Status and Future of EBAC

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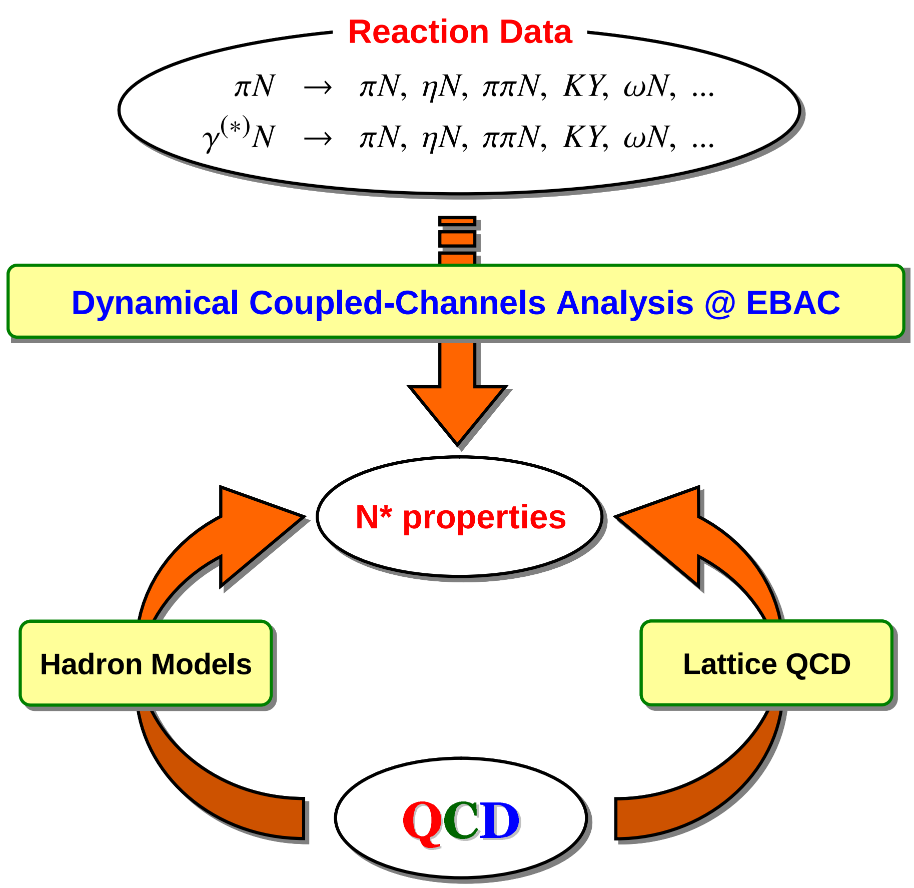

Contents

I. INTRODUCTION

The objective of the 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). This is being pursued at EBAC by using a dynamical coupled-channels (DCC) approach to extract the nucleon resonances (N^*) parameters from the *world* data of πN, γN, $N(e,e')$ reactions in the nucleon resonance region. In particular, the extensive and high precision data from JLab and other electron facilities around the world allow EBAC-DCC analysis to (1) determine the electromagnetic N-N^* transition form factors for the well-established resonances whose quantum numbers, masses and widths are already reasonably well known, (2) search for new N^* states.

The EBAC-DCC analysis is based on a multi-channels multi-resonances model[1] within which the reaction amplitudes $T_{\alpha,\beta}(p,p';E)$ are calculated from the following coupled-channels 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 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, 3, 4, 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.

The EBAC-DCC model is one of the possible dynamical models of meson-nucleon reactions, such as the AAY model[6], the Flinders' model[7], and the Jülich model[8], as briefly reviewed in Ref.[1]. Each model is an approximation of the exact field theory formulation and involves necessary phenomenological aspects, such as the form factors for regularizing the driving terms $V_{\alpha,\beta}$ of Eq.(1). Thus all existing dynamical models, K-matrix models, and S-matrix approaches based on dispersion relations differ from each other in determining the analytic structure of the predicted reaction amplitudes[17], while all of them must satisfy the unitarity conditions. One of the main challenges in this field is to examine how the extracted nucleon resonance parameters depend on the model used in the analysis and try to minimize the model dependence. Thus EBAC has been interacting with other analysis groups by organizing workshops and discussion meetings, aiming at developing a collaborative effort to make progress in this direction.

At high energies with invariant mass W larger than about 2 GeV, the usual partial-wave analysis as well as EBAC-DCC become difficult. Therefore a approach based on Regge phenomenology has also been developed at EBAC in a collaboration with Jülich group.

In section II, we report on the development of EBAC-DCC analysis. The main accomplishments are summarized in section III. In section IV, we propose research plans in the next three years. The papers published or submitted to refereed Journals, manpower and funding, workshop organizations, and visitors are listed in Appendices.

II. DEVELOPMENT OF EBAC-DCC ANALYSIS

The Excited Baryon Analysis Center (EBAC) was established at Jefferson Laboratory in the Spring of 2006. A decision was soon made to apply a multi-channels multi-resonances reaction model[1] (MSL), which is a direct extension of the well-established Sato-Lee model[9] in the Δ (1232) region, to develop a dynamical coupled-channels (DCC) approach. A collaboration was subsequently formed in June, 2006 to develop analysis strategies.

The first task at EBAC was to determine the basic hadronic parameters of the considered DCC model by analyzing the πN scattering data in the nucleon resonance region. This was accomplished[10] in the fall of 2006. During the same time, the EBAC collaboration had also worked with some members of the CLAS collaboration to determine[11] the Q^2-dependence of the $\gamma^* N \to \Delta$ (1232) form factors by analyzing the $p(e, e'\pi)N$ data from JLab.

EBAC's effort in 2007 had two parts. First was to explore the numerical procedures for determining the electromagnetic parameters of the DCC model by performing a analysis [12] of the single pion photo-production data. The second part was to develop[14] an analytic continuation method for extracting the resonance parameters from the DCC reaction model. In parallel, two pilot projects had been developed to extend the DCC code to analyze the data of η production [13] and ω production data[16]. The lack of hadronic reaction data prevent us from making progress to include ωN and KY channels in the analysis. Fortunately these two channels are rather weak in the $W \leq 2$ GeV region, with production cross sections a factor of about 10 (100) lower than the π (2π) production, and can be neglected in this first stage of the development of EBAC-DCC analysis.

