Electroweak excitation of baryon resonances*

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Abstract. We discuss the cases of $N$ to $\Delta(1232)$ and $N$ to $N^\ast(1535)$ transitions to examine the measured electroweak responses and to compare them with predictions from the present generation of the QCD-inspired models. In both cases, there is a significant discrepancy between the two. Future exploration of baryon resonances by electroweak probes points to very high quality data from new facilities like the Jefferson Lab in the USA, on the experimental side, and the rigorous investigations of QCD on lattice, on the theoretical one.

Resumen. Se discuten los casos de las transiciones de $N$ a $\Delta(1232)$ y $N$ a $N^\ast(1535)$ para examinar las respuestas electro-débiles medidas y compararlas con las predicciones de la presente generación de modelos inspirados en QCD. En ambos casos hay una discrepancia significativa entre ambas. La exploración futura de resonancias bariónicas con pruebas electro-débiles apunta a datos de muy alta calidad de nuevas instalaciones como el Jefferson Lab en EE.UU., del lado experimental, y a investigaciones rigurosas de QCD en la red en el lado teórico.

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1. Introduction

Let me first express my great pleasure being able to attend the twentieth edition of the Oaxtepec symposium on nuclear physics in the magnificent setting of Oaxtepec, Morelos, Mexico. I first pay tribute to Prof. Moshinsky and others for creating this symposium and the current organizers for their tireless efforts to bring this special edition and make it a great success.

Since my talk is the first one in the symposium exclusively devoted to baryon excitations, let me first answer the question, "Why is baryon physics in a nuclear physics symposium?" The answer to this question is, of course, well-known to this audience. Nuclei are made of hadrons, that is, mesons and baryons, the latter being nucleons and their excitations or isobars. Hadrons, in their turn, are made of quarks and gluons, interactions of which are described by the standard model, consisting of the gauge symmetry $[SU(2) \times U(1)]_f \times SU(3)_c$, the first part being quantum flavor dynamics or QFD and the second part, quantum chromodynamics or QCD. Physics of interactions in energy scales from zero up to the masses of the $W$ and $Z$ bosons are, in principle, now understood. Our particular job is to understand nuclear interactions in terms of QCD. For this, electroweak probes, exhibiting interactions well-known in QFD, are very helpful and baryon resonances allow us to learn using QCD in the "simplest" nuclei, proton and neutron.

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From there, our adventure begins in more complicated nuclei! There should be a warning here: we might not be able to compute accurately all properties of hadrons and nuclear physics starting from standard model, just as we are not able now to calculate everything in condensed matter physics, starting from quantum electrodynamics or QED. We must try to see how far we can go, and time will tell what the outcome is going to be. A broad understanding from the basic theoretical framework would be satisfactory.

Below I shall first make some remarks about the usefulness of electroweak production of pseudoscalar mesons in the resonance region in probing the nucleon structure. Next I shall show that current generation of QCD-inspired models, including those of the symposium co-organizer, Bijker and his collaborators [1], all fall short of being able to describe the electromagnetic form factors in the N to Δ(1232) [2,3] and N to N*(1535) transitions [4,5], both at low and high \( q^2 \), the square of the four-momentum transfer. This, I submit to you, is a fundamental problem in subatomic physics to explore. Since QCD is the theory of strong interaction, it should be able to explain it. Finally, I shall remind you of the new experimental prospects at places like the recently opened Jefferson Lab in the USA in this field of physics.

2. ELECTRO-WEAK PRODUCTION OF SEUDOSCALAR MESONS

The pseudoscalar mesons, made out of \( u, d \) and \( s \) quarks, in the orbital angular momentum state of \( L = 0 \) in the simplest \( q\bar{q} \) configuration, form the ground-state SU(3) nonet: these are the three \( I = 1 \) \( \pi \)'s, the two \( I = \frac{1}{2} \) \( K \)'s and the two \( \bar{K} \)'s and the two \( I = 0 \) \( \eta \) and \( \eta' \). Photo- and electro-production of these mesons go through a set of reasonably well-known lowest-order Born terms \([2,4,6,7]\). Our special interest is to isolate the graph in which there is the excitation of an \( s \)-channel resonance. For example, in the process

\[
\gamma + N \rightarrow \Delta(1232) \rightarrow N + \pi, \tag{1}
\]

we have the possibility of studying the electromagnetic \( A_{1/2} \) and \( A_{3/2} \) transverse helicity amplitudes for the nucleon to Delta transition, in the case of real photon excitation, and additionally the longitudinal amplitude \( A_{1/2} \) in the case of virtual photon reaction. In the weak process

\[
\nu + N \rightarrow \Delta(1232) \rightarrow N + \pi, \tag{2}
\]

we have the opportunity not only to sample the three vector form factors we can in the last case above, but also the three axial vector form factors. While the process (2) is harder to study than (1), it is richer in amplitudes! For the rest of the talk, I shall concentrate on the processes (1). The subject of exploration of resonances via weak interaction is still in experimental infancy. We discuss it elsewhere in greater detail \([8,9]\).

3. THE \( N \rightarrow \Delta(1232) \) TRANSITION

The interest here is to determine the sizes of the resonant \( E2 \) and the \( M1 \) amplitudes, which are respectively tiny and big at the photon peaks. The former is sensitive to the
effects of the color hyperfine interaction in the quark model and the latter is interesting in terms of the question “which of the partons carry the transition magnetism” in this case. For a history of this old subject, we refer the readers to Ref. 2, where older papers are quoted.

