NUCLEON RESONANCES FROM DYNAMICAL COUPLED CHANNEL APPROACH OF MESON PRODUCTION REACTIONS*

TORU SATO

*Department of Physics, Osaka University,
Toyonaka, Osaka, 560-0043 Japan
tsato@phys.sci.osaka-u.ac.jp*

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Properties of the nucleon resonances are investigated within a coupled channel model of $\pi N, \gamma N \rightarrow \pi N, \eta N, K\Lambda, K\Sigma$ and $\pi\pi N$ reactions. The pole positions and the residues of the nucleon resonances are extracted by using the analytic continuation of the scattering amplitudes.

Keywords: Nucleon resonance; Meson production reaction; coupled channel model.

1. Introduction

One of the important issue in hadron physics is to understand the baryon spectrum and the structure of excited states within Quantum Chromodynamics (QCD). The excited nucleon states are unstable and couple strongly with the meson-baryon continuum states to form resonances in πN and γN reactions. Therefore, the study of the excitations of nucleon resonances in πN and γN reactions has been a well recognized important task in advancing our understanding of the structure of baryons.

The extraction of nucleon resonances has a long history and several different approaches have been developed.¹⁻¹¹ In this paper, we report on our recent results¹ on the nucleon resonances from the dynamical coupled-channel model(DCC) developed in Ref. 12. In the past few years, we have applied DCC to analyze πN and γN reactions with πN ,¹³⁻¹⁵ ηN ,¹⁶ and $\pi\pi N$ ¹⁷ final states. The nucleon resonances are extracted by using careful analytic continuation of the scattering amplitudes.¹⁸ The resonances obtained from the previous DCC model¹³ are presented in Refs. 18,19,20. Here, we have extended the dynamical coupled-channels model to include the $K\Lambda$ and $K\Sigma$ channels and have completed a combined analysis of the data of $\pi N, \gamma N \rightarrow \pi N, \eta N, K\Lambda, K\Sigma$ reactions and extracted the resonance parameters.

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In Sec. 2, we briefly describe the formulation of our DCC model, the procedures for determining the model parameters and the fits to the data. The extracted nucleon resonances are discussed in Sec. 3.

2. Meson Production Reaction in Dynamical Coupled Channel Approach

The reaction amplitude $T_{\alpha,\beta}(p_\alpha, p_\beta; E)$ is defined by a set of coupled channel integral equations

$$T_{\alpha,\beta}(p_\alpha, p_\beta; E) = V_{\alpha,\beta}(p_\alpha, p_\beta) + \sum_\delta \int p^2 dp V_{\alpha,\delta}(p_\alpha, p) G_\delta(p, E) T_{\delta,\beta}(p, p_\beta, E), \quad (1)$$

with

$$V_{\alpha,\beta}(p_\alpha, p_\beta) = v_{\alpha,\beta}(p_\alpha, p_\beta) + \sum_{N^*} \frac{\Gamma_{N^*,\alpha}^\dagger(p_\alpha) \Gamma_{N^*,\beta}(p_\beta)}{E - M_{N^*}^0}, \quad (2)$$

where $\alpha, \beta, \delta = \gamma N, \pi N, \eta N, K\Lambda, K\Sigma$ and $\pi\pi N$ which has $\pi\Delta, \rho N, \sigma N$ resonant components, $G_\delta(p, E)$ is the propagator of channel δ , $M_{N^*}^0$ is the mass of a bare excited nucleon state N^* , $v_{\alpha,\beta}$ is defined by the meson-exchange mechanisms, and the vertex interaction $\Gamma_{N^*,\beta}$ defines the $N^* \rightarrow \alpha, \beta$ decay.

The model parameters are determined by fitting the data of pion- and photon-induced πN , ηN , $K\Lambda$, and $K\Sigma$ production reactions off a proton. For the $\pi N \rightarrow \pi N$ data, we rely on the database of SAID.²¹ For simplicity, we fit their single energy solutions of πN partial-wave amplitudes instead of fitting the original πN elastic scattering data. We include the data of $\pi N \rightarrow \pi N$ up to $W = 2.3$ GeV to make sure that the N^* resonances with masses near about 1.9 GeV are properly identified within our model. For the data of $\pi N \rightarrow \eta N, K\Lambda, K\Sigma$ and $\gamma N \rightarrow \pi N, \eta N, K\Lambda, K\Sigma$, we use the database of Bonn-Gatchina group⁴ with some differences: (i) we only include the data up to $W = 2.1$ GeV; (ii) following the discussion in Ref. 16, the data for $\pi^- p \rightarrow \eta n$ differential cross sections used in our analysis are different from those of Bonn-Gatchina group; and (iii) we include the new data of the polarization G of $\gamma p \rightarrow \pi^0 p$ from CBELSA/TAPS Collaboration.²²

Due to the many-parameters problem and the limitation of the current computation power in the χ^2 -minimization, it is practically not possible to get convergent results if all of the model parameters are allowed to vary *simultaneously* in the χ^2 -minimization processes. We therefore take the following strategy. First we determine the parameters associated with the meson-exchange potentials $v_{MB,M'B'}$ to some extent. The parameters associated with the bare N^* states are then determined. This two-step procedure is essential since the most time-consuming part of the computation is to calculate the meson-exchange amplitude $t_{MB,M'B'}$ from the meson-exchange potentials $v_{MB,M'B'}$ by solving the coupled-channels equations. This procedure has to be repeated many times to make sure that we have reached the limitation of the model in the χ^2 -minimization.

In Figs. 1, we present our results for the $\pi N \rightarrow \pi N$ PWA up to $W = 2.3$ GeV. Clearly, very good fits to the data of SAID²¹ have been obtained. Comparing with the dotted curves of our previous analysis (JLMS),¹³ which were obtained by the fit to the PWA data only up to F -wave ($L = 3$) and $W = 2$ GeV, there are significant improvements in the S_{31} , P_{31} , D_{35} partial waves.

In Figs. 2, we see that these rather extensive data below about $W = 1.9$ GeV can be fitted very well. Overall, we are able to fit more data of $\gamma p \rightarrow \pi^0 p, \pi^+ n$ than

Fig. 1. PWA of πN scattering with isospin $I = 3/2$. Left (right) panels are for real (imaginary) parts of the amplitudes. (Red solid curves) current results; (green dotted curves) results from our previous analysis.

Fig. 2. (Color online) $d\sigma/d\Omega$ of $\gamma p \rightarrow \pi^0 p$.

the previous analysis.¹⁴ Not only we cover the $W \geq 1.6$ GeV region, our fits to the data in the low energy region with $W \leq 1.2$ GeV are much better. We however still cannot fit accurately the data in the W region close to 2.0 GeV.

3. Nucleon Resonances

To find the resonance poles, we analytically continue the scattering amplitudes to complex W -plane by using the method detailed in Ref. 18. The main step is to choose appropriate momentum-integration paths in solving Eq. (1). The Laurant series of the scattering amplitude in the complex W -plane at the resonance pole can be written as

$$T_{M'B',MB}(k_{M'B'}^R, k_{MB}^R; W \rightarrow M_R) = \frac{R_{M'B',MB}(M_R)}{W - M_R} + B_{M'B',MB}(M_R). \quad (3)$$