By the end of 2007, EBAC moved to investigate the complex 2-π production reactions. This was completed[15] in the summer of 2008 with the results showing that the parameters associated with the unstable particle channels $\pi\Delta$, ρN, and σN within the EBAC-DCC model are consistent to a very large extent with the available $\pi N \to \pi\pi N$ data. In parallel, the first results[17] from analyzing the $p(e, e'\pi)N$ data from CLAS had been obtained and some investigations of K production had been made.

In the first half of 2009, EBAC focused on the theoretical issues concerning the extraction of the nucleon resonance parameters from the meson-baryon reaction amplitudes. By applying the analytic continuation method developed[14] in a EBAC-Osaka University collaboration, the nucleon resonance parameters had been extracted[18] from the constructed DCC model[10]. With this major step completed, EBAC can now start to perform a first complete coupled-channels analysis of the world data of $\pi N, \gamma^* N \to \pi N, \eta N, \pi\pi N$, aiming at extracting the electromagnetic form factors associated with the nucleon resonances. In parallel, a collaboration with the CLAS collaboration had been formed to develop a procedure for extracting the KY photoproduction amplitudes as model independent as possible from the forthcoming over-complete measurements of $\gamma N \to K\Lambda$ reactions to be performed in Hall B. As a first step, progress is being made to examine the extent to which the sin-

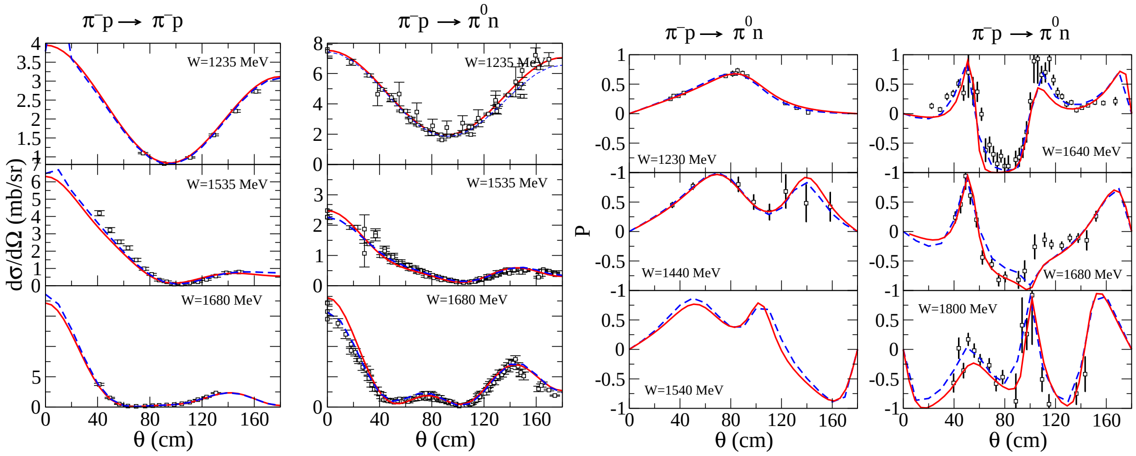

FIG. 1: Differential cross section $(d\sigma/d\Omega)$ (left) and Polarization (P) (right) of $\pi^- p \to \pi^- p, \pi^0 n$. The solid red curves are from EBAC-DCC analysis [10]. The dashed blue curves are from GWU-VPI group [2].

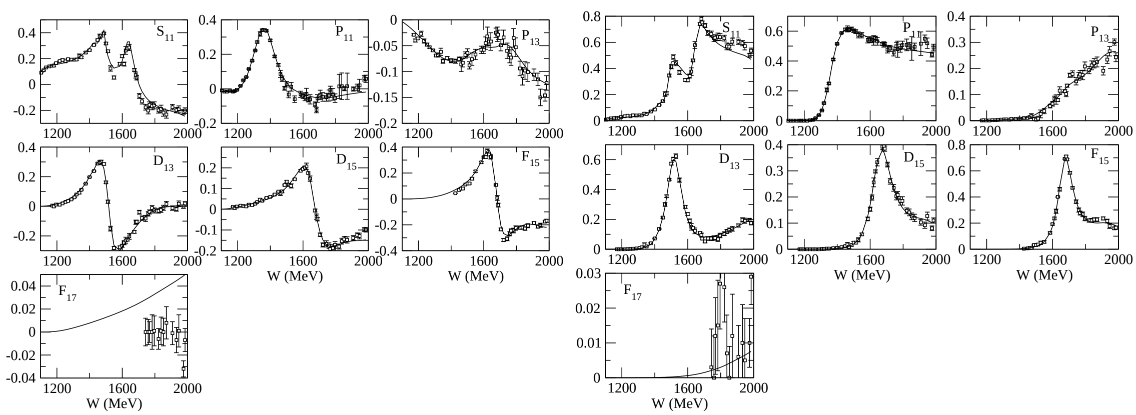

FIG. 2: Isospin $I = 1/2$ πN scattering amplitudes. Left: real parts, right: imaginary parts. The solid curves are from EBAC-DCC analysis [10]. The data are from GWU-VPI group [2].

gle pion photoproduction multipole amplitudes can be determined from the available data without using a model.

III. ACCOMPLISHMENTS

The objective of developing EBAC-DCC analysis is to achieve a NSAC milestone set in 2003:

"Complete the combined analysis of available single π, η and K photoproduction data for nucleon resonances and incorporate analysis of two-pion final states into coupled-channel analysis of resonances."

