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Theoretical Aspects of Electroweak and Other
Interactions in Medium Energy Physics — Final Project Report for the Grant
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Abstract

The project, supported by the Department of Energy grant, deals with the theory of electroweak and other interactions of nucleons and nuclei, with emphasis on the electromagnetic production of mesons, and the theory of hadron structure inspired by quantum chromodynamics. On these topics, twenty-seven papers and other scientific communications have been completed during the current project period, April 1988 to present, including a number of invited papers presented at international meetings and workshops. One student has got his Ph.D. degree, and two are working towards it; the latter have been rewarded by the organizers of the PANIC-XII Conference at MIT (June 1990) with financial support to present their papers. A DEC-3100 workstation has been installed for the dedicated use of this project, and it has been upgraded with additional funding from Rensselaer and Digital Equipment Corporation. A new research collaboration with Professor F. Iachello, a theorist from Yale University has been started.

MASTER

I. INTRODUCTION

The present document is the final progress report covering the grant period April 1, 1988, to March 31, 1991, on the project entitled "Theoretical Aspects of Electroweak and Other Interactions in Medium Energy Nuclear Physics", supported by the U.S. Department of Energy Grants #DE-FG02-88ER40448, .A001, .A002. Two interim progress reports have been already filed in December 1988 and December 1989. This report is being submitted along with an application for a new three-year grant to continue this research at Rensselaer Polytechnic Institute, which would continue to give a vital theoretical support to a five-member nuclear experimental team working at the Bates Laboratory, Brookhaven and CEBAF, besides being an independent intellectual focus in the Physics Department.

During the current grant period (April 1988 to March 1991), a significant progress has been made in all areas of research, originally proposed to DOE in the Fall of 1987. This is discussed in detail in Section II. Twenty-seven scientific communications have been made and one Ph.D. thesis has been completed [3-30]. Two students associated with this program have been awarded the PANIC-XII grants to present their work at that international meeting hosted by MIT in June, 1990. These students are making satisfactory progress towards their Ph.D. degrees.

Other Sections of this report are organized as follows: Section III contains a list of cited references, including our completed papers in the current project period, specifically indicated in Section IV. Section V contains the abstract of the Ph.D. dissertation completed in the current research period. Section VI lists graduate students working for advanced degrees and other personnel associated with the program. Section VII contains a list of seminars and colloquia given by the principal investigator at various institutions. This section also contains a list of outside research presentations and contributions by the graduate students associated with our program. Appendix 1 documents our overlap with the CEBAF and other outside laboratories. Appendix 2 contains an attachment of papers published or submitted for publication, during the current project period.

II. PROGRESS IN THE CURRENT PROGRAM PERIOD

The present program of research at Rensselaer Polytechnic Institute (RPI), supported by the DOE Grant #DE-FG-S8ER40448 and its two extensions, is an outcome of an effort started by the principal investigator (NCM) in the Fall of 1981, when he joined the RPI Physics Department after seven years of research in the medium energy theory at the Swiss Institute of Nuclear Research (SIN) in Switzerland (now called Paul Scherrer Institute). This effort, from the outset, have had a strong overlap with RPI nuclear experimentalists represented by five tenured faculty members and two research associates, along with their students. Quoting from NCM's first proposal to the DOE, funded in July, 1983, "The hope here is to open up new research vistas at RPI, in the theoretical medium energy physics, not only as a strong counterpoint to the local experimental program, but also participating in exciting developments elsewhere, strengthening the links with broader spectrum of physics of lepton and meson factories, thus making it attractive for bright students at RPI to join this challenging field of physics". From a modest start of one graduate student, this research program has attached some of the brightest students coming to RPI from around the world, making this program one of the strongest foci of the RPI physics department. Between 1983 and present, eight graduate students have been associated with this program; four have earned Master's degrees, three have got PhD degrees, and two are on their way to the doctorate degree. Two of our PhD's have been awarded the highest distinction in research from the Institute, and two current students have received external awards.

Below we give an overview of the progress made in the current program period (April 1988 to March 1991), based on the works to date. A perusal through this section will allow the reader to put the proposed program (Section III) for the next grant period (April 1991 to March 1994) in perspective.

