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THE NATURE OF THE $N^*(1535)$

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Abstract

Electromagnetic properties provide independent tests of models of strongly interacting systems. In the unitary chiral approach, the $N^*(1535)$ appears dynamically generated from the interaction of mesons and baryons. We evaluate the $A_{1/2}$ and $S_{1/2}$ helicity amplitudes as a function of the photon virtuality for the $N^*(1535) \to \gamma^* N$ transition. Within the same formalism we evaluate the cross section for the reactions $\gamma N \to \eta N$ and several ratios of observables. The global results provide a strong support to the idea of this resonance being dynamically generated, hence, largely built up from meson baryon components.

1 Introduction

The traditional picture of baryons as being made from three constituent quarks [1] is giving room in some cases to more complicated structures. One of the ideas which has caught strength in recent times is that low lying resonances of $J^P = 1/2^-, 3/2^-$ seem to be well represented in terms of ordinary resonances generated by the meson baryon interaction in $L = 0$; in the $1/2^-$ case from the interaction of the octet of mesons of the π with the octet of baryons of the p [2–9] and in the $3/2^-$ from the interaction of the same mesons with the decuplet of baryons of the $\Delta(1232)$ [10, 11]. The $\Lambda(1405)$, which actually comes as two poles in chiral theories [6], with this two pole structure supported by experiment [12], has been for long thought of as a kind of meson baryon molecule of the $\bar{K}N$ and $\pi\Sigma$ states [13, 14], a structure similar to that provided by the chiral approaches mentioned above. The

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$N^*(1535)$ is one more resonance that appears in the two octets and one singlet of dynamically generated resonances coming from the interaction of the octet of mesons of the π with the octet of baryons of the p [6]. In fact, it was early noted in [15], before the systematics of [6] was established, that the interaction provided by chiral Lagrangians put as kernel of the Lippmann Schwinger equation generated this resonance, which also appears in other works [16, 17] done along similar lines.

The $N^*(1535)$ plays an important role in all processes of η production since it couples very strongly to ηN. This feature is actually provided automatically by the chiral theories, one of the points of support for the nature of this resonance as dynamically generated. A recent study of the model dependence of the properties of this resonance is seen in [18].

From the point of view of a dynamically generated resonance the $N^*(1535)$ leads to fair descriptions of the $\pi N \to \eta N$ and $\gamma N \to \eta N$ reactions [15,17,19] and produces reasonable numbers for the ηN scattering lengths [2, 17]. Yet, it has been argued that one of the important tests of the nature of a resonance is its electromagnetic form factors. Indeed, a meson baryon resonance should get the Q^2 dependence basically from the meson cloud. If this is a pion, this light particle has a fairly large extend in the wave function, as a consequence of which, the form factor of the resonance should fall relatively fast compared to ordinary quark models which confine the quarks at smaller distances. This is also the case for the proton at small Q^2, due to its meson cloud, which stabilizes later on at larger values of Q^2 where the quark components take over, as shown in chiral quark models [20–22]. We shall see that something special happens for the $N^*(1535)$, but in any case this is a very stringent test, since the chiral theory provides the normalization and the Q^2 dependence for the different transition form factors without any free parameter, once the parameters used in πN scattering with its coupled channels are fixed to scattering data.

Radiative decays of resonances from the point of view of their dynamically generated nature have been addressed in [23] for the $\Lambda(1520)$, in [24] for the $\Delta(1700)$ and in [26] for the two $\Lambda(1405)$ states. It concerns the decay of the resonances into a baryon and a real photon. Some work with virtual photons from this point of view is done in [2] for the electroproduction of η in the vicinity of the $N^*(1535)$ resonance. Meanwhile experimental analyzes have succeeded in extracting the helicity transition form factors $A_{1/2}$ and $S_{1/2}$ for $N^*(1535) \to N\gamma$, for both $N = p, n$, in a relatively wide range of Q^2 values [27].

We undertake the task [25] of evaluating these form factors from the point of view of the $N^*(1535)$ as a dynamically generated resonance. For that purpose we shall extend the formalism of [24, 26] to virtual photons.

