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A proposed U.S./China theoretical/experimental collaborative effort on baryon resonance extraction*

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Abstract In this paper we discuss the reasons for our work towards establishing a new collaboration between Jefferson Lab (JLab) and the Institute of High Energy Physics (IHEP) in Beijing. We seek to combine experimentalists and theorists into a dedicated group focused on better understanding the current and future data from JLab and from the Beijing Electron Positron Collider (BEPC). Recent JLab results on the extraction of single- and double-polarization observables in both the 1π- and 2π-channel show their high sensitivity to small production amplitudes and therefore their importance for the extraction of resonance parameters. The Beijing Electron Spectrometer (BES) at the BEPC has collected high statistics data on J/ψ production. Its decay into baryon-antibaryon channels offers a unique and complementary way of probing nucleon resonances. The CEBAF Large Acceptance Spectrometer, CLAS, has access to N* form factors at high Q^2, which is advantageous for the study of dynamical properties of nucleon resonances, while the low-background BES results will be able to provide guidance for the search for less-dominant excited states at JLab. Moreover, with the recently approved experimental proposal Nucleon Resonance Studies with CLAS12 and the high-quality data streaming from BES-III and CLAS, the time has come for forging a new Trans-Pacific collaboration of theorists and experimentalists on NSTAR physics.

Key words baryon resonances, electromagnetic form factors, J/ψ production, CEBAF Large Acceptance Spectrometer (CLAS), Jefferson Laboratory (JLab), Beijing Electron Spectrometer (BES), Beijing Electron Positron Collider (BEPC), Institute of High Energy Physics (IHEP)

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1 Introduction

Understanding the nature of the strong force through a quantum field theory framework, just as theory currently describes the electromagnetic or weak force, exemplifies one of the greatest intellectual challenges facing science today. Indeed, the highest priority recommendation in the DOE/NSF Nuclear Science Advisory Committee (NSAC) Long-Range Plan (Dec. 2007) reads:[2]

Recommendation I: We recommend completion of the 12 GeV CEBAF Upgrade at Jefferson Lab. The Upgrade will enable new insights into the structure of the nucleon, the transition between the hadronic and quark/gluon description of nuclei, and the nature of confinement.

In this paper we discuss the need for establishing a new collaboration between Jefferson Lab (JLab) and the Institute of High Energy Physics (IHEP) in Beijing. We seek to combine experimentalists from the CLAS[3] and BES[4] collaborations and theorists from IHEP and JLab into a dedicated group focused on better understanding the current and future data from JLab and from the Beijing Electron Positron Collider. (BEPC) The goal of a CLAS/BES working group is ambitious and timely; we seek to understand where the mass comes from in the transition from the hadronic to the quark/gluon picture of the proton. We are now poised to hone the requisite experimental and theoretical tools for attacking the fundamental

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2) Ralf W. Gothe, Kyungseon Joo, Steffen Strauch, Volker D. Burkert, Latifa Elouadrhiri, Victor Mokeev, T.-S. Harry Lee, Debra M. Easterly, Angela V. Petit, Kevin Kelley, Scott Galer, ZHAO Qiang, ZOU Bing-Song, QIAO Cong-Feng, LI Xue-Qian, HU Bi-Tao, and Inna Aznauryan. See Ref. [1].

question of what makes a proton a proton. Through our work on CLAS data, our series of workshops on NSTAR Physics with CLAS12, which culminated in the 57 page theory whitepaper,[5] and our recently-approved CLAS12 experiment on N*s,[6] we are well positioned on the JLab experimental side for this project. But in our view, this is not enough for addressing this issue of the origin of the quark mass and the 12 GeV upgrade will not get us all the way there. The physics objectives of the newly-installed detector BESIII[7, 8] and the upgrade for CLAS, CLAS12,[9, 10] are wide ranging, but are mostly quite separate; they only have significant overlap in the light-hadron physics sector, and in particular, in the spectroscopy of baryons. Creating a CLAS/BES working group with established lines of communication between IHEP and JLab will provide the catalyst for solving the very fundamental problem of what is meant by mass in the proton.

2 Motivation

In his summary talk, Why N*s are important, [11] given at the Workshop on Excited Nucleons and Hadronic Structure in 2000 (NSTAR2000),[12] Nathan Isgur stated:

The first is that nucleons are the stuff of which our world is made. As such they must be at the center of any discussion of why the world we actually experience has the character it does. I am convinced that completing this chapter in the history of science will be one of the most interesting and fruitful areas of physics for at least the next thirty years.

My second reason is that they are the simplest system in which the quintessentially nonabelian character of QCD is manifest. There are, after all, N_c quarks in a proton because there are N_c colors.

The third reason is that history has taught us that, while relatively simple, baryons are sufficiently complex to reveal physics hidden from us in the mesons. There are many examples of this, but one famous example should suffice: Gell-Mann and Zweig were forced to the quarks by $3\otimes3\otimes3$ giving the octet and decuplet, while mesons admitted of many possible solutions.

Although quite obvious to this NSTAR audience, it still bears repeating: ever since the beginning of subnuclear physics, nucleons and baryons in general have played an important role in the development of the quark model and of QCD. Indeed, the very concept of quarks was manifested through the study of baryon resonances. Over the course of the past many years, the properties of the ground state and the excited states of baryons have been treated in terms of isobars or constituent quarks. We are now poised at the threshold of a new era in describing these states in terms of the QCD degrees of freedom.

3 Light-quark interaction in the three-quark system

Recent lattice QCD calculations for heavy quarks of mass around 10 GeV[13, 14] show evidence for the "Y"-shaped gluon-flux tube (see leftmost and rightmost picture in Fig. 1), which would argue for a genuine three-body force between quarks in baryons and would therefore argue against a dominant two-body force, which would be identified as a "Δ"-shaped gluon-flux tube (not shown). This three-body force is an essential feature of QCD — and as indicated by Nathan Isgur in point 3 in the Motivation section above — this force can only be studied in the three-quark baryon system and its dynamics currently can only be measured at Jefferson Lab.

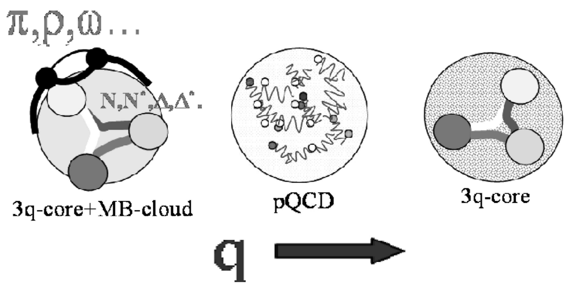

Fig. 1. These pictures depict various physical processes at different quark separation distances, i.e. quark momentum p. The leftmost picture shows the 3-quark core with a cloud of mesons surrounding the nucleon or baryon, or Meson-Baryon (MB) Cloud. At higher momentum transfers, the constituent quarks dominate the action (middle picture). And the rightmost picture resolves the proton in the regime of asymptotic freedom.

The physics goals of the N* studies with CLAS12 have two primary foci a) explore the interactions between the dressed quarks, which are responsible for the formation for both ground and excited nucleon states; and b) probe the mechanisms of light current quark dressing, which is responsible for over 97% of nucleon mass. With these goals in mind, the three objectives of our recently approved experiment Nucleon Resonance Studies with CLAS12[6, 15] are:

1. Map out the quark substructure of N*s from the data of exclusive meson electroproduction reac-

tions. This will allow us to better understand how the internal core of dressed quarks emerges from QCD and how the strong interaction is responsible for the formation of N* states.

2. Investigate the dynamics of dressed-quark interactions inside the nucleon core and understand how these interactions emerge from QCD.

3. Study the Q^2 dependence of nonperturbative dynamics of QCD.

The third item bears upon how the effective mass of the quark in the baryon depends on its momentum. At low momentum, the light quark, i.e. the constituent quark, has a mass of roughly 1/3 that of a proton ($M_q \simeq 300$ MeV), and at high momentum, in the asymptotically-free regime, this quark is nearly massless. This momentum-dependent mass of the quark, $M(p)$ is illustrated in Fig. 2, where the "data points" are from a Lattice QCD (LQCD)[16] computation with the overlaid curves being from a Dyson-Schwinger Equation (DSE) calculation[17—19] for different bare masses of the pion. It is noteworthy that these two very different calculations agree so well. What is altogether lacking is data on the Q^2 evolution of the form factors in the transition region. That is to say, there are no data above Q^2 of 5 GeV^2 or a momentum p of 0.75 GeV per quark. Mapping out the $Q^2 > 5$ GeV^2 domain will give the exigent experimental verification of this momentum dependence and hence will advance our understanding of nonperturbative QCD dynamics. In October 2008, a three-day workshop[5, 20] was held at JLab dedicated to the theoretical interpretation of the baryon resonance parameters in studying the sensitivity of extracting the transition form factor measurements to different parameterizations of momentum dependence of the quark mass. And through these studies, one may address the question of how baryon structure emerges from confinement and the dynamical chiral symmetry breaking of QCD. The main points summarizing the workshop are listed below.

Transition form factors for the baryon resonances $\Delta(1232)P_{33}$, $\mathrm{N}(1440)P_{11}$, $\mathrm{N}(1520)D_{13}$, and $\mathrm{N}(1535)S_{11}$ have been measured over large Q^2 range.

—no sign of approaching asymptotic QCD limit, which means a critical need for the 12 GeV upgrade

—pion dressing of vertex needed to describe form factors

The roper $\mathrm{N}(1440)P_{11}$ transition form factor determined for the first time.

—zero crossing of magnetic form factor

—behaves like a Q^3-radial excitation at short distances

—$Q^2 < 0.7$ GeV^2 determined from the 1π and 2π exclusive channels, as well as from a combined analysis of both these channels, are in a good agreement.

Reliable results on N* electrocouplings from meson electroproduction data have been extracted.

—$\mathrm{N}(1440)P_{11}$ and $\mathrm{N}(1520)D_{13}$: The 1π and 2π channels have completely different nonresonant mechanisms yet are in agreement.

—description of all observables in both these channels with common N* electrocouplings are a good testing ground for efficacy of the JLab/GWU-SAID/MAID reaction models

There exists good prospects to relate QCD and Q^2 evolution of N*s within the framework of Dyson-Schwinger and Bethe-Salpeter approaches and Lattice QCD (with the caveat of more powerful computers) as determined through light-cone wavefunctions.

There has been healthy progress in constituent quark models

Reliable information on extracting the N* electrocouplings from combined fits of multiple polarization observables in Nπ, Nππ, pη, and KY in electro- and photoproduction is needed to resolve ambiguities in baryon resonance analysis.

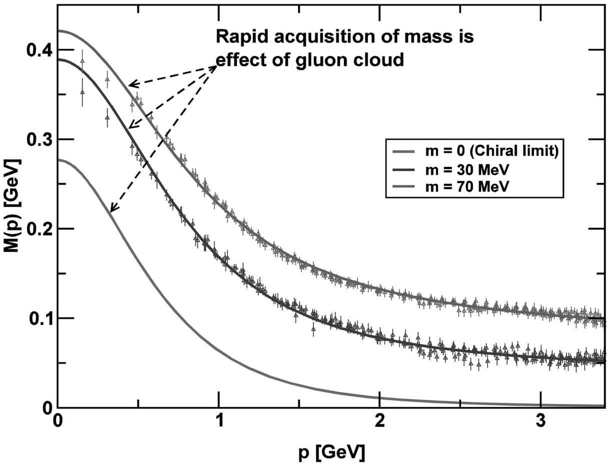

Fig. 2. Running quark masses, where the dressed-quark mass M is a function of the momentum, p. The solid circles with error bars are from an unquenched lattice QCD calculation[16] under three different lattice spacings as characterized by the pion mass m. The solid curves are a Dyson-Schwinger Equation result.[17, 18] Note the rapid acquisition of mass as the gluons 'dress' or attach to form the constituent quarks. To convert momentum p to Q^2 per quark, one needs to multiply the abscissa value by 3 and square it, i.e. $Q^2 = (3p)^2$. With our proposed exeriment,[6] we expect to reach photon virtualities of $Q^2 = 12$ GeV^2.

The Excited Baryon Analysis Center is essential to support the baryon resonance program with coupled channel calculations.

4 Trans-Pacific developments

By forging a trans-Pacific alliance and working together, the research teams at CLAS and BES will strengthen the global baryon resonance studies effort. BES is in the process of collecting high-statistics data on J/ψ from electron-positron collisions. The decay of the J/ψ into baryon-antibaryon channels offers a unique and complementary way of probing nucleon resonances (N*) in the mass region up to 2 GeV as can be seen in Fig. 3. With the precision electron and photon beams afforded by JLab, not only would the existence of these new N* states be confirmed, but it would further allow for their properties to be precisely mapped out, such as depicted in Fig. 5 for the helicity conserving amplitude $A_{\frac{1}{2}}$ in the electroproduction of pion(s).

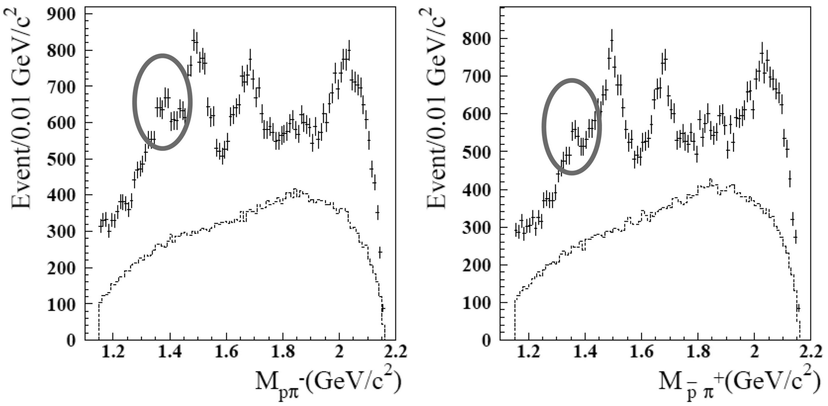

Fig. 3. The above plots come from Fig. 5 in the BES collaboration paper: Observation of Two New N* Peaks in $J/\psi \rightarrow p\pi^-\bar{n}$ and $\bar{p}\pi^+n$ Decays.[65] The $p\pi^-$ and $\bar{p}\pi^+$ invariant mass spectra for $J/\psi \rightarrow p\pi^-\bar{n}$ (left) and $\bar{p}\pi^+n$ (right), compared with phase space. The circled peak around 1360 MeV/c^2 marks the first direct observation of the Roper Resonance, i.e. the N(1440)P_{11}. From the IHEP partial wave analysis (in units of MeV): $M=1358\pm17$ and $\Gamma=179\pm56$.

4.1 BESIII

The new Beijing Electron Spectrometer (BESIII) at the upgraded Beijing Electron Positron Collider (BEPCII) is presently collecting high statistics data on J/ψ production. The J/ψ decay into baryon-antibaryon channels offers a unique and complementary way of probing nucleon resonances (N*). As can be seen in Table 1, with the soon achievable 500 Million J/ψs from BESIII, there will be 3 million events in the $p\bar{p}\pi^+\pi^-$ channel, with a comparable number in the integrated single-pion (π^- and π^0) channel. Over the course of the data-taking period of BESIII, it is expected there will be over 10 billion J/ψs produced, which will yield a twenty-fold increase in statistics over what is tabulated in column 3 of Table 1.

So far, several N* states have already been seen at BESII in the mass region of 2 GeV[65] as depicted in Fig. 3. These data from BES provide a remarkably clean signal in that — to our knowledge — this is the first time the N(1440)P_{11} resonance has been seen as a 'bump' in the mass spectrum as opposed to being extracted through partial-wave (or any other) analyses.

Table 1. Measured J/ψ decay branching ratios (BR×10^3) for channels involving baryon/antibaryon/meson(s). (From Table 10.2 of Ref. [7]).

$J/\psi \rightarrow N^*\bar{N} \rightarrow$	$BR\times10^3$	500 M J/ψs
$p\bar{n}\pi^-$	2.4 ± 0.2	1,200,000
$p\bar{p}\pi^0$	1.1 ± 0.1	500,000
$p\bar{p}\pi^+\pi^-$	6.0 ± 0.5	3,000,000
$p\bar{p}\eta$	2.1 ± 0.2	1,000,000
$p\bar{p}\omega$	1.3 ± 0.3	650,000
$p\bar{\Lambda}K^-$	0.9 ± 0.2	450,000
$\Lambda\bar{\Sigma}^-\pi^+$	1.1 ± 0.1	550,000
$p\bar{\Sigma}^0K^-$	0.3 ± 0.1	150,000
$p\bar{p}\phi$	0.045 ± 0.015	22,500

4.2 CLAS

Recent CLAS results on the extraction of single- and double-polarization observables in both the 1π- and 2π-channel show their high sensitivity to small production amplitudes and therefore their importance for the extraction of resonance parameters.

JLab has access to N* form factors at Q^2 of up to 4 GeV^2 for single-pion production and $\simeq 1.0$ GeV^2 for the double-pion channel. Baryon transition form factors in the single-pion[21—36] and double-pion[37—40] decay channel have been investigated in Hall B at JLab using the CEBAF Large Acceptance Spectrometer (CLAS). And these data demonstrate that the separation of resonance and background contributions and therefore the extraction of the electrocoupling amplitudes[35, 41—44] of resonances become cleaner at higher four-momentum transfers (Q^2). There is a further advantage of extracting resonances at higher Q^2; it is easier to isolate N*s than at the real photon point. Furthermore, the 2π channel[45, 46] shows a higher sensitivity to higher-lying resonances, and with the combined analyses of the 1π and 2π channels, the model-dependent uncertainties will be rigidly constrained.

CLAS is on the path towards DOE Milestone 2012, which is to measure the electromagnetic excitations of low-lying baryon states (< 2 GeV) and their transition form factors over the range $Q^2 =$ 0.1 to 7 GeV^2 and measure the electro- and photoproduction of final states with one and two pseudoscalar mesons. This Q^2 evolution is advantageous for the study of dynamical properties of nucleon resonances,[48—57] while the low-background BESIII results will be able to provide guidance for the search for less-dominant excited states at JLab.

Anchored with polarization observables in meson photoproduction with linearly-polarized photons ($Q^2 = 0$) from the Coherent Bremstrahlung Facility onto unpolarized and polarized protons in CLAS,[58—64] and with the precision electroexcitations which orded by CLAS12, not only would the existence of new N* states be confirmed, but it would further allow for their properties to be precisely mapped out as functions of Q^2 up to values of photon virtualities of 12 GeV^2[15].

As depicted in Fig. 4, six amplitudes, corresponding to various helicities of the initial virtual photon-proton state, fully describe the N* electroexcitation. Parity conservation reduces the number of independent amplitudes to three: two transverse $A_{\frac{1}{2}}$ (nonspin flip) and $A_{\frac{3}{2}}$ (spin flip) and one longitudinal $S_{\frac{1}{2}}$. The corresponding transition form factors are given by unique linear combinations of these extracted Q^2-dependent helicity amplitudes.

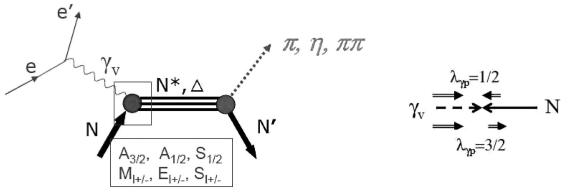

Fig. 4. Resonant amplitudes in meson electroproduction allowing access to both the longitudinal and to the two transverse helicity amplitudes, which are functions of Q^2.

The nonspin-flip transverse ($A_{\frac{1}{2}}$) and longitudinal ($S_{\frac{1}{2}}$) electrocoupling amplitudes of the Roper resonance (N(1400)P_{11}) are shown in Fig. 5 for $0 < Q^2 < 4$ GeV^2. One observes that there is good agreement between the electrocouplings obtained from the Nπ and Nππ channels, which lends strong evidence for having a reliable measure of the electrocouplings. Moreover, the electrocouplings for $Q^2 > 2.0$ GeV^2 are consistent with the N(1400)P_{11} structure as being a 3-quark radial excitation. And the zero crossing for the $A_{\frac{1}{2}}$ amplitude has been observed for the first time, indicating the importance of light-front dynamics.

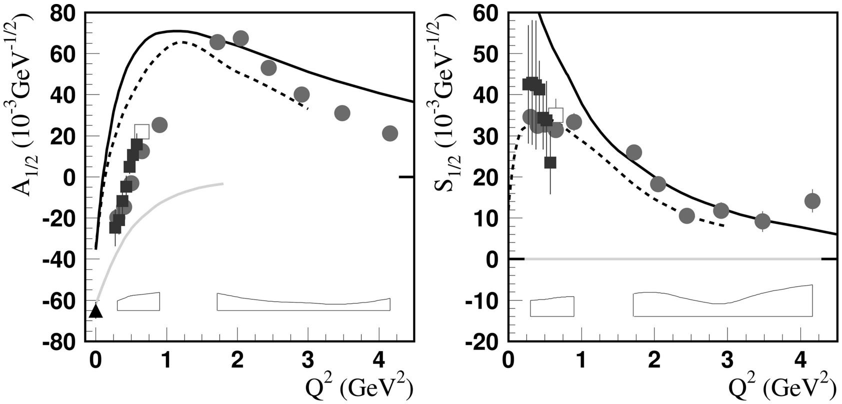

Fig. 5. Helicity amplitudes for the $\gamma^*p \rightarrow$ N(1400) P_{11} transition[36, 40] in units of 10^{-3} GeV$^{-\frac{1}{2}}$. (left) transverse helicity-conserving amplitude: $A_{\frac{1}{2}}$ and (right) longitudinal helicity amplitude: $S_{\frac{1}{2}}$. (color online) red: 1π data (with statistical errors only), blue: 2π data (statistical + systematic errors). The solid and dashed black lines are light-front models from I.G. Aznauryan[42] and S. Capstick,[66] respectively. The green line: hybrid N(1440)P_{11},[67] i.e. qqqg. The bands represent the systematic uncertainties of the 1π analyses.

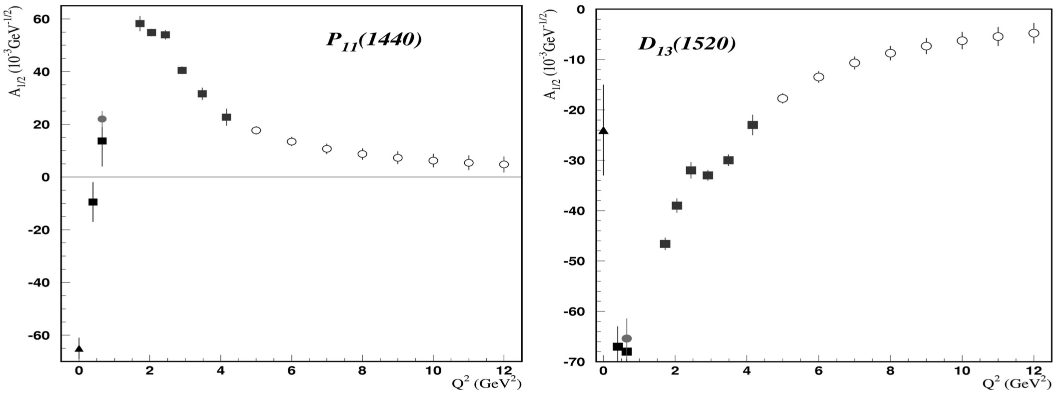

Fig. 6. CLAS12 projections for the N* transitions[6] of the $A_{\frac{1}{2}}$ helicity-conserving amplitudes. (left) $\gamma^*\mathrm{p} \rightarrow$ N(1400) P_{11} and (right) $\gamma^*\mathrm{p} \rightarrow \mathrm{N}(1520)D_{13}$. The closed points are published and the open circles are for anticipated CLAS12 data.

For the foreseeable future, CLAS12 will be the only facility worldwide, which will be able to access the N* electrocouplings in the Q^2 regime of 5 GeV^2 to 10 GeV^2, where the quark degrees of freedom are expected to dominate as can be seen Fig. 6.

4.3 Complementarity

In essence, the Roper resonance reflects the very complementarity of BES and CLAS; in Fig. 3 the circled 'bump' is identified and in Fig. 5 the dynamics are mapped out. In metaphorical language, BES tells us where to dig and CLAS brings the steam shovel. The low-background BES results will be able to provide guidance for the search for less-dominant excited states at JLab. Two new N* peaks have been seen in the BES πN mass spectrum, the aforementioned Roper resonance and the N*(2065). In the IHEP ***K***-matrix approach to the partial-wave analysis of the J/ψ to baryon resonance channel,[68, 69] the mass and full width is found to be $M = 2068 \pm 3$ MeV and $\Gamma = 165 \pm 14 \pm 40$ MeV. Morever, due to the isospin selectivity of the $\mathrm{J}/\psi \rightarrow \mathrm{n}\bar{\mathrm{N}}^*(2065)$ (with $L = 0$), its spin-parity J^P is restricted to values of either $\frac{1}{2}^+$ or $\frac{3}{2}^+$. With CLAS12 not only would the existence of this new N*(2065) state be confirmed, but it would further allow for its properties to be precisely mapped out at various distances or Q^2.

Consistent results on N* electrocouplings obtained in analyses of various meson channels (e.g., ηp, ππN) with entirely different nonresonant amplitudes are requred to show that they are determined reliably. In particular, the analysis of both the BES and CLAS datasets, each having very different contributions to the production background, and with their unique N* signatures, it will become incumbent upon our proposed collaboration of experimentalists and theorists to develop refined theoretical tools to extract complementary resonance production amplitudes. And this requires a good line of communication between IHEP and JLab so that the IHEP PWA[69] approach can be compared to the results[70—75] of another major analysis effort of the Excited Baryon Analysis Center (EBAC)[76] at JLab.

5 Path forward

To understand how mass is generated within the proton, we need to understand how strong interactions evolve from pQCD to the quark confinement regime in baryons as depicted in Figs. 1 and 2. And this can only be done by understanding N* structure from the complementary data from BES and CLAS. We require overarching funding so that

1) experimentalists from BES and CLAS and theorists from EBAC and IHEP can collaborate;

2) open opportunities for young bright physicists on both sides of the Pacific to work on this fundamental problem of the structure of nucleons.

We therefore wish to grow our established network into a productive international collaboration, wherein our group will be positioned at both ends of the data stream: ranging from producing and analyzing the wealth of forthcoming data, extracting reliable resonance parameters, which will enable significant discovery potential of new nucleon resonances, and through our world-class theoretical support, to contributing significantly to a deep and thorough understanding of the scale-dependent strong interaction. This experimental program and its attendant theoretical interpretation will take at least ten years to complete. Our proposed collaboration therefore has great potential to grow and to flourish far beyond the next five years.

And even though we did not receive an NSF PIRE award,[1] we recently received funding for a pilot program to support one student to work on N* physics from BES, which is a crucial first step. This feasibility study will open lines of communication between BES and CLAS experimentalists and, hopefully, will lead to ultimately coordinating the experimental and theoretical resources of JLab and IHEP on baryon resonance research.

In the words of the venerable Chinese philosopher Lao Tse: "The longest march begins with a small step." We have made that small step.

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1 The List of Participants for PIRE: Nucleon Resonance Studies: Philip L. Cole, Ralf W. Gothe, Kyungseon Joo, Steffen Strauch, Volker D. Burkert, Latifa Elouadrhiri, Victor Mokeev, T.-S. Harry Lee, Debra M. Easterly, Angela V. Petit, Kevin Kelley, Scott Galer, ZHAO Qiang, ZOU Bing-Song, QIAO Cong-Feng, LI Xue-Qian, HU Bi-Tao, Inna Aznauryan. PIRE is the acronym for the NSF Program for International Research and Education.We submitted a preliminary proposal to PIRE for the 2009 solicition, and although we did make it to the invite-to-proposal stage, we did make significant progress on establishing an N* working group between CLAS and BES. The next PIRE solicitation is anticipated to be announced in 2011

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