1 of 1

PROGRESS REPORT

Nimai C. Mukhopadhyay

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ym

CONTENTS

ABSTRACT	ii
1. INTRODUCTION	1
2. DETAILS OF PROGRESS IN THE CURRENT PROGRAM PERIOD . .	3
3. LITERATURE CITED	19
4. PAPERS AND OTHER SCIENTIFIC COMMUNICATIONS IN THE CURRENT PROGRAM PERIOD	23
5. M.S. AND Ph.D. DISSERTATIONS COMPLETED IN THE CURRENT PROGRAM PERIOD	24
6. STUDENTS ASSOCIATED WITH THE CURRENT PROGRAM	25
7. EXTERNAL INSTITUTIONS HOSTING THE PRINCIPAL INVESTI- GATOR FOR SEMINARS, COLLOQUIA, AND OTHER RESEARCH VISITS	26
8. EXTERNAL PRESENTATIONS BY STUDENTS DURING THE PRO- GRAM PERIOD	28
9. PERSONNEL	29
10. CURRENT SUPPORT	30
11. BIOGRAPHICAL INFORMATION	31
12. APPENDIX: A SAMPLE OF PAPERS AND OTHER SCIENTIFIC COM- MUNICATIONS	32

ABSTRACT

A three-year theoretical physics program is proposed to continue the research in the Theory of Electroweak and Other Interactions in Medium Energy Nuclear Physics at Rensselaer Polytechnic Institute (RPI). The main thrust of this research program is the understanding of the structure of hadrons in the framework of the standard model. The hadrons are either in their free state or as constituents of nuclei. A particular focus will be on the elucidation of the electromagnetic amplitudes of baryon resonances in the mass range from one to two GeV, readily accessible at the emerging accelerator, CEBAF. We summarize here the research progress made in the current grant period (April 1991 to March 1994), of the U.S. Department of Energy Grant #*DE - FG02 - 88ER40448.A003, .A004 and .A005*. In this period, nineteen papers have been completed, along with one M.S. Thesis and two Ph.D. Dissertations. Thirteen other scientific communications have been made. Two graduate students have been awarded prizes for research excellence at RPI. The principal investigator has been awarded a Fellowship from the Division of Nuclear Physics of the American Physical Society.

1. INTRODUCTION

This report attempts to summarize the progress made in period April 1991 to March 1993, in the research program on the theoretical aspects of the electroweak and other interactions in the medium energy nuclear physics. This research has been done by Professor Nimai C. Mukhopadhyay (NCM), his students and external collaborators, under the auspices of the U.S. Department of Energy Grants #*DE - FG02 - 88ER40448.A003*, *.A004* and *.A005*. This research in hadron theory has a strong overlap with the experimental work to be done by the colleagues from Rensselaer Polytechnic Institute (RPI), in the emerging continuous-wave electron accelerator, CEBAF, in the area of the study of baryon resonances, both in the Hall C and in the Hall B. It also overlaps with the objectives of other high flux or specialized electron and photon facilities. NCM's external collaborators have included Prof. C. Carlson (College of William and Mary), Prof. F. Iachello (Yale), Dr. P. Herczeg (LANL), Dr. M. Benmerrouche (Saskatchewan Acc. Lab., Canada), and Dr. R. M. Davidson (University of Mainz, Germany).

The progress report for the current grant period, Section 2, summarizes our successes in the current program. We shall put this in the context of the history of this program. A quick perusal of the list of papers and other communications in the present program period [1-34] will give the reader the context in which this proposal is being made. This is also an indication of the solid progress made in the current program period. Two Ph.D degrees [20,21] have been awarded, under the auspices of this Grant in the present program period, to students, who have been awarded the Huntington Prize for best research in their respective years of graduation at the RPI physics Department. The principal investigator has been awarded the Division of Nuclear Physics Fellowship of the American Physical Society in the current program period, for his research contributions, some of which are reported in the next section.

