Dynamical coupled-channels: the key to understanding resonances

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Abstract. Recent developments on a dynamical coupled-channels model of hadronic and electromagnetic production of nucleon resonances are summarized.

1 Introduction

The analysis of nucleon resonance production and subsequent decay is possibly the best tool to study the most striking aspects of non-perturbative QCD. Following this fact a large multinational effort has been devoted during the last two decades to gather detailed information about resonance excitation both using hadronic and electromagnetic probes.

In recent years most of the emphasis has fallen on the electroexcitation of resonances seen in meson electroproduction experiments, [1, 2], and a large amount of accurate data has been collected at Jefferson Laboratory (JLab), Mainz, Bonn, GRAAL, and Spring-8. The involved nature of the problem, which comprises excitation of resonances and multistep meson-baryon processes is nowadays believed to demand a dynamical coupled-channels approach. In this work we will consider the one developed recently, MSL, and which is explained in great detail in Ref. [3].

The starting point of the MSL model is a set of Lagrangians describing the interactions between mesons (including the photon) \((M = \gamma, \pi, \eta, \rho, \omega, \sigma, \ldots)\) and baryons \((B = N, \Delta, N^*, \ldots)\). By applying a unitary transformation method \([4]\), an effective Hamiltonian, with an energy independent set of potentials, is then derived from the considered Lagrangian.

The resulting meson-baryon \((MB)\) scattering amplitudes are,

\[
T_{\alpha,\beta}(E) = \alpha,\beta(E) + t_{\alpha,\beta}(E),
\]

\[\text{(1)}\]
where \( \alpha, \beta = \gamma N, \pi N, \eta N, \pi \pi N \). The full amplitudes, e.g. \( T_{\pi N, \pi N}(E), T_{\eta N, \pi N}(E), T_{\pi N, \gamma N}(E) \) can be directly used to, within the same framework, compute \( \pi N \rightarrow \eta N \) and \( \gamma N \rightarrow \pi \pi N \), scattering observables. The non-resonant amplitude \( t_{\alpha, \beta}(E) \) in Eq. (1) is defined by the coupled-channels equations,

\[
t_{\alpha, \beta}(E) = V_{\alpha, \beta}(E) + \sum_{\delta} V_{\alpha, \delta}(E) G_{\delta}(E) t_{\delta, \beta}(E)
\]

with

\[
V_{\alpha, \beta}(E) = v_{\alpha, \beta} + Z^{(E)}_{\alpha, \beta},
\]

where \( v_{\alpha, \beta} \) are the non-resonant \( M \bar{B} \) potentials and \( Z^{(E)}_{\alpha, \beta} \) is due to the one-particle-exchange between unstable \( \pi \Delta, \rho N, \sigma N \) states which are the resonant components of the \( \pi \pi N \) channel.

The second term in the right-hand-side of Eq. (1) is the resonant term defined by

\[
t^R_{\alpha, \beta}(E) = \sum_{N^*_i, N^*_j} \tilde{\Gamma}_{\alpha \rightarrow N^*_i}(E)[D(E)]_{i,j} \tilde{\Gamma}_{N^*_j \rightarrow \beta}(E),
\]

with

\[
[D^{-1}(E)]_{i,j} = (E - M^0_{N^*_i})\delta_{i,j} - \sum_{\delta} \Gamma_{N^*_i \rightarrow \delta} G_{\delta}(E) \tilde{\Gamma}_{\delta \rightarrow N^*_j}(E).
\]

where \( M^0_{N^*_i} \) is the bare mass of the resonant state \( N^*_i \). The dressed vertex interactions in Eq. (1) and Eq. (5) are (defining \( \Gamma_{\alpha \rightarrow N^*_i} = \Gamma^I_{N^*_i \rightarrow \alpha} \))

\[
\tilde{\Gamma}_{\alpha \rightarrow N^*_i}(E) = \Gamma_{\alpha \rightarrow N^*_i} + \sum_{\delta} t_{\alpha, \delta}(E) G_{\delta}(E) \tilde{\Gamma}_{\delta \rightarrow N^*_i},
\]

\[
\Gamma_{N^*_i \rightarrow \alpha} = \Gamma_{N^*_i \rightarrow \alpha} + \sum_{\delta} \Gamma_{N^*_i \rightarrow \delta} G_{\delta}(E) t_{\delta, \alpha}(E).
\]

### 2 Revisiting the electroexcitation of the \( \Delta(1232) \)

To illustrate the procedure that is being followed in our current work we will first consider a simplified version of the model sketched above. We consider only two channels, \( \gamma N \) and \( \pi N \), and will concentrate on the \( \Delta \) (1232) region. The full framework is described in great detail in Ref. [5]. It is a revision of the Sato-Lee model [4] with one important improvement: we extract the \( N^- \Delta \) form factors by fitting all of the available pion electroproduction data at energies close to the \( \Delta \) position.

The vertex \( \tilde{\Gamma}_{\gamma N \rightarrow N^*_i}(E) \) appearing in Eq. (6) can be written in terms of three form factors \( G_E(Q^2), G_M(Q^2) \) and \( G_C(Q^2) \) which are referred to as dressed form factors. Similarly the vertex, \( \Gamma_{\gamma N \rightarrow N^*_i}(E) \), accepts a similar decomposition in terms of \( G_E(Q^2), G_M(Q^2) \) and \( G_C(Q^2) \), which are called bare form factors.

