Meson production in hadron- and photon-induced reactions

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Abstract. The meson production and associated excited-baryon-analysis program by the Jülich-Athens/GA-Washington/DC Collaboration is presented. The program's analysis is based on a dynamical coupled-channels approach developed by the Collaboration [1-4], where the basic symmetries, such as the two-body unitarity, analyticity, and gauge invariance are respected. In particular, gauge invariance is enforced as dictated by the generalized Ward-Takahashi identity. In the hadronic reactions sector, the πN , ηN , $K\Lambda$, and $K\Sigma$ channels are included, in addition to the effective $\pi\pi N$ channels σN , ρN , and $\pi\Delta$. Energies up to $\sqrt{s} = 2$ GeV are considered. In the photon-induced reactions sector, the neutral and charged pion photoproduction processes are considered up to $\sqrt{s} = 1.65$ GeV so far [4]. These are currently being extended to higher energies including the ηN , $K\Lambda$, and $K\Sigma$ channels.

1 Introduction

In this contribution, we report on the results of the latest resonance analysis in hadron- and photon-induced reactions by the Jülich-Athens/GA-Washington/DC collaboration [1]. For hadronic processes, the world data for the set of reactions $\pi^- p \rightarrow \eta n$, $K^0\Lambda$, $K^0\Sigma^0$, $K^+\Sigma^-$, and $\pi^+ p \rightarrow K^+\Sigma^+$, together with $\pi N \rightarrow \pi N$ scattering are considered. The analysis is based on a dynamical coupled-channels (DCC) approach employing the phenomenological effective Lagrangians of the latest extension of the Jülich hadronic model [2]. It includes the channels πN , ηN , $K\Lambda$ and $K\Sigma$, as well as the three effective $\pi\pi N$ channels $\pi\Delta$, σN and ρN . The considered energy range has been extended up to about 2.2 GeV and resonances up to $J = 9/2$ are included in this study. The γN channel is also included in our coupled-channel model in the one-photon approximation; both the neutral and charged pion photoproduction processes have been investigated for energies up to 1.65 GeV [4]. The current effort is the first step towards a global analysis of pion- and photon-induced production of πN , ηN , $K\Lambda$ and $K\Sigma$ within our DCC approach. This will allow us, in particular, to address the photoproduction data of unprecedented accuracy that have been measured recently at ELSA, MAMI, JLab and elsewhere for the KY final states.

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2 Results

In this section, we present some selected results from our latest resonance analysis as described briefly in the Introduction.

2.1 Pion-induced reactions

The $\pi N \rightarrow \pi N$ reaction is constrained by the energy-dependent partial-wave solution of the GWU/SAID analysis [6] up to H waves and energies from threshold up to about 2.2 GeV. The overall quality of the results is good, especially, considering the fact that we include about 2500 energy-dependent-partial-wave-solution points over 20 partial waves to be reproduced with only four tunable parameters for the tree-level $\pi N \rightarrow \pi N$ non-pole transitions, in addition to 128 parameters (bare masses and couplings) related to the bare resonances in the pole amplitude affecting directly the elastic πN channel. The four adjustable parameters in the non-pole transitions are the form factor of the πNN vertex with N in the u -channel, one form factor for the σ - and one for the ρ -exchange, and one for the $\pi N \Delta$ vertex with Δ in the u -channel. Of these four parameters, two appear also in different transitions, e.g. $\pi N \rightarrow \pi \Delta$ with N or Δ in the u -channel; thus, those two parameters tune also the inelasticities at the same time as they fit the $\pi N \rightarrow \pi N$ transition. There is, therefore, only very little freedom in the fit of the non-pole amplitude. Some limited additional freedom comes from coupled-channel effects, through which also other parameters have influence on the non-pole $\pi N \rightarrow \pi N$ amplitudes. There are, however, some shortcomings in certain partial waves which should be improved in future work. These shortcomings might be due to channels not yet included in the approach such as the ωN channel.