(1) Spectrum generating algebra for mesons

This is result of a collaboration between RPI and Yale, in which the principal

investigator and his graduate student Lisheng Zhang from RPI, work with Professor Franco Iachello of the Sloan Physics Laboratory of Yale University. We explore the implications of the dynamic symmetry arising from the spin-flavor group $SU_s(2) \otimes SU_f(2n)$ and the compactified version $U(4)$ of the group $U(3,1)$, representing the radial and orbital excitation of the meson as a color string, where n is the number of quark flavors. Thus, we start with a spectrum generating algebra [3,4]:

$$G = U(4) \otimes SU_s(2) \otimes SU_f(n) \otimes SU_c(3), \quad (1)$$

where the subscripts s , f and c represent spin, flavor and color. The color group does not have many non-trivial implications for the meson configuration $q\bar{q}$. We choose the following dynamic symmetry chains

$$U(4) \supset SO(4) \supset SO_L(3) \supset SO_L(2), \quad (2)$$

$$\begin{aligned} SU_f(6) &\supset SU_f(5) \otimes U_{Y',\dots}(1) \\ &\supset SU_I(2) \otimes U_{Y'}(1) \otimes U_{Y''}(1) \otimes U_{Y'''}(1) \otimes U_{Y''''}(1), \end{aligned} \quad (3)$$

where I is the isospin quantum number for (u,d) quarks, Y , Y' , etc. are the additional "hyper" quantum numbers for quarks of flavors s , c , b , t . Using the Regge feature of the relativistic strings given by the mass dependence $M^2 \propto L$, where L is the angular momentum of the string, we use an expansion for M^2 linear in quantum numbers, which is expressed in the flavor basis as:

$$\begin{aligned}
\langle c_i \bar{q}_j | M^2 | q_i \bar{q}_j' \rangle = & \delta_{ii'} \delta_{jj'} \left\{ M_{ij}^2 + S(a_s + a_s' M_{ij}) \right. \\
& \left. + \nu(a_\nu + a_\nu' M_{ij}) + L(q_L + a_L' M_{ij}) + J(a_J + a_J' M_{ij}) \right\},
\end{aligned}
\tag{4}$$

where ν is the quantum number for radial excitation, $M_{ij} = m_i + m_j$, m_i being mass of the quark of flavor i . This is our basic mass formula for meson masses.

Correcting the above formula for the ground state π , k and η mesons as Goldstone bosons corresponding to the spontaneously broken chiral symmetry group $SU_A(3)$, and for flavor-diagonal quark-antiquark annihilation effects [31], we derive a mass formula [4] which gives a reasonable account of the meson masses, particularly for the mesons with quarks of lighter flavors. Overall, this formula describes mass squared of 65 relatively well-established [32] meson states with an average deviation of 5.2%, compared with the semi-relativistic quark-model approach [31] with an average deviation of 6.6%. This is very encouraging.

In the proposed research (Section III), we shall return to the possible improvements and critical tests of this approach, and attempts to extend it to more complicated hadrons.

(2) Perturbative QCD and the Bloom-Gilman Duality

This line of work is a result of a new collaboration [9,10] between the principal investigator and Professor Carl E. Carlson of College of William and Mary. Bloom and Gilman [33] noted some twenty years ago that the prominent resonances in inelastic electron-proton scattering do not disappear with increasing momentum transfer squared, q^2 , but actually fall at the same rate as the smooth background contributions. They also observed that the smooth scattering limit, seen at high Q^2 and W , for the structure functions $\nu W_2(\omega')$ is the same as the average for resonance peaks at lower Q^2 and W , but at the same ω' , where ω' is the Bloom-Gilman scaling variable given by $\omega' = 1 + W^2/Q^2$, Q^2 is the

invariant mass squared of photon and W is the invariant mass of the hadronic final state. These two observations together, known as the Bloom–Gilman duality, have been believed to be explainable in QCD terms, after DeRùjula, Georgi and Politzer [34] showed that, at moderate Q^2 , higher twist effects are small for the lower moments of the structure function.

Carlson and the principal investigator have demonstrated [9,10] that QCD expectations for the baryon transition form factors do lead to the observed constancy with momentum transfer of the resonance/"background" ratio, one point of the Bloom–Gilman duality. The same argument also explains the curve that the resonance contribution follows as a function of Q^2 , the other point of the duality.