An important step in the current program period is the beginning collaboration of two young physicists, Drs. J. and L. Zhang, as part-time postdoctoral associates of the program, thanks to the support of the RPI Physics Department, which has made this possible in the current program period. A firm hope in the proposed program (enclosed in a separate document) is to maintain this postdoctoral support under the auspices of the Grant. Section 3 lists the references cited in this proposal. Other sections document various activities in the current program, along with lists of publications, personnel and other pertinent facts, in support of the proposed program. Some publications in the current program period are appended.

2. DETAILS OF PROGRESS IN THE CURRENT PROGRAM PERIOD

The present research program of NCM at RPI, supported by the DOE Grant #*DE - FG02 - 88ER40448* and its extensions, is a growth of a modest program that started when the principal investigator joined the RPI Dept. of Physics in 1981, after a long sojourn of eight years in Europe, first at CERN, and then at the Swiss Institute for Nuclear Research(SIN), now the Paul Scherrer Institute (PSI). The first proposal from NCM to DOE, funded in July 1983, contained the hope of establishing a first-rate research program in theoretical interface between particles and nuclei, and then building a solid program of research in that area, at RPI. The present proposal is a development from that modest beginning. Some of the best graduate students of RPI have successfully completed the research training under the auspices of this program. Between 1983 and present, eleven graduate students have been associated with this program; five have earned Master's degrees, five have got Ph.D degrees, four of them winning the award of research excellence (Huntington Prize) from the RPI physics department. Three post-doctoral associates have been connected with this program, two currently under part-time basis. Two graduate students have won external awards. This year, NCM has been elected a Fellow of the American Physical Society in the Division of Nuclear Physics, for works that have been partly supported by the present Grant.

We review below the progress made during the current program period (April 1991 to March 1994), to put the proposed research for the grant period April 1994 to March 1997 (see the enclosed proposal) in perspective. In the current program period, nineteen papers have been completed [1-19], along with one M.S. Thesis and two Ph. D. dissertations [20,21], and thirteen other scientific communications [22-34].

2.1 Spectrum generating algebra (SGA)

The SGA is helpful to study the spectrum and transition properties of a quantum mechanical system, hadrons in our case, by choosing first a suitable algebra G , and expanding the operators of the problem onto G and its subalgebras. For the $q\bar{q}$ mesons, Professor F. Iachello (Yale), NCM and L. Zhang have expanded the SGA [2, 3]

$$G = U(4) \otimes SU_s(2) \otimes SU_f(5) \otimes SU_c(3), \quad (2.1)$$

where the subscripts stand for spin, flavor and color respectively.

We have shown that the dynamical symmetry $U(4) \supset SO(4)$ of the above SGA does a reasonable job in fitting the 57 well-established mesons in the Particle Data Group (PDG)[35] summary table, in a mass formula that describes masses of these mesons to an accuracy comparable to that obtained by the quark shell model approach of Godfrey and Isgur [36]. Our derived mass formula singles out states like $a_0(980)$ that are misfits in the $q\bar{q}$ scheme, adding one more argument to the already existing ones that $a_0(980)$ is not a $q\bar{q}$ state [37]. A typical observable is displayed in the Fig 2.1.

NCM and Zhang [11] have studied the classifications of the mesonic spectral intervals according to the subalgebras of the $U(4)$ chain. We thus find three such intervals O , U and N types: O types, in which the spectral interval decreases as a function of the excitation energy, is the most numerous in the known meson spectrum [for example, the sequence $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$]. The U type, in which the spectral interval increases as a function of excitation energy, is much less frequent [a possible example could be $\psi(3.69)$, $\psi(4.04)$ and $\psi(4.41)$]. The N type interval stays constant as a function of excitation energy [a possible example, $\pi^\pm$, $\pi(1.3)$ and $\pi(1.7)$ states].

We are now studying the mixing of these subalgebra and their dynamical origins.

