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LETTER TO THE EDITOR

QUASI-ELASTIC KNOCKOUT OF MESONS FROM THE NUCLEON. DEVELOPMENTS AND PERSPECTIVES

V. G. NEUDATCHIN, I. T. OBUKHOVSKY and N. P. YUDIN

Institute of Nuclear Physics, Moscow State University, Vorobievy Gory, Moscow 119899, Russia   E-mail address: obukh@nucl-th.sinp.msu.ru

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The electroproduction of pions and kaons at the kinematics of quasi-elastic knockout is a powerful tool for investigation of mesonic cloud. A model of scalar $q\bar{q}$ ($^3\mathrm{P}_0$) fluctuation in the non-trivial QCD vacuum is used to calculate pion and kaon momentum distributions in the channels $\mathrm{N}\rightarrow\mathrm{B}+\pi$, $\mathrm{B}=\mathrm{N}$, Δ, N^*, N^{**}, and $\mathrm{N}\rightarrow\mathrm{Y}+\mathrm{K}$, $\mathrm{Y}=\Lambda$, Σ_0.

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Investigation of structure of a composite system by means of quasi-elastic knockout of its constituents has been playing a very important role in microphysics. In a broad sense, the term "quasi-elastic knockout" means that a high-energy projectile (electron, proton, etc.) instantaneously knocks out a constituent – an electron from an atom, a nucleon or a few-nucleon cluster from a nucleus, or a meson from a nucleon – transferring a high momentum in an "almost free" binary collision to the knocked-out particle and leading to controllable changes in the internal state of the target. Exclusive quasi-elastic knockout experiments resolve individual states of the final system. By varying kinematics, one can directly measure the momentum distribution (MD) of a constituent in different channels. The formal description of the quasi-elastic knockout of composite particles (clusters) from atomic nuclei is a well-developed procedure [1]. In a channel of virtual decay $A_\mathrm{i} \rightarrow (A-4)_\mathrm{f} + \alpha_n$, the wave function of mutual motion $(A-4)_\mathrm{f} - \alpha_n$ can be defined as $\Psi_\mathrm{i}^{\mathrm{f}\alpha_n}(\boldsymbol{R}) = c < (A-4)_\mathrm{f}\, \alpha_n \,|\, A_\mathrm{i} >$, where c is a constant factor. The integration is carried out over the internal variables of the subsystems $(A-4)_\mathrm{f}$ and α_n and the nondiagonal amplitudes $\mathrm{p}+\alpha_n \rightarrow \mathrm{p} + \alpha_0$ should be taken into account [2]. The observable MD of the virtual α-particles in the mentioned channel is, in fact, a squared sum of a few different comparable components $\Psi_{\mathrm{i}}^{\mathrm{f}\alpha_n}(\boldsymbol{q})$ taken for each n with its own amplitudes of $\alpha_n \to \alpha_0$ deexcitation. The MDs for various final states f may differ greatly from each other.

The physical content of the "microscopic" hadron theory corresponds, in general, to this concept. It is true, at least, for QCD-motivated quark models taking into account the $q\bar{q}$ pair creation, the flux-tube breaking model [3] or merely the "naive" $^3\mathrm{P}_0$ model [4]. At relatively low energies, the physical nucleon can be described in terms of a Fock column of "bare" nucleons and mesons. The "bare" hadrons in its turn are composed of constituent quarks:

$$|N>= \left(\begin{array}{ccc} N & & \\ N & + & \pi \\ N & + & \rho \\ \Delta & + & \pi \\ \Lambda & + & K \\ & \dots & \end{array}\right) \longleftrightarrow \left(\begin{array}{ccc} (3q)_{\mathrm{N}} & & \\ (3q)_{\mathrm{N}} & + & (q\bar{q})_\pi \\ (3q)_{\mathrm{N}} & + & (q\bar{q})_\rho \\ (3q)_\Delta & + & (q\bar{q})_\pi \\ (2qs)_\Lambda & + & (q\bar{s})_{\mathrm{K}} \\ & \dots & \end{array}\right).$$