The essence of the argument can be explained by examining the helicity amplitude G_+ for the electroproduction of a resonance, characterized by the mass M_R and the width Γ_R . The leading order QCD diagram for the amplitude G_+ is shown in Fig. 1. The gluon exchanges

Fig. 1: Leading order diagram in QCD for the transition amplitude G_+ for exciting a resonance. The external wavy line is a photon and internal wavy lines are gluons. Solid lines are quarks.

ensure that the final quarks, like the initial ones before being hit by the photon, have low relative momenta, so that no powers of Q^2 come from the initial or final wave functions. The amplitude G_+ is then made of one power of Q for each unbroken quark line, a factor of $1/Q$ for each internal fermion propagator, and a factor of $1/Q^2$ for each gluon propagator, G_+ being characterized by no flip of quark helicity. The amplitudes G_0 and G_- require flipping one or two quark helicities respectively, costing an additional factor of $1/Q$ for each quark helicity flip. Thus,

$$G_+ = \frac{g_+}{Q^3}, G_0 = \frac{g_0}{Q^4}, \text{ and } G_- = \frac{g_-}{Q^5}, \quad (5)$$

where $g_{\pm,0}$ are constants up to factors of $\log Q^2$. This gives for the structure function

$$\nu W_2 \propto (\omega' - 1)^3. \quad (6)$$

A similar argument yields an identical dependence resulting for "background" as well. Hence the observed constancy with the momentum transfer of the resonance/"background" ratio in the Bloom–Gilman duality.

The above line of argument also leads to a new prediction of scaling for the longitudinal inelastic distribution function. We predict a scaling rule

$$\sigma_L \sim (\omega' - 1)^4 \quad (7)$$

for the longitudinal cross-section, for $\omega' \rightarrow 1$. It may be possible to test this prediction at CEBAF.

This sets the scene for future work proposed in collaboration with Professor Carlson in the area of perturbative QCD (pQCD), to be discussed in Section III.

(3) Effective Lagrangian Theory and Photoproduction of Pions in the delta (1232) region

Starting from the effective Lagrangian theory incorporating chiral symmetry, Davidson, Wittman and NCM [12] have been investigating theoretical uncertainties and model dependence in the extraction of the nucleon–delta (1232) electromagnetic transition amplitudes. The latter are of great interest in the context of testing realistic hadron models inspired by QCD [14]. Color magnetic interaction arising from the one–gluon exchange between quarks [35] can give rise to the SU_6 –violating configurations in nucleon and delta

wave functions, resulting in a non-zero value of the resonant E2 amplitude. Difficulties in the past has been in the extraction of this small amplitude from the existing data. In the approach we have adopted, the tree level theory contains pseudovector nucleon Born terms, leading t-channel vector meson exchanges and s- and u- channel delta exchanges. We insist on unitarity and express the nucleon-delta transition magnetic dipole (M1) and electric quadrupole (E2) amplitudes in terms of two independent gauge couplings at the $\gamma N \Delta$ vertex, and fit these to various multipole data sets.

Our extracted E2/M1 ratio (EMR) is negative [11,12], in agreement with all realistic models [14]. The magnitude of the EMR is found from this approach to be around 1.5%, very different from the value of unity, expected in the domain of perturbative QCD [36]. Our extracted magnitude of this quantity lies between the predictions of quark shell model [37] and the Skyrme model [38], and is in agreement with the model-independent approach described in the next sub-section; it agrees in sign and order of magnitude (-3.1%) with other recent model-dependent approaches [39].

As illustrations of our calculation, we display below the differential cross-section, photon asymmetry, recoil nucleon polarization and target asymmetry for the $\gamma p \rightarrow n \pi^+$ process for $E_\gamma = 380$ MeV (Figs. 2-5).

Fig. 2: Differential cross-section in $\mu\text{bs/sr}$ for $\gamma p \rightarrow n \pi^+$ vs. cm angle in degs. at $E_\gamma = 380$ MeV. Curves show various unitarization procedures for the data analysis [12].

Fig. 3: Photon asymmetry for $\gamma p \rightarrow n \pi^+$ vs. cm angle at $E_\gamma = 380$ MeV. The theoretical curves are from Davidson et al. [12].

Fig. 4: Recoil nucleon polarization for $\gamma p \rightarrow n \pi^+$ vs. cm angle at $E_\gamma = 380$ MeV. Theory is from Ref. [12].

Fig. 5: Target asymmetry for $\gamma p \rightarrow n \pi^+$ at $E_\gamma = 380$ MeV vs. cm angle. Theory is from Ref. [12].

