Probing of nucleon mesonic structure by means of quasi-elastic knock-out processes like p + e → e^0 + ^+ + n

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Abstract

The momentum distributions \( \frac{d^2 \sigma}{dQ^2 dW^2 dt} \) of pions and -mesons in the nucleon are extracted from experiment. Perspectives of the quark microscopic theory of mesonic cloud are outlined.

1 Introduction

It is well known that the theoretical description of the pion photoproduction on nucleon encounters the complicated set of problems: a number and a type of used diagrams, their gauge invariance, necessity of inclusion of form factors, taking into account o-shell effects, and so on. But the situation becomes significantly simpler for virtual photons in the electroweak process \( p + e \rightarrow e^0 + ^+ + n \) at sufficiently high values of the momentum square transfer \( Q^2 = q^2 \geq 2GEV^2 > c^2 \). In this case the diagram with the pion pole in the t-channel (the "pion-in-ight" diagram) becomes dominant under the standard conditions of quasielastic knock-out process: \( m^2 + m^2 \leq (p_R + p_f)^2 \) is the mass of final hadronic state \( R + \) (\( R = N ; \bar{N} \), etc.). For the first time the dominance of pion-in-ight diagram in the longitudinal part of differential cross section (integrated over the azimuthal angles) \( d^3 \sigma \) was pointed in the paper [1]. Later in Ref. [2] the analysis of the momentum distribution of pions in the nucleon was given in the frame of light cone dynamics. In our works [3,4] the discussion of the knock-out process is given in the laboratory system and just in this frame we end the momentum distribution (MD) of pions (starting from experimental data [4] on \( L \)). The similar situation is also for the transverse virtual photon \( \gamma \) (really the knock-out of a vector meson with simultaneous transformation of \( \gamma \) into the pion). It can provide a valuable information on the properties of vector mesons in nucleon [1]. These facts open a new possibility for the direct investigation of the mesonic structure of nucleon.

2 Study of the pion and -meson momentum distribution in the nucleon

Our approach to the problem is very similar to the standard methods of nuclear physics, where the process of nucleon knockout has been used for a long time as a mighty tool for investigation of...
of the momentum distribution of nucleons in nuclei. The cross section of quasi-elastic pion knockout from nucleus can be written in the form:

\[
\frac{d L ( p \! \to \! n^+) }{d k^2} = \frac{F^2 (Q^2)}{8 \pi (m^2 + M_N^2)} \frac{M (p \! \to \! n^+)^2}{t - m} \frac{q^2}{Q^2} \frac{4}{4 (p \! \to \! q \frac{p \! \to \! q}{q^2} )^2};
\]

where asterisk symbols are for values written in the center of mass of the \( p + n \) collision. The "wave function" \((W, F)\) of a virtual pion in the nucleon is the following \( k \)-dependent factor of \( L \):

\[
\frac{n^+_p (k^2)}{k_0} = N_1 \frac{M (p \! \to \! n^+)}{k_0} !(k^2); \quad N_1 = \frac{4}{(2)^2 2M_N 2E_N (k^2)!};
\]

which can be related to the matrix element of the pion creation operator

\[
h\pi^+ + \bar{p}^0, \pi^- M (p \! \to \! n^+)_{t - m} = \frac{N_1}{k_0} !(k^2)^n_p (k^2);\]

Recall that for the standard \( NN \) vertex the transition amplitude can be written in the form

\[
\frac{M (p \! \to \! n^+)}{k_0} ! (k^2) = 2k^2 g^2_{NN} F^2_{NN} (k^2); \quad F_{NN} (k^2) = \frac{2}{k^2 + k^2};
\]

As the normalization of all the above factors is xed the norm of such \( WF \) denotes a "spectroscopic factor" \((SF)\) of the \( n^+ \) state in the proton

\[
S_p^n = \sum_{\text{virtual}} \frac{Z_1}{N_1} !(k^2)^n_p (k^2) d k;
\]