Latest to join the fray is a paper reporting experimental results from Mainz [10] with polarized photons, which has just appeared in the PRL. Conclusions that can be drawn from this beautiful work are [11]

\[ M1 = 282 \pm 2, \quad E2 = -7.4 \pm 1.1, \]  

while the estimates from quark model are [12]

\[ M1 = 206, \quad E2 = -2.0, \]  

and the lattice calculations give [13]

\[ M1 = 210 \pm 25, \quad E2 = 6.3 \pm 17, \]  

all in the usual units of \( 10^{-3} \text{GeV}^{-1/2} \). Thus, there is a significant shortage of transition magnetism, and the famous \( E2 \) to \( M1 \) ratio is just too big compared, at least, to the quark model estimates. No QCD-inspired model can currently explain the results in (3)—an important failure at \( q^2 = 0 \). On the positive side, both (3), (4), and (5) agree on the conclusion for the \( N \rightarrow \Delta \) helicity amplitudes

\[ A_{3/2} \sim A_{1/2}, \quad \text{for} \quad q^2 = 0, \]  

i.e., in the non-perturbative domain of QCD, there is a complete violation of the helicity conservation rule.

At large \( q^2 \), QCD predicts [14]

\[ A_{1/2} \gg A_{3/2}, \]  

implying

\[ M1 \sim E2. \]  

There is some experimental evidence that, at \( -q^2 \geq 6 \text{GeV}^2 \), the data exhibit QCD scaling [15]. A clear test of (7) and (8) is still in the future. Where perturbative domain of QCD begins itself is a fundamental question, both in theory and in experiment.

4. THE \( N \rightarrow N^*(1535) \) TRANSITION

A good way to study this region is via the process [4, 5]

\[ \gamma + N \rightarrow N + \eta. \]  

Recently this has been studied at Bates [16], Bonn [17] and, particularly accurately, at Mainz [18], with real photons. The \( N \) to \( N^*(1535) \) electromagnetic transition is an \( E1 \)
type. We can determine, from the Mainz data, an electrostrong parameter, for both proton and neutron targets [4]

\[
\xi_p = 2.20 \pm 0.15, \\
\xi_n = -1.86 \pm 0.20,
\]

(10)

at the photon point. The quark model estimates of Capstick and Roberts [19] yield about half of the above value, while the approach of Bijker et al. [1] cannot describe the large width of N*(1535) in the \(\eta\)-N channel, in the framework of a three-quark configuration. We, thus, have a severe crisis of the quark model, at \(q^2 = 0\), in this case. There is a shortage of transition electricity here, even in the most successful versions.

Analyzing the data on electroproduction of \(\eta\) exacerbates the above problems [5], as we have reported recently in a PRL. The electrostrong form factors as a function of \(q^2\) falls much more slowly than the predictions of quark models [20]. Thus, we are revisiting the problem we have encountered earlier in the case of N to \(\Delta(1232)\) transition.

5. OTHER PROBLEMS

We have discussed above two cases of interest in detail. The cases of N to N*(1440) and N to N*(2080) can be cited as two other examples [21], where the quark model results are of questionable accuracy. Due to space limitations, we do not discuss them any further here. Two very important questions are: Where are the missing baryons around 2 GeV predicted in quark models? Are there hybrid baryons? Suffice to say, much more theoretical and experimental researches are needed to handle many of these basic issues in the baryon resonance physics.

6. QCD: Quo vadis?

Quoting Isgur, “Baryons are the stuff of which our world is made.” Thus it is of vital importance in nuclear physics that we know as much as we can about baryon structure. That has been my concern here, using electromagnetic probes and exciting resonances of these baryons. It is like playing a violin and learning about the stuff of which its strings are made.

In summary, I wanted to draw your attention to the following: Electroweak structure studies with baryon resonances so far have exposed severe problems in the current generation of QCD-inspired models. We have discussed above two examples of this genre, excitation of the \(\Delta(1232)\) and the N*(1535), in some detail, to document the nature of these problems. How would QCD solve them? By using it more rigorously! With this in mind, lattice QCD studies [13] have been started with great enthusiasm. Time will tell how these efforts work, as computing becomes more sophisticated. Meanwhile, great experimental frontiers are open at new facilities, like the Jefferson Lab in the USA, those in Mainz, Germany, and Grenoble, France, just to give some examples. These are expected to yield exclusive reaction studies before long, with the help of polarized beams and targets and large solid angle detectors. From simple nucleons to complex nuclei is
another big step for QCD, where the nuclear medium presents a new colorful territory to explore. When and how we get there will be a major theme in future nuclear research. These exciting developments before long should make future Oaxtepec Symposia a lot of fun!

_Hasta la vista. Let us stay tuned!

_Muchas gracias!_

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**References**


20. Bijker and collaborators [1] do not predict a fall-off as fast as other quark models do, but for them, the dipole behavior is *an input*; in any case, they cannot get the width of $N^*(1535)$ in the $\eta$-N channel treating it as a $(q)^3$ state. See also R. H. Stanley and H. J. Weber *Phys. Rev. C* **52** (1995) 435.