(4) Residues of K-matrix poles for the pion photoproduction in the delta region

In view of the model-dependence in the extraction of the resonant amplitudes discussed in the earlier subsection, Davidson and NCM [11] have investigated the model-independent extraction of the K-matrix poles and residues in the $\Delta(1232)$ region directly from the pion photoproduction multipole data. Let us write the K-matrix in terms of rapidly varying resonant piece and a "smooth" background:

$$K_{\gamma\pi} = \frac{A}{M-W} + B, \quad (8)$$

$$K_{\pi\pi} = \frac{C}{M-W} + D,$$

where W is the energy, M is the location of the K-matrix pole, and A, B, C, D are smooth functions of W . Writing the T matrix in the usual way,

$$T = K(1 - iK)^{-1} = K(1 + iT), \quad (9)$$

and ignoring Compton corrections, we can show

$$(\text{Im } T_{\pi\pi})_{W=M} = i, \quad \left[\frac{d}{dW} (\text{Re } T_{\pi\pi}) \right]_{W=M} = -1/C, \quad (10)$$

and

$$(\text{Im } T_{\gamma\pi})_{W=M} = \frac{A}{C}, \quad (11)$$

$$-C^2 \left[\frac{d}{dW} \text{Re } (T_{\gamma\pi}) \right]_{W=M} = A.$$

Eqs. (10,11) are free from background. Using first of the Eq. (11), we have

$$(\text{Im } T_{\gamma\pi})_{W=M}^{E \ 1+} / (\text{Im } T_{\gamma\pi})_{W=M}^{M \ 1+} = \frac{A_E}{A_M}, \quad (12)$$

thus giving us this important ratio independent of background and strong interaction physics. Numerically, the ratio of residues for E2 to M1 amplitudes, the EMR, to be

$$\text{EMR} = (-1.07 \pm 0.37)\%, \quad (13)$$

is accord with our model-dependent analysis [12], discussed earlier.

(5) Problems of describing spin $-3/2$ baryon resonances in the effective Lagrangian Theory

Benmerrouche, Davidson and NCM have investigated [27] several issues associated with the theoretical treatments of the spin $-\frac{3}{2}$ particles. We have made use of the most general interaction Lagrangian preserving the so-called point transformation symmetry [40] of the free spin $-\frac{3}{2}$ particles. This introduces some arbitrary parameters in the theory, which determines the off-shell contribution of spin $-\frac{3}{2}$ fields. We have shown that the choice of these parameters in the recent work of Nath *et al.* [41] are not theoretically satisfactory. Examples of related problems can be found in theories of massive vector and spin $-\frac{3}{2}$ particles in the discussion of pion decay and supersymmetry. Finally, we show why the interesting theoretical attempt of Peccei [42] to eliminate the spin $-\frac{1}{2}$ part of the πN transition amplitude cannot succeed, using very general arguments.

These discussions should trigger new investigations in the study of baryon resonances with spins greater than $\frac{1}{2}$, excited from free hadrons and in complex nuclei.

(6) Lack of Current Conservation in the Quark Shell Model and the Skyrme Model

Among the many subtle questions in the hadron structure and electroweak interactions, one problem that we have been concerned about is that of current conservation in the quark shell model. This issue was first raised in the work of the principal investigator with M. Bourdeau [43], a former student of this program, in the context of $\gamma_V N \rightarrow \Delta$ (1232)

transition, wherein the relationship between the longitudinal multipole, L_{1+} , and the scalar multipole, S_{1+} , derived from the conservation of the electromagnetic current,

$$k L_{1+} = k_0 S_{1+}, \quad (14)$$

where $k_\mu(k_0, \vec{k})$ is the four-momentum of the virtual photon, is found to be badly broken in many versions of the quark shell model. In a recent comment [44], Abbas has wondered as to whether the model proposed by Vento *et al.* [45] is also deficient in this regard. Bourdeau and NCM [7] have shown that this is indeed the case. Thus, at the virtual photon mass squared of -0.3 GeV^2 , they have obtained two different values of L_{1+} ; thus, $L_{1+} = -8.9$ and 11.9 estimated by current and charge approaches respectively, using the wave functions of Vento *et al.* for nucleon and delta [the multipole here is in the usual units of $10^{-3} \text{ GeV}^{-1/2}$]. In a model, where the electromagnetic gauge invariance is not broken due to model truncation and other approximations, these two should be equal.