These effective degrees of freedom could be tested in exclusive experiments on quasi-elastic pion (kaon) knockout, $\mathrm{p}(\mathrm{e},\mathrm{e}'\pi^+)\mathrm{B}$, $\mathrm{B=n}, \Delta, \mathrm{N}^*, \mathrm{N}^{**}$, and $\mathrm{p}(\mathrm{e},\mathrm{e}'\mathrm{K}^+)\mathrm{Y}$, $\mathrm{Y}=\Lambda$, Σ^0, by few-GeV electrons.

In this work, the results of calculations performed on the basis of two approaches, meson-baryon and constituent quark model (CQM), are compared with the data [5] on longitudinal and transverse differential cross sections at specific kinematics of quasi-elastic knockout: a high-momentum ($|\mathbf{k}'| \gtrsim 1-2\,\mathrm{GeV}/c$) final pion (kaon) at forward angles and a nucleon(baryon)-spectator with small recoil momenta ($|\mathbf{k}| \lesssim 0.3-0.5\,\mathrm{GeV}/c$). The quantitative evaluations performed earlier for the $\mathrm{p}(\mathrm{e},\mathrm{e}'\pi^+)\mathrm{n}$ reaction on the basis of light-cone wave functions [7] and in terms of non-covariant formalism [8] have demonstrated that both pion and ρ-meson MD can be separately measured in coincidence (missing mass) experiments at quasi-elastic kinematics. The meson pole diagrams (Fig. 1) dominate in this region, and contributions of π and $\rho(\omega)$ poles can be separately measured if the cross section is separated into longitudinal and transverse parts

$$\mathrm{d}^3\sigma/\mathrm{d}Q^2\mathrm{d}W\mathrm{d}t = 2\pi\Gamma[\epsilon\,\mathrm{d}\sigma_{\mathrm{L}}/\mathrm{d}t + \mathrm{d}\sigma_{\mathrm{T}}/\mathrm{d}t].$$

In the meson-pole region the cross section is factorized on electro-magnetic (e.-m.)

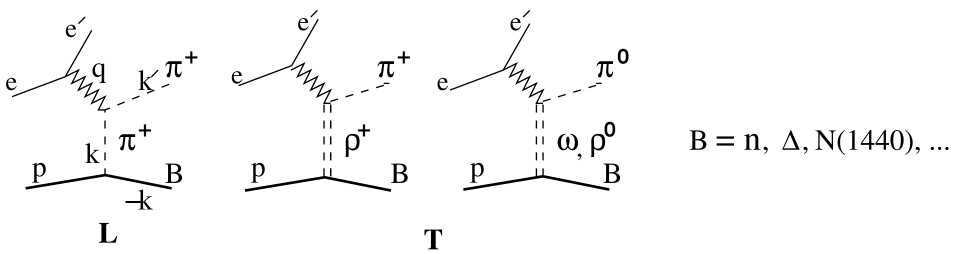

Fig. 1. Meson pole diagrams dominating in the pion quasi-elastic knockout.

and strong (str) parts

$$\frac{\mathrm{d}\sigma_{\mathrm{L,T}}}{\mathrm{d}t} = \frac{1}{16W^2}\,\frac{1}{|\mathbf{q}^*||\mathbf{q}_r^*|}\,\frac{\overline{|\mathcal{M}_{str}|^2}}{(t-m_M^2)^2}\times\begin{cases}\alpha\,F_\pi^2(Q^2)|k+k'|^2_{\mathrm{L,T}} & \text{(pion pole)}\\ (g^2_{\rho\pi\gamma}/4\pi)F^2_{\rho\pi\gamma}(Q^2)\,|\hat{\boldsymbol{\rho}}\times\mathbf{q}|^2_{\mathrm{T}} & (\rho\text{-meson pole}),\end{cases}$$