Here the higher order terms $(W - M_R)^n (n \geq 1)$ are neglected. The resonance masses are defined by the pole positions M_R and the coupling constants of resonances with meson-baryon channels are determined from the residues $R_{MB,M'B'}(M_R)$, for $MB = \gamma N, \pi N$ and $M'B' = \pi N, \eta N, K\Lambda, K\Sigma$. The nucleon resonance pole positions $M_R = (Re(M_R), -Im(M_R))$ extracted from our analysis are shown in Fig. 3, where we list the resonances with the width less than 400 MeV and the mass less than 2 GeV. We compare the 3-stars and 4-stars N^* listed by Particle Data Group (PDG)²³ (PDG, black, first row), our values (AO, red, second row) and those extracted by the Jülich analysis² (J, blue, third row) and Bonn-Gatchina analysis⁴ (BG, green, fourth row). We see that we agree well with PDG for the N^* states below 2 GeV except : (a) we do not have 2nd and 3rd N^* states in $\frac{3}{2}^-(D_{13})$, (b) we don't have 3rd state in $\frac{3}{2}^+(P_{33})$, (c) we have 2nd state in $\frac{3}{2}^-(D_{33})$. The first N^* states from four results agree well except : (a) the $\frac{3}{2}^+(P_{13})$ from Bonn-Gatchina is about 200 MeV higher than others, (b) Jülich analysis does not have $\frac{3}{2}^+(P_{31})$, (c) only Jülich analysis has $\frac{3}{2}^+(F_{17})$, (c) Jülich and Bonn-Gatchina do not have $\frac{3}{2}^-(D_{35})$. For higher mass states, the number of states and their positions from four results do not agree well.

The differences between four results seen in Fig. 3 could be due to the differences in the employed analysis methods and the data included in the analysis. The K-matrix model used in the BG analysis is very different from the DCC model used in the AO and Jülich analyses. In the BG analysis, like other K-matrix model analysis, the parameters in different partial waves are varied independently in the fits. On the other hand, the parameters of meson-exchange mechanisms in the AO and Jülich analyses are not independent of partial waves and channels. Thus the BG analysis is more flexible and efficient in fitting the data; in particular in the area where the data have fluctuating structure with large uncertainties. Much more divergent results for the second and third states could also be due to the fact that in the high $W > \text{about } 1.6$ GeV region, the available data are far from complete to determine the partial wave amplitudes model independently.

Fig. 3. Results (red bars) of the N^* spectrum determined by ANL-Osaka Collaboration (AO) are compared with 4-star and 3-star states listed by the PDG, Jülich analysis (J), and Bonn-Gatchina (BG). For each nucleon resonances, $\text{Re}(M_R) \pm \text{Im}(M_R)$ band is plotted. The spin and parity of states are denoted as $J\pi$ with $\pi = \pm$ and the associated πN partial wave.

4. Summary

We have extended the dynamical coupled-channels model to include the $K\Lambda$ and $K\Sigma$ channels and have completed a combined analysis of the data of $\pi N, \gamma N \rightarrow \pi N, \eta N, K\Lambda, K\Sigma$ reactions. The pole positions and residues of nucleon resonances with masses below 2 GeV and total widths less than 400 MeV have been extracted. From the extracted residues, we have determined the $N^* \rightarrow \gamma N, \pi N, \eta N, K\Lambda, K\Sigma$ transition amplitudes at the resonance positions. How these information can be related to the results from the hadron models and lattice QCD calculations is an important challenge in advancing our understanding of the structure of the nucleon and its excited states.

To improve our analysis in the higher mass region, we need to include the data of $\pi N, \gamma N \rightarrow \pi\pi N$ reactions which dominate the πN and γN reaction cross sections at $W \gtrsim 1.7$ GeV. To proceed, we need more detailed data for these two processes. So far, only the rather old data of the total cross sections with rather large uncertainties and very limited invariant mass distributions can be found in the literatures. The situation can be improved greatly when the data from the new experiments on $\pi N \rightarrow \pi\pi N$ reactions at J-PARC become available in the near future.²⁴

We also need to extend the analysis to include the ωN channel which has significant contributions to the πN and γN reaction cross sections at $W \gtrsim 1.7$ GeV. Here we need to extend the formulation of Ref. 12 to account for the $\pi\pi\pi N$ unitarity condition at least approximately.

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