Final Report on
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and its extensions

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Foreword: For most of the duration of this grant award, Professor Mukhopadhyay was the principal investigator. Tragically, Professor Mukhopadhyay passed away shortly after the most recent renewal of this grant (April 1, 2000). During most of the remainder of the Grant (until March 31, 2002), Dr. Richard M. Davidson acted as Principal Investigator. This Final Report has been written by Dr. Davidson and Prof. Paul Stoler, former friends and colleagues of Professor Mukhopadhyay.
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Scope of the Performed Research

The primary goal of the performed research was the theoretical understanding of the quark-gluon structure of nuclei and hadrons, as revealed through their electroweak interactions. This theoretical research program had strong overlap with the experimental programs as labs such as JLab, Brookhaven and Bates in the U.S., Bonn and Mainz in Germany and GRAAL in France. The research topics included phenomenological nuclear amplitudes, photomeson production off nuclei and nucleons, quark model calculations of electroweak transitions, soliton models of hadrons, algebraic models of mesons, and aspects of perturbative QCD. This research was performed by Prof. Mukhopadhyay, his post-doctoral assistants and numerous students, and was also involved many collaborators including: Prof. C. Carlson (College of William and Mary), Prof. P. Herzeg (LANL), Prof. K.F. Liu (Kentucky), Prof. B. Holstein (U. Mass., Amherst), Prof. F. Iachello (Yale), Prof. R. Bhallerao (Tata Inst., India), Profs. E. Oset and V. Vento (Valencia, Spain), Dr. K. Junker (PSI, Switzerland) and Dr. B. Saghai (Saclay, France).

Summary of Performed Research

The results of the performed research have been documented in 56 refereed journal publications, including 17 in Physical Review Letters, and numerous other conference proceedings, etc. In general, these works have been well received by the hadron physics community, most articles receiving numerous citations. In recognition of his years of excellent research, Prof. Mukhopadhyay received the Humboldt prize from Germany in 1998.

The backbone of this research was the effective Lagrangian approach to the theories of pion\(^1\) [8,9,13], eta [18,28,36] and eta-prime [31,39] photo- and electroproduction. Of primary interest was the extraction of the N-N' electromagnetic transition amplitudes from the extant data [5,11,21,23,30,35,37,40,41,47,50,51,52], both at the real photon point and as a function of the four-momentum-transfer squared. Formal aspects of the production amplitude were also investigated [1,20,54,55]. In conjunction with this work, efforts were also made to understand the transition amplitudes, as well as other hadron properties, in terms of quark models [7,10,27,32,45,46], soliton models [24,26], algebraic models [15,16,17], NJL models [56] and lattice QCD [53].

In the first resonance region, the main interest was in the M1 and E2 amplitudes in the N \(\rightarrow\) \(\Delta\) transition [5,11,13,23,41,50,51]. At the real photon point, after more than 15 years of work, most issues have been clarified. The M1 and E2 amplitudes can be accurately and rather model-independently extracted from the data [51]. This work was one of the motivating factors leading to the establishment of a benchmark data set to be used for testing model dependence versus dataset dependence.

Away from the real photon point, things are less certain [30]. However, up to 4 GeV\(^2\), it

\(^1\) The citation numbers refer to the publication list.
is clear that the $\Delta$ is not following pQCD expectations [50]. In particular, the M1 amplitude is falling faster than pQCD predicts, and the E2/M1 amplitude remains small and negative ($\approx -2\%$), in contradiction with the pQCD prediction of $+100\%$. A possible explanation of this behavior is provided in [48].

In the second resonance region, eta photo- and electroproduction [18,28,35,36,40,52] was used to study the electromagnetic excitations of the $S_{11}$ (1535) and the $D_{13}$ (1520) resonances. Many properties of these resonances, of great interest as tests of QCD-inspired baryon models, have been extracted from the data in a nearly model-independent manner. For example, the ratio of the electromagnetic transition amplitudes $A_{3/2}$ to $A_{1/2}$ for the $D_{13}$ (1520) was found to be $-2.5 \pm 0.2 \pm 0.4$, the first error coming from the data and the second from uncertainties in the strong properties of this resonance, such as the total width. This ratio is in strong disagreement with the one extracted from analyses of pion photoproduction, a mystery that remains to be solved.

The possible role of pQCD in the explanation of the Bloom-Gilman duality [12,22,49] and the observed resonant helicity amplitudes [19,29,42,48] has been investigated. Interesting interpolation formulas for the $Q^2$ developments of the $N - \Delta$ electromagnetic transition amplitudes were found by taking into non-perturbative constraints in the $Q^2 \to 0$ limit, and pQCD constraints as $Q^2 \to \infty$. These formulas give guidance as to where the pQCD behavior will manifest itself in this reaction.

Another important part of this research program was electroweak nuclear physics. Nuclear pion photoproduction [6,34] was used as an additional reaction to constrain phenomenological nuclear structure [14,33]. In addition, nuclear processes were used to probe the fine details of the standard model [2,3,4,25,38,43,44]. For example, relationships between nuclear neutrino reactions and muon capture [43,44] were worked out. Using the muon capture rate on $^{12}$C as a calibration, the nuclear weak response could be predicted at the 10% level or better. This work has important relevance to the LSND and KARMEN neutrino oscillation experiments. Finally, an estimate of charge symmetry in nuclear deep inelastic scattering and its affect on the extraction of the Weinberg angle from such experiments was made [42].

**Educational Aspects**

Numerous students participated in this research program. Some finished with Master's
degrees while others decided to pursue other fields. A total of seven graduate students earned their Ph.D.'s in this program, working on a wide variety of topics:

<table>
<thead>
<tr>
<th>Name</th>
<th>Year of Ph.D.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>R. Wittman</td>
<td>1986</td>
<td>Nuclear pion photoproduction</td>
</tr>
<tr>
<td>R. Davidson</td>
<td>1987</td>
<td>Excitation of the Δ (1232)</td>
</tr>
<tr>
<td>B. Doyle</td>
<td>1989</td>
<td>Phenomenological nuclear amplitudes</td>
</tr>
<tr>
<td>M. Benmerrouche</td>
<td>1992</td>
<td>Eta photoproduction</td>
</tr>
<tr>
<td>L. Zhang</td>
<td>1993</td>
<td>Chiral soliton model</td>
</tr>
<tr>
<td>J. Liu</td>
<td>1996</td>
<td>Weak transitions in the quark model</td>
</tr>
<tr>
<td>N. Mathur</td>
<td>2000</td>
<td>Proton spin content from lattice QCD</td>
</tr>
</tbody>
</table>

The undergraduate students M. Pierce, G. Mantry and J. Napolitano also participated in this research through the REU program.

Apart from training students to be research physicists, Prof. Mukhopadhyay and Dr. R. Davidson also taught many graduate courses in physics. In 1999, Prof. Mukhopadhyay received the John Wiley Distinguished Professor award from Rensselaer.

Journal Publications During Grant Award Duration

11. R.M. Davidson and Nimai C. Mukhopadhyay, *Model-independent determination of
31. M. Benmerrouche, J.-F. Zhang and Nimai C. Mukhopadhyay, Photoproduction of the


