Q²-EVOLUTION OF ΔNγ FORM FACTORS UP TO 4 (GEV/C)² FROM JLAB DATA

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We present the results on the ratios \( E^{(3/2)}/M^{(3/2)} \) and \( S^{(3/2)}/M^{(3/2)} \) for the \( \gamma^* N \rightarrow \Delta(1232) \) transition at \( Q^2 \leq 4 \text{ (GeV/c)}^2 \) extracted from the \( p(e, e'p)\pi^0 \) cross section using two approaches: dispersion relations and modified version of unitary isobar model. The obtained results are in good agreement with the results of other analyses obtained using truncated multipole expansion at \( Q^2 = 0.4, 0.525, 0.65, 0.75, 0.9, 1.15, 1.45, 1.8 \text{ (GeV/c)}^2 \) and within dynamical and unitary isobar models at \( Q^2 = 2.8, 4 \text{ (GeV/c)}^2 \). According to obtained results the ratio \( E^{(3/2)}/M^{(3/2)} \) remains small in all investigated region of \( Q^2 \) with very unclear tendency to cross zero above 2 \((\text{GeV/c})^2\). The absolute value of the ratio \( S^{(3/2)}/M^{(3/2)} \) is clearly increasing with increasing \( Q^2 \), while it should be a constant value in the pQCD asymptotics. So, at \( Q^2 \leq 4 \text{ (GeV/c)}^2 \) there is no evidence of approaching pQCD regime for these ratios. None of the soft approaches gives satisfactory description of the obtained results.

1. Introduction
It is known that for about 20 years the question: which is the scale of transition from soft to hard mechanism of QCD in exclusive processes, is the subject of controversy. Detail discussion of this problem can be found, for example, in papers 1,2,3. The point of view, that this scale should be large, i.e. much larger than now available \( Q^2 \), is based mainly on the utilization of asymptotic wave function and is confirmed by the results obtained using local quark-hadron duality 4. On the other hand there are arguments, based mainly on the utilization of the Chernyak-Zhitnitsky wave function 5, that hard mechanism of QCD can be observed at quite small \( Q^2 \). Experimental data on proton elastic form factors and form factors for the second and third resonance peaks extracted from inclusive data 3, indeed, manifest the features which are characteristic of pQCD starting with very small \( Q^2 \), about 2 – 3 GeV². However, for \( \gamma^* N \rightarrow \Delta(1232) \) the strong numerical
suppression of the leading order amplitude is obtained using the wave functions of CZ type. By this reason, in distinction to other form factors, the hard mechanism is expected for $\gamma^* N \to \Delta(1232)$ at much higher $Q^2$. Information on the $Q^2$-evolution of the ratios $E^{(3/2)}_{1+}/M^{(3/2)}_{1+}$, $S^{(3/2)}_{1+}/M^{(3/2)}_{1+}$ for the $\gamma^* N \to \Delta(1232)$ transition will allow to check this expectation, because the transition from soft to hard mechanism is characterized by a striking change in the behaviour of $E^{3/2}_{1+}/M^{3/2}_{1+}$, $S^{3/2}_{1+}/M^{3/2}_{1+}$ from

$$E^{3/2}_{1+}/M^{3/2}_{1+} \approx 0, \quad S^{3/2}_{1+}/M^{3/2}_{1+} \approx 0$$  \hspace{1cm} (1)$$

at $Q^2 = 0$ to

$$E^{3/2}_{1+}/M^{3/2}_{1+} = 1, \quad S^{3/2}_{1+}/M^{3/2}_{1+} = \text{const}$$  \hspace{1cm} (2)$$

in the pQCD regime. By this reason, investigation of the $Q^2$-evolution of the ratios $E^{(3/2)}_{1+}/M^{(3/2)}_{1+}$, $S^{(3/2)}_{1+}/M^{(3/2)}_{1+}$ is very informative for understanding of the mechanisms and the scale of transition to pQCD regime.

In this report, we present the results on the ratios $E^{(3/2)}_{1+}/M^{(3/2)}_{1+}$, $S^{(3/2)}_{1+}/M^{(3/2)}_{1+}$ for the $\gamma^* N \to \Delta(1232)$ transition at $Q^2 = 0.4, 0.525, 0.65, 0.75, 0.9, 1.15, 1.45, 1.8, 2.8, 4 (GeV/c)^2$. These results are extracted from the JLab data on $p(e, e'p)\pi^0$ cross section using two approaches: dispersion relations and modified version of the unitary isobar model of Ref.\textsuperscript{9}. The detail description of the approaches is done in Ref.\textsuperscript{10}.

2. Results and discussion

The obtained results for the ratios $E^{(3/2)}_{1+}/M^{(3/2)}_{1+}$, $S^{(3/2)}_{1+}/M^{(3/2)}_{1+}$ are presented in Figure 1.

In this Figure the results obtained by truncated multipole analysis of at $Q^2 = 0.4, 0.525, 0.65, 0.75, 0.9, 1.15, 1.45, 1.8 (GeV/c)^2$ and using dynamical and unitary isobar models at $Q^2 = 2.8, 4 (GeV/c)^2$ are also presented.