From the quark model point of view there is also much work done on these helicity form factors [28–32]. A comparison of their prediction with experiment plus a compilation of results from different experiments can be seen in [27]. There are appreciable differences from one quark model to another and relativistic effects seem to be important, particularly in the $S_{1/2}$ helicity transition form factor.

In our approach the quarks enter through the meson and baryon components of the resonance and the Q^2 dependence is tied to the meson and baryon form factors, which we take from experiment, plus the particular Q^2 dependence of the loop functions from the meson baryon coupled channels that build up the resonance. Thus, the final Q^2 dependence is a nontrivial consequence of chiral dynamics, which provides the coupling of the resonance to open and closed channels, the Q^2 dependence of the different loops and the form factors of the mesons and baryons, particularly the mesons, as we shall see.

2 Formalism

In our approach, the $N^*(1535)$ resonance is dynamically generated in the s-wave scattering of the coupled channels πN, ηN, $K\Lambda$, and $K\Sigma$, for total charges of $Q = 0$ and $Q = 1$. The scattering amplitudes for the $N^*(1535)$ resonance are described in Ref. [17] by means of the Bethe-Salpeter equation for meson baryon scattering given formally by

$$T = V + VGT \ . \tag{1}$$

Based on the N/D method and the dispersion relation [5], this integral scattering equation can be reduced to a simple algebraic equation

$$T = \frac{1}{1 - VG} V \tag{2}$$

where the matrix V is the s-wave meson-baryon interaction provided by the lowest order of chiral perturbation theory, given by the Weinberg-Tomozawa interaction. The diagonal matrix G is the meson baryon loop function evaluated in dimensional regularization. It provides the right-hand cut of the scattering amplitude and ensures exact unitarity through its imaginary part. Furthermore, and this distinguishes the formalism from K-matrix approaches, it is analytic and thus has a real part. Provided attraction in a given channel, this leads to the formation of poles in the complex plane of the scattering energy $s^{1/2}$. The pole is identified with resonances and its residues provide the couplings g_i of the resonance to the channels that are included: in the

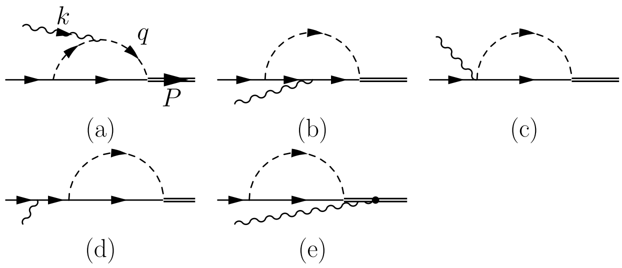

Figure 1: Feynman diagrams for the transition form factor of $N(1535)$ at one loop level. The solid, dashed, wavy and double lines denote octet baryons, mesons, photon, and $N^*(1535)$, respectively.

transition from channel $i \to j$, the amplitude can be expanded around the pole as

$$T^{ij}_{N^*}(\sqrt{s}) = \frac{g_i g_j}{\sqrt{s} - M_R + i\Gamma_R/2} + T_{\rm BG}. \tag{3}$$

The empirical evidence of larger coupling of $N(1535)$ to ηN than that to πN is reproduced in this model. In addition, the couplings to ΣK and ΛK are also large. This implies that the $N(1535)$ has large components of strangeness. The basic model has been refined in Ref. [17] by including the $\pi\pi N$ channel and form factors at higher energies. We leave these additional ingredients out, as they play a minor role in the S_{11} channel and their inclusion in the coupling to the photon is beyond the scope of this study.