$$\text{where}\quad \overline{|\mathcal{M}_{\mathrm{str}}|^2} = \begin{cases}\overline{|\mathcal{M}(\mathrm{N}\to\pi+\mathrm{N})|^2} = 2g^2_{\pi\mathrm{NN}}\mathbf{k}^2F^2_{\pi\mathrm{NN}}(\mathbf{k}^2)\\ \overline{|\mathcal{M}(\mathrm{N}\to\rho+\mathrm{N})|^2} = 2(1+\kappa_\rho)^2g^2_{\rho\mathrm{NN}}\mathbf{k}^2F^2_{\rho\mathrm{NN}}(\mathbf{k}^2).\end{cases}$$

that allows to introduce the "wave function" (w.f.) of meson M ($=\pi,\rho,\mathrm{K}$) in the nucleon

$$\frac{\overline{|\Psi_{\mathrm{N}}^{\mathrm{BM}}(k)|^2}}{\omega^2_{\mathrm{M}}(k)} = \frac{\overline{|\mathcal{M}(\mathrm{N}\to\mathrm{M}+\mathrm{B})|^2}}{(t-m_{\mathrm{M}})^2}$$

with an invariant normalization on "a spectroscopic factor" (the number of mesons in the nucleon)[1]

$$S_{\mathrm{N}}^{\mathrm{BM}} = \int\frac{\mathrm{d}^3k}{(2\pi)^3}\;\frac{4\overline{|\Psi_{\mathrm{N}}^{\mathrm{BM}}(k)|^2}}{2E_{\mathrm{N}}(p)2E_{\mathrm{B}}(p')2\omega_{\mathrm{M}}(k)}\,.$$

In principle, all components of Fock column can be studied in knock-out experiments, but really the w.f. defined with a measured cross section includes contributions from all intermediate virtual states of a given process. For example, at forward angles the longitudinal part of the p(e,e$'\pi^+$)n cross section is only determined by the pion pole

$$\frac{\mathrm{d}\sigma_{\mathrm{L}}}{\mathrm{d}t}\sim\frac{|R_{\mathrm{p}}^{\mathrm{n}\pi^+}(k)|^2}{4\pi} = \frac{4\overline{|\Psi_{\mathrm{p}}^{\mathrm{n}\pi^+}(k)|^2}}{(2\pi)^3 2M_{\mathrm{N}}2E_{\mathrm{N}}(k)2\omega_\pi(k)},$$

while the transverse part at large $Q^2 \gtrsim 2-4\ \mathrm{GeV}^2/c^2$ is determined by the ρ-meson pole $\mathrm{d}\sigma_{\mathrm{T}}/\mathrm{d}t\sim|R_{\mathrm{p}}^{\mathrm{n}\rho^+}(k)|^2/(4\pi)$, because of a large contribution of the e.-m. M1 transition[2]

$$\rho^+ + \gamma^*_{\mathrm{T}}\to\pi^+,\quad \rho^0+\gamma^*_{\mathrm{T}}\to\pi^0,\quad \omega+\gamma^*_{\mathrm{T}}\to\pi^0.$$

for transverse (T) photons. Hence the Fock states n+π^+ and n+ρ^+ (or N+π^0, N+ρ^0, and N+ω for neutral mesons) can be separately measured with the $\mathrm{d}\sigma_{\mathrm{L}}/\mathrm{d}t$ and $\mathrm{d}\sigma_{\mathrm{T}}/\mathrm{d}t$ [7, 8].