L. Zhang and NCM [6] have been working on the excitation of other baryons in the quark shell model. As the Figs. 6–7 demonstrate, the problem gets worse for the electro excitation of heavier baryons.

Our research [6] shows that the above problem also occurs in the traditional approach of the Skyrmons. For both vector and chiral axial vector currents, standard skyrmion wave functions exhibit trouble with current conservation. Going from the version of the Skyrme Lagrangian without the vector mesons [38], this problem does not go away, indicating its subtle origin.

In the proposed research (Section III), we shall return to this problem and present our ideas on possible origins of this problem, along with projected ways to solve it. The tackling of current conservation in an adequate fashion is of fundamental relevance in understanding the electroweak excitation of baryon resonances at CEBAF.

$$\gamma_v + \text{PROTON} \rightarrow S_{11}(1535)$$

Fig. 6: The longitudinal form factor computed in the process $\gamma_v + \text{proton} \rightarrow S_{11}(1535)$ as a function of virtual photon mass squared computed in the Isgur-Karl model. The upper curve and the lower curve are obtained in the charge and current approaches respectively (from Zhang and Mukhopadhyay, to be published).

Fig. 7: The caption same as Fig 6, the process being $\gamma_v + \text{nucleon} \rightarrow \text{F}_{37}(1910)$.
 From Zhang and Mukhopadhyay, to be published.

(7) Eta Photoproduction Near Threshold

One of the exciting prospects in the study of electromagnetic excitation of baryon resonances is the prospect of the study of the $S_{11}(1535)$ resonance excitation via the photoproduction of eta mesons. The focus of our work thus far has been to study the contrast of this process near threshold to the photoproduction of pi-zero mesons. Benmerrouche and the principal investigator have first concentrated on this difference, by studying the reaction $\gamma p \rightarrow \eta p$ in the effective Lagrangian approach, with a view of understanding first the structure of the amplitude at the tree-level [15–18]. Our principal conclusions thus far can be summarized by the following: (a) The E_{0+} amplitude, in which $S_{11}(1535)$ resonance is excited, receives three important Born (or background) contributions. The s and u-channel nucleon exchanges, and the t-channel vector meson exchanges. (b) It is very sensitive to the nature of the coupling at the meson–nucleon vertex: unlike the pi-zero production [46] near threshold, the pseudoscalar coupling seems to be preferred to explain the existing data. (c) The contribution of the s-channel $S_{11}(1535)$ excitation to the E_{0+} amplitude is very large even near threshold: a contrast from the relatively unimportant rôle of the $\Delta(1232)$ contribution for the pi-zero production near threshold [46].

Our analysis for the existing data on cross-section and polarization derived from the eta photoproduction experiments [47]48] is continuing. Our best fits of the higher energy data yield predictions for the recent data at $E_\gamma = 725$ and 750 MeV from the Bates Laboratory obtained by S. Dytman et al. [48], shown in Figs. 8. These as yet unpublished data suggest a stronger rôle of the background multipoles at the lower energy than our higher energy fits would imply. This is a serious discrepancy that must be understood theoretically. On the plus side, these data confirm our general tree-level theory, differences of which are very striking from the corresponding pi-zero photoproduction case near threshold. We shall return to this topic further in our proposal (section III).

Fig. 8: Angular distribution of eta mesons photoproduced off protons at lab photon energies $E_\gamma = 725$ and 750 MeV (Dytman et al. [48]), compared with our phenomenological prediction based on the effective Lagrangian theory.

(8) Phenomenological Transition Amplitudes Extracted from the Data on Electroweak Processes in Light Nuclei

In his Ph.D. thesis [20] completed in 1989, B. Doyle, a graduate student associated with this research program for a number of years, has done a thorough study of the extraction of nuclear transition density matrix elements from the low-energy electromagnetic and weak processes. This approach originally stressed by Donnelly and Walecka [49], is complementary to the standard many-nucleon shell-model approach wherein an effective Hamiltonian is diagonalized in the chosen basis. The classic work in the latter genre is that of Cohen and Kurath [50] in the 1p-shell nuclei. The transitions investigated by Doyle [20,21] are: ${}^6\text{Li}_{\text{g.s.}} \rightarrow {}^6\text{Li}^* (3.56 \text{ MeV})$, ${}^{12}\text{C}_{\text{g.s.}} \rightarrow {}^{12}\text{C}^* (15.11 \text{ MeV})$ and ${}^{14}\text{N}_{\text{g.s.}} \rightarrow {}^{14}\text{N}^* (2.313 \text{ MeV})$, workhorses in nuclei laboratories for a variety of investigations.