To extract the \( N^- \Delta \) dressed (and bare) form factors, we abandon the simple parameterization used in Ref. [4] and perform \( \chi^2 \) fits to available experimental electroproduction data at each \( Q^2 \) by adjusting the values of the bare form factors. The resulting bare form factors are shown as symbols in Fig. [1].
Figure 1. Bare form factors for the $\gamma N \rightarrow \Delta$ transition as a function of $Q^2$. The points have been obtained by performing individual fits for each $Q^2$ value to the corresponding pion electroproduction data given explicitly in Ref. [5]. The dashed curves are from the front form quark model calculations of Ref. [6]. The dotted curves are from the instant form quark model calculations of Ref. [7].

3 Interpretation of the extracted form factors

Like any reaction involving composite systems, such as the atomic and nuclear reactions, the full amplitude describing the process has a non-resonant part and a resonant part, see Eq. (1).

Qualitatively speaking, the non-resonant amplitude, $t$, is due to the fast process through some direct particle exchange mechanisms, and the resonant amplitude $t^R$ is due to the time-delayed process where the incoming particles lose their identities and form an unstable system which then decays into various final states. The unitarity condition $\text{Im} T = T^\dagger T$ implies that $t$ and $t^R$ are not independent from each other. The close relation between the resonant and non-resonant amplitude is not specific to the formulation considered here, but is the consequence of a very general unitarity condition.

Thus the extracted dressed form factors $G_M(Q^2)$, $G_E(Q^2)$, $G_C(Q^2)$ of the resonant amplitude can only be compared with the hadron structure calculations of current matrix element $<\Delta|J^\mu_{em} \cdot \epsilon_\nu|N>$ which contain meson loops. The bare form factors may in principle be compared to those obtained from phenomenological calculations which do not include meson clouds, e.g. quark models or specific lattice QCD simulations.

In Fig. 1 we compare our extracted bare form factors to two relativistic
quark model studies, Refs. [6] and [7]. The comparison shows that both agree reasonably well for the magnetic and electric form factors but fail to capture the behavior of $G_C$. The next necessary step is to connect the current description to the extant lattice QCD simulations of the $\gamma N \rightarrow \Delta$ transition.

4 Full coupled-channels model (I): Meson-baryon interaction

After the discussion in the previous section we go back to the full coupled-channels model which will be used to analyze the experimental electroproduction data at center of mass energies below 2 GeV. First we consider the meson-baryon interactions involving $\pi N, \eta N, (\pi \Delta, \sigma N, \rho N)$ and use the extensive database for $\pi N \rightarrow \pi N$ (and also the $\pi N \rightarrow \eta N$) to fix the non-resonant parameters entering in the phenomenological lagrangians. The parameter values used in this model are given in Ref. [9]. Once the meson-baryon sector is fixed we will, in a first stage, leave it unchanged and produce a first description of the single meson photoproduction data.

With the non-resonant amplitudes generated from solving Eq. (2), the resonant amplitude $t^R_{MB,M'B'}$ Eq. (4) then depends on the bare mass $M^0_{N\ast}$ and the bare $N\ast \rightarrow MB$ vertex functions, which are parametrized in Ref. [9].

In figure 2 we depict the real part of $T_{\pi N,\pi N}$ compared to the energy independent extraction of the GWU group [8], the agreement is quite good in almost all $S, P, D$, and $F$ waves. More importantly, the model describes successfully the differential cross section and target polarization asymmetries as shown in Ref. [9].

The fit to $\pi N$ elastic scattering cannot fully constrain the bare $N\ast \rightarrow \pi \Delta, \rho N, \sigma N$ parameters. Thus the results for these unstable particle channels
must be refined by fitting the $\pi N \to \pi \pi N$ data, this is currently being pursued \[10\].

5 Full coupled-channels model (II): Photoproduction reactions

With the hadronic parameters determined in the previous section we proceed to analyze the extensive database of $\pi$ photoproduction. Here the only parameters that need to be determined are the bare $\gamma N \to N^*$ vertex interactions of Eq. (6) similarly to what we did in the simplified model of Section 2.

The strategy is to start with the bare helicity amplitudes of resonances at the values given by the PDG \[11\]. Then, we allow small variations with respect to those values and also in a preliminary step also allow small variations of a selected set of non-resonant parameters. At this stage we can only present preliminary results which are at the present time being further improved and will be reported elsewhere.

First, our main emphasis is set on understanding the region up to 1.6 GeV but keeping a reasonable description up to 2 GeV extending in that way previous works where only the $\Delta$ (1232) region was studied \[4, 12, 5\]. In figure 3 we depict angular distributions for both $\pi^+ n$ and $\pi^0 p$ photoproduction differential cross sections in the $\Delta$(1232) region and also give an example of the prediction of the model for higher center of mass energies at a fixed angle. The effect of intermediate meson-baryon states different from $\pi N$ is also depicted. The importance of multi-step processes is clear and confirms previous studies done in a similar framework.

6 Future Developments

The model described in detail in Refs. \[3, 9\] has already been used to study $\pi N$ scattering and $\pi$ photoproduction reactions as presented in this contribution. In the near future we expect to extend these studies and perform a consistent
study of meson-baryon scattering, single meson electro(photo) production \cite{13} and two-meson photoproduction.

At the same time an important effort is being pursued to reliably extract meaningful resonance parameters from the coupled-channels formalism \cite{13}.

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