[1] In the I.M.F., it gives a momentum distribution of mesons as partons

$$p\to\infty:\quad S^{\mathrm{BM}}_{\mathrm{N}\infty} = \int\frac{\mathrm{d}^2k_\perp}{(4\pi)^2}\,\frac{\mathrm{d}x}{x(1-x)}\,\frac{\overline{|\mathcal{M}(\mathrm{N}\to\mathrm{M}+\mathrm{B})|^2}}{(M^2_{\mathrm{N}}-W^2(k^2_\perp,x))^2},\quad W^2(k^2_\perp,x)=\frac{m^2_{\mathrm{B}}+k^2_\perp}{1-x}+\frac{m^2_{\mathrm{M}}}{x}.$$

[2] Note that the most natural process for vector mesons p+e $\to\rho^+$+n+e$'$ (with the real ρ-meson production) proceeds according to a totally different (vector dominance) scheme with the Pomeron exchange.

In this work, the model w.f.'s $R_{\rm N}^{\rm N\pi}(k)$ were calculated on the basis of

1) phenomenological vertex form factors (f.f.) and coupling constants

$$F_{\pi\rm NN}(\mathbf{k}^2) = \frac{\Lambda_\pi^2}{\Lambda_\pi^2 + \mathbf{k}^2}, \quad F_{\rho\rm NN}(\mathbf{k}^2) = \frac{\Lambda_\rho^2}{\Lambda_\rho^2 + \mathbf{k}^2}, \tag{1}$$

$with \Lambda_\pi \approx m_\rho,\ \Lambda_\rho = 2m_\rho,\ g_{\pi\rm NN} = 13.2,\ g_{\rho\rm NN} = 2.9,\ \kappa_\rho = 6.1,\ g_{\rho\pi\gamma} = 0.609\mu_{\rm p} m_\pi;$

2) phenomenological π-N potentials of a separable form

$$V(k, k'; E) = \frac{f_0(k) f_0(k')}{E - M_{\rm N_0} + 0} - h_0(k) h_0(k'),$$

fitted to the π-N elastic scattering [9, 10], for which the w.f. of πN system

$$R_{\rm p}^{\rm n\pi^+}(k) = \frac{f(k, E = M_N)}{M_{\rm N} - \omega_\pi(k) - E_{\rm N0}} \tag{2}$$

is a residue of the exact πN propagator[3] $G(k, k'; E) = f(k, E)\, f(k', E)/(E - M_{\rm N})$ in the nucleon pole $E = M_{\rm N}$, $E_{\rm N0} = \sqrt{M_{\rm N0} + \mathbf{k}^2}$, where $M_{\rm N_0}$ is a "bare" nucleon mass;

3) the CQM with taking into account a scalar $q\bar{q}$ ($^3\rm P_0$) fluctuation in the non-trivial QCD vacuum [3, 4, 6].

Note that the relation of the phenomenological $^3\rm P_0$ models [3, 4] to the first principals of QCD has not been clearly established because of the essentially non-perturbative mechanism of low-energy meson emission. However, the models [3, 4] have their good points: they satisfy the OZI rule and they make possible reasonable predictions for the transition amplitudes. The most general prediction of the $^3\rm P_0$ model is that the meson momentum distribution in the cloud replicates the quark momentum distribution in the nucleon. For such a prediction, the details of different $^3\rm P_0$ models are not important, and we start here from a universal formulation proposed in Ref. [6]. The interaction Hamiltonian is written in a covariant form as a scalar source of $q\bar{q}$ pairs

$$H_s = g_s \int {\rm d}^3x\, \bar{\psi}_q(x)\psi_q(x) = g_s \int {\rm d}^3x\, [\bar{u}(x)u(x) + \bar{d}(x)d(x) + \bar{s}(x)s(x)], \tag{3}$$

where $u(x)$, $d(x)$ and $s(x)$ are Dirac fields for the triplet of constituent quarks (the color part is omitted). Amplitudes of meson emission N→M+B and M→