Figure 2.1: The plot of the mass splitting $\Delta_L(M^2) = M^2(L=1) - M^2(L=0)$ as a function of the quark mass sum $M_{ij} = M_i + M_j$ for flavors i and j . Fit A is a separate fit of the light and heavy meson family, while Fit B is the global fit of all mesons. This is a typical plot of the quality of algebraic approach. From Iachello, Mukhopadhyay and Zhang[3].

2.2 "Vibrational" spectra in the heavy quarkonia

Graduate student L. Zhang and NCM [6] have studied the dependence of the spectroscopic interval

$$\Delta_v = M_v^2 - M_{v-1}^2 \quad (2.2)$$

on the nature of the $q\bar{q}$ confining potential, as a function of v , the vibrational quantum number of the states vs ($v \geq 0$) of the heavy quarkonia, M_i being the mass of the meson state, i . After initial bending, the quantity Δ_v approximately saturates only in the case of linear confinement, as v increases. Thus, the vibrational spectroscopic information can be regarded as a "fingerprint" of the confining $q\bar{q}$ potential, an important aspect of the frontiers of the heavy quarkonia spectroscopy. The initial bending resembles the 't Hooft phenomenon of similar sort in the $1+1$ dimensional field theory [38].

These intervals can be investigated, both by the exact numerical solution of

Figure 2.2: The vibrational spectroscopic interval $M_v^2 - M_{v-1}^2$ for the $c\bar{c}$ family as a function of the quantum number v for various potentials. $\times$ linear potential, $\star$ Lichtenberg-Wills, $\diamond$ Martin, $+$ Quigg-Rosner. These potentials are discussed in details in Mukhopadhyay and Zhang[6]

the appropriate radial differential equation [6], or by using the approximate WKB methods.

A demonstration of the dependence of the vibrational interval on the heavy quark potential is shown in Fig. 2.2.

2.3 Chiral soliton (Skyrmion) model

The Ph.D. thesis [21] of the graduate student L. Zhang, honored in the RPI Physics Department with the 1993 Huntington Prize for best research, has had the ambitious goal of developing a chiral soliton (Skyrmion) model that is consistent with the requirements of QCD. The previous marker in this field has been set by the work of Schechter and Meißner and collaborators [39] who have tackled the model framework of the $\pi\rho\omega$ soliton. The natural goal in the RPI work has been thus to extend this framework to that of a $\pi\rho\omega a_1(f_1)$ chiral soliton, the mesons listed being the ones properties of which are described by the chiral meson Lagrangian.

The result here is very satisfying [19, 23, 26, 30]: the diagonal nucleon properties and the transitional properties to the $\Delta(1232)$ state are better described in this approach. This includes the vector and the axial vector diagonal and off-diagonal form factors and other leading order baryon observables, calculated in the N_c^{-1} expansion (N_c , the number of colors) in the spirit of Witten [40].

Examples of diagonal and transitional form factors obtained in this approach are displayed in Fig 2.3.

An attempt to take into account the properties of the non-strange ϕ -decay, particularly trying to understand the OZI violation in a simple model, does not lead to any phenomenological improvement in the properties of the solitons; in fact, quite the contrary happens: the soliton properties get worse in comparison to the experiment!

We are going to continue our investigations on the description of the nucleon polarizabilities, understanding the OZI rule for the cause of the non-strange ϕ decay and its implications on the soliton properties, and the description of subleading effects.

2.4 Pi-zero photoproduction from protons with polarized photons in the Delta(1232) region

The Laser Electron Gamma Source (LEGS) has been used by Blanpied *et al.* [41] to study the reaction $p(\gamma, \pi^0)$ reaction, looking for the E2 transition amplitude in the nucleon to Delta transition, of great interest to the understanding of the structure of these baryons [1]. Our work on the pion photoproduction using effective Lagrangian approach has yielded, on the basis of the existing old data, the following multipole amplitudes,

$$M1 = 285 \pm 37, \quad E2 = -4.60 \pm 2.58, \quad (2.3)$$

Figure 2.3: Diagonal and transitional magnetic form factors of the nucleon. The isovector magnetic form factor $G_M^{I=1}$ is shown in (a) and the off-diagonal form factor $G_M^*/3G_D$, G_D being the dipole form, is in (b). The solid lines represent our best model estimates A and B, B being the one that does not attempt to reproduce the nucleon axial-vector coupling. The dashed line is the $\pi\rho\omega$ model prediction. From Zhang and Mukhopadhyay[19].