2.1 Phototransition

In the meson-baryon picture of the $N(1535)$ resonance, the photoproduction of the resonance from the nucleon is formulated through the well-known photon couplings to the mesons and baryons that constitute the resonance. Photon couplings and gauge invariance in the case of chiral unitary amplitudes are discussed in Ref. [33]. Here we follow a similar approach as developed in Refs. [23, 24, 26] for real photons, extending it to virtual ones. Feynman diagrams for the transition form factors at the one-loop level are shown in Fig.1. In the loops, all possible octet mesons and baryons contribute. In the diagrams (a) and (b), the photon attaches to the meson and baryon in the loop, respectively. The diagram (c) has the Kroll-Ruderman coupling which is the contact interaction of the photon, meson and baryon. The diagrams (d) and (e) have to be taken into account to keep gauge invariance.

We calculate the transition amplitudes both in non-relativistic and relativistic formulations. The momenta of the baryons are small enough to describe the transition amplitudes in the non-relativistic formulation. In addition, as can be seen in Ref. [17], in the construction of the $N^*(1535)$ in meson-baryon scattering, we have used the non-relativistic formulation in the elementary vertex and the baryon propagators. Therefore, to keep consistency of the calculation of the photon couplings with the construction of the N^* resonance, the non-relativistic calculation is preferable. Nevertheless, it is somewhat complicated to prove gauge invariance in the calculation of the amplitude, since one needs to take into account all the possible diagrams including negative energy contributions, which are refereed to as Z-diagrams. To avoid this complication, we will perform the calculation of the amplitudes also in relativistic formulation, in which the negative energy contributions are automatically counted without introducing Z-diagrams, and we have shown that the relativistic calculation is exactly gauge invariant. This guarantees that each term in the $1/M$ expansion is gauge invariant. Exploiting this fact, in the non-relativistic framework, we calculate diagrams for leading amplitudes relying upon gauge invariance and show that the next-to-leading terms are relatively small.

Lorentz invariance and momentum conservation require the transition current J^μ to be written, in general, by the following three Lorentz scalar amplitudes:

$$J^\mu = (\mathcal{M}_1\gamma^\mu + \mathcal{M}_2 P^\mu + \mathcal{M}_3 k^\mu)\gamma_5. \tag{4}$$

The gauge invariance $k \cdot J = 0$, tells us that there are only two independent amplitudes among these three amplitudes, $\mathcal{M}_i$, giving the following relation:

$$(M_{N^*} + M_N)\mathcal{M}_1 + k \cdot P\mathcal{M}_2 + k^2\mathcal{M}_3 = 0 \ . \tag{5}$$

Using the transition current (4), we evaluate the helicity amplitudes, $A_{1/2}$ and $S_{1/2}$, in the rest frame of the $N(1535)$ resonance. After some algebra, the helicity amplitudes are written in terms of the amplitude $\mathcal{M}_2$ and $\mathcal{M}_3$ by

$$A_{1/2} = \sqrt{\frac{2\pi\alpha}{q_R}}\sqrt{\frac{E_i + M_N}{2M_N}}\frac{1}{e}\frac{\sqrt{2}}{M_{N^*} + M_N}\left(k \cdot P\mathcal{M}_2 + k^2\mathcal{M}_3\right) \tag{6}$$

$$S_{1/2} = \sqrt{\frac{2\pi\alpha}{q_R}}\sqrt{\frac{E_i + M_N}{2M_N}}\frac{1}{e}\frac{-|\vec{k}|}{M_{N^*} + M_N}\left(M_{N^*}\mathcal{M}_2 + (M_{N^*} - M_N)\mathcal{M}_3\right); \tag{7}$$

the result for the non-relativistic amplitudes is similar.

In the non-relativistic formulation, the leading terms of the $1/M$ expansions are the diagrams (a) and (c) in Fig.1. The diagram (b) is found to be the next leading order due to the $1/M$ factor in the γBB coupling. In the

CM frame of the N^*, which we take for the non-relativistic calculation, the diagram (d) vanishes, since there is a direct transition of $1/2^+$ to $1/2^-$. The diagram (e) has some contribution in this frame, but it is also found to be the next leading order, since the contribution to the diagram (e) is confirmed to vanish in the large M limit. One of the advantage that Eq. (5) provides is the fact that only the terms proportional to the external momenta $k \cdot P$, k^2 have to be considered. For the non-relativistic calculation this means that the loop integrals are finite for these terms. In Ref. [24] it has been shown that the consideration of these finite terms is equivalent to a calculation of all divergent loop diagrams for which the infinities cancel in the sum. In the present case, this is again the case for the charge $Q = 0$ sector; for $Q = 1$ one needs, however, higher order terms to cancel the infinities, as they are automatically provided in a fully relativistic calculation.