[3]In this model, the w.f. $R_{\rm p}^{\rm n\pi^+}(k)$ satisfies a non-trivial normalisation condition

$$\int |R_{\rm p}^{\rm n\pi^+}(k)|^2 k^2 dk + (M_{\rm N} - M_{\rm N_0})^{-1} \left(\int R_{\rm p}^{\rm n\pi^+}(k) k^2 dk \right)^2 = 1, \quad S_{\rm p}^{\rm n\pi^+} = \int |R_{\rm p}^{\rm n\pi^+}(k)|^2 k^2 dk < 1.$$

M_1+M_2 are defined as matrix elements $\mathcal{M}(\mathrm{N} \to \mathrm{M} + \mathrm{B}) =< M| < B|H_\mathrm{s}|N >$, $\mathcal{M}(\mathrm{M} \to \mathrm{M}_1 + \mathrm{M}_2) =< M_1| < M_2|H_\mathrm{s}|M >$, where the initial and final states are basis vectors of constituent quark model (CQM). In the first order of v/c, one can obtain (see Ref. [11] for details)

$$\mathcal{M}(\mathrm{N}\to\pi_\alpha+\mathrm{N}) = \frac{5}{3}\frac{\mathrm{i}g_s}{m_\pi m_q}\frac{(2\pi b_\pi^2 m_\pi^2)^{3/4}}{(1+\frac{2}{3}x_\pi^2)^{3/2}} F_{\pi\mathrm{NN}}(\mathbf{k}^2)\tau_\alpha^{(\mathrm{N})\dagger}\boldsymbol{\sigma}^{(\mathrm{N})}\cdot\left[\mathbf{k} - \frac{\omega_\pi(k)}{2M_\mathrm{N}}(\mathbf{P}+\mathbf{P'})\right], \tag{4}$$

where b and b_π are parameters of CQM (nucleon and pion radii respectively), $x_\pi = b_\pi/b \approx 0.5$ and the strong πNN form factor has a Gaussian form $F_{\pi\mathrm{NN}}(\mathbf{k}^2) = \exp\left[-\frac{1}{6}k^2b^2\left(1+\frac{1}{6}x_\pi^2/(1+2x_\pi^2/3)\right)\right]$ characteristic of the harmonic oscilator (h.o.) wave functions. Equation (4) should be compared with the standard definition of pseudo-vector (P.V.) vertex for point-like nucleons and pions to obtain the normalization condition for g_s on the P.V. coupling constant $f_{\pi\mathrm{NN}} \approx 1.0$

$$f_{\pi\mathrm{NN}} = \frac{5}{3}\frac{g_\mathrm{s}}{m_q}(2\pi b_\pi^2 m_\pi^2)^{3/4}(1+\frac{2}{3}x_\pi^2)^{-3/2}, \quad g_{\pi\mathrm{NN}} = \frac{2M_\mathrm{N}}{m_\pi}f_{\pi\mathrm{NN}}. \tag{5}$$

Starting from this value of g_s, we have calculated amplitudes for all transitions N$\to \pi^\alpha$+B and N$\to$K$^\alpha$+Y. For the ρNN and $\rho\pi\gamma$ vertexes, we have obtained

$$\mathcal{M}(\mathrm{N}\to\rho_\alpha^{(m)}+\mathrm{N}) = \frac{g_{\rho\mathrm{NN}}}{2M_\mathrm{N}}\tau_\alpha^{(\mathrm{N})\dagger}\boldsymbol{\epsilon}_\rho^{(m)*}\cdot\{\mathbf{P}+\mathbf{P'} - (1+\kappa_\rho)\mathrm{i}[\boldsymbol{\sigma}^{(\mathrm{N})}\times\mathbf{k}]\}F_{\rho\mathrm{NN}}(\mathbf{k}^2) \tag{6}$$

$$\text{and} \quad \mathcal{M}(\boldsymbol{\rho}+\boldsymbol{\gamma}\to\boldsymbol{\pi}) = g_{\rho\pi\gamma}\frac{|\mathbf{q}|}{m_\pi}\boldsymbol{\epsilon}_\gamma^{(m)}\cdot[\hat{\boldsymbol{\rho}}\times\hat{\mathbf{q}}][\boldsymbol{\rho}\times\boldsymbol{\pi}]_{I_z=0}F_{\rho\pi\gamma}(\mathbf{q}^2), \tag{7}$$

