Dynamical coupled-channels study of meson production reactions from EBAC@JLab

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Abstract. We present the current status of a combined and simultaneous analysis of meson production reactions based on a dynamical coupled-channels (DCC) model, which is conducted at Excited Baryon Analysis Center (EBAC) of Jefferson Lab.

Keywords: Dynamical coupled-channels analysis, meson production reactions

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INTRODUCTION

An understanding of the spectrum and structure of the excited nucleon ($N^*$) states is a fundamental challenge in the hadron physics. The $N^*$ states, however, couple strongly to the meson-baryon continuum states and appear only as resonance states in $\pi N$ and $\gamma N$ reactions. Such strong couplings to the meson-baryon continuum states influence significantly the $N^*$ properties and cannot be neglected in extracting the $N^*$ parameters from the data and giving physical interpretations. It should also be emphasized that at present even the existence is still uncertain for most of the couplings among relevant meson-baryon reaction channels are fully taken into account.

During the developing stage of EBAC in 2006-2009, hadronic and electromagnetic parameters of the EBAC-DCC model were determined by analyzing $\pi N \to \pi N$ [3] and $\pi N \to \eta N$ [4] up to $W = 2$ GeV, and $\gamma N \to \pi N$ [5] and $N(e,e'\pi)N$ [6] up to $W = 1.6$ GeV. Then, the model was applied to $\pi N \to \pi \pi N$ [7] and $\gamma N \to \pi \pi N$ [8] to predict cross sections and examine consistency of the coupled-channels framework. Also, nucleon resonance poles were extracted from the model and a new interpretation for the dynamical origin of $P_{11}$ nucleon resonances was proposed [9].

It is thus well recognized nowadays that the comprehensive study of all relevant meson production reactions with $\pi N$, $\eta N$, $\pi \pi N$, $K\Sigma$, $\omega N$, ⋅⋅⋅ final states based on a coupled-channels framework is inevitable for reliable extraction of such higher $N^*$ states.

To make a progress to this direction, the Excited Baryon Analysis Center (EBAC) of Jefferson Lab is conducting a dynamical coupled-channels (DCC) analysis of $\pi N$, $\gamma N$, and $N(e,e')$ reactions in the resonance region. The analysis is based on an unitarized coupled-channels model, the EBAC-DCC model (see Ref. [2] for the details), within which the couplings among relevant meson-baryon reaction channels are fully taken into account.

In this model, the reaction amplitudes $T_{a,\beta}(p,p';E)$ are calculated from the following coupled-channels integral equations,

$$T_{a,\beta}(p,p';E) = V_{a,\beta}(p,p') + \sum_{\gamma} \int_0^\infty q^2 dq V_{a,\gamma}(p,q)G_{\gamma}(q,E)T_{\gamma,\beta}(q,p',E),$$  

$$V_{a,\beta} = v_{a,\beta} + \sum_{N^*} \frac{\Gamma_{N^*,\alpha}^{*\gamma} \Gamma_{N^*,\beta}}{E - M^{*}},$$  

where $a, \beta, \gamma = \gamma N, \pi N, \eta N, \pi \pi N, K\Lambda, K\Sigma, \omega N$ (the $\pi \pi N$ channel contains the quasi two-body $\pi \Delta, \rho N, \sigma N$ channels); $v_{a,\beta}$ is a meson-exchange interaction including only ground state mesons and baryons, which is derived from phenomenological Lagrangians; $\Gamma_{N^*,\beta}$ describes the excitation of the nucleon to a bare $N^*$ state with a mass $M^*$; $G_{\gamma}(q,E)$ is the meson-baryon Green function for the channel $\gamma$. The second term of Eq. (2) thus describes the $s$-channel exchange of bare $N^*$ states. Through the reaction processes, the bare $N^*$ states couple to the meson-baryon continuum states (reactions channels) and become resonance states. On the other hand, the meson-exchange potential $v_{a,\beta}$ can also generate molecule-like resonances dynamically. The physical nucleon resonances will be a “superposition” of these two pictures in general.

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In our analysis, we follow the strategy described in Ref. [4] for how to currently performing a combined analysis of wave is mainly due to an inclusion of one bare our early model [3]. Other partial waves are the same quality as the early model. The improvement in the (curves) Our previous model [3]. The data points are the energy-independent solution of SAID, which are taken from Ref. [10].