As mentioned above, the non-relativistic framework for the photon loops ensures consistence with the hadronic part of the model. The purpose of a relativistic calculation of these loops is to confirm gauge invariance of our formulation. Without the $1/M$ expansion, which has been performed in the non-relativistic calculation, all the diagrams shown in Fig.1 have been calculated to make the amplitudes gauge-invariant at the one loop level. Each diagram has a divergence from the loop integral. It has been found that the divergence appears only in the $\mathcal{M}_1$ term.

We have also included standard form factors for the virtual photon in the calculation, as well as a non-relativistic treatment of the anomalous magnetic momenta which introduce a small correction.

3 Results

In order to compare our results to the experimentally extracted helicity amplitude, there is an important caveat: The hadronic width of the resonance, as well as the branching ratio, enter the normalization of the experimentally extracted amplitudes [34–36]. It is, thus, the Q^2-dependence of the form factor rather than absolute numbers which should be considered, taking into account the large experimental uncertainties of the width of the $N^*(1535)$. In Fig. 2, the results for $A_{1/2}$ and $S_{1/2}$ are plotted. For $A_{1/2}$, the slope coincides well whereas the strength is underestimated, most probably due to the mentioned ambiguities in the experimental extraction of this quantity. A rescaling shows good agreement with data. Furthermore, the relativistic corrections are rather small in this case (dashed vs. unrescaled solid line). Note that in the most recent MAID analysis [41] a value of $A_{1/2}(Q^2 = 0) = 66 \cdot 10^{-3}\,\mathrm{GeV}^{-1/2}$ is given, quite in agreement with the

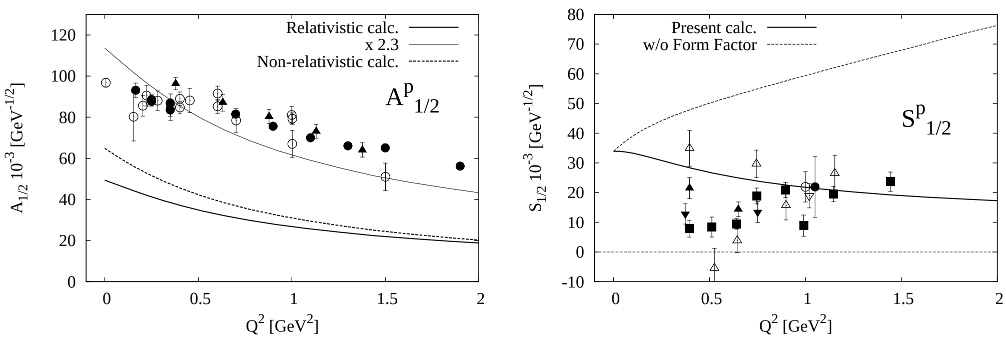

Figure 2: Modulus of $A_{1/2}$ and $S_{1/2}$. The data are from Refs. [36–40]. See text for an explanation of the curves. The sign of $S_{1/2}$ relative to $A^p_{1/2}$ is negative, both in experiment and theory.

present findings. For $S_{1/2}$, we also observe good agreement. For comparison, the quantity $S_{1/2}$ without form factors for the pions and kaons is also plotted (dashed line). The observed rise with Q^2, also present for $A_{1/2}$ (not shown), comes from the momentum dependence of the photon loops from Fig. 1. The loops are responsible for the relatively slow fall-off of $A_{1/2}$ with rising Q^2.