where Eq. (7) is the (spin-flip) matrix element calculated with the spin part of isovector e.-m. quark current $\sim \tau_z^{(q)}(e/2m_q)\mathrm{i}[\boldsymbol{\sigma}^{(q)}\times\mathbf{q}]$; $\hat{\boldsymbol{\rho}}$ is the ρ-meson polarisation vector, $\hat{\mathbf{q}} = \mathbf{q}/|\mathbf{q}|$, $\boldsymbol{\epsilon}_\gamma^{(m)}$ is the photon polarization vector with transverse sperical components $m = \pm 1$ only, and $\boldsymbol{\rho}$, $\boldsymbol{\gamma}$ and $\boldsymbol{\pi}$ are isovectors. The coupling constants $g_{\rho\mathrm{NN}}$, $(1+\kappa_\rho)g_{\rho\mathrm{NN}}$, and $g_{\rho\pi\gamma}$ are calculated with the fractional parentage coefficients technique on the basis of CQM

$$g_{\rho\mathrm{NN}} = \frac{g_\mathrm{s}}{m_q}\frac{m_\pi}{3m_\rho}(2\pi b_\rho^2 m_\rho^2)^{3/4}(1+\frac{2}{3}x_\rho^2)^{-3/2}, \quad 1+\kappa_\rho = 5, \quad g_{\rho\pi\gamma} = \frac{2}{3}\frac{em_\pi}{2m_q}. \tag{8}$$

The momentum distribution of pions in the nucleon $|R_\mathrm{p}^{\mathrm{n}\pi^+}|^2$ calculated [Eq. (2)] with phenomenological πN potentials [9, 10] and with the monopole (Λ_π = 0.6 GeV/c) vertex f.f. (1) are shown in Fig. 2 (left panel, solid line). The dashed line coresponds to Afnan's πN potential [9], and the dash-dotted line to the Lee's potential [10]. We see that the latter is rather far from the solid line and, consequently, from the experimental data. The MD and strong form factors for the channels π+N, $\pi+\Delta$, $\pi+\mathrm{N}_{1/2^-}$ (N*) and $\pi+\mathrm{N}_{1/2^+}$ (N**) calculated on the basis of the

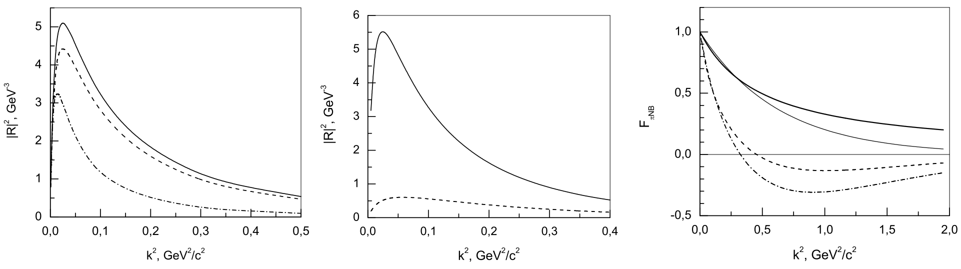

Fig. 2. The pion MD calculated in 1) phenomenological πN models [9, 10] (left panel); 2) the ^{3}P$_0$ model (central panel: for $\pi + \mathrm{N}$ and $\pi + \Delta$ channels, right panel: strong form factors for $\pi + \mathrm{N}$, $\pi + \mathrm{N}^*$ and $\pi + \mathrm{N}^{**}$ channels.

