Annual Report on EBAC
T.-S. H. Lee, October 12, 2007

I. INTRODUCTION

During the year of October 1, 2006 - November 30, 2007, eight research projects have been developed at EBAC :

1. πN scattering
2. π and η production
3. $\pi\pi$ production
4. Resonance Poles
5. ω production
6. K production
7. Regge Model of $\gamma N \to \pi^{\pm} N$
8. LQCD and Dynamical Model

Three papers from EBAC have been published[1–3], two accepted[4, 5], and three being prepared[6–8]. In the following sections, we report on the development of each project.

II. πN SCATTERING (*JULIA-DIAZ, LEE, MATSUYAMA, SATO*)

As a first step to analyze the electromagnetic meson production reactions in the nucleon resonance region, the parameters of the hadronic interactions of a dynamical coupled-channel model developed in Ref.[1] are determined by fitting the πN scattering data. The channels included in the calculations are πN, ηN and $\pi\pi N$ which has $\pi\Delta$, ρN, and σN resonant components. The non-resonant meson-baryon interactions of the model are derived from a set of Lagrangians by using a unitary transformation method. One or two bare excited nucleon states in each of S, P, D, and F partial waves are included to generate the resonant amplitudes in the fits. The parameters of the model are first determined by fitting as much as possible the empirical πN elastic scattering amplitudes of SAID up to 2 GeV. We then refine and confirm the resulting parameters by directly comparing the predicted differential cross section and target polarization asymmetry with the original data of the elastic $\pi^{\pm} p \to \pi^{\pm} p$ and charge-exchange $\pi^{-} p \to \pi^{0} n$ processes. The predicted total cross sections of πN reactions and $\pi N \to \eta N$ reactions are also in good agreement with the data.

A paper[4] reporting on these results has been accepted by Physical Review C. The developed code CCEBA is the starting point of most of the projects described in the following sections. In a collaboration with Saclay Group (*Durand and Saghai*), the parameters associated with the ηN channel is being refined by also fitting the differential cross section data of $\pi N \to \eta N$ reaction.

III. π AND η PRODUCTION (*JULIA-DIAZ, LEE, MATSUYAMA, SATO, SMITH*)

Within the coupled-channel model developed in Ref.[1], the code CCEBA developed in the πN scattering project described in section II has been extended to investigate the electromagnetic pion production reactions. The differential cross sections of $\gamma p \rightarrow \pi^0 p$ and $\gamma p \rightarrow \pi^+ p$ up to invariant mass $W = 1.6$ GeV have been fitted to extract the helicity amplitudes of $\gamma p \rightarrow N^*$ associated with the $S_{11}, P_{11}, D_{13}, P_{33}$ πN partial waves. The coupled-channel effects have been demonstrated. The meson cloud effects have been identified for interpreting the N-N^* form factors extracted by CLAS collaboration. A paper[6] reporting on these results is being prepared for publication.

Our next step is to analyze the world data of photoproduction and electroproduction of π and η, in particular the data from JLab. The N-N^* transition form factors up to $Q^2 \sim 6$ GeV^2 for all low-lying N^* will be extracted. Attempts will be made to confirm and/or discover new N^* resonances at $W > 1.7$ GeV.

A collaboration with the Saclay group (*Durand, Saghai*) is being planned to analyze the η photoproduction data by using the predictions from a constituent quark model.

IV. $\pi\pi$ PRODUCTION (*JULIA-DIAZ, KAMANO, LEE, MATSUYAMA, SATO*)

To refine the parameters associated with $\pi\Delta$, ρN ,and σN in the dynamical coupled-channel model developed in section II, the $\pi N \rightarrow \pi\pi N$ data must be included in the fits. We will start with the code of Kamano and Arima. The first step is to extend this code to include the $\pi N \rightarrow N^* \rightarrow \pi\Delta, \rho N, \sigma N$ amplitudes and account for the initial πN interactions. We then perform χ^2-fits to the available data of total cross sections and invariant mass distributions of $\pi N \rightarrow \pi\pi N$ by adjusting the parameters of $N^* \rightarrow \pi\Delta, \rho N, \sigma N$ transitions as well as some poorly known parameters.

In parallel to the above work, we will use the model developed in section II to perform the coupled-channel calculations of $\gamma N \rightarrow \pi\pi N$ using the code developed by Matsuyama. This work will start when Julia-Diaz visits Osaka, October-December, 2007.

V. RESONANCE POLES (*IKEDA, LEE, SATO, SUZUKI*)

A numerical method has been developed for extracting the nucleon resonance poles from the amplitudes generated from the dynamical coupled-channel model described in section II. It is based on searching for the zeros of $1/T_{\pi N,\pi N}(p_c, p_c, Z)$, where p_c is on the momentum integration path which defines the analytical continuation of the elastic πN amplitude $T_{\pi N,\pi N}(p, p, Z)$ to the complex energy plane. Results have been obtained and a paper[8] is being prepared for publication.

The next step is to investigate how our method differs from what have been used by other groups. Furthermore, the relations between the extracted poles and the bare parameters of the Hamiltonian of the considered dynamical coupled-channel model must be investigated for understanding the structure of the identified N^* states.

VI. ω PRODUCTION (*LEE, PARIS, SATO*)

The ω production project started during December, 2006 with an initial participation of Tsushima. The main task is to develop subroutines for calculating the non-resonant potentials associated with the ωN channel using the Lagrangians given in the MSL paper. This step is straightforward since they involve calculations of only about 10 matrix elements and all of the them are similar to that for the ρN channel which have been well coded in CCEBA.