For a real photon at $Q^2 = 0$ we obtain the ratio $A^n_{1/2}/A^p_{1/2} = -0.79+0.11i$, which is almost a real value, and its modulus 0.80. A multipole analysis [42] using the inclusive experimental data of Ref. [34] gives the negative sign value -0.84 ± 0.15 for $A^n_{1/2}/A^p_{1/2}$. Values of $|A^n_{1/2}|/|A^p_{1/2}|$ which are extracted from the ratio of the eta photoproduction cross sections, σ_n/σ_p, are reported as 0.82 ± 0.04 in Ref. [43] and 0.819 ± 0.018 in Ref. [44]. The result obtained in our approach agrees with the experimental data in both sign and magnitude. This comparison is free from the normalization uncertainty.

As a boundary condition, we have also checked that our model reproduces η photoproduction data in the reaction $\gamma p \to \eta p$, although the resonance turns out relatively narrow. Furthermore, we could reasonably well reproduce the available data on the ratio of η photoproduction on the neutron over that on the proton, σ_n/σ_p.

4 Conclusions

In this work we have addressed the evaluation of the electromagnetic helicity form factors for the electroproduction of the $N^*(1535)$ resonance considered as a dynamically generated resonance. The agreement with the $A^p_{1/2}$ amplitude of the proton $N^*(1535)$ resonance is good up to the normalization problem that we discussed. The slow fall-off of the slope is a consequence of the structure of the photon loops that provide the phototransition in the picture of dynamical generation.

The results obtained for the $S_{1/2}$ amplitude are also in fair agreement with experiment, both in size and the relative sign to the $A_{1/2}$ amplitude. As well, sign and size of $A^n_{1/2}/A^p_{1/2}$ are in good agreement with data. We have also ensured that η photoproduction data and the associated ratio σ_n/σ_p are reasonably well reproduced.

Altogether, the information extracted in this study [25] provides support for the idea of the $N^*(1535)$ resonance as being dynamically generated from the interaction of mesons and baryons, the dynamics of which seems to be well accounted for by chiral Lagrangians together with a proper coupled channels unitary treatment of the interaction, as provided by the chiral unitary approach.

References

[1] N. Isgur and G. Karl, Phys. Rev. D 18, 4187 (1978); S. Capstick and N. Isgur, ibid. 34, 2809 (1986); L. Y. Glozman and D. O. Riska, Phys. Rep. 268, 263 (1996); L. Y. Glozman, Z. Papp, and W. Plessas, Phys. Lett. B 381, 311 (1996); see also the review by S. Capstick and W. Roberts, Prog. Part. Nucl. Phys. 45, S241 (2000), and references therein.

[2] N. Kaiser, T. Waas and W. Weise, Nucl. Phys. A **612**, 297 (1997).

[3] E. Oset and A. Ramos, Nucl. Phys. A **635**, 99 (1998).

[4] E. Oset, A. Ramos and C. Bennhold, Phys. Lett. B **527**, 99 (2002) [Erratum-ibid. B **530**, 260 (2002)].

[5] J. A. Oller and U. G. Meissner, Phys. Lett. B **500**, 263 (2001).

[6] D. Jido, J. A. Oller, E. Oset, A. Ramos and U. G. Meissner, Nucl. Phys. A **725**, 181 (2003).

[7] C. Garcia-Recio, J. Nieves, E. Ruiz Arriola and M. J. Vicente Vacas, Phys. Rev. D **67**, 076009 (2003).

[8] C. Garcia-Recio, M. F. M. Lutz and J. Nieves, Phys. Lett. B **582**, 49 (2004).

[9] T. Hyodo, S. I. Nam, D. Jido and A. Hosaka, Phys. Rev. C **68**, 018201 (2003).

[10] E. E. Kolomeitsev and M. F. M. Lutz, Phys. Lett. B **585** (2004) 243 [arXiv:nucl-th/0305101].

[11] S. Sarkar, E. Oset and M. J. Vicente Vacas, Nucl. Phys. A **750** (2005) 294 [Erratum-ibid. A **780** (2006) 78]

[12] V. K. Magas, E. Oset and A. Ramos, Phys. Rev. Lett. **95** (2005) 052301

[13] R. H. Dalitz and S. F. Tuan, Phys. Rev. Lett. **2**, 425 (1959).