^{3}P$_0$ model are shown in the central and right panels of Fig. 2. For comparison, the form factor (1) for $\Lambda_\pi = 0.7$ GeV/c (thick solid line) is also shown. One can see that the ^{3}P$_0$ predictions are in a good egreement with this monopole f.f. up to $|t| \approx 0.5$ GeV$^2/c^2$. However, the experimental data on Rosenbluth separation [5] are not of high accuracy to resolve a wide interval of Λ_π from 0.7 to 1.2 GeV/c, as it is seen from Fig. 3, where the calculated $\mathrm{d}\sigma_L/\mathrm{d}t$ is compared with the data [5] at $Q^2 = 0.7$ and 3.3 GeV$^2/c^2$. Nevertheless, it is important to note here that both the absolute value of cross section $\mathrm{d}\sigma_L/\mathrm{d}t$ and the shape of its dependence on $t\,(\approx -\mathbf{k}^2)$ are well reproduced by the microscopical models (CQM + ^{3}P$_0$). In particular, as Fig. 2 (right panel) shows, both the shape of monopole f.f. and the empirical value[4] $\Lambda_\pi \approx 0.6 \div 0.7$ GeV/c find its microscopical foundation. So, our predictions for N$\to \pi$+B, B= Δ, N*, N** seem to be useful for future exclusive experiments.

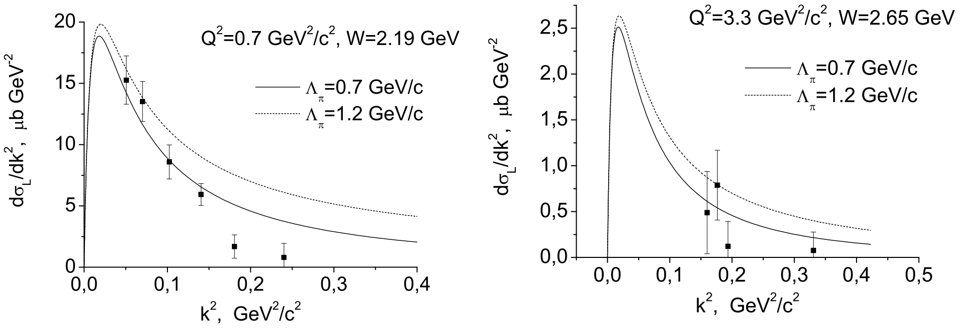

Fig. 3. The longitudinal cross section calculated with phenomenological monopole strong form factors Eq. (1). The data from [5].

The ρ-meson pole contribution to the transverse cross section of pion electroproduction is shown in Fig. 4 in comparison with the data [5] for $Q^2 = 0.7$ and 3.3 GeV$^2/c^2$. The contribution of pion pole is shown by the dashed line and the sum of ρ and π contribution by the solid line. It is seen that the ρ-pole contri-

[4]It appears close to the result by Phandaripande et al. [12] related to very different physics.

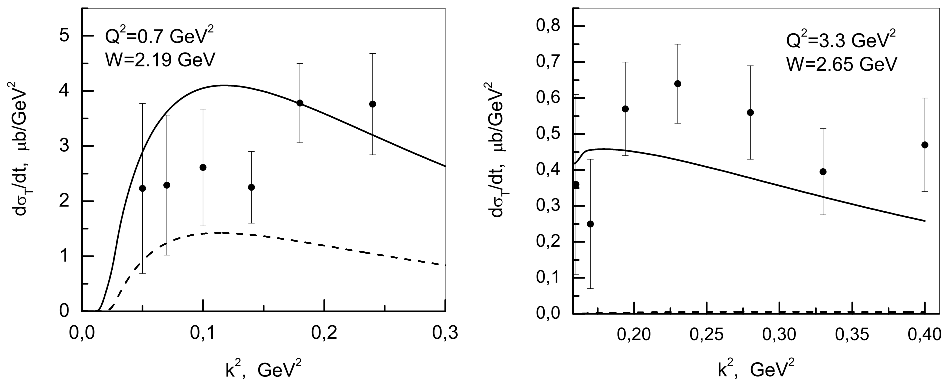

Fig. 4. The transverse cross section calculated in the $^3\mathrm{P}_0$ *model.* π*- and* ρ*-pole contributions (see comments in the text). The data from Ref. [5].*