Figure 1 shows our model result (red solid curves) for the πN scattering amplitude in the P_{11} partial wave state together with the energy-dependent (black dashed curves) and the single-energy (solid circles) GWU/SAID solutions [6]. We emphasize that our model result is a fit result to the energy-dependent GWU/SAID solution which exhibits a smooth energy dependence around $E \equiv \sqrt{s} = 1.65$ GeV, and not to the single-energy solution. The latter exhibits a structure in this energy region. Most interestingly, our model result matches the single-energy solution (not included in the fit) better than the energy-dependent solution that we fit. The appearance of this structure in the present analysis is a direct consequence of the inclusion of a P_{11} resonance with the mass of ~ 1680 MeV which is strongly required to describe the $\pi^- p \rightarrow K^0 \Lambda$ differential cross section and polarization data, but not to fit the smooth energy-dependent GWU/SAID solution [6] for the πN elastic scattering amplitude in the P_{11} partial wave. In short, the structure seen in the single-energy solution of the analysis of $\pi N \rightarrow \pi N$ [6] is consistent with the existing data for the $\pi^- p \rightarrow K^0 \Lambda$ reaction.

Fig. 1. πN scattering amplitude in the P_{11} partial wave. The left panel displays the real part of the amplitude while the right panel, the imaginary part. The red solid curves represent the present model result which is a fit to the energy-dependent GWU/SAID solution [6] (black dashed curves). The filled circles correspond to the energy-independent GWU/SAID solution [6].

Fig. 2 shows the present model results for the cross sections and recoil polarizations in the reactions $\pi^- p \rightarrow K^0 \Lambda$, $\pi^- p \rightarrow K^0 \Sigma^0$, and $\pi^+ p \rightarrow K^+ \Sigma^+$. Overall, the data are nicely reproduced.

The resonance parameters (mass, width, and coupling constants) have been extracted for the present model by analytically continuing the amplitude in the complex energy plane and searching

Fig. 2. Selected results for differential cross sections (left column) and recoil polarizations (right column) for $\pi^-p \rightarrow K^0\Lambda$ (upper row), $\pi^-p \rightarrow K^0\Sigma^0$ (middle row), and $\pi^+p \rightarrow K^+\Sigma^+$ (bottom row), as a function of the cosine of the scattering angle θ in the center-of-mass frame. Different panels correspond to different energies $z \equiv \sqrt{s}$ as indicated in each panel. The (red) solid curves are the present model results [1]. The (green) dashed curves are the results of our previous model from 2011 quoted in Ref. [2]. The data are from various sources as quoted in Ref. [1].

for the pole positions in the second Riemann sheet and extracting the corresponding residues. We found a total of 13 nucleon resonances and 11 Λ resonances, most of which were also found in the GWU/SAID analysis [6]. However, a few resonances found in the latter analysis [6] were not found in our analysis and vice-versa. A detailed account on this and other issues will be reported in Ref. [1].

2.2 Photon-induced reactions

As mentioned in the Introduction, our DCC model includes the γN channel in a fully gauge invariant manner as dictated by the Ward-Takahashi identity, a feature that is lacking in the majority of existing

Fig. 3. Differential cross sections (left column) and photon beam asymmetries (right column) for $\gamma p \rightarrow \pi^+ n$ (upper row), $\gamma p \rightarrow \pi^0 p$ (middle row), and $\gamma n \rightarrow \pi^- p$ (bottom row), as a function of the scattering angle θ in the center-of-mass frame. Different panels correspond to different energies $(E_\gamma, \sqrt{s})$ in units of MeV as indicated in each panel. The (red) solid curves are the model results reported in Ref. [4]. The data are from various sources as quoted in Ref. [4].

photoproduction models. The cross section and beam asymmetry results for $\gamma p \rightarrow \pi^+ n$, $\gamma p \rightarrow \pi^0 p$, and $\gamma n \rightarrow \pi^- p$ are shown in Fig. 3 as functions of the center-of-mass scattering angle for energies up to $\sqrt{s} = 1.65$ GeV. The overall agreement with the data is very good. Analogously to the pion-induced reaction, the resonance electromagnetic transition couplings are being extracted from the residues associated with the poles of the photoproduction amplitude in the complex energy plane. Currently, we also include the ηN , $K\Lambda$ and $K\Sigma$ photoproduction channels into our model, in addition to extending the energy up to $\sqrt{s} \sim 2$ GeV.