[14] R. H. Dalitz and S. F. Tuan, Annals Phys. **10**, 307 (1960).

[15] N. Kaiser, P. B. Siegel and W. Weise, Phys. Lett. B **362** (1995) 23

[16] J. Nieves and E. Ruiz Arriola, Phys. Rev. D **64** (2001) 116008

[17] T. Inoue, E. Oset and M. J. Vicente Vacas, Phys. Rev. C **65** (2002) 035204

[18] A. Kiswandhi, S. Capstick and S. Dytman, Phys. Rev. C **69** (2004) 025205

[19] M. Döring, E. Oset and D. Strottman, Phys. Rev. C **73** (2006) 045209

[20] A. W. Thomas, S. Theberge and G. A. Miller, Phys. Rev. D **24** (1981) 216.

[21] E. Oset, R. Tegen and W. Weise, Nucl. Phys. A **426** (1984) 456 [Erratum-ibid. A **453** (1986) 751].

[22] V. E. Lyubovitskij, T. Gutsche and A. Faessler, Phys. Rev. C **64** (2001) 065203

[23] M. Döring, E. Oset and S. Sarkar, Phys. Rev. C **74** (2006) 065204

[24] M. Döring, Nucl. Phys. A **786**, 164 (2007)

[25] D. Jido, M. Döring, and E. Oset, to appear soon

[26] L. S. Geng, E. Oset and M. Döring, Eur. Phys. J. A **32**, 201 (2007)

[27] V. D. Burkert and T. S. H. Lee, Int. J. Mod. Phys. E **13** (2004) 1035

[28] F. E. Close and Z. P. Li, Phys. Rev. D **42** (1990) 2194.

[29] M. M. Giannini, E. Santopinto and A. Vassallo, Prog. Part. Nucl. Phys. **50** (2003) 263

[30] D. Merten, U. Loring, K. Kretzschmar, B. Metsch and H. R. Petry, Eur. Phys. J. A **14** (2002) 477

[31] S. Capstick and B. D. Keister, Phys. Rev. D **51** (1995) 3598

[32] B.D. Keister, S. Capstick, N* Physics, edited by T.-S. H. Lee, W. Roberts (World Scientific, Singapore, 1997) p. 58.

[33] B. Borasoy, P. C. Bruns, U. G. Meissner and R. Nissler, Phys. Rev. C **72**, 065201 (2005) [arXiv:hep-ph/0508307].

[34] B. Krusche *et al.*, Phys. Rev. Lett. **74** (1995) 3736.

[35] C. S. Armstrong *et al.* [Jefferson Lab E94014 Collaboration], Phys. Rev. D **60**, 052004 (1999) [arXiv:nucl-ex/9811001].

[36] H. Denizli *et al.* [CLAS Collaboration], Phys. Rev. C **76**, 015204 (2007) [arXiv:0704.2546 [nucl-ex]].

[37] R. Thompson *et al.* [CLAS Collaboration], Phys. Rev. Lett. **86**, 1702 (2001) [arXiv:hep-ex/0011029].

[38] F. W. Brasse *et al.*, Nucl. Phys. B **139**, 37 (1978); F. W. Brasse *et al.*, Z. Phys. C **22**, 33 (1984).

[39] U. Beck *et al.*, Phys. Lett. B **51**, 103 (1974).

[40] H. Breuker *et al.*, Phys. Lett. B **74**, 409 (1978).

[41] S. Kamalov, talk at the NSTAR2007 Workshop, September 2007, Bonn.

[42] N. C. Mukhopadhyay, J. F. Zhang and M. Benmerrouche, Phys. Lett. B **364**, 1 (1995) [arXiv:hep-ph/9510307].

[43] P. Hoffmann-Rothe *et al.*, Phys. Rev. Lett. **78**, 4697 (1997).

[44] J. Weiss *et al.*, Eur. Phys. J. A **16**, 275 (2003) [arXiv:nucl-ex/0210003].