The pion-baryon structure of nucleus can be described in terms of a set of such spectroscopic factors: \( S_p^n, S_p^N \), etc. When the longitudinal cross section is factorizable in the form:

\[
d_L (p \! \to \! n^+) = \frac{F^2 (Q^2)}{8 \pi (m^2 + M_N^2)} \frac{M (p \! \to \! n^+)^2}{t - m} \frac{q^2}{Q^2} \frac{4}{4 (p \! \to \! q \frac{p \! \to \! q}{q^2} )^2};
\]

(e.g. in terms of the pion-in- light mechanism) the \( W \), \( F \), and \( SF \) should be observable values in the coincidence experiments (at \( Q^2 \) and \( M_R \)). Then one can determine (in analogy with the standard definitions in the nuclear cluster physics) the "total number of pions in the nucleon" as a sum \( S = \sum_p S_p^n \), where \( p = N, N \), etc. are all the possible virtual baryons in the nucleus. In Figs. 1 and 2 the longitudinal cross sections calculated on the basis of the above pion-in- light mechanism (at the value of \( Q^2 = 0.7 \) and \( 1.2 \) \( GeV \)) are compared with the old \( p(e^+ e^-)n \) data [1] at \( Q^2 = 0.7 \) and \( 3.3 \) \( GeV^2 \). One can see that at both high and intermediate \( Q^2 \), this mechanism is in rough agreement with the data if the cut-off parameter is not so large (0.7 \( GeV/c \)), but new more exact data on \( L \) at high \( Q^2 \) would be desirable.

The pole diagram with the \( \pi \) meson as a virtual state in the nucleon provides the main contribution to the transverse cross section \( \tau (p \! \to \! n \! \to \! \pi^0) \) at high \( Q^2 \) & \( 3 \) \( GeV^2 \) (see Fig. 3). However, the spectroscopic factor for the \( n^+ \) channel \( S_p^n \) cannot be determined from the experiment as the data are only available for too low \( k^2 \) as compare with \( m^2 \).

3 Pion-baryon structure of the nucleon in the \( ^3P_0 \) model

Non-diagonal transitions \( p \! \to \! B \) for the pion-in- light mechanism of pion knock out can be considered on the same footing, i.e. on the basis of the eikonal-theory vertex function, but the standard expressions

\[
M (p \! \to \! B^+) = \frac{4M_N M_{B^+}}{m^2} 2k^2 F_{NB^+}^2 (k^2);
\]
Free parameters would be more effective. For example, the microscopic coupling constant from only one free parameter, the amplitude of the vacuum quark fluctuation (normalized on the effective quark coupling constant $f_{qq} = \frac{3}{5}f_{NN}$), but predict all the coupling constants $f_{NN}$ and form factors $F_{NBJ}$ of the interest starting from the standard quark-shell model techniques \[5, 6\]. Paramaters of the constituent quark model have already been fixed and are not free in our approach. All the form factors $F_{NBJ}$ only depend on two quark-shell model parameters $b_N$ and $b_B$ (quark radii of $N$ and $B$) fixed earlier. At the standard values $b_N = 0.6$ fm and $b_B = 0.3$ fm we have obtained the predictions for $N$ wave functions in the nucleon (see Figs. 4 and 5), where $B_1 = N_1$; $N = N_{1-2} (1535)$ and $N = N_{1-2} (1440)$. In the used proper normalization of the $W_F$'s we are able to determine the $S_F$'s for these virtual states in the nucleon \[9\]. This values could be extracted from coincidence experiments similar to the above cited \[9\]. Such experiments would be more difficult because of too small predicted cross sections for $N + B_1$ channels, but they will be very informative for understanding the hadron structure in terms of

**Figure 1:** Longitudinal cross section at $Q^2 = 0.7 \text{ GeV}^2/c^2$. The data are from Ref. [9].

**Figure 2:** Longitudinal cross section at $Q^2 = 3.3 \text{ GeV}^2/c^2$.

**Figure 3:** Transverse cross section at $Q^2 = 3.3 \text{ GeV}^2/c^2$. 

$Q^2=0.7 \text{ GeV}^2/c^2$, $W=2.19 \text{ GeV}$

$Q^2=3.3 \text{ GeV}^2/c^2$, $W=2.65 \text{ GeV}$
Figure 4: Pion momentum distribution in the nucleon for B channels $^+N$ and $^+N$. quark and meson degrees of freedom.

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