Fig. 9: ${}^6\text{Li}$, 3.56 MeV M1 form factor with various extracted nuclear amplitudes (after Doyle [20]).

Fig. 10: ${}^6\text{Li}(\gamma, \pi^+){}^6\text{He}_{\text{g.s.}}$ differential cross-section at $E_\gamma = 179 \text{ MeV}$, obtained theoretically with extracted nuclear amplitudes from Fig. 9. Data are from the unpublished RPI-Bates work (after Doyle [20]).

From his analysis, Doyle has determined reliable ranges of kinematic in the electroweak data from which one-body nuclear densities can be reliably obtained as a function of momentum transfer without sizable contamination from the two-body effects. He then has used these amplitudes as inputs to the calculation of meson photoproduction processes in the relevant nuclei, improving upon the theoretical uncertainties in the nuclear amplitude.

As an illustration of this work, we show in Fig. 9 the range of momentum transfer suitable for extracting the one-body nuclear amplitudes in the ${}^6\text{Li}(e,e'){}^6\text{Li}^*(3.56\text{ MeV})$. Fig. 10 demonstrates the description of the ${}^6\text{Li}(\gamma,\pi^+){}^6\text{He}_{\text{g.s.}}$ differential cross-section computed in Doyle's approach, confronting it with the recently obtained unpublished results of the RPI experimentalist working at the Bates Laboratory [51]. The quality of agreement between the calculation, using the nuclear amplitude obtained from the (e,e') data of Fig. 9, and the experiment on nuclear photoproduction is excellent.

Doyle, Goulard and principal investigator have used this approach to show that the meson exchange corrections to the nuclear β -decay of ${}^6\text{He}_{\text{g.s.}}$ are very small ($<10\%$) [25–26], compared to the impulse amplitude.

(9) Possible Time-Reversal Violating Effects in the Nuclear Weak Interaction

Despite extensive searches, only one system has been found in nature so far, explicitly exhibiting the CP-violation: the well-known weak decay of the neutral K-meson. One of the fundamental issues in physics remains why this is so, and if there are other systems exhibiting this symmetry violation. Since CPT symmetry is believed to be exact, an alternative handle to search for the CP violation is to search for T-violations in various processes or systems.

In the minimal standard model, T violating effects are extremely tiny, to make them experimentally inaccessible, in charged-current semi-leptonic processes that we study in nuclear physics. However, in the extended models, such as the left-right symmetric models,

models with charged Higgs bosons, exotic fermions, leptoquarks etc. [52], it is possible to have at the tree-level T-violating effects. Hence the study of T-violation is attractive to look beyond the standard model.

In their first report [23], P. Herczeg of Los Alamos National Laboratory and the principal investigator have examined muon capture reaction in nuclei and analyzed, from the currently available data, possible constraints on the T-violating exotic couplings.

In the new proposal, we shall return to this topic and explain our continuing interest in this subject by specific examples of T-violation searches via muon capture. Experiments, to be attempted at the Paul Scherrer Institute, are difficult, but would access interesting regime of high-energy physics on which very little information is currently available.

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IV. PAPERS AND SCIENTIFIC COMMUNICATIONS IN THE CURRENT PROJECT PERIOD

(see citations in Section III)

1. Journal and major research articles in conference proceedings: fourteen articles. See Refs. [3], [7], [10–12], [14], [17–19], [22], [26–27], [29–30].
2. Conference abstracts and short contributions: thirteen. See Refs. [4–6], [8], [9], [13], [15], [16], [21], [23–25], [28].
3. Book: one (co–edited by the principal investigator). See Ref. [1].
4. Ph.D. Dissertation: one (see Section V).

V. PH.D. DISSERTATION COMPLETED IN THE CURRENT PROJECT PERIOD

Brian C. Doyle: Ph.D. Thesis defended May 1989.

Dissertation entitled: "Phenomenological Transition Amplitudes: Consequences
for Pion and Eta Photoproduction in 1p-Shell Nuclei".

VI. RESEARCH ASSOCIATES AND GRADUATE STUDENTS WITH THE PROGRAM
IN THE CURRENT GRANT PERIOD

- * Dr. R. Davidson, Research Associate
- † B. Doyle
- ** M. Benmerrouche
- †† L.S. Zhang
- * Lecturer, Department of Physics, supported by RPI. Associated with the current program through September 30, 1988.
- † Associated with the current program through February 1989 under the DOE support.
- ** Research Assistant under DOE support throughout the current program.
- †† Research Assistant under DOE support from Summer, 1988.

VII. (A) INSTITUTIONS HOSTING THE PRINCIPAL INVESTIGATOR DURING THE
GRANT PERIOD FOR INVITED SEMINARS, COLLOQUIA OR INVITED TALKS

1988

- *1. International Conf. on Interface between Nuclear and Particle Physics, Rockport, ME.
- 2. Excited Baryon Collaboration Meeting, Herndon, VA.
- *3. Summer Workshop, CEBAF, Newport News, VA.
- 4. Theory Seminar, Paul Scherrer Institute, Villigen, Switzerland.
- 5. Excited Baryon 1988 Workshop, Troy, NY.
- 6. Physics Colloquium, University of Massachusetts, Amherst, MA.
- 7. Nuclear and Particle Physics Seminar, Carnegie-Mellon University, Pittsburgh, PA.

1989

- 1. Saurashtra University, Rajkot, India.
- 2. Tata Institute of Fund. Res., Bombay, India.
- 3. Bhabha Atomic Res. Center, Calcutta, India.
- 4. Nuclear and Particle Physics Seminar, University of Virginia, Charlottesville, VA (3 lectures).
- 5. College of William and Mary, Williamsburg, VA.
- 6. Theory Seminar, Paul Scherrer Institute, Villigen, Switzerland.
- 7. International Conference on Weak and Electromagnetic Interaction (WEIN-89), Montreal, Canada.

1990

- 1. International Conference on Low Energy Muon Physics – Prospects in the Nineties, PSI, Switzerland.
- *2. International Conference on Particles and Nuclei – PANIC XII, MIT, Boston, MA.

1990 continued

3. Meson Physics Division Colloquium, Los Alamos National Laboratory, Los Alamos, NM.
- *4. International Conference on Particle Production Near Threshold, Indiana University, IN.
5. Division of Nuclear Physics, American Physical Society, Champaign—Urbana, IL.
6. Physics Colloquium, Union College, Schenectady, NY.
7. Nuclear Physics Seminars, Université de Montreal, Canada.

* Invited Contribution.

VII. (B) EXTERNAL RESEARCH CONTRIBUTIONS/PRESENTATIONS BY
STUDENTS ASSOCIATED WITH THE PRESENT PROGRAM

M. Benmerrouche

- 1988: EXCITED BARYONS – 1988 CONF., Troy, NY, one paper on Eta Photoproduction (co author, with NCM).
- *1988: CONF. ON INTERSECTIONS BETWEEN PARTICLES AND NUCLEI, ROCKPORT, ME. One paper on Eta Photoproduction (coauthor, with NCM).
- *1988: CEBAF SUMMER WORKSHOP. One paper on K-matrix analysis (coauthor, with NCM).
- 1990: AM. PHYS. SOC., SPRING MEETING, WASHINGTON, D.C. One paper on Eta Photoproduction (coauthor, with NCM).
- *1990: PANIC-XII, MIT, Boston, MA. One paper on Eta Photoproduction (coauthor, with NCM).
- 1990: CONF. ON PARTICLE PRODUCTION NEAR THRESHOLD, NASHVILLE, IN. One paper on Eta Photoproduction (coauthor, with NCM).

B. Doyle

- 1988: EXCITED BARYONS – 1988 CONF., TROY, NY One paper on effective nuclear amplitudes.
- *1989: WEIN-89, MONTREAL, CANADA One paper on meson exchange current (coauthor, with NCM and B. Goulard).

L. Zhang

- 1990: AM. PHYS. SOC. SPRING MEETING, WASHINGTON, D.C. One paper with NCM on the quark shell model, Skyrme model and current conservation.
- 1990: PANIC-XI, MIT, BOSTON, MA. Two papers; one on meson spectroscopy coauthored with NCM and F. Iachello (Yale); another^{*} on current conservation on hadron models, coauthored with NCM.

L. Zhang continued

1990: AM. PHYS. SOC., FALL DNP MEETING, CHAMPAIGNE, IL. One paper on the electromagnetic moments of various delta states. Coauthor, with NCM.

*Invited Contribution.

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