bution increases with Q^2 and becomes predominant at a few GeV^2/c^2. Therefore, the ρNN and $\rho\pi\gamma$ vertices can be studied in exclusive π^+ electro-production experiments, but new more precise data on the Rosenbluth separation are necessary. This is also true for π^0 electro-production, where an interference between ρ^0 and ω contributions can be studied in the transverse cross section.

Unfortunately, the longitudinal and transverse cross sections of the channel N→Y+K are not separated in the available data, and we cannot extract the MD of kaons from the experiment as we did for pions. Here we only use an estimated value $\mathrm{d}\sigma_L/\mathrm{d}t \approx \frac{1}{2}\mathrm{d}\sigma/\mathrm{d}t$ [5] to compare the $^3\mathrm{P}_0$-model prediction for $\mathrm{d}\sigma_L/\mathrm{d}t$ with the data Ref. [5] at $Q^2 = 1.35\ \mathrm{GeV}^2/c^2$ (Fig. 5, left panel). So, our calculated results for the MDs of kaons in the channels p → Λ+K and p → Σ+K need verification in future experiments with longitudinal virtual photons. Our calculations of these MDs within the $^3\mathrm{P}_0$ model are shown in Fig. 5 (right panel). Predicted spectroscopic factors are $S_{\mathrm{p}}^{\mathrm{K}\Lambda} = 0.076$ and $S_{\mathrm{p}}^{\mathrm{K}\Sigma} = 0.003$ (for comparison, $S_{\mathrm{N}}^{\pi\mathrm{N}} = 0.25$).

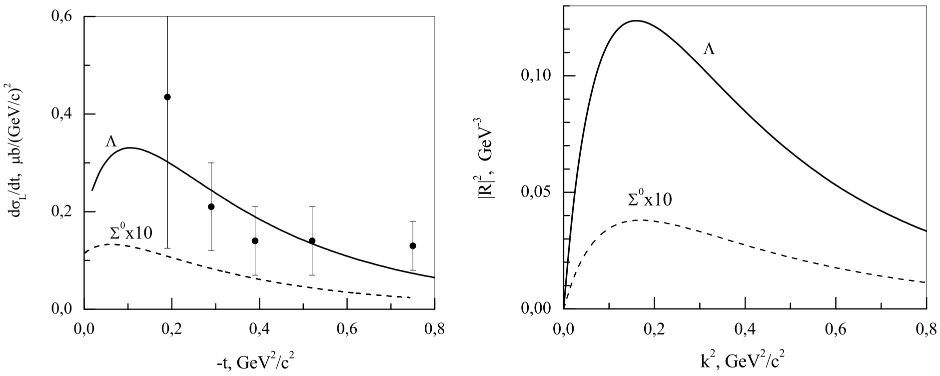

Fig. 5. The $\mathrm{d}\sigma_\mathrm{L}/\mathrm{d}t$ *cross section (left) and MD (right) for* $\mathrm{p}+\mathrm{e} \to e' + \mathrm{K}^+ + \Lambda(\Sigma_0)$.

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KVAZILASTIČNO IZBIJANJE MEZONA IZ NUKLEONA. RAZVOJ I BUDUĆNOST

Elektrotvorba piona i kaona u uvjetima kvazielastičnog izbijanja je moćna metoda za istraživanje elektronskog oblaka. Primijenili smo model skalarnih fluktuacija $q\bar{q}$ (^{3}P$_0$) u netrivijalnom QCD vakuumu radi računanja raspodjela impulsa piona i kaona u kanalima N$\rightarrow$B$+\pi$, B = N, Δ, N*, N**, i N$\rightarrow$Y + K, Y=Λ, Σ_0.