or, equivalently, the following helicity amplitudes

$$A_{1/2} = -135 \pm 16, \quad A_{3/2} = -251 \pm 33 \quad (2.4)$$

in units of $10^{-3} \text{GeV}^{-1/2}$. These imply an $E2/M1$ ratio [1]

$$E2/M1 = -(1.57 \pm 0.72)\%. \quad (2.5)$$

All realistic hadron models predict the ratio to be negative. The first lattice gauge calculations by Leinweber *et al.* [42] has just appeared in the literature, yielding a rather noisy number

$$E2/M1 = (+3 \pm 8)\%. \quad (2.6)$$

The main goal of the LEGS experiments [41] has been to determine this ratio.

We have analyzed the new LEGS data [41] and found [14, 29] that the new data suggest a value for the E_{1+} amplitude for the π^0 photoproduction substantially different from the old data:

$$E_{1+}^{\pi^0(\text{new})} = 2.1 E_{1+}^{\pi^0(\text{old})}, \quad (2.7)$$

if we keep other multipoles fixed. This, on the face of it, will suggest an upward revision of the $E2/M1$ ratio by about a factor of two from the value (5) obtained from the old data base. Also, the apparent differences between different theoretical approaches in the prediction of the ratio of cross-sections $d\sigma_{\parallel}/d\sigma_{\perp}$ can be traced to the role of the M_{1-} multipole in the $T = 1/2$ channel, which is sensitive to the u-channel Delta contribution.

Fig.2.4 illustrates these points graphically.

2.5 Compton scattering in the Delta(1232) region

M. Benmerrouche and NCM [8, 9] have examined the two-channel problem for the diagonal channels $\pi N \rightarrow \pi N$ and $\gamma N \rightarrow \gamma N$, exploring Grushin *et al.*'s

Figure 2.4: The BNL data for $d\sigma_{||}/d\sigma_{\perp}$, compared with three variations of the DMW model[1]. From Davidson and Mukhopadhyay[14]

[43] independent determinations of the real and the imaginary parts of the pion photoproduction multipoles. By using the unitarity relations, we have been able to extract the imaginary part of the magnetic Compton amplitude at the photon lab energy of $E_{\gamma} = 348 \text{ MeV}$ ($W = 1239 \text{ MeV}$):

$$\text{Im} f_{MM}^{1+} = 15.4 \pm 0.2, \quad (2.8)$$

in units of $10^{-4}/m_{\pi^+}$. We have made use of the VPI phase shifts [44] here. We have also tested the conclusions from an earlier work of Pfeil *et al.* [45] as to whether there is any problem of the existing data [46] with the unitary lower bound. The answer, illustrated in Fig.2.5, is that there is no problem with the unitarity. Likewise, the most recent data from the Saakachewan also pass this unitarity test without problem [47]. Also, using the optical theorem, we can determine the photohadron cross-section at $E_{\gamma} = 320 \text{ MeV}$ to be

$$\sigma_T = 523 \pm 22 \mu b, \quad (2.9)$$

Figure 2.5: The unitary lower bound for differential cross-section (with horizontal and vertical error bars) vs. Compton scattering experiments (vertical error bars). The angle of scattering is $\theta_{CM} = 90^\circ$, from Benmerrouche and Mukhopadhyay[9].

in fine agreement with the measured cross-sections [48]

$$\sigma_T = 527 \pm 8\mu b, \quad \sigma_T = 478 \pm 8\mu b \quad (2.10)$$

at $E_\gamma = 315$ and 340MeV . Finally, we have been able to pinpoint the region of sensitivity of the Compton observables to the famous $E2/M1$ ratio.