Despite a late start in the spring of 2006, we have now completed the necessary developments for achieveing this goal and beyond and have made the following accomplishments:

- We have obtained good description of the *world* data of πN elastic scattering up to invarint mass $W = 2$ GeV. The hadronic parameters of EBAC-DCC have then been determined for performing the first-stage analysis of electromagnetic meson production reactions.
- We have demonstrated, the first time in the long history of the study of πN reactions, the important coupled-channels effects on $\pi N \to \pi\pi N$ reactions up to $W = 2$ GeV. The predicted cross sections supersede all previous works in reproducing both the magnitudes and energy dependence of the available limited data.
- We have obtained good description of the *world* data of single π photoproduction and electroproduction reactions up to $W = 1.6$ GeV.
- The meson cloud effects on the $\gamma N \to N^*$ form factors for all low lying N^* states have been determined within the EBAC-DCC model.
- We have extracted 14 nucleon resonance pole positions from EBAC-DCC model using an analytic continuation method.
- In the P_{11} partial wave, we have found that two poles near the Roper $N^*(1440)$ and the next higher mass pole originate from the same bare state with a mass of 1763 MeV.

In the following subsections A - C, we explain these accomplishments. The subsection D describes the development of a Regge model of π photoproduction.

A. Dynamical coupled-channels analysis of $\pi N \to \pi N, \pi\pi N$ reactions

As a first step to analyze the data of electromagnetic production of πN, $\pi\pi N$, ηN, $K\Lambda$, $K\Sigma$, and ωN, it is necessary to first determine the hadronic parameters of the EBAC-DCC model by analyzing the available πN reaction data. This was completed[10] with accurate descriptions of *all* available πN elastic scattering data. Two sample results are shown in Figs.1-2. In Fig.1, we see that our results (solid red) are similar to the results from the K-matrix parameterization fits (dashed blue) by the GWU-VPI group[2] in describing the data of differential cross sections (left) and polarization observable P (right). The predicted πN scattering amplitudes are in good agreement with the energy independent solutions of the GWU-VPI group[2], as seen in Fig.2.

In Fig.3, we show that our predictions[15] (solid curves) of the total cross sections of $\pi N \to \pi\pi N$ reactions are in reasonable agreement with the available data both in magnitudes and energy dependence. Here we also show the large coupled-channels effects up to $W = 2$ GeV which are demonstrated for the first time in the long history of the study of πN reactions. The coupled-channels effects are found to be even more drastic on differential cross sections, as seen in Fig.4 for the invariant mass distributions. Here we also see that our predictions (full curves) are in reasonable agreement with the data both in magnitudes and shapes, while the quality of the data is not high.

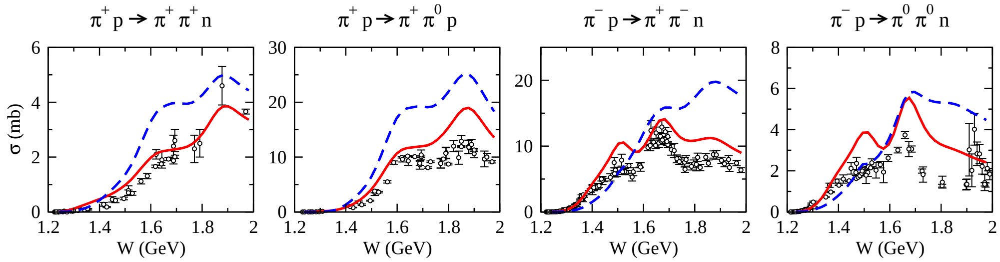

FIG. 3: The coupled-channels effects on $\pi N \to \pi\pi N$ reactions. The solid curves are from full calculations, the dotted curves are obtained from turning off coupled-channels effects on the final $\pi\pi N$ states.

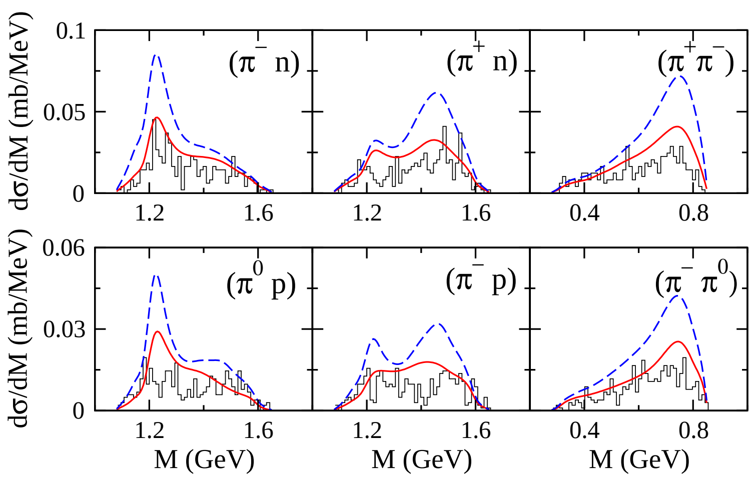

FIG. 4: The coupled-channels effects on the invariant mass distributions of $\pi^- p \to \pi^+\pi^- n$ (upper panels), $\pi^-\pi^0 p$ (lower panels) reactions at $W = 1.79$ GeV. The solid curves are from full calculations, the dotted curves are obtained from turning off coupled-channels effects on the final $\pi\pi N$ states.

The results shown in Figs.3-4 indicate the necessary refinements of our model. We however have found that this can not be achieved easily and more detailed $\pi N \to \pi\pi N$ data, such as angular distributions for all final states, are needed. We thus have organized a US-Japan joint workshop, to be held at Hawaii, Oct. 11-13, 2009, to motivate new experiments to obtain such data at JPARC which has started its operation.

B. Dynamical coupled-channels analysis of electromagnetic π production reactions

With the hadronic parameters determined in our analysis of πN reactions, as described in section III.A, the only freedom in our investigation of electromagnetic π production is the bare $\gamma N \to N^*$ parameters. We have found[11, 12, 17] that we are able to obtain good description of all of the available data at invariant mass $W \leq 1.6$ GeV. Examples are shown in Fig.5 for differential cross sections and Fig.6 for photon asymmetry of π^0 photoproduction. In Fig.7 we show one of our results in fitting the CLAS data of the structure functions of $p(e, e'\pi^0)p$. Our calculations have demonstrated, the first time in the field, the coupled-