3 Some basic open issues

In this section, we point out some of the current basic open issues we face within the DCC approaches based on phenomenological effective Lagrangians. First, the scarcity of (two-body) hadronic reactions data is a chronic experimental issue that hinders the construction of more accurate reaction models. Apart from the πN scattering data, the few existing data for other meson-nucleon channels are of low accuracy, and some of them are even inconsistent with each other. The situation is aggravated by the lack of hadron facilities where new measurements can be performed. In this context, there are some limited initiatives at the J-PARC facility to measure the kaon-induced reactions. Also, the HADES Collaboration at GSI is planning to measure the cross sections for $\pi N \rightarrow \omega N$ and $\pi N \rightarrow \rho N$. Second, from the theoretical side, the major open issues are:

- a) *Connection to QCD and/or QCD based models*: The so-called bare resonance parameters (bare masses and coupling strengths) – which enter as free parameters in DCC models and are adjusted to reproduce the experimental data – are the quantities that should contain quark dynamics and, as such, they should be linked to QCD based models. In fact, there are some efforts underway to make the connection of the extracted bare resonance parameters to the results of Constituent Quark Model and /or Dynamical Dyson-Schwinger approaches. This connection, however, is not straightforward, for the bare resonance parameters extracted from DCC approaches are highly model-dependent. A valid connection, therefore, requires a consistent matching between the DCC approaches (which use the hadronic degrees of freedom) and the QCD models (using the quark degrees of freedom).
- b) *Low-energy behavior*: At low energies, close to threshold, the pion photo- and electro-production reactions are nowadays completely understood thanks to Chiral Perturbation Theory (ChPT). Any meson-exchange DCC model such as the present one should, in principle, have built in the constraints of ChPT. It is, however, not a simple task to account for all the constraints dictated by ChPT and, in general, only a few basic constraints are taken into account in practice. Indeed, building in the chiral constraints into meson-exchange models is one of the major improvements needed for these models.
- c) *Theoretical uncertainties*: Statistical uncertainties due to the uncertainties in the experimental data used to extract the model parameters are relatively straightforward to be quantified in principle. However, systematic uncertainties inherent in all phenomenological effective Lagrangian approaches like the present one are very difficult to be assessed and quantified because of the absence of a precise ordering scheme for refining the approximations. These stem from the implementation (or violation) of unitarity, analyticity, Lorentz covariance, and (for photoprocesses) gauge invariance, from the truncation of reaction channels and from how many intermediate resonances are taken into account. Perhaps a better understanding of the systematic errors of phenomenological effective Lagrangian approaches can only be obtained by comparing the results of different formalisms/models.
- d) *Three-body singularities and unitarity*: Three-body singularities arise from the kinematic singularities of the driving potential in the scattering equation. They may be dealt by a momentum integration over the rotated axis in the complex momentum plane and extrapolation of the resulting amplitude to on-shell real momenta. The three-body unitarity issue arises whenever the energy is large enough to open the $\pi\pi N$ channel and it becomes relevant for processes with three particles in the final state. The existing models account for three-body unitarity only in an approximate manner and a more rigorous treatment of three-body unitarity is still missing.

4 Outlook

Table 1 shows a short overview of our collaboration's accomplishments so far and the near-future plans in baryon spectroscopy program. We note that our gauge-invariant approach to photoproduction reactions can be readily applied to electroproduction processes. Also, a gauge invariant formalism for two-pion photoproduction has been already developed [7] (see the talk of H. Haberzettl in parallel session C4 of this meeting).

Table 1. Summary of planned activities within our DCC approach.

hadron-induced reactions	status	remarks
$\pi N \rightarrow \pi N$	done	will fit the observables
$\pi N \rightarrow \eta N, K\Lambda, K\Sigma$	done	
$\pi N \rightarrow \omega N$	next	
$\pi N \rightarrow \pi\pi N$	next next	
photon-induced reactions	status	remarks
$\gamma N \rightarrow \pi N$	done	will be extended to $\sqrt{s} \sim 2 \text{ GeV}$
$\gamma N \rightarrow \eta N, K\Lambda, K\Sigma$	in progress	
$\gamma N \rightarrow \omega N$	next	
$\gamma^* N \rightarrow \pi N$	next	
$\gamma N \rightarrow \pi\pi N$	next next	

For those meson-nucleon channels where the two-body hadronic reaction data in the resonance-energy region are inexistent or extremely scarce (such as $\eta' N$ and ϕN), we consider in our resonance analysis other hadronic processes for which data exist, such as meson production in NN collisions which have been studied at the COSY facility in Jülich, in conjunction with the corresponding data in photoproduction. For a recent analysis of the η' production reactions in particular, see the talk of F. Huang (parallel session B3) in this meeting and Ref. [8].

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