The second task is to develop a code for performing χ^2-fit to both the $\pi N \to \omega N$ and $\gamma N \to \omega N$ data. To get the starting parameters, it is sufficient to perform the fits by using a three-channel ($\gamma N \oplus \pi N \oplus \omega N$) model with an effective $\pi N \to \pi N$ potential defined by the off-shell $t_{\pi N,\pi N}$ amplitudes generated from CCEBA. Some preliminary results have been obtained and presented at MENU2007. With further refinements and checking, a paper[7] reporting these results will be submitted for a publication.

The next step is to extend the code to fit ω electroproduction data for extracting the N-N^* form factors and confirming/discovering N^* states with mass larger than 1.7 GeV.

The last step is to implement the developed subroutine for $v_{\pi N,\omega N}$, $v_{\omega N,\omega N}$, and $v_{\gamma N,\omega N}$ into CCEBA to perform a six-channel fit to the $\pi N \to \omega N$ and $\gamma N \to \omega N$ data, while the good fits to the πN data achieved in the project on πN scattering are maintained. Here we need to also include additional interactions involving ωN. In particular the $\omega N \to \rho N$ transition, σ and Pomeron exchanges in $\omega N \to \omega N$, as discussed in the previous works on ω production, must be considered.

VII. K PRODUCTION (*LEE, SIBIRTSEV, TSUSHIMA*)

The K production project started during September, 2007. The first task is to develop a code for calculating all tree-diagram amplitudes of $\gamma N \to KY$ using SU(3) Lagrangians. The construction of such SU(3) Lagrangians is almost completed for developing a code for calculating $\gamma N \to KY$ observables. The second task is to develop a code for performing χ^2-fit to the available $\gamma N \to K\Lambda$ data. This has been completed and is being further tested. The plan is to obtain preliminary results using these two codes by fitting all of the recent $\gamma N \to K\Lambda$ data including the very challenging polarization observables from JLab.

The next step is to include KY final state interactions. Since there exists no data on KY scattering, we will first simply multiply each multipole amplitudes by a phenomenological phase factor and include these factors in the fit. The hope is that by that time we have already determined the N^* parameters from the π η, and $\pi\pi$ production projects described in sections II-IV, these KY phases can be extracted with sufficient accuracy from fitting very extensive data from CLAS. These KY phases will provide information for developing a KY interaction model which is needed in extending the current EBAC's dynamical coupled-channel analysis to include KY channel.

VIII. REGGE MODEL OF $\gamma N \to \pi^{\pm} N$ AT $W > 2$ GEV
(*SIBIRTSEV, HAIDENBAUER, KREWALD, LEE, MEISSNER, THOMAS*)

The Regge model has been used to fit the world data of charged pion photoproduction for photon energies from 3 to 8 GeV. The deviations of the predicted cross sections from the data in the $W < 2$ GeV nucleon resonance region have been identified. It is found that the available photon asymmetry data show promising resonance signatures at $W \sim 2$ GeV. The constructed model can be used to analyze the forthcoming CLAS data[9] for identifying possible resonances in the $W \sim 2.5$ GeV region.

A paper[5] reporting on these results have been accepted by European Physics Journal.

IX. LQCD AND DYNAMICAL MODEL (*B. JULIA-DIAZ, R. YOUNG*)

The aim of this project is to reconcile the description of the electromagnetic structure of resonances obtained using lattice QCD methods and the one which results from the dynamical coupled channel analysis. As a first step we have concentrated on the $\gamma^* N \rightarrow \Delta$ transition, which has been studied in lattice QCD calculations by the Leinweber *et al.* and Alexandrou *et al.* groups. An apparent discrepancy between these groups appears to have been resolved. At the present status, there is still a significant disagreement with the experimental form factor data. A study of the chiral extrapolation and quenching artifacts is currently underway in an attempt to resolve this disagreement. As described within the dynamical model, one would anticipate significant enhancement associated with the pion cloud in the low-Q^2 regime. At high Q^2 (≈ 2 GeV^2) the effect of the pion cloud is known to be not very relevant and thus a simple chiral extrapolation of the lattice results should be reliable. Comparison in this domain will be a good testing ground for the study of any further systematic artifacts, beyond the pion cloud, that are present in the simulations. Once a reliable description of the results can be obtained over the full range of Q^2, it should be very instructive to substract the chiral effects from the lattice QCD calculations and compare with the bare form factors extracted from the dynamical model of Julia-Diaz, Lee, Sato and Smith. Good agreement here will provide strong support for extending the techniques to other N^* resonances which have, to date, been studied less thoroughly in lattice or experiment.

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[4] B. Julia-Diaz, T.-S. H. Lee, A. Matsuyama, T. Sato, accepted by Phys. Rev. C (2007); arXiv:0704.1615 [nucl-th]

[5] A. Sibirtsev, J. Haidenbauer, S. Krewald, T.-S. H. Lee, U. Meissner, A.W. Thomas, accepted by Euro. Phys. J. (2007); arXiv:0706.0183 [nucl-th]

[6] B. Julia-Diaz, B. Julia-Diaz, T.-S. H. Lee, A. Matsuyama, T. Sato, L.C. Smith, in preparation

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[8] N. Suzuki, T. Sato, N. Ikeda, T.-S. H. Lee, in preparation

[9] Haiyan Gao, private communications at 2007 DNP meeting, Newport News, VA.