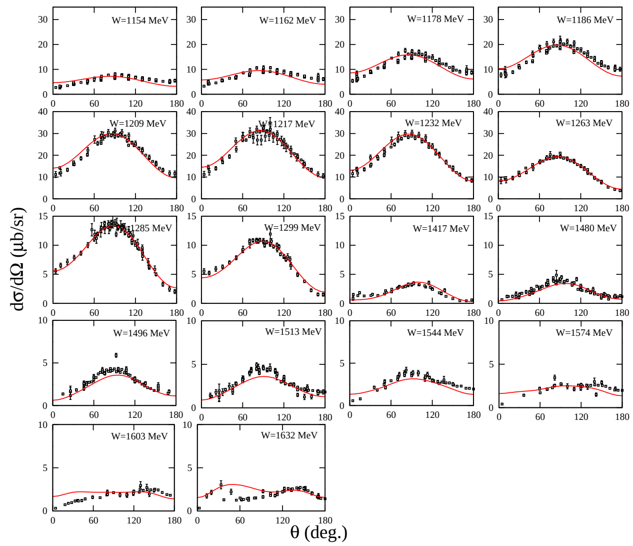

FIG. 5: $\gamma p \to \pi^0 p$ differential cross sections. Solid curves are from EBAC-DCC analysis[12].

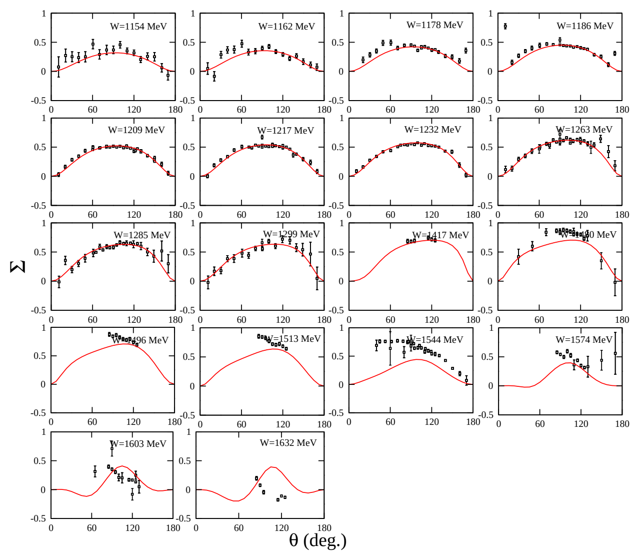

FIG. 6: $\gamma p \to \pi^0 p$ photon asymmetry. Solid curves are from EBAC-DCC analysis[12].

channels effects on electromagnetic π production processes, as illustrated in Fig.8 for the five-folded differential cross sections of $p(e, e'\pi^0)p$.

We however are not able to describe the data at $W >$ about 1.6 GeV. This is understandable since the hadronic parameters of the current EBAC-DCC model still needs to be refined to describe the $\pi N \to \pi\pi N$ data in the same higher W region, as discussed in section III.A.

In a dynamical approach defined by Eqs.(1)-(2), the resonances originated from the bare N^* states must be dressed by meson cloud because of the embodied unitarity condition. For the $\gamma N \to N^*$ transition, this is illustrated in the top panel of Fig.9. Thus we have also predicted meson cloud effects on N^* states with mass less than about 1.6 GeV. In the bottom panel of Fig.9, we show our results for the magnetic M1 $\gamma N \to \Delta$ (1232). The

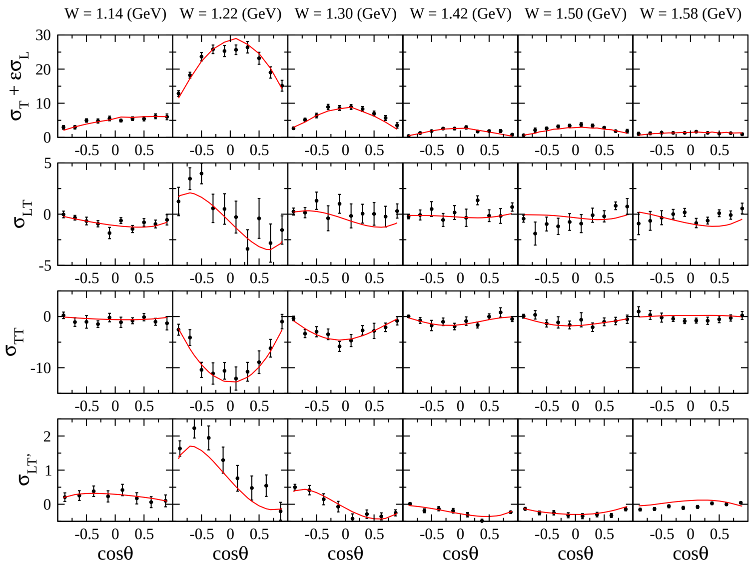

FIG. 7: Structure functions of $p(e, e'\pi^0)p$ at $Q^2 = 0.4$ (GeV/c)^2 and $W \leq 1.6$ GeV. Solid curves are from EBAC-DCC analysis[12].

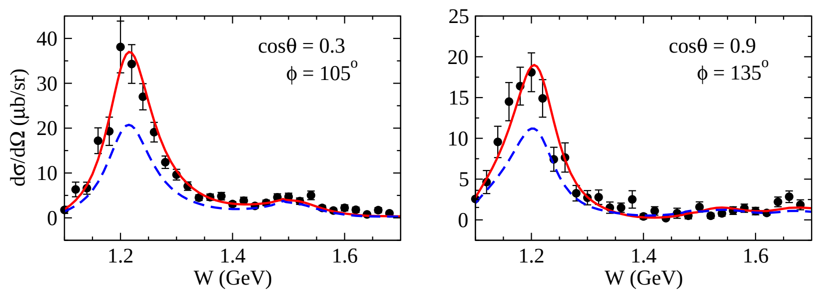

FIG. 8: Five-dimensional differential cross section $\Gamma_\gamma^{-1}[d\sigma^5/(dE_{e'}d\Omega_{e'}d\Omega_\pi^*)]$ of $p(e, e'\pi^0)p$ at $Q^2 = 0.4$ (GeV/c)^2. Solid curves are from EBAC-DCC analysis[17]. The dashed curves are obtained from turning off coupled-channels effects on the final electromagnetic transition to πN state.

large meson cloud effect at low Q^2 has now been well recognized as an important element in understanding the baryon structure within QCD, while its model dependence must be considered in interpreting it.

C. Extraction of nucleon resonances from dynamical coupled-channels model

Extractions of resonances from multi-channels reaction amplitudes has been a long-standing problem. Our investigation[14] has clearly demonstrated that the traditional time-delayed method and speed-plot method have their limitations and in general are not reliable. Our main accomplishment is to develop an exact method based on an analytic continuation of the multi-channels multi-resonances reaction amplitudes defined by Eqs.(1)-(2).

The method has been applied [18] to extract the nucleon resonances from the EBAC-DCC

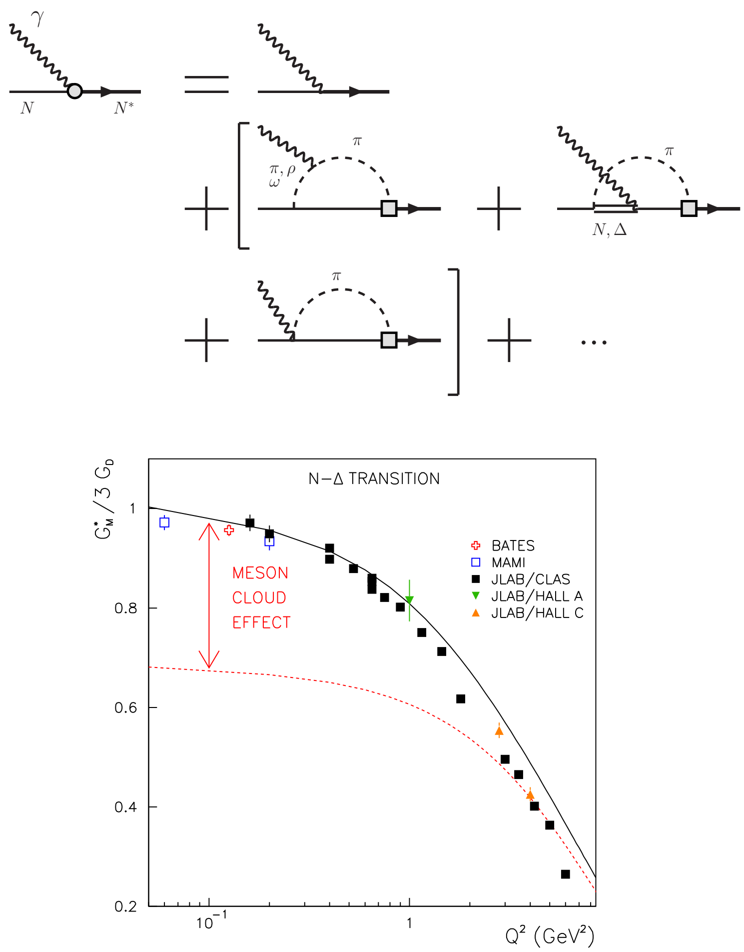

FIG. 9: Top: mechanisms of meson cloud effects on $\gamma N \rightarrow N^*$, Bottom: the meson cloud effects on the magnetic M1 form factor of the $\gamma N \rightarrow \Delta$ (1232) transition. Curves are the results from EBAC[11] analysis.

model constructed[10] in 2006. In Table I, we see that our results agree well with the 3-stars and 4-stars values listed by the Particle Data Group [24] in most of the cases. However, we do not find any resonance poles in the P_{13} and P_{31} cases, although our fits to πN elastic scattering data are as good as the previous analysis by GWU-VPI group, as seen in Fig.1. More significantly, for the P_{11} case, we find two poles near the PDG's value of the Roper resonance $(1350 - 1380, 80 - 110)$. This two-pole structure agrees well with the analysis of GWU-VPI[19] and Jülich[20] groups. By gradually weakening the couplings of the bare N^* state with the reaction channels in Eqs.(1)-(2), we are able to demonstrate that all three P_{11} resonance poles in Table I originate from the same bare state with a mass at 1763 MeV. Our finding is illustrated in Fig. 10, where the extracted P_{11} resonance poles in the complex energy plane are shown in the left-hand panel and the evolution of three poles from the same bare state is depicted in the right-hand panel. This result has provided new information for resolving the long-standing problem in understanding the mysterious Roper resonance.

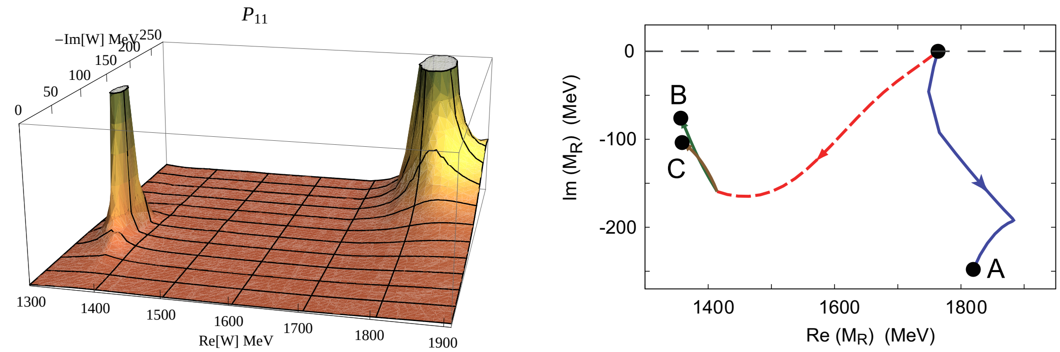

FIG. 10: Left: P_{11} resonances on complex energy plane, extracted[18] within EBAC-DCC model[10]. The vertical axis (arbitrary unit) is the absolute value of the calculated πN scattering amplitude. Right:Trajectories of the evolution of the extracted P_{11} resonance poles, indicated by A, B, and C and listed in Table I, from the bare state at 1736 MeV on the complex energy plane.

TABLE I: Nucleon resonance poles for the different partial waves obtained from the analytical continuation of Eqs.(1)-(2) to complex energy plane are compared to the 3-stars and 4-stars values in the PDG [24]. The "—" indicates that no resonance pole has been found in the considered complex energy region, Re(W) < 2000 MeV and −Im(W) < 250 MeV.