Let us note, that presented results correspond to the so called "dressed" $\gamma N\Delta$ vertex, i.e. are extracted from the whole magnitudes of multipoles $M^{(3/2)}_{1+}$, $E^{(3/2)}_{1+}$, $S^{(3/2)}_{1+}$ at the resonance position, where $\delta^{(3/2)}_{1+} = \pi/2$. Extraction of "bare" multipoles can be made only using models and is model-dependent.

Note also, that there are two sets of results at $Q^2 = 0.65, 0.75, 0.9 (GeV/c)^2$, which is connected with two kinds of measurements of $p(e, e'p)\pi^0$ cross section in\textsuperscript{8} at different energies of initial electron.

From Figure 1 it is seen that the results obtained using different approaches agree with each other. The ratio $E^{(3/2)}_{1+}/M^{(3/2)}_{1+}$ remains small
Figure 1. The ratios $E^{(3/2)}/M^{(3/2)}$, $S^{(3/2)}/M^{(3/2)}$ for the $\gamma^* N \rightarrow \Delta(1232)$ transition extracted from the $p(e,e'p)\pi^0$ cross section. Results of our analysis are obtained using dispersion relations (full circles) and our modified version of unitary isobar model (full squares). Open squares correspond to truncated multipole analysis, open circles are obtained within dynamical and unitary isobar models in Ref. 11. The predictions of the light-cone relativistic quark models are presented by solid and dotted curves, dashed-dotted curve corresponds to relativized quark model, and dashed curves are the results of Ref. 15.

in all $Q^2$ region up to 4 (GeV/c)$^2$, revealing some tendency to cross zero above $Q^2 > 2$ (GeV/c)$^2$. However, this tendency is not clear, and only measurements at higher $Q^2$ can clear up the situation. The absolute value of the ratio $S^{(3/2)}/M^{(3/2)}$ is clearly increasing with increasing $Q^2$, and does not reveal the tendency of approaching the constant value. So, at $Q^2 \leq 4$ (GeV/c)$^2$ there is no indication of approaching pQCD regime for the ratios $E^{(3/2)}/M^{(3/2)}$ and $S^{(3/2)}/M^{(3/2)}$.

Therefore, it is reasonable to conclude, that the behaviour of the ratios
$E_{1+}^{(3/2)}/M_{1+}^{(3/2)}$ and $S_{1+}^{(3/2)}/M_{1+}^{(3/2)}$ at $Q^2 \leq 4 \text{ (GeV/c)}^2$ is related to the soft mechanisms. By this reason in Figure 1 the predictions based on the soft approaches are presented. These are light-cone relativistic quark model predictions \(^{12,13}\), predictions of relativized quark model \(^{14}\), and the results of Ref. \(^{15}\) obtained by interpolation between very low and very high $Q^2$.

Both light-cone relativistic quark models give qualitatively good description of the ratio $S_{1+}^{(3/2)}/M_{1+}^{(3/2)}$, but in the case of $E_{1+}^{(3/2)}/M_{1+}^{(3/2)}$ they contradict the obtained results. In contrast with this, the relativized quark model predictions \(^{14}\) for $E_{1+}^{(3/2)}/M_{1+}^{(3/2)}$ are close to the results extracted from experimental data, however, in the case of $S_{1+}^{(3/2)}/M_{1+}^{(3/2)}$ the prediction of this model: $S_{1+}^{(3/2)}/M_{1+}^{(3/2)} \approx 0$, disagrees with these results. The predictions of Ref. \(^{15}\) contradict the obtained results for both ratios. So, none of the soft approaches gives satisfactory description of the ratios $E_{1+}^{(3/2)}/M_{1+}^{(3/2)}$ and $S_{1+}^{(3/2)}/M_{1+}^{(3/2)}$ in the investigated region of $Q^2$.

3. Conclusion

In summary, we have analysed JLab data on $p(e,e'p)\pi^0$ cross section at $Q^2 \leq 4 \text{ (GeV/c)}^2$ in the $\Delta(1232)$ resonance region within two approaches: dispersion relations and modified version of unitary isobar model. As a result, we have obtained information on $Q^2$-evolution of the ratios $E_{1+}^{(3/2)}/M_{1+}^{(3/2)}$ and $S_{1+}^{(3/2)}/M_{1+}^{(3/2)}$, which are of interest for understanding the scale and mechanisms of transition from soft to hard regime of QCD in exclusive processes. The obtained results show that there is no evidence yet of approaching pQCD regime for the $\gamma^*N \rightarrow \Delta(1232)$ transition, and for investigation of the scale, where hard mechanism for this transition begin to work, measurements at higher $Q^2$ are needed. We have compared the results on $E_{1+}^{(3/2)}/M_{1+}^{(3/2)}$ and $S_{1+}^{(3/2)}/M_{1+}^{(3/2)}$ with existing predictions obtained within soft approaches. It turned out, that none of the soft approaches gives simultaneously satisfactory description of these ratios. This means, that more detail investigations of soft mechanisms for $\gamma^*N \rightarrow \Delta(1232)$ are necessary.

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