Status of EBAC Research Program

(September 22, 2010, by T.-S. Harry Lee)

The objective of Excited Baryon Analysis Center (EBAC) is to establish the baryon spectrum and to provide information for understanding the baryon structure within the framework of Quantum Chromodynamics (QCD). Our main task is to perform a dynamical coupled-channels analysis of *world* data of meson production from πN, γN, and $N(e, e')$ reactions to extract nucleon resonances (N^*).

In FY2010 we continue to make progress in this direction, taking into account the recommendations of the 2009 EBAC Review Committee and the 2009 DOE review Committee for Nuclear Theory Groups at National Laboratories. We have made the following advances:

1. We have extended and improved the EBAC dynamical coupled-channels (EBAC-DCC) code to perform *combined* fits to world data of $\pi N, \gamma N \rightarrow \pi N, \eta N, K\Lambda, K\Sigma$ reactions for high precision extractions of nucleon resonance parameters. Preliminary results have been obtained.

2. We have investigated the model-dependence problem of nucleon resonances. Our results for P_{11} resonances have firmly established the double-poles structure associated with the Roper resonance and have indicated the need of high precision data for confirm/discover resonances in the higher invariant mass $W > 1.6$ GeV region.

3. We have applied an analytic continuation method to extract the $\gamma^* N \rightarrow N^*$ form factors from the pion electro-production data of CLAS. The theoretical questions on the differences between our results at resonance poles and the form factors extracted from using the Breit-Wigner parametrization have been analyzed.

4. We have collaborated with members of CLAS Collaboration to develop an approach for extracting the pseudo-scalar meson photo-production amplitudes from the complete measurements to be performed at Hall B. The approach has been applied to extract the $\gamma p \rightarrow K^+\Lambda$ amplitudes from the available CLAS data, demonstrating the need of complete measurements.

5. As a first step to develop an approach for extracting meson resonances from the experiments to be performed under the GlueX project, we have applied the dynamical coupled-channels approach of EBAC to investigate 3-π production reactions. We are getting results for investigating the necessary corrections on the isobar model which has been commonly used to extract meson resonances with large 3-π decay widths.

6. We organized an one-week discussion meeting, during May 24-28, 2010, to address the model-dependence problem of nucleon resonances. We are now planning the next meeting to compare results from all major nucleon resonance analysis groups in order to develop a collaborative effort to reduce, if not resolve, the model-dependence problem.

In the following sections, the details of each item are given. The manpower for EBAC effort in FY2010 and needed in FY2011-FY2012 are reported in section VII.

I. COMBINED COUPLED-CHANNELS ANALYSIS

The EBAC-DCC analysis is based on a dynamical coupled-channels model [1] within which the reaction amplitudes $T_{\alpha,\beta}(p,p';E)$ are calculated from the following coupled integral equations

$$T_{\alpha,\beta}(p,p';E) = V_{\alpha,\beta}(p,p') + \sum_{\gamma}\int_0^\infty dq V_{\alpha,\gamma}(p,q)G_{\gamma}(q,E)T_{\gamma,\beta}(q,p',E)\,, \tag{1}$$

$$V_{\alpha,\beta} = v_{\alpha,\beta} + \sum_{N^*}\frac{\Gamma^{\dagger}_{N^*,\alpha}\Gamma_{N^*,\beta}}{E-M^*}\,, \tag{2}$$

where $\alpha,\beta,\gamma = \gamma N, \pi N, \eta N, \omega N, KY$, and $\pi\pi N$ which has $\pi\Delta, \rho N, \sigma N$ resonant components, $v_{\alpha,\beta}$ is a meson-exchange interaction deduced from phenomenological Lagrangian, $\Gamma_{N^*,\beta}$ describes the excitation of the nucleon to a bare N^* state with a mass M^*, and $G_\gamma(q,E)$ is a meson-baryon propagator. Compared with the K-matrix approaches, which are currently used by several groups [2–5] to extract nucleon resonances, the EBAC-DCC approach has one distinct feature that the analysis can distinguish the molecular-type resonances due to the meson-baryon interaction $v_{\alpha,\beta}$ and the *genuine* resonances due to the coupling of the reaction channels with the bare state N^*. Thus the analysis results will provide new information, in addition to the resonance parameters, for understanding the baryon structure.

During the developing stage of EBAC in 2006-2009, the EBAC-DCC model parameters were determined by analyzing separately the following data: $\pi N \to \pi N$ [6]; $\pi N \to \eta N$ [7]; $\pi N \to \pi\pi N$ [8]; $\gamma N \to \pi N$ [9]; and $N(e,e'\pi)N$ [10]. To have a high precision extraction of nucleon resonances, it is necessary to perform a *combined* simultaneous coupled-channels analysis of all meson production reactions. Furthermore, we have since identified several theoretical constraints on the model parameters which must be implemented into the EBAC-DCC code to improve the χ^2 fits to the data.

In FY2010 we have significantly extended and improved the EBAC-DCC code and have started to perform a combined coupled-channels analysis of all the world's data on $\pi N, \gamma N \to \pi N, \eta N, K\Lambda, K\Sigma$ reactions. Preliminary results have been obtained. Fig. 1 shows that the new fits (red solid curves) to the pion photo-production data at $W > 1.6$ GeV are much better than our previous results [9] (dashed black curves). Figs. 2-3 show our fits to the CLAS data of $\gamma p \to K^+\Lambda$ reactions. We expect to complete this complex and computationally intensive combined analysis by the end of FY2011 or the Spring of FY2012.

II. MODEL-DEPENDENCE PROBLEM OF NUCLEON RESONANCES

One of the recommendations of the 2009 EBAC Review Committee and the 2009 DOE Review Committee for Nuclear Theory Groups at National Laboratories is to examine the model-dependence of nucleon resonances. As a first step to address this problem, we have investigated the extractions of the complicated P_{11} resonances.

By performing extensive fits to the available P_{11} partial-wave amplitudes, we have shown that two P_{11} nucleon resonance poles near the $\pi\Delta$ threshold, obtained in several analyses, are stable against large variations of parameters within the EBAC-DCC model. By also performing an analysis based on a model with a bare nucleon state, similar to the model used in Ref. [15], we find that this two-pole structure is insensitive to the analytic structure

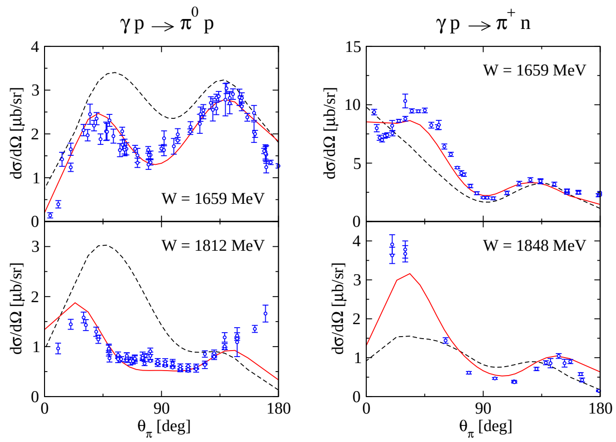

FIG. 1: The differential cross sections of pion photo-production reactions. The dotted curves are from Ref. [9]. The red solid curves are from our combined fits of FY2010.

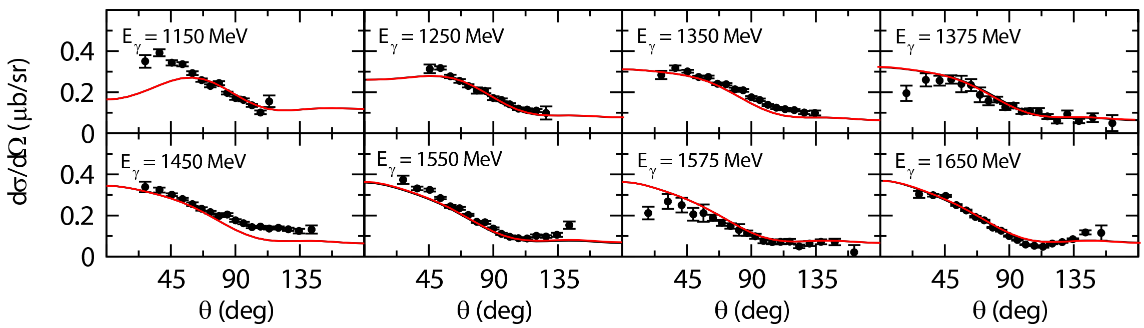

FIG. 2: Fits to the CLAS data of differential cross sections of $\gamma p \to K^+\Lambda$ reaction.

of the amplitude in the $W \leq m_N + m_\pi$ below πN threshold region. Our results are $M_{pole} = [(1361 \pm 4),\ -i\,(78 \pm 5)]$ MeV and $[(1370 \pm 7),\ -i\,(114 \pm 12)]$ MeV. We also demonstrate that the number of poles in the 1.5 GeV $\leq W \leq$ 2 GeV region could be more than one, depending on how the structure of the single-energy solution of SAID [2] is fitted. For three-pole solutions, our best estimated result of a pole near $N^*(1710)$ listed by Particle Data Group is $[(1798 \pm 30),\ -i\,(184 \pm 95)]$ MeV which is close to several previous analysis. Our results indicate the need of more accurate πN reaction data in the $W > 1.6$ GeV region for high precision resonance extractions.

Our results have been published in Phys. Rev. C **81**, 065207 (2010). Similar analysis will be carried out for all nucleon resonances in order to assign theoretical uncertainties of the resonance parameters extracted from our combined EBAC-DCC analysis described in section I.

III. TRANSITION FORM FACTORS FOR NUCLEON RESONANCES

We have applied an analytic continuation method we developed [11, 12] in 2009 to extract the $\gamma^* N \to N^*$ transition form factors from the pion electro-production data of CLAS. Results, defined at the resonance pole positions, have been obtained for the well isolated P_{33} and D_{13}, and the complicated P_{11} resonances. We explain the important differences between

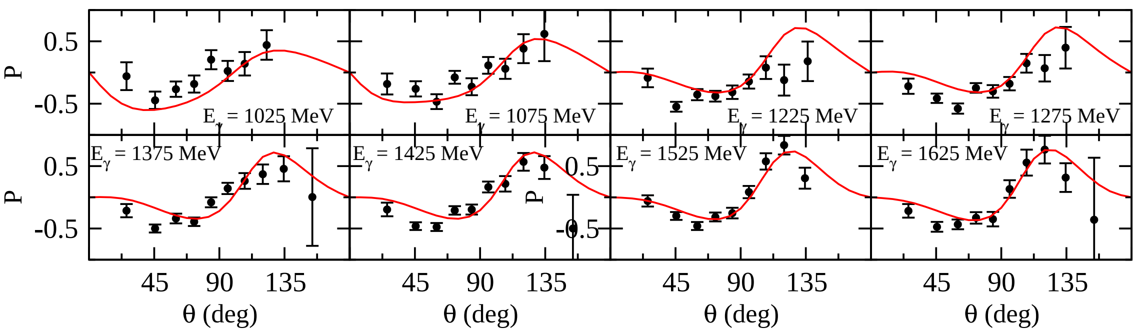

FIG. 3: Fits to the CLAS data of polarization observable P of $\gamma p \rightarrow K^+\Lambda$ reaction.

our approach, which is consistent with the earlier formulations of resonances, and the phenomenological approaches using the Breit-Wigner parametrization of resonant amplitudes to fit the data.

Our results for P_{11} resonances are shown in Fig. 4 which pose a challenge to the current hadron structure calculations. To simplify the theoretical interpretations of the results for the $P_{11}(1356)$ and $P_{11}(1364)$ poles, which are near the $\pi\Delta$ threshold but are on different Riemann sheets, we have developed a formula to give an unified representation of their transition form factors.

We also find that a formula, with its parameters determined in the Laurent expansions of the EBAC-DCC amplitudes at resonance poles, can reproduce to a very large extent the exact EBAC-DCC amplitudes at energies near the real parts of the extracted resonance positions. Our results are illustrated in Fig. 5 for D_{13} partial wave.

A paper (arXiv:1006.2196 [nucl-th]) on this work has been submitted for a publication in Phys. Rev. C. We are investigating the extent to which the Breit-Wigner parametrization can be related to the Laurent-expansion formula within EBAC-DCC model. This will provide useful information to understand the origins of the model-dependence problem of nucleon resonances.

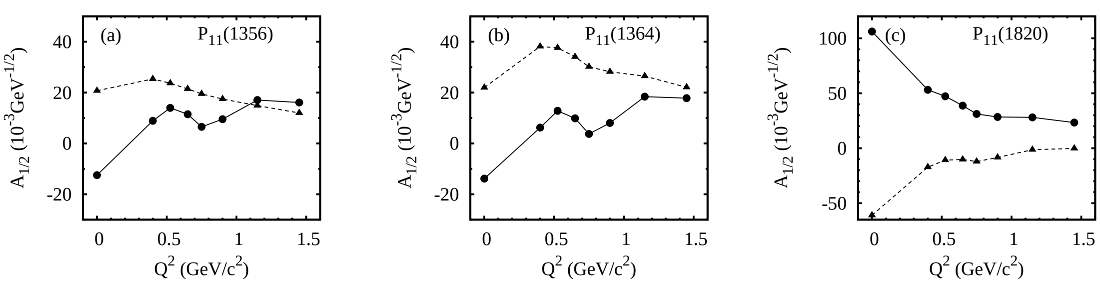

FIG. 4: The extracted $\gamma N \rightarrow N^*$ form factors, $A_{1/2}(Q^2)$, for three P_{11} resonance poles; (a): $P_{11}(1357)$, (b): $P_{11}(1364)$ and (c): $P_{11}(1820)$. They are on different Riemann sheets. The solid circles (solid triangles) are their real (imaginary) parts.

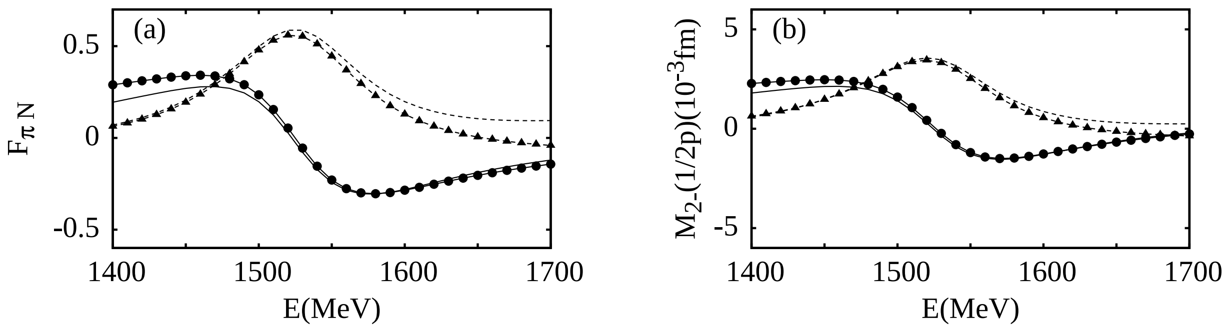

FIG. 5: Energy dependence of the D_{13} partial-wave amplitudes: (a) for $\pi N \to \pi N$ and (b) for $M_{2-}(1/2p)$ of $\gamma N \to \pi N$. The solid circles (triangles) are the real(imaginary) parts of the amplitudes calculated using the leading two terms of the Laurent expansions of the full EBAC-DCC amplitudes at the resonance pole position. The solid (dashed) curves are the real(imaginary) parts of the exact EBAC-DCC amplitudes.

IV. AMPLITUDE EXTRACTIONS FROM COMPLETE MEASUREMENTS

We have collaborated with members of the CLAS Collaboration to develop an amplitude analysis procedure, which is as model-independent as possible, for extracting $K\Lambda$ photo-production amplitudes from the complete measurements to be performed at Hall B. Combined with the results to be obtained from the combined EBAC-DCC analysis, as described in section I, this collaboration is essential to establishing the existence and nature of new resonances that are only accessible through the $K\Lambda$ and $K\Sigma$ channels.

Our first step is to derive expressions that allow the direct calculations of matrix elements with arbitrary spin projections from the Chew-Goldberger-Low-Nambu (CGLN) amplitudes and uses these to clarify sign differences that exist in the literature. Comparing to the MAID [3] and SAID [2] analysis codes, we have found that the implied definitions of six double-polarization observables are the negative of what has been used in comparing to recent experimental data. Our main focus is on the triple-polarization observables which have conflicting conventions in the literature. We confirm our conventions by direct numerical calculations using our expressions in terms of CGLN amplitudes.

We have applied our amplitude analysis procedure to demonstrate that the available $K\Lambda$ photo-production data are far from enough for identifying new resonances since the extracted $\gamma N \to K^+\Lambda$ amplitudes depend sensitively on their initial values in the χ^2 fits. In Fig. 6 we show that several solutions from our fits with almost the same χ^2 do not converge. Our results clearly indicate the need of complete measurements for high precision extraction of nucleon resonances.

A paper on this work is being prepared for a publication in Phys. Rev. C.

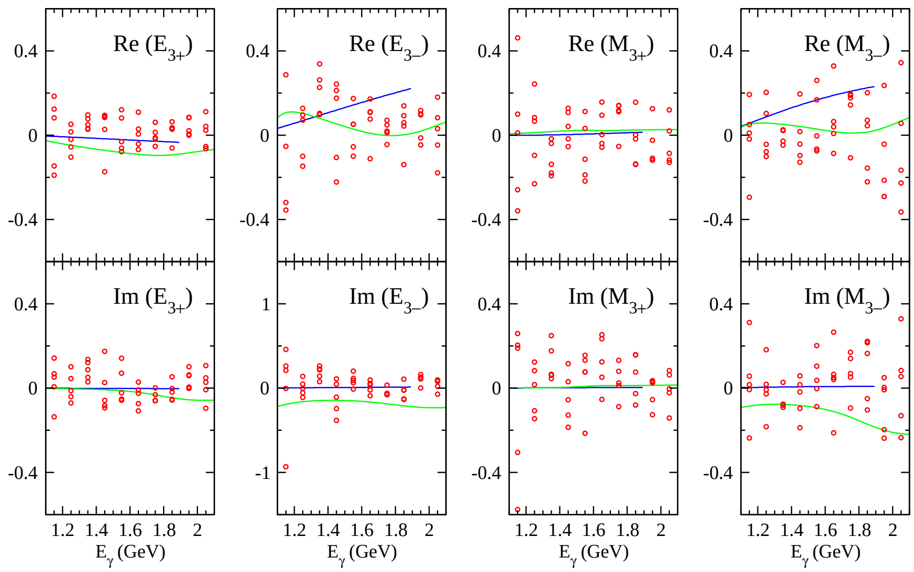

FIG. 6: Several sets of multipole amplitudes of $\gamma p \to K^+\Lambda$ obtained from using different initial values of the multipoles in the χ^2 fits of CLAS data. All fits have almost same χ^2 values.

V. MESON RESONANCES IN 3π PRODUCTION REACTIONS

It is common to extract the properties of excited mesons (M^*), which decay primarily into 3π, by using the isobar model within which the $\pi\pi$ sub-system forms a resonance m^* and does not interact with the third pion. We have applied the EBAC-DCC approach, based on the formulation of Ref. [1], to examine the extent to which such an isobar model approach is valid, aiming at developing an unitary approach to identify excited mesons from the experiments to be conducted under the GlueX project.

Following the isobar model analysis of Refs. [13, 14], we assume that 3-π states are dominated by resonant channels $\pi m^* = \pi\sigma$, $\pi f_0(980)$, $\pi f_2(1280)$, and $\pi\rho(760)$. The three-particle unitarity condition requires that these resonant channels must interact with each other through the one-meson-exchange (Z-diagram) mechanisms induced by $m^* \to \pi\pi, K\bar{K}$ decays. Thus the decay of a meson resonance M^* into 3π must have a $M^* \to \pi m^*_a \to \pi m^*_b \to \pi\pi\pi$ process which is neglected in the isobar model analysis [13, 14]. Our objective is to investigate the effect of these 3-π final state interactions on the excitation and decay of a meson resonance M^*. Within the unitary formulation of Ref. [1], our first step is to solve the following coupled-channels equations in each partial-wave

$$t_{a,b}(k_a,k_b,E) = Z_{a,b}(k_a,k_b,E) + \sum_c \int_0^\infty Z_{a,c}(k_a,k_c,E)\frac{t_{c,b}(k_c,k_b,E)k_c^2 dk_c}{E - E_\pi(k_c) - E_{m^*_c}(k_c) - \Sigma_{m^*_c}(k_c,E)}, \quad (3)$$

where $a,b,c = \pi\sigma, \pi f_0, \pi\rho, \pi f_2$. The self-energy $\Sigma_{m^*_c}(k_c,E)$ in the propagator of Eq. (3) is calculated from a $\pi\pi$ model which has $m^* \to \pi\pi, K\bar{K}$ vertex interactions and appropriate separable interactions to fit the $\pi\pi$ scattering data. One of our fits is shown in Fig. 7. With the determined $m^* \to \pi\pi, K\bar{K}$ vertex functions, the driving term $Z_{a,b}(k_a,k_b,E)$ of Eq. (3) can also be evaluated.

In the presence of the πm^* interactions as defined by Eq. (3), the propagation of a meson resonance M^*, which decays into 3π via a vertex interaction $\Gamma_{M^*,a}$ with $a = \pi\sigma, \pi f_0, \pi\rho, \pi f_2$, is defined by the following propagator

$$G_{M^*}(E) = \frac{1}{E - m^0_{M^*} - \Sigma_{M^*}(E)}\,, \tag{4}$$

where $m^0_{M^*}$ is a bare mass, and the self-energy is defined by

$$\Sigma_{M^*}(E) \;=\; \sum_c \int_0^\infty q^2 dq \frac{\bar{\Gamma}_{M^*,c}(q)\Gamma^*_{M^*,c}(q)}{E - E_\pi(q) - E_{m^*_c}(q) - \Sigma_{m^*_c}(q,E)}\,. \tag{5}$$

The dressed vertex in the above equation is defined by

$$\bar{\Gamma}_{M^*,a}(q) \;=\; \Gamma_{M^*,a}(q) + \sum_c \int_0^\infty \Gamma_{M^*,c}(k) \frac{t_{c,b}(k,q,E)k^2 dk}{E - E_\pi(k) - E_{m^*_c}(k) - \Sigma_{m^*_c}(k,E)}\,. \tag{6}$$

The difference between our approach and the isobar model analysis of M^* decay is the presence of the second term of the above equation, which contains πm^* scattering amplitude $t_{c,b}(k,q,E)$ determined by Eq. (3).

The resonance poles E_R can be found from searching for the zeros of the denominator of M^* propagator Eq. (4)

$$E_R - m^0_{M^*} - \Sigma_{M^*}(E_R) = 0\,. \tag{7}$$

To find solutions of Eq. (7), we apply the analytic continuation method developed in Ref. [11] to solve Eqs. (3)-(6) for E on the unphysical sheets of Riemann energy surface.

The code for carrying out this investigation has been developed. We are in the process of getting results for investigating the effects of 3-π interactions on the resonance pole positions. In addition, we will also apply our approach to investigate heavy meson decays. We expect to complete this work by the end of 2010.

Our next step is to develop a formulation for calculating $\gamma N \rightarrow M^* N \rightarrow \pi\pi\pi N$ cross sections. To make direct contact with experimental data, we will examine the influence of 3-π interactions in determining the Dalitz plot of 3-π distributions.

VI. MEETING ORGANIZATIONS

A. EBAC-Hall B meetings

We held several EBAC-Hall B meetings to discuss physics on nucleon resonances and related subjects. Members of EBAC had given lectures on the theoretical framework within which resonances are defined and extracted. Members of Hall B had given a comprehensive review of the available meson photo-production data of CLAS. We also invited outside speakers to give talks on their hadron structure calculations.

We will continue to organize similar meetings in FY2011.

B. Discussion meeting on resonance extractions and interpretations

To address the model-dependence problem of nucleon resonances, as recommended by the 2009 EBAC Review Committee and the 2009 DOE Review Committee for Nuclear