	$M^0_{N^*}$ (MeV)	M_R (MeV)	PDG (MeV)
S_{11}	1800	(1540, 191)	(1490 - 1530, 45 - 125)
	1880	(1642, 41)	(1640 - 1670, 75 - 90)
P_{11}	1763	(1357, 76)	(1350 - 1380, 80 - 110)
	1763	(1364, 105)	
	1763	(1820, 248)	(1670 - 1770, 40 - 190)
P_{13}	1711	—	(1660 - 1690, 57 - 138)
D_{13}	1899	(1521, 58)	(1505 - 1515, 52 - 60)
D_{15}	1898	(1654, 77)	(1655 - 1665, 62 - 75)
F_{15}	2187	(1674, 53)	(1665 - 1680, 55 - 68)
S_{31}	1850	(1563, 95)	(1590 - 1610, 57 - 60)
P_{31}	1900	—	(1830 - 1880, 100 - 250)
P_{33}	1391	(1211, 50)	(1209 - 1211, 49 - 51)
	1600	—	(1500 - 1700, 200 - 400)
D_{33}	1976	(1604, 106)	(1620 - 1680, 80 - 120)
F_{35}	2162	(1738, 110)	(1825 - 1835, 132 - 150)
	2162	(1928, 165)	
F_{37}	2138	(1858, 100)	(1870 - 1890, 110 - 130)

D. Regge Model of π photoproduction

The usual partial-wave analysis of single π photoproduction from the proton become difficult at W larger than about 2 GeV. Therefore we developed[21] a model based on Regge theory including absorptive corrections.

We first apply this model to analyze the charged $\pi^{\pm}$ photoproduction data. We are able to fit reasonably well many data available in the 2 GeV $\leq W \leq$ 3 GeV region. This is illustrated in Fig.11. We found that the most crucial observables for identifying high mass resonances from this reaction are recoil and target asymmetries. The photon asymmetry as well as double polarization parameters G and H are less sensitive.

The model was then applied[22] to analyze backward pion photoproduction for the reactions $\gamma+p\rightarrow\pi^0+p$ and $\gamma+p\rightarrow\pi^++n$ at invariant mass W above 3 GeV region. A comparison with older data on neutral and charged pion photoproduction at 180 degrees indicates that the high-energy limit as given by the Regge model could be reached possibly at invariant $W\sim 3$ GeV. In the energy region below $W = 2.5$ GeV, covered recently by the new measurements of neutral pion photoproduction differential cross sections at large angles at ELSA, JLab, and LEPS, we see no clear signal for a convergence towards the Regge results. We see that some baryon resonances are missed with respect to our Regge classification.

We also employed[23] our Regge model in a global analysis of the world data on neutral pion production for photon energies from 3 to 18 GeV. In this region resonance contributions are expected to be negligible so that the available experimental information on differential cross sections and single and double polarization observables allow us to determine the non-resonant part of the reaction amplitude reliably. The model amplitude is then used to predict observables for photon energies below 3 GeV. A detailed comparison with recent data from the CLAS and CB-ELSA Collaborations in that energy region has been made.

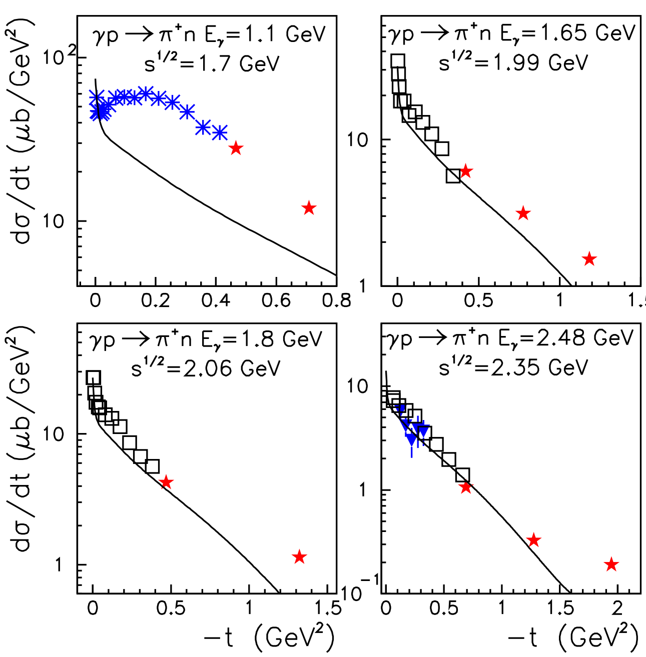

FIG. 11: Regge model fits[21] of differential cross section of $\pi^{\pm}$ photoproduction.

IV. PLANS FOR EBAC-DCC ANALYSIS

In the past three years, EBAC and the CLAS collaboration have jointly organized two workshops at JLab. They were focused on discussion of the theoretical challenges of N^* physics and the opportunities presented by the 12 GeV CEBAF upgrade. The research proposed in this section is largely based on conclusions drawn from these meetings and the White Paper that was completed at the beginning of 2009 [25].

The EBAC program in the next three years will have four main components:

1. Use the electroproduction data to determine the electromagnetic N-N^* transition form factors for the well-established resonances whose quantum numbers, masses and widths are already reasonably well known and are confirmed by EBAC, as reported in section III.C.

2. Search for new states by focussing on photoproduction of various final states; in particular the $K\Lambda$ and $K\Sigma$ states.

3. Develop connection with hadron structure calculations.

4. Extension of EBAC analysis to high $W >$ about 2 GeV.

We propose to accomplish these by conducting the research projects described in the following three subsections.

A. Combined coupled-channels analysis

As explained in Sec. II, the past three years of dedicated effort have produced the EBAC-DCC code and seen it comprehensively tested. So far the EBAC-DCC model parameters were determined by analyzing separately the following data: $\pi N \to \pi N$ [10]; $\pi N \to \eta N$[13]; $\pi N \to \pi\pi N$[15]; $\gamma N \to \pi N$[12]; and $N(e, e'\pi)N$[17].

We have already begun work on improving this preliminary parameter set by performing a *combined* simultaneous coupled-channels analysis of all the world's data on $\pi N, \gamma^* N \to \pi N, \eta N, \pi\pi N$ reactions. Our highest priority in the next three years is to complete this very complex and computationally intensive analysis so as to arrive at a final determination of the parameters that characterize nucleon resonances with mass below roughly 2 GeV. New data from JLab, and from Bonn and Mainz, will be incorporated in this exhaustive global analysis and fitting effort.