We present only the result of two partial waves, (FIGURE 2. The differential cross sections (left two columns) and the photon asymmetry (right two columns) of the previous model [5]. The data are taken from the database of Ref. [10]. Although the model constructed in the early analysis successfully describes the data in the wide energy region, it is still far from our goal because only \( \pi N \) reactions are used and, only the electromagnetic parameters are varied). To proceed further, we have started a full combined analysis of \( \pi N, \eta N, \pi \pi N, K \gamma, oN \) channels recently, in which all parameters are varied simultaneously. We are currently performing a combined analysis of \( \pi N, \gamma N \rightarrow \pi N, \eta N, K \Lambda, K \Sigma \) reactions as a first step. In this contribution, we present the status of our current effort for the analysis.

**CURRENT STATUS OF THE EBAC-DCC ANALYSIS**

The \( \pi N \rightarrow \pi N \) and \( \gamma N \rightarrow \pi N \) reactions: The partial wave amplitudes of the \( \pi N \) scattering are shown in Fig. 1. Here we present only the result of the energy region for the analysis is extended from \( W \leq 1.6 \text{ GeV} \) to \( W \leq 2 \text{ GeV} \), and (b) data of the unpolarized differential cross sections and photon asymmetry \( \Sigma \) are used in our previous analysis. In Fig. 2, our preliminary result (red solid curves) of \( \gamma N \rightarrow \pi N \) at the energies \( W > 1.6 \text{ GeV} \) is compared to our previous model (black dashed curves) as well as the experimental data. We can actually observe a visible improvement of the model in \( W > 1.6 \text{ GeV} \).

The \( \pi N \rightarrow \eta N \) reaction: It is known that for the \( \pi^- p \rightarrow \eta n \) reaction underlying inconsistencies exist among data sets from different experimental groups [4]. In our analysis, we follow the strategy described in Ref. [4] for how to
select the data to be used for our analysis. In Fig. 3, we present the current status of the $\pi^- p \to \eta n$ reactions. We find that at present our result describes reasonably well the differential cross section data up to $W = 1.9$ GeV. The analysis of $\gamma p \to \eta p$ is also underway.

The $\pi N \to KY$ and $\gamma N \to KY$ reactions: Now we move to showing the current status of the analysis for the $KY$ reactions. In Fig. 4, we present the differential cross sections of the $\pi N \to KY$ reactions for three different charge states. At present we have included the data up to $W = 2.1$ GeV for the analysis. The current result describes the data of the considered energy region reasonably well.

Finally, we present the current status of the $\gamma p \to K^+ \Lambda$ analysis. This strangeness-production reaction is expected to be one of the most promising reactions to provide critical information for confirming/rejecting not well-established $N^*$'s and/or discovering new $N^*$'s. Because of this, measurement of the polarization observables, which are more exclusive than unpolarized cross section, for $\gamma p \to K^+ \Lambda$ becomes very active at electron beam facilities. For example, first measurement of the $O_{x'z}', O_{z'z}'$, and $T$ asymmetries has been reported recently by GRAAL [16]. Furthermore, the so-called “(over-) complete experiments” is planned at CLAS, in which all 15 polarization observables are measured, and so extensive data will be available in near future.

In Fig. 5, the differential cross sections and the polarization observables $P, C_x, C_z$ are compared with those measured in the CLAS-g11a [14] and CLAS-g1c [15] experiments. Here we note that care must be taken in calculating the polarization observables because incompatibility exist in the expressions of the observables in the literature (see Ref. [13] for the detail). In our analysis, we follow the definitions explicitly described in Ref. [13]. Although it must be further improved, our model describes qualitatively the available differential cross sections and polarization

FIGURE 3. The differential cross sections of the $\pi^- p \to \eta n$ reactions. Red solid curves are the current result (preliminary). See Ref. [4] for the details of the data used.

FIGURE 4. The preliminary result for the differential cross sections of $\pi^+ p \to K^+ \Sigma^+$ (left panels), $\pi^- p \to K^0 \Sigma^0$ (middle panels), and $\pi^- p \to K^0 \Lambda^0$ (right panels). The data are from Refs. [11, 12].
observables. In order to describe the data of all polarization observables measured in upcoming experiments at CLAS, however, we may need to introduce additional bare $N^*$ states to reproduce such extensive data. Then the introduced bare $N^*$ states may generate new resonance states.

In summary, the Excited Baryon Analysis Center of Jefferson Lab makes a continuous effort for a combined and simultaneous coupled-channels analysis of all relevant meson-production reactions toward the ultimate goal of establishing the $N^*$ spectrum and extracting $N^*$ parameters. We are currently performing a combined analysis of the $\pi N, \gamma N \rightarrow \pi N, \eta N, K\Lambda, K\Sigma$ reactions. Although further improvements are necessary, our current model describes the reactions reasonably well from threshold up to $W \sim 2$ GeV. Once this analysis is completed, we will gradually extend our analysis by including other reactions with final states such as $\pi\pi N$ and $\omega N$.

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