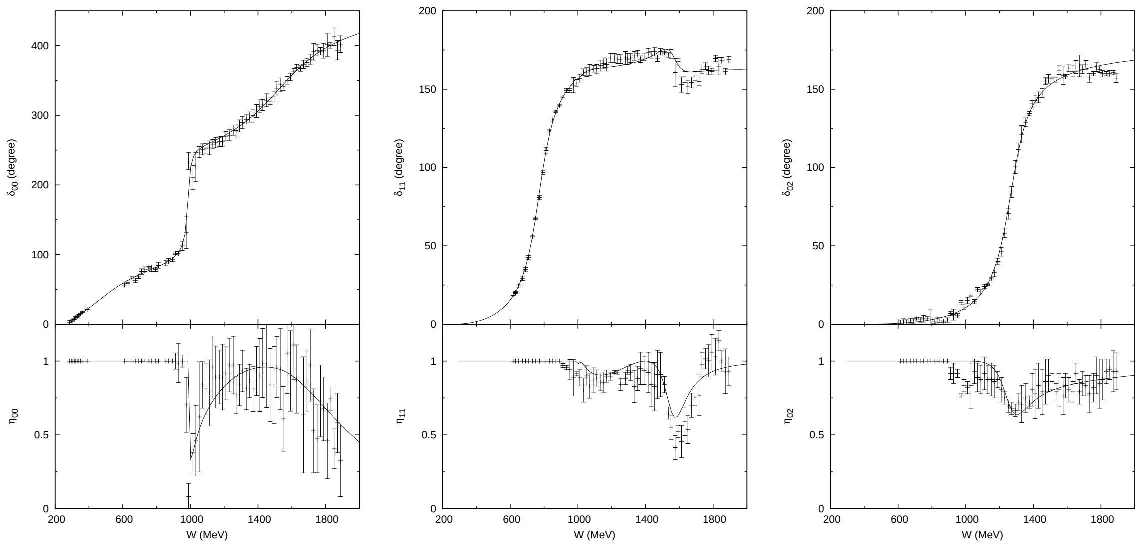

FIG. 7: The phase shift δ_{IJ} and in-elasticity η_{IJ} of $\pi\pi$ scattering in $J = I = 0$ (left), $J = I = 1$.(center), and $J = 2, I = 0$ (right) partial waves. The solid curves are from a $\pi\pi$ model which has a bare state m^* in each partial wave, vertex interactions $m^* \to \pi\pi, K\bar{K}$, and separable background interactions $v_{i,j}$ with $i, j = \pi\pi, K\bar{K}$.

Theory Groups at National Laboratories, we hosted an one-week meeting at EBAC, May 24-28, 2010. All active nucleon resonance analysis groups were invited to participate in the discussions.

In the first three days of the meeting, each group gave a 90-minutes presentation on their approach, focusing on their methods of resonance extractions. Then we had unlimited time for discussions after each presentation. All of their presentations are available at EBAC website for later references. We provided office space for participants to work and to conduct more detailed discussions.

The main outcome of this meeting was to identify the problems in comparing resonance parameters extracted by each group as well as those listed by Particle Data Group. It was clear that there are very important differences in defining the resonance positions and N-N^* transition form factors for all resonances except the well isolated $\Delta(1232)$ resonance. We agreed to have a similar meeting in 2011 before the NSTAR2011 workshop, to be held at JLab, to find a solution of the model-dependence problem.

For hosting the next discussion meeting, EBAC will work with all groups to define a "homework" problem for each group to apply their methods to extract resonance parameters from the same set of amplitudes. The main focus of the next meeting is to compare the results and to find a common ground for developing a collaborative effort to reduce, if not resolve, the model-dependence problem.

Participants of this meeting are:

- Dubna-Mainz-NTU/MAID : Lothar Tiator and Shin Nan Yang
- Bonn-Gatchina : Andrey Sarantsev
- CLAS : Volker Burkert, Inna Aznauryan, Victor Mokeev, Andy Sandorfi
- Zagreb: Alfred Svarc

- IHEP(Beijing)-BES : Bingsong Zou
- Jülich-Georgia: Michael Döring and Kanzo Nakayama
- IHEP(Beijing)-Saclay: Bijan Saghai and Qiang Zhao
- EBAC: Bruno Julia-Diaz, Hiroyuki Kamano, T.-S. Harry Lee, Toru Sato, Satoshi Nakamura

To develop the interactions between the resonance analysis groups and the theoretical efforts in calculating hadron structure, a 1+1/2 day workshop was held after the three-days discussion meeting. We had presentations on calculations using Lattice QCD, Dyson-Schwinger Equations, and relativistic constituent quark models. We also had presentations on the extractions and interpretations of meson resonances. The objective was to see how the approaches of nucleon resonance analysis groups can be applied/extended to extract meson resonances under the GlueX project of JLab.

The workshop had about 40 participants from 12 institutes. An outcome of organizing this workshop is the development of a new EBAC project on 3-pions production reactions, as described in section V.

VII. MANPOWER

In FY2010 the EBAC-DCC analysis, as described in this report, has been conducted by two EBAC postdocs, Hiroyuki Kamano and Satoshi Nakamura, T.-S. Harry Lee (1/4 effort) and Toru Sato (Osaka University, not supported by EBAC). To complete the very complex and computationally intensive combined fits to world data for high precision extraction of nucleon resonances, it is essential to maintain this work force until the end of FY2012. This will then enable EBAC to reach the DOE milestones HP03 and HP07 by the end of 2012.

The contributions from other EBAC collaborators during 2006-2009 were reduced greatly in FY2010 because of the changes of their employments and interests. We need to attract new collaborators and train the incoming postdoc to develop new approaches for analyzing the forthcoming data from experiments with 12 GeV upgrade.

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