B. Amplitude extractions from complete measurements

It is imperative that EBAC extends its interaction with the CLAS Collaboration in order to develop a procedure, which is as near model-independent as possible, for extracting $K\Lambda$

photo-production amplitudes from over-complete Hall-B experiments. Combined with the resonance parameter determination described in Sec. IV A, this expanded collaboration is essential to establishing the existence and nature of new resonances that are only accessible through the $K\Lambda$ and $K\Sigma$ channels. These steps are necessary precursors to the development of analogous methods for extracting amplitudes from nearly complete photo-production and electro-production experiments on πN and ηN channels, which will also be performed in Hall-B.

C. Connection with hadron structure calculations

All N^* parameters in the EBAC-DCC model have hitherto been determined by fitting data. While this has greatly improved our knowledge of the spectrum it has not improved our understanding within QCD. Encouragingly, in that connection progress has been made on relating the parameters of the $\Delta(1232)$ resonance to hadron structure calculations using constituent-quark models [26], Dyson-Schwinger equations [27] and lattice-regularized QCD [28]. However, much more is necessary and, as described in the White Paper [25], EBAC has detailed plans for working with theory groups worldwide to improve this situation and provide a QCD perspective on the properties of higher-mass resonances.

For example, EBAC will work with groups employing the Dyson-Schwinger equations to incorporate their anticipated predictions for N^* form factors into our coupled-channels calculations. This will serve to greatly reduce the unconstrained degrees of freedom within the EBAC-DCC analysis and by that means further improve our determination and understanding of resonance parameters. The Dyson-Schwinger equations provide the only extant framework that can relate hadron observables to the momentum-evolution of the dressed-quark mass, which is such a fundamental feature of QCD. This connection will be essential in analyzing and understanding data that becomes available after the 12 GeV upgrade. The upgrade will enable experiments to probe the dressed-quark mass function on the momentum domain within which it changes most rapidly and thereby chart the transition region between nonperturbative and perturbative behavior.

We will also work with the groups developing relativistic constituent quark models. In particular, their capability of predicting many N-N^* form factors could be used complementarily in the EBAC-DCC analyis to explore the extent to which the constituent quark model is valid.

In addition, EBAC will work with the JLab lattice-QCD group, which has completed a first calculation of N-$P_{11}(1440)$ transition form factors [29], in order to ascertain how coupled-channels effects calculated using the EBAC-DCC model can assist in the analysis of lattice-QCD simulations. The first steps will focus on the nature of the Roper resonance, revealed by EBAC and described in Sec. III C.

D. Extension of EBAC analysis to high W

The EBAC-DCC analysis becomes difficult at high $W >$ about 2 GeV, because of the importance of multi-meson channels. In addition to the Regge model being developed in a EBAC-Jülich collaboration, we will also develop other appoaches. For example, we can apply the diffractive optical potential approach, well developed in the studies of high energy nuclear reactions, to describe the effects due to the neglected multi-particles channels within the EBAC-DCC framework. These efforts are also needed in developing an approach to analyze the data from GLUEX project of 12 GeV upgrade.

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APPENDIX A: PAPERS PUBLISHED OR SUBMITTED

1. Dynamical Coupled-Channel Model of Meson Production Reactions in the Nucleon Resonance Region

   A. Matsuyama, T. Sato, T.-S. H. Lee

   Phys. Rep., **439**, 193 (2007).

2. Extraction and Interpretation of $\gamma N \rightarrow \Delta$ Form Factors within a Dynamical Model

   B. Julia-Diaz, T.-S. H. Lee, T. Sato, L. C. Smith

   Phys. Rev. C **75**, 015205 (2007).

3. Dynamical Coupled-channel Model of πN scattering in the W $\leq$ 2 GeV nucleon resonance region

   B. Julia-Diaz, T.-S. H. Lee, A. Matsuyama, T. Sato

   Phys. Rev. C **76**, 065201 (2007).

4. Study of Nucleon Resonances with Electromagnetic Interactions

   T.-S. H. Lee, L. C. Smith

   J. Phys. G **34**: S83-S106 (2007).

5. Regge Approach to Charged-Pion Photoproduction at Invariant Energies above 2-GeV

   A. Sibirtsev, J. Haidenbauer, S. Krewald, T.-S. H. Lee, U. Meißner, A. W. Thomas

   Eur. Phys. J. **A34**, 49-68 (2007).

6. Dynamical coupled-channels effects on pion photoproduction

   B. Julia-Diaz, T.-S. H. Lee, A. Matsuyama, T. Sato, L.C. Smith

   Phys.Rev. C **77**, 045205 (2008).

7. Coupled-channels study of the $\pi^- p \rightarrow \eta n$ process

   J. Durand, B. Julia-Diaz, T.-S. H. Lee, B. Saghai, T. Sato

   Phys. Rev. C **77**, 045205 (2008).

8. Extraction of resonances from meson-nucleon reactions

   N. Suzuki, T. Sato, T.-S. H. Lee

   Phys. Rev. C **79**, 025205 (2009).

9. Dynamical coupled-channels study of $\pi N \rightarrow \pi\pi N$ reactions

   H. Kamano, B. Julia-Diaz,T.-S. H. Lee, A. Matsuyama, T. Sato

   Phys. Rev. C **79**, 025206 (2009).

10. Dynamical coupled channel calculation of pion and omega meson production

    M. W. Paris

    Phys. Rev. C **79**, 025208 (2009).

11. On the methods for constructing meson-baryon reaction models within relativistic quantum field theory

    B. Julia-Diaz, H. Kamano, T.-S. H. Lee, A. Matsuyama, T. Sato, N. Suzuki

    Chin. J. Phys. **47**, 142 (2009).

12. Dynamical models of the excitations of nucleon resonances

    T. Sato, T.-S. H. Lee

    J. Phys. G **36**, 073001 (2009).

13. Backward pion photoproduction

    A. Sibirtsev, J. Haidenbauer, F. Huang, S. Krewald, U.-G. Meißner

    Eur. Phys. J. **A40**, 65 (2009).

14. Neutral pion photoproduction at high energies

    A. Sibirtsev, J. Haidenbauer, S. Krewald, U.-G. Meißner, A. W. Thomas

    Eur. Phys. J. **A41**, 71 (2009).

15. Dynamical coupled-channels analysis of $p(e, e'\pi)N$ reactions

    B. Julia-Diaz, H. Kamano, T.-S. H. Lee, A. Matsuyama, T. Sato, N. Suzuki

    JLAB-1.CS.001-09-966, submitted to Phys. Rev. C (2009), arXiv:0904.1918.

16. Structure and dynamical evolution of low-lying nucleon resonances

    N. Suzuki, B. Julia-Diaz, H. Kamano, T.-S. H. Lee, A. Matsuyama, T. Sato

    Submitted to Phys. Rev. Lett. (2009).

APPENDIX B: MANPOWER FUNDING

The EBAC research effort has almost completely been conducted by non-JLab theorists. The only local effort is associated with the hiring of one postdoctoral fellow in October, 2006, and his replacement by two fellows in October, 2007. The present budget supports these two fellows, 1/4-effort of T.-S. Harry Lee (ANL) and 1/2-effort of A. Sibirtsev (U. Bonn, Germany). It is anticipated that a new postdoctoral fellow will join EBAC in FY10. In an attempt to ensure continuity, his appointment will overlap for one year with the two fellows currently supported.

In order to achieve the goals described in Sec. IV, it is necessary for EBAC to add at least one full-time staff scientist. This FTE's role will be to direct the program, and maintain and expand the network of non-JLab theorists on whose expertise depends the success of the Center.

Such a commitment to a long-term future for EBAC is essential in order for non-JLab experts to justify their continued involvement, in the face of pressures, for some, from their own funding agencies and, for others, of career development and progression imperatives. In signalling that EBAC is an integral part of JLab's mission, top-class early-career researchers could be drawn to the Center, and external national and international funding agencies encouraged to continue and expand their level of support.

APPENDIX C: MEETING ORGANIZATIONS AND VISITORS

EBAC and Hall B of JLab had organized two workshops for discussing N^* physics:

1. Workshop N^* Analysis, JLab, 4-5 November 2006,
2. Workshop on electromagnetic N-N^* transition form factors, JLab, Oct 13-15, 2008 FY2006.

A meeting for discussing the extractions of nucleon resonances will be held at EBAC July 20-23, 2009.

We are a co-organizer of a US-Japan joint workshop on JLab-JPARC Physics, to be held at Hawaii, Oct. 11-13, 2009, to motivate new experiments at JPARC to obtain hadronic meson production data which are essential for N^* physics.

Because of the budgetary limitation, the majority of EBAC visitors are collaborators for developing EBAC-DCC analysis during FY2006-2008. The situation has been improved in FY2009 and we hope that the visitor program can be further extended in future.

The visitors of EBAC since the spring of 2006 are:

2006:

1. Apr. 1 - Apr. 5 — Simon Capstick (Florida University)
2. Apr. 1 - Apr. 14 — A. Kiswandhi (Florida University)
3. May 1 - May 5 — Kanzo Nakayama (University of Georgia)
4. Jun. 19 - Jun. 23 — Bruno Julia-Diaz (University of Barcelona)
5. Nov. 3 - Nov. 11 — Siegfried Krewald (Jülich)
6. Nov. 25 - Dec. 15 — Bruno Julia-Diaz (University of Barcelona)
7. Nov. 25 - Dec. 16 — Toru Sato (Osaka University)
8. Nov. 25 - Dec. 4 — Nobuhiko Suzuki (Osaka University)
9. Nov. 26 - Dec. 16 — Akihiko Matsuyama (Schizuoka University)

2007:

1. Feb. 28 - Mar. 24 — Kazuo Tsushima (University of Salamanca)
2. Jun. 16 - Jun. 23 — Johan Durand (Sacley)
3. Jun. 18 - Jul. 7 — Siegfried Krewald (Jülich)
4. Jun. 27 - Jul. 3 — Helmut Haberzettl (George Washington University)
5. Jul. 23 - Aug. 30 — Bruno Julia-Diaz (University of Barcelona)
6. Aug. 7 - Sep. 1 — Kazuo Tsushima (University of Salamanca)
7. Aug. 26 - Aug. 31 — Richard Arndt (George Washington University)
8. Sep. 30 - Oct. 14 — Toru Sato (Osaka University)
9. Sep. 30 - Oct. 14 — Nobuhiko Suzuki (Osaka University)

2008:

1. Jan. 7 - Feb. 2 — Yoichi Ikeda (Osaka University)
2. Oct. 5 - Oct. 18 — Bruno Julia-Diaz (University of Barcelona)
3. Oct. 5 - Oct. 18 — Akihiko Matsuyama (Schizuoka University)
4. Oct. 5 - Oct. 19 — Toru Sato (Osaka University)
5. Oct. 5 - Oct. 19 — Qiang Zhao (IHEP, Beijing)

2009:

1. Feb. 16 - Feb. 22 — Toru Sato (Osaka University)
2. Feb. 16 - Feb. 23 — Yoichi Ikeda (Osaka University)
3. Apr. 15 - Apr. 18 — Tetsuro Mizutani (VPI)
4. Jun. 8 - Jun. 11 — Satoshi Nakamura (ANL)
5. Jul. 5 - Aug. 6 — Iraj Afnan (Flinders University)
6. Jul. 14 - Jul. 25 — Michael Doering (Jülich)
7. Jul. 17 - Jul. 25 — Seigfried Krewald (Jülich)
8. Jul. 19 - Jul. 24 — Andrey Sarantsev (Bonn University)
9. Jul. 19 - Jul. 24 — Richard Arndt (George Washington University)
10. Jul. 19 - Aug. 7 — Bruno Julia-Diaz (University of Barcelona)
11. Jul. 19 - Jul. 24 — Toru Sato (Osaka University)
12. Jul. 22 - Jul. 24 — Boris Blankleider (Flinders University)
13. Jul. 22 - Jul. 24 — Daniel Phillips (Ohio University)