This work is beginning to have a strong impact on the analysis of the Compton scattering experimental results coming out photon factories at Brookhaven, Mainz and other labs. An entire session [49] of the PANIC-93 have been devoted to this research. Likewise, an invited session of the Asilomer meeting [50] of the Division of Nuclear Physics in the Fall of 1993 has been devoted to it.

2.6 Nucleon magnetic polarizability and the role of the Delta resonance

From the low energy Compton scattering experiments at Illinois [51] and Mainz [52], we have gained knowledge on the electric and magnetic polarizabilities of proton. Thus, the magnetic energy of a polarizable system is $E = \frac{1}{2}\beta\vec{B}^2$, where $\vec{B}$ is an

external magnetic field. In the transverse gauge, β for the proton can be written as

$$\beta = \beta_p - \beta_d \quad (2.11)$$

where β_d , the diamagnetic polarizability can be estimated using the experimental information on the size of the proton. From there, we get the measured value of β_p to be $(15.0 \pm 3.0) \times 10^{-4} fm^3$.

Prof. A. Nathan (Illinois), graduate student L. Zhang and NCM have asked the question to what extent the value of β_p , inferred from the experiment is coming from the virtual excitation of the Delta resonance [12]. We used the formula

$$\beta_p = 2\Sigma \frac{|\langle n | \mu_z | 0 \rangle|^2}{E_n - E_0}, \quad (2.12)$$

where μ_z is the magnetic dipole (M1) operator. Using the value of the M1 amplitude that the RPI group have extracted [1] from the pion photoproduction data, we get

$$\beta_p^\Delta = (12.6 \pm 2.7) \times 10^{-4} fm^3, \quad (2.13)$$

practically saturating the experimentally inferred value. The non-relativistic quark model gives a value [53]

$$\beta_p^\Delta(QM) \simeq 8.5 \times 10^{-4} fm^3, \quad (2.14)$$

considerably less than the experimental value. This is another signal for the spin crisis in the quark model. We are currently investigating the ability of the Skyrme model to obtain this quantity reliably.

2.7 Eta photo- and electroproduction

The Ph.D thesis of the graduate student M. Benmerrouche [20] and the first Letter [4] by Benmerrouche and NCM set out the methodology in the effective Lagrangian approach to analyze the *existing* eta photo- and electroproduction data

in the $S_{11}(1535)$ resonance region. The thesis work of Benmerrouche has been rewarded with the Huntington Prize of the RPI Physics Dept. in the year 1992.

The basic analytical framework is provided by the effective Lagrangian approach, which treats the leading contributions at the tree level. The nucleon Born amplitudes are well-known, and the $S_{11}(1535)$ excitation amplitude is extracted from a fit to the data.

Fig.2.6 shows the differential cross-section of the η photoproduction in the $S_{11}(1535)$ region. The dominance of this resonance is clear from our analysis, which yields the product [4]

$$\Gamma_\eta^{1/2} A_{1/2} = (26 \pm 3) \times 10^{-3} \quad (2.15)$$

where Γ_η is the $\eta - N$ -decay partial width of the S_{11} resonance and $A_{1/2}$ is the photoexcitation amplitude for the proton to S_{11} excitation. Using the literature value of $\Gamma_\eta = 75 \text{ MeV}$ [5], we get

$$A_{1/2} = (95 \pm 11) \times 10^{-3} \text{ GeV}^{-1/2}, \quad (2.16)$$

in good agreement with the value known from the pion photoproduction experiments [35]

$$A_{1/2} = (73 \pm 14) \times 10^{-3} \text{ GeV}^{-1/2}. \quad (2.17)$$

Theoretical predictions of this helicity amplitude (16,17) range from 54 to 162 in units of $10^{-3} \text{ GeV}^{-1/2}$ [54]. This is not satisfactory, given the accuracy we have reached in the extraction of the amplitude from the data. New theoretical directions are needed in examining the quark model framework to reduce the theoretical uncertainty. This is part of our future research plans, discussed in the Section 3. We are also continuing the examination of the data on the electroproduction of eta mesons. Research associate Dr. J. Zhang is collaborating with NCM on this project, as is Dr. M. Benmerrouche (SAL, Canada).

Figure 2.6: The differential cross-section for the η photoproduction as a function of the laboratory photon energy at cm angle 50° , with a composite of old and new data. The dotted curve is the theoretical prediction for background. Thus, the $N(1535)$ resonance dominance is obvious. From Benmerrouche and Mukhopadhyay[4].

From the existing data on the eta photoproduction from protons, we have extracted the following quantity for the $\gamma p \rightarrow S_{11}(1535) \rightarrow \eta p$ process sequence:

$$a \equiv (\chi \Gamma_\eta)^{1/2} A_{1/2} / \Gamma_T = (0.22 \pm 0.02) \times 10^{-3} \text{MeV}^{-1}, \quad (2.18)$$

where χ is the kinematic factor Mk/qM_R , M , M_R being the nucleon and the resonance mass respectively, k and q being the photon and eta meson cm momenta for $W = M_R$. This quantity awaits an interpretation by the hadron models.

2.8 Perturbative QCD (pQCD)

One of the important issues in the resonance structure functions is the understanding of the Bloom-Gilman duality [55] between the scaling and the resonance region of the inelastic structure functions $\nu W_2(\omega')$, where ν and ω are the appropriate kinematic variables. In the current grant period, Carl E. Carlson (college of William and Mary) and NCM have focussed on two related issues. First is the possible perturbative QCD signature of hybrid hadrons [7] and second is the investigation

Figure 2.7: Examples of lowest order Feynman diagrams for electroproduction of (a) a three-quark baryon, (b) a pure hybrid (q^3G) baryon from a nucleon, (c) a pure hybrid baryon from the q^3G Fock component of a nucleon.

of the duality in the $\Delta(1232)$ region [13, 27, 31]. A hybrid hadron is defined to be one which has significant Fock components involving valence gluons. For a long time, there has been a controversy as to whether the Roper resonance ($N(1440)$) is a hybrid [56]. Carlson and NCM have investigated [7] the pQCD behavior of the transverse and longitudinal structure functions for exciting hybrids, as contrasted with “normal” hadrons. They have found that the transverse electroproduction of hybrid baryons is small, relative to ordinary ones, but their *longitudinal* electroproduction has size and scaling behavior like normal baryons. Thus, an experimental test of a hybrid is to contrast this transverse versus longitudinal behavior. Such a test could settle if the Roper resonance is a hybrid.

Fig.2.7 gives the Feynman diagrams for electroproduction of normal baryons vs. hybrids. These diagrams are helpful to distinguish the leading order scaling behaviors of the inelastic structure functions.

The other pQCD investigation, still continuing, concerns the duality in the inelastic structure function and the disappearing Delta resonance. Carlson and

NCM [13, 27, 31] have examined the structure function $\nu\omega_2$, averaged over suitable range of the Bjorken variable x . One part of the Bloom-Gilman duality is that the resonances generally fall at roughly the same rate with increasing Q^2 , as the background under them. The $\Delta(1232)$ resonance has been found to be an exception: it falls much faster relative to the background. The question arises as to whether the $\Delta(1232)$ resonance also violates the second aspect of the duality, viz, the smooth scaling curves seen at high Q^2 for a given x is an accurate average over the resonance bumps seen at the same x , but at lower Q^2 .

Carlson and NCM find [13] that *the second aspect of the duality does not fail, even in the $\Delta(1232)$ region*. This is demonstrated in the Fig.2.8, where the Nachtmann variable ξ is used as an integration variable in the calculation of the following quantities

$$I_i = \int_{\Delta\xi} d\xi F_2(\xi, Q^2), \quad (2.19)$$

and

$$S_i = \int_{\Delta\xi} d\xi F_2^{scaling}(\xi), \quad (2.20)$$

where $\Delta\xi$ corresponds to a byte of ξ for the region of the cm energy W covering the given resonance region, i . We compare the ratio

$$R_i = I_i/S_i \quad (2.21)$$

and plot it in Fig.2.8. The scaling functions for $F_2 = \nu W_2$ are taken from phenomenological investigations [57].

2.9 Nuclear muon capture

The low-energy muon factories continue to push for new frontiers [15, 16, 28] to test the standard model (SM) and find possible new vistas for effects beyond the SM. Thus, the low-energy muon science (LEMS) series conferences, held once every two years approximately, continue to bring eager experts on this subject from

Figure 2.8: A plot of the ratio involving integrals of νW_2 in various resonance regions, using the Nachtmann variable ξ . The saturation of the ratio R is an indication of the pQCD scaling.

around the world. The most recent one in this series, LEMS-93, took place in Santa Fe, NM, under the auspices of the Los Alamos Meson Physics Facility (LAMPF) in the Spring of 1993. NCM presented there an update on the research frontiers of nuclear muon capture [15]. New experiments, under way at TRIUMF, Canada, and PSI, Switzerland, were the primary motivating forces of this conference. Among the topics discussed were the use of polarized targets in the nuclear muon capture, a subject that NCM and coworkers at SIN (now PSI) developed in the late seventies and early eighties [58].

At the PANIC-93 in Perugia, Italy, NCM was invited to present his contribution [16] "Test of Standard Model in Nuclear Muon Capture". In this talk, he discussed the reaction

$${}^6\text{Li} + \mu^-(1s) \rightarrow \nu_\mu + {}^6\text{He}_{g.s.} \quad (2.22)$$

superallowed in the sense of Wigner's supermultiplet or $SU(4)$ scheme. The Gamow-Teller operator dominance makes the above reaction an ideal tool to study the possible renormalization [59] of the axial-vector coupling constant, g_A , in nuclei. The

Ph.D thesis of Doyle [60], under the auspices of this program, has allowed us to obtain the relevant nuclear amplitudes directly from the electromagnetic observables. Using the Doyle amplitudes, NCM has obtained an estimate of the rate of the above reaction to be

$$W^{IA} = 1.23 \times 10^3 s^{-1} \quad (2.23)$$

in the impulse approximation (IA), using the $\mu - e$ universality for the axial-vector coupling. Correcting for the meson exchange effect(MEX), he gets

$$W^{IA+MEX} = 1.33 \times 10^3 s^{-1}. \quad (2.24)$$

This is in good agreement with Delorme's estimate of the above rate in the so-called Elementary-Particle Approach, $(1.38 \pm 0.16) \times 10^3 s^{-1}$, but in disagreement with an old experimental result [63]

$$W^{exp} = (1.6_{-0.12}^{+0.33}) \times 10^3 s^{-1}. \quad (2.25)$$

In view of the fundamental nature of this reaction, a new experimental investigation is urgently needed, and a proposal from the Louvain group, headed by J. Deutsch, is expected at PSI, Switzerland, in the near future[64].

3. LITERATURE CITED

- [1] R.M. Davidson, N.C. Mukhopadhyay and R.S. Wittman, Phys. Rev. **D43**, 71 (1991).
- [2] F. Iachello, N.C. Mukhopadhyay and L. Zhang, Phys. Lett. **B256**, 295 (1991).
- [3] F. Iachello, N.C. Mukhopadhyay and L. Zhang, Phys. Rev. **D44**, 898 (1991).
- [4] M. Benmerrouche and N.C. Mukhopadhyay, Phys. Rev. Lett. **67**, 1070 (1991).
- [5] M. Benmerrouche and N.C. Mukhopadhyay, "Eta Photoproduction near threshold", Invited Paper, Proc. Int. Conf. on Particle Production near Threshold, Indiana Univ., Am. Inst. of Phys. (New York, 1991).
- [6] N. C. Mukhopadhyay and L. Zhang, Phys. Rev. **D44**, 2085 (1991).
- [7] C.E. Carlson and N.C. Mukhopadhyay, Phys. Rev. Lett. **67**, 3745 (1991).
- [8] N.C. Mukhopadhyay and M. Benmerrouche, "Compton Scattering and the Delta Excitation", Invited Paper, Conf. on Medium and High Energy Nuclear Physics (M. K. Pal *et al.*, Editors), World Scientific, Singapore (1992) p.159.
- [9] M. Benmerrouche and N.C. Mukhopadhyay, Phys. Rev. **D46**, 101 (1992).
- [10] N.C. Mukhopadhyay, "Recent Progress in Baryon Spectroscopy", Invited Papers, Proc. 1992 CEBAF Summer Workshop (F. Gross and R. Holt, Editors), Am. Inst. Phys. New York, 1992.
- [11] N. C. Mukhopadhyay and L. Zhang, "Dynamic Symmetry in Hadron Physics: A Mesonic Puzzle for the $U(4) \supset SO(4)$ chain", Invited Paper, in *Symmetries in Science VI: From the Rotation Group to Quantum Algebras*, (B. Cruber, Editor), Plenum, New York, 1992.
- [12] N. C. Mukhopadhyay, A. M. Nathan and L. Zhang, Phys. Rev. **D47**, R7 (1993).
- [13] C.E. Carlson and N.C. Mukhopadhyay, Phys. Rev. **D47**, R1737 (1993).
- [14] R.M. Davidson and N.C. Mukhopadhyay, Phys. Rev. Lett. **70**, 3834 (1993).
- [15] N.C. Mukhopadhyay, "Nuclear Muon Capture", Invited Paper, Proc. Conf. on Low Energy Muon Science 1993 Santa Fe, NM, (M. Leon, Editor), Phil. Mag., in press.

- [16] N.C. Mukhopadhyay, "Test of Standard Model in Nuclear Muon Capture", Invited Contribution, Proc. Conf. on Particles and Nuclei (PANIC-93), in press.
- [17] C.E. Carlson and N.C. Mukhopadhyay, "Logarithmic corrections to baryon form factors", Invited Paper, Elba Workshop on Perturbative Phenomena, to be published in the proceedings.
- [18] N. C. Mukhopadhyay and M. Benmerrouche, "Complementarity between electromagnetic and hadronic production of eta mesons", Invited Paper, Conf. on Future Directions in Particle and Nuclear Physics at Multi-GeV Hadron Beam Facilities, Brookhaven National Lab. Report #BNL-52389 (1993), p.498.
- [19] L. Zhang and N. C. Mukhopadhyay, "Baryon physics from mesons: properties of the nucleon and Delta(1232) in the $\pi\rho\omega a_1(f_1)$ chiral soliton model", submitted to Phys. Lett. **B**.
- [20] M. Benmerrouche, "Photo- and electroproduction of eta meson in the $S_{11}(1535)$ region", Ph.D. Thesis, RPI, June 1992.
- [21] L. Zhang, "Baryon Physics from mesons in the realistic chiral soliton model", Ph.D. Thesis, RPI, June 1993.
- [22] M. Benmerrouche and N. C. Mukhopadhyay, Bull. Am. Phys. Soc. **36**, 1231 (1991).
- [23] L. Zhang and N. C. Mukhopadhyay, Bull. Am. Phys. Soc. **36**, 1247 (1991).
- [24] M. Benmerrouche and N. C. Mukhopadhyay, "Relationship between pion photoproduction and Compton scattering in the $\Delta(1232)$ region", contributed paper, **Baryon-92**, #26.
- [25] M. Benmerrouche and N. C. Mukhopadhyay, "Electromagnetic transition form factor of the $\gamma p \rightarrow S_{11}(1535)$ from eta electroproduction", contributed paper, **Baryon-92**, #12.
- [26] N. C. Mukhopadhyay and L. Zhang, "Electroweak nucleon to Delta transition properties in the realistic Skyrme model", contributed paper, **Baryon-92**, #72.
- [27] C.E. Carlson and N.C. Mukhopadhyay, "Bloom-Gilman γ disappearing Delta resonance", contributed paