the Q^2-evolution of these contributions can be described by the same dependences of the form

$$\begin{aligned} F_1^i(W,Q^2) &= C_{0,1}^i(W) + \frac{C_{1,1}^i(W)}{Q^2} + \frac{C_{2,1}^i(W)}{Q^4} + \ldots, \\ F_2^i(W,Q^2) &= C_{0,2}^i(W) + \frac{C_{1,2}^i(W)}{Q^2} + \frac{C_{2,2}^i(W)}{Q^4} + \ldots. \end{aligned} \tag{6}$$

In each interval in W, the data on the Q^2-evolution of integrated cross sections of the exclusive $\pi^+ n$, $\pi^0 p$, $K^+\Lambda$, and $K^+\Sigma^0$ electroproduction were interpolated in the $Q^2 < 5$ GeV^2 range, where the CLAS experimental data [21] are available, and extrapolated to the Q^2

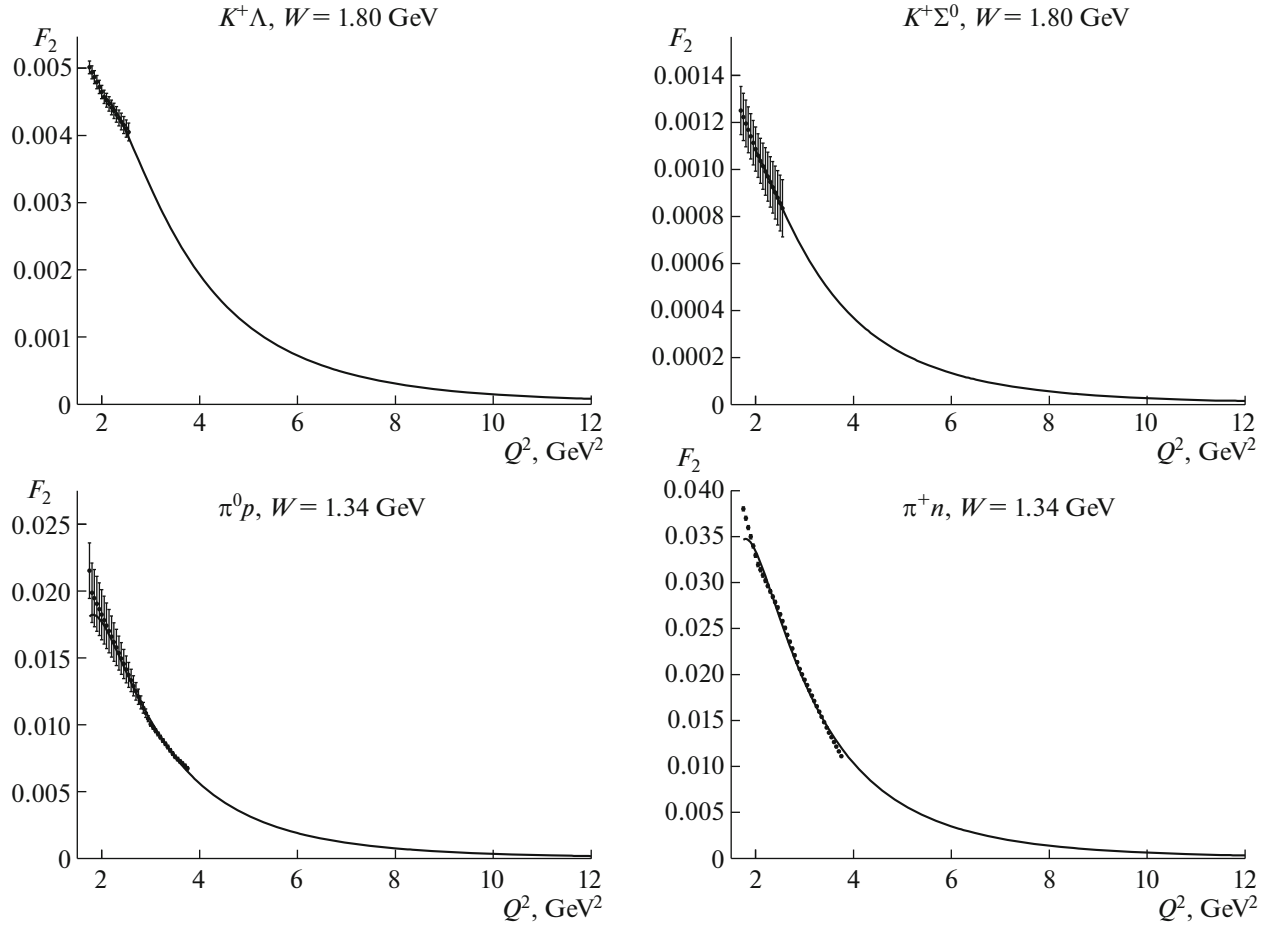

Fig. 2. The interpolation and extrapolation of the contributions of exclusive electroproduction channels $ep \to e\pi^+ n$, $ep \to e\pi^0 p$, $ep \to eK^+\Lambda$, and $ep \to eK^+\Sigma^0$ to the structure function $F_2(W, Q^2)$ in the range of photon virtualities of $Q^2 < 12$ GeV^2. Points with error bars are the result of interpolation of experimental data from CLAS Physics Database [17]. The results of parameterization of the Q^2 dependences of the experimental data using formula (6) are shown with solid lines.

range from 5 to 12 GeV^2, in which cross sections of the above-mentioned exclusive channels will be obtained in experiments with the CLAS12 detector [2, 8, 10]. We restricted ourselves to three parameters: $C^i_{0,j}$, $C^i_{1,j}$, and $C^i_{2,j}$ ($j = 1, 2$) in expansion (6), which were determined from the condition of the best presentation of experimental data on the contributions of the $\pi^+ n$, $\pi^0 p$, $K^+\Lambda$, and $K^+\Sigma^0$ exclusive channels to the inclusive structure functions $F_1(W, Q^2)$ and $F_2(W, Q^2)$. The extraction of the coefficients $C^i_{0,j}$, $C^i_{1,j}$, and $C^i_{2,j}$ ($j = 1, 2$) from the data was conducted independently in each interval in W; in this case the requirement was imposed that the fraction of the exclusive channel contribution to inclusive structure functions, $R^i(W, Q^2) = \dfrac{F^i_{1,2}(W, Q^2)}{F_{1,2}(W, Q^2)}$, be within an interval from 0 to 1 at any W and Q^2. The contributions of exclusive channels to structure functions were extrapolated to the $5 < Q^2 < 12$ GeV^2 range, according to (6), with the parameters $C^i_{0,j}$, $C^i_{1,j}$, and $C^i_{2,j}$ ($j = 1, 2$), defined as described above. Figures 1 and 2 show examples of interpolation and extrapolation of contributions of the $\pi^+ n$, $\pi^0 p$, $K^+\Lambda$, and $K^+\Sigma^0$ exclusive channels to the inclusive structure functions $F_1(W, Q^2)$ and $F_2(W, Q^2)$. The points with error bars in Figs. 1 and 2 are obtained by interpolation of the initial experimental data in the CLAS Physics Database [21] to a grid with a step of 0.05 GeV^2 in Q^2.

From the obtained contributions of the $\pi^+ n$, $\pi^0 p$, $K^+\Lambda$, and $K^+\Sigma^0$ exclusive channels to the inclusive structure functions $F^i_1(W, Q^2)$ and $F^i_2(W, Q^2)$, according to (4), the integrated cross sections of these channels, $\sigma^i_T(W, Q^2)$ and $\sigma^i_L(W, Q^2)$, were calculated at $5 < Q^2 < 12$ GeV^2. The unpolarized integrated sections within this photon virtuality range were calculated from

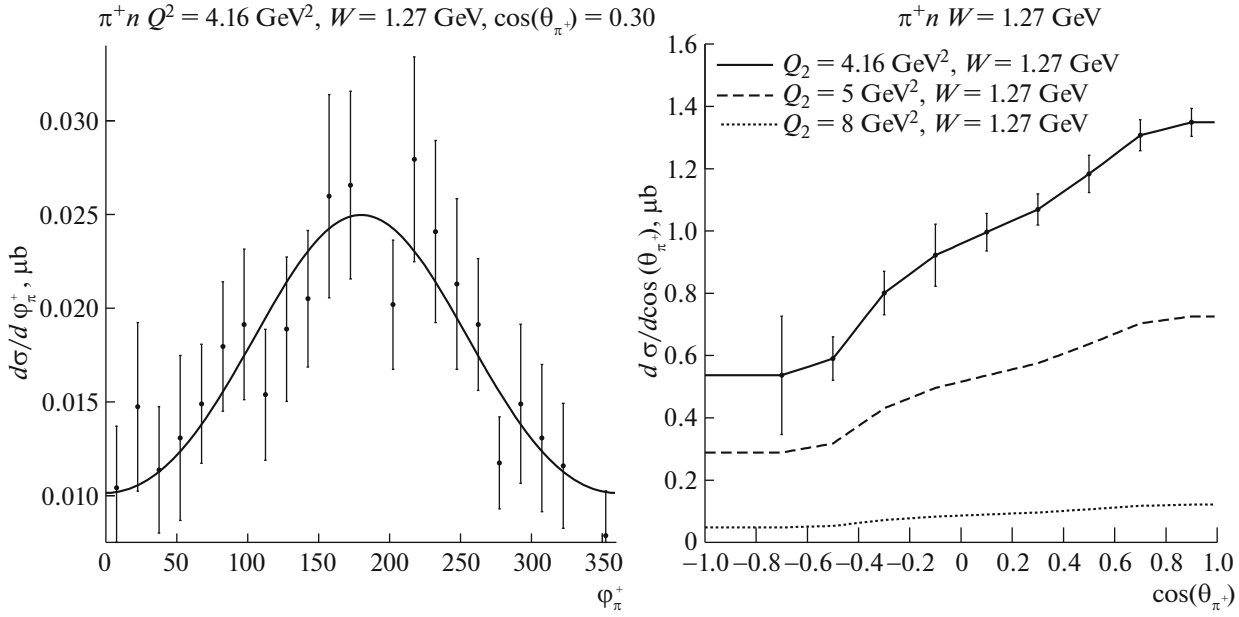

Fig. 3. A description of the π^+ two-fold differential distribution $\frac{d^2\sigma(W,Q^2)}{d\varphi d\cos(\theta_{\pi^+})}$ in the reaction of $\pi^+ n$ electroproduction off protons in the center-of-mass frame of final hadrons according to (7) (on the left). The π^+ one-fold differential angular distributions $\frac{d\sigma(W,Q^2)}{d\cos(\theta_{\pi^+})}$ in the final hadrons center-of-mass frame, extrapolated in $Q^2 > 5$ GeV^2 (on the right).

σ_T^i (W, Q^2) and σ_L^i (W, Q^2) for the given electron-beam energy or virtual photon polarization degree ε (2).

1.2. Extrapolation of Differential Cross Sections

Differential cross sections of exclusive channels of $\pi^+ n$, $\pi^0 p$, $K^+\Lambda$, and $K^+\Sigma^0$ electroproduction off protons in the one-photon exchange approximation are described as follows:

$$\frac{d\sigma}{d\cos(\theta)d\varphi} = A(W,Q^2,\theta) + B(W,Q^2,\theta)\cos(2\varphi) + C(W,Q^2,\theta)\cos(\varphi), \quad (7)$$

where θ and φ are the polar and azimuthal angles of the meson emission in the reaction center-of-mass frame. The integration of (7) with respect to the angle φ yields the following expression for the one-fold differential cross section depending on the angle θ

$$\frac{d\sigma}{d\cos(\theta)} = A(W,Q^2,\theta)2\pi. \quad (8)$$

Differential cross sections of the above-mentioned exclusive reactions, depending on the polar angle θ, were determined from experimental data on two-fold differential cross sections based on the condition of their best description by relationship (7) according to (8). During the extrapolation of one-fold differential cross sections $\frac{d\sigma}{d\cos(\theta)}$ to the $5 < Q^2 < 12$ GeV^2 range, their form is assumed to remain the same as at the maximum $Q^2_{\max}$, where experimental data are available. The one-fold differential cross sections are extrapolated in the following way:

$$\frac{d\sigma}{d\cos(\theta)}(W,Q^2,\theta) = \frac{d\sigma}{d\cos(\theta)}(W,Q^2_{\max},\theta)\frac{\sigma^i(W,Q^2)}{\sigma^i(W,Q^2_{\max})}, \quad (9)$$

where $\sigma^i(W, Q^2)$ and σ^i (W, $Q^2_{\max}$) are the unpolarized integrated cross sections of the $\pi^+ n$, $\pi^0 p$, $K^+\Lambda$, and $K^+\Sigma^0$ channels at Q^2 in the extrapolation range and at $Q^2_{\max}$ where the data are available. The two-fold differential cross sections $\frac{d\sigma}{d\cos(\theta)d\varphi}$ at Q^2 values in the extrapolation range ($5 < Q^2 < 12$ GeV^2) are obtained from the one-fold differential cross sections $\frac{d\sigma}{d\cos(\theta)}$ according to (7) on the assumption that the ratios $\frac{B(W,Q^2,\theta)}{A(W,Q^2,\theta)}$ and $\frac{C(W,Q^2,\theta)}{A(W,Q^2,\theta)}$ at Q^2 in the extrapolation range are the same as at the maximum $Q^2_{\max}$ where the data are available. Figure 3 shows an example of the evaluation of angle dependences of one-fold differential cross sections of the

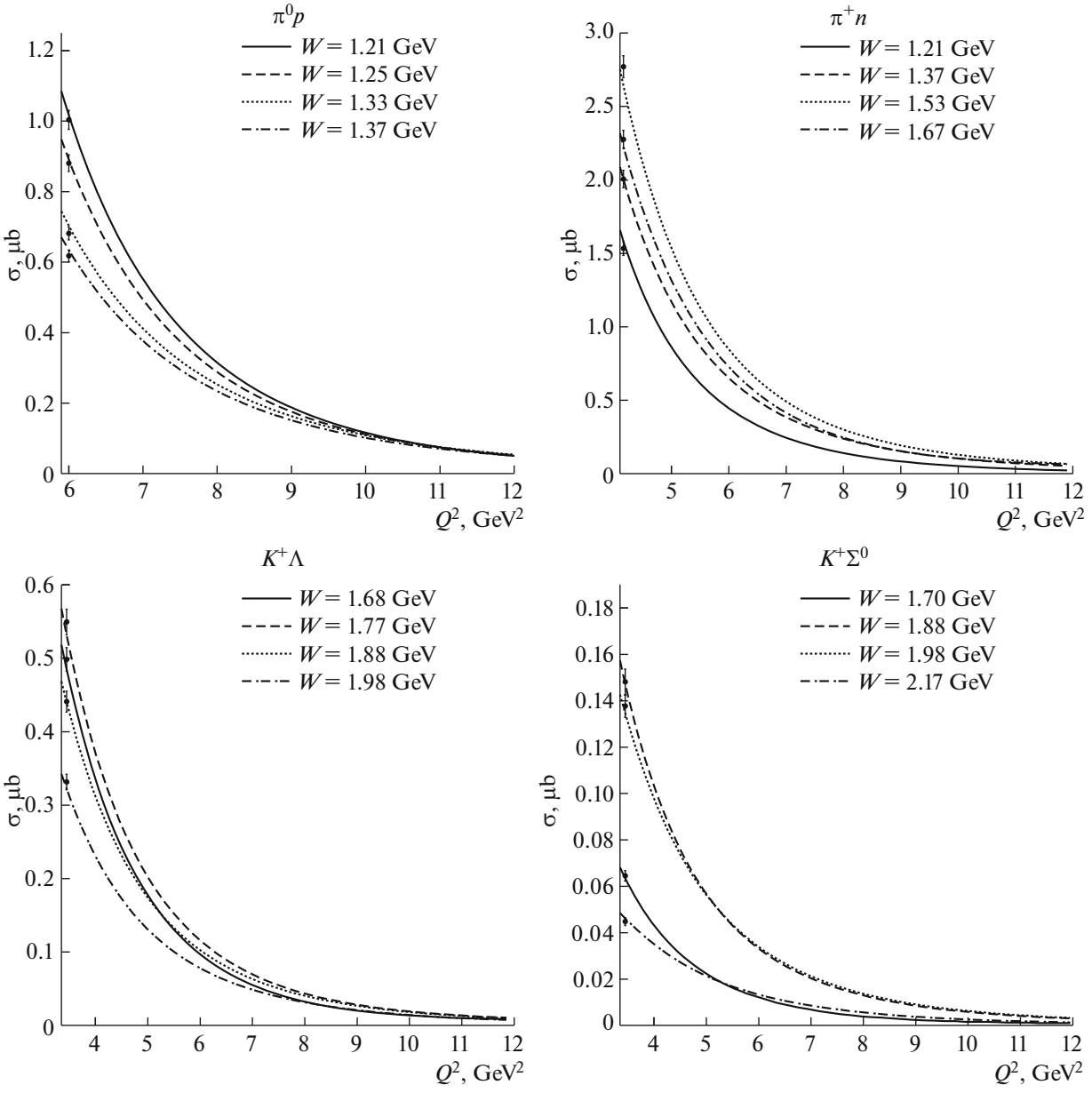

Fig. 4. The Q^2 dependences of integrated cross sections of electroproduction $ep \to e\pi^+ n$, $ep \to e\pi^0 p$, $ep \to eK^+\Lambda$, and $ep \to eK^+\Sigma^0$ that were calculated from the evaluated contributions of these channels to inclusive structure functions $F_1(W, Q^2)$ and $F_2(W, Q^2)$ at photon virtualities of $5 < Q^2 < 12$ GeV^2 and the electron-beam energy $E_e = 11$ GeV.

channel of $\pi^+ n$ electroproduction off protons at $Q^2 > 5$ GeV^2 from experimental data on two-fold differential cross sections of this reaction at $Q^2 < 5$ GeV^2.

1.3. Extrapolation of Integrated Cross Sections in W

Experimental data for integrated cross sections of $\pi^+ n$, $\pi^0 p$, $K^+\Lambda$, and $K^+\Sigma^0$ electroproduction off protons are obtained in the limited range of invariant masses of the final hadron system W. To evaluate these integrated cross sections in the entire range of $W < 2.5$ GeV, the extrapolation of experimental data in W was performed. The experimental data on integrated cross sections of photoproduction of the mentioned exclusive channels in CLAS Physics Database [21] were used for the extrapolation. The extrapolated integrated cross sections of the $\pi^+ n$, $\pi^0 p$, $K^+\Lambda$, and $K^+\Sigma^0$ electroproduction off protons are obtained in the following form:

$$\sigma^i(W, Q^2) = \sigma^i(W_{\max}, Q^2)\frac{\sigma^i(W, Q^2 = 0)}{\sigma^i(W_{\max}, Q^2 = 0)}, \quad (10)$$
$$i = \pi^+ n, \pi^0 p, K^+\Lambda, K^+\Sigma^0,$$

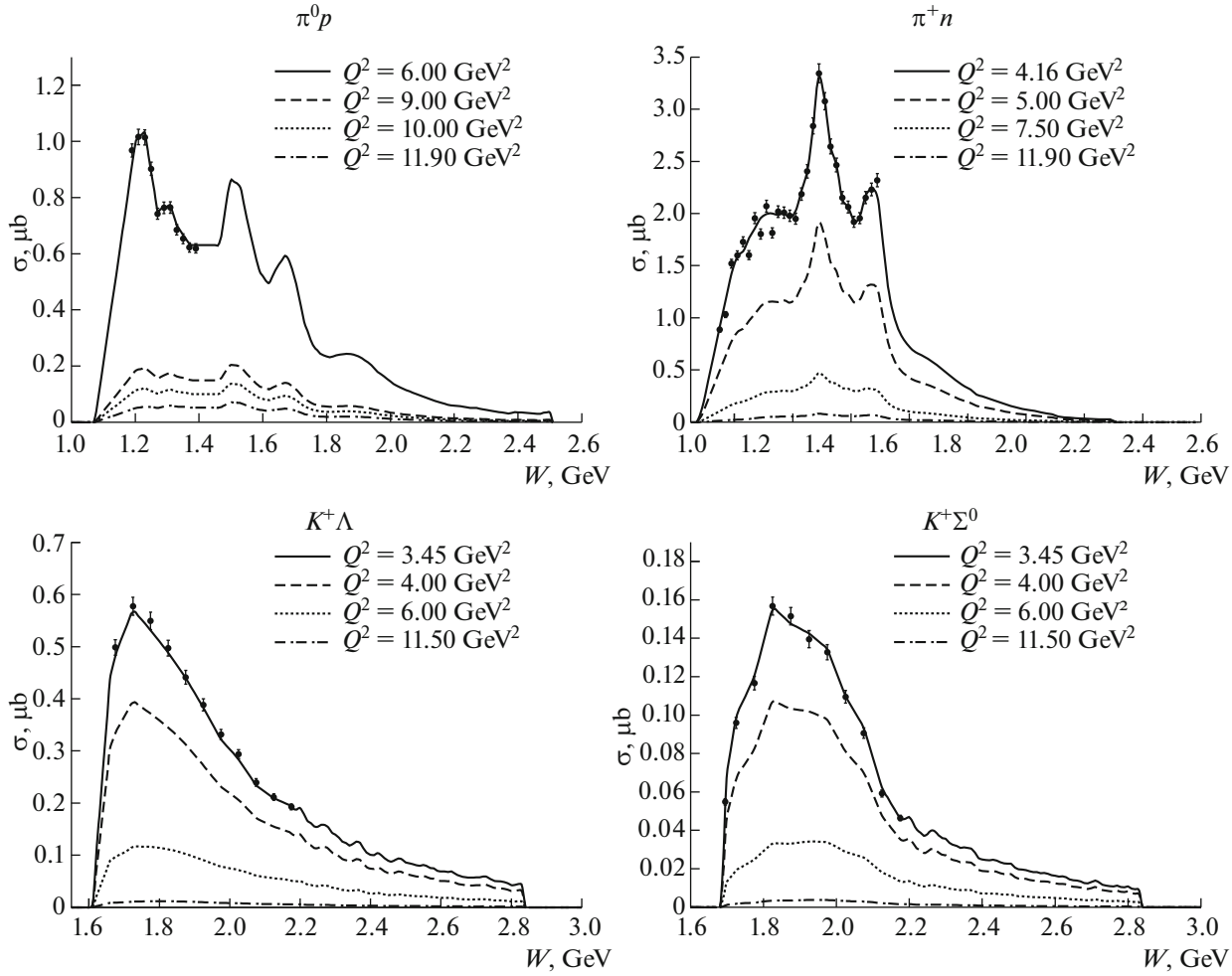

Fig. 5. The W dependences of integrated cross sections of electroproduction $ep \to e\pi^+ n$, $ep \to e\pi^0 p$, $ep \to eK^+\Lambda$, and $ep \to eK^+\Sigma^0$ that were obtained after the experimental data extrapolation in W, are shown by curves passing through the experimental data (points with error bars). The unpolarized integrated cross sections, as calculated from the evaluated contributions of these channels to inclusive structure functions $F_1(W, Q^2)$ and $F_2(W, Q^2)$, are also given at photon virtualities of $5 < Q^2 < 12$ GeV^2 and the electron-beam energy $E_e = 11$ GeV.

where $W_{\max}$ is the maximum W value at which there are data on electroproduction reactions at the photon virtuality Q^2, while the cross sections at $Q^2 = 0$ correspond to photoproduction. The results of extrapolation of the experimental data on integrated cross sections of $\pi^+ n$, $\pi^0 p$, $K^+\Lambda$, and $K^+\Sigma^0$ electroproduction in the context of the described procedure are given in Fig. 5.

2. THE RESULTS OF THE EVALUATION OF EXCLUSIVE CROSS SECTIONS OF PION AND KAON ELECTROPRODUCTION

Examples of the interpolation and the Q^2 extrapolation ($Q^2 < 12$ GeV^2) of the CLAS Physics Database experimental data [21] on the contributions of the exclusive channels of $\pi^+ n$, $\pi^0 p$, $K^+\Lambda$, and $K^+\Sigma^0$ electroproduction to inclusive structure functions $F_1(W, Q^2)$ and $F_2(W, Q^2)$ are given in Figs. 1 and 2. A good presentation of experimental data is achieved by dependences (6) with $\frac{\chi^2}{d.p.} < 1$, which were used for the Q^2 interpolation and Q^2 extrapolation of these channel contributions to the inclusive structure functions $F_1(W, Q^2)$ and $F_2(W, Q^2)$. Relationships (4) and (5) allow the prediction of values of integrated cross sections of $\pi^+ n$, $\pi^0 p$, $K^+\Lambda$, and $K^+\Sigma^0$ electroproduction from evaluations of contributions of these channels to the inclusive structure functions $F_1(W, Q^2)$ and $F_2(W, Q^2)$ for any given values of the electron-beam energy E_e or longitudinal polarization parameter ε of virtual photons. The Q^2 dependences of integrated cross sections of $\pi^+ n$, $\pi^0 p$, $K^+\Lambda$, and $K^+\Sigma^0$ electroproduction at different W values, which were obtained for the elec-

tron-beam energy $E_e = 11$ GeV, are shown in Fig. 4. The experimental data on the W dependences of the integrated cross sections of these reactions and the predictions of their behavior at $Q^2 > 5$ GeV^2 are shown in Figs. 4 and 5. Data on these cross sections will be obtained in future experiments with the CLAS12 detector [7, 8, 10]. Evaluations of cross sections of the π^+n, π^0p, $K^+\Lambda$, and $K^+\Sigma^0$ electroproduction off protons obtained in this work are necessary to develop methods for extracting these cross sections from the experimental data at $5 < Q^2 < 12$ GeV^2, in particular, to create Monte Carlo event generators and to develop methods for taking radiation effects into account.

The resonance maxima correspond to the contributions of the $\Delta(1232)3/2^+$ resonance and the resonances of the second ($W \approx 1.5$ GeV) and third ($W \approx 1.7$ GeV) resonance regions. The integrated cross sections of $K^+\Lambda$ and $K^+\Sigma^0$ electroproduction exhibit a wide maximum near the threshold, both in the experimental data and in the predicted W-dependences of cross sections at $Q^2 > 5$ GeV^2. Both non-resonance mechanisms (by forming structures in the W dependence due to hadron interactions in final states) and nucleon resonances with masses above 1.6 GeV can contribute to this maximum. The nature of the given structure is the subject of current studies of CLAS data on the reactions of $K^+\Lambda$ and $K^+\Sigma^0$ electroproduction within the model of [28].

CONCLUSIONS

Evaluation of integrated and differential cross sections of π^+n, π^0p, $K^+\Lambda$, and $K^+\Sigma^0$ electroproduction at nucleon resonance excitation energies $W < 2$ GeV was performed in the unexplored range of high photon virtualities of $5 < Q^2 < 12$ GeV^2. The evaluation was obtained from the CLAS experimental data on the cross sections of these reactions at $Q^2 < 5$ GeV^2 with allowance for constraints imposed by experimental data on the Q^2-evolution of inclusive structure functions $F_1(W, Q^2)$ and $F_2(W, Q^2)$ at $Q^2 < 12$ GeV^2. The results we obtained will be used to analyze the data of the experiment in [8] with the CLAS12 detector for studying the nucleon resonance structure at high photon virtualities. The first data of this experiment will be obtained in the first half of 2018. The performed evaluations of cross sections are of considerable interest for the extensive program of exploration of exclusive meson electroproduction reactions with the new CLAS12 detector, which reveals the dynamics of the strong interactions that form the ground and excited nucleon states for quarks and gluons.

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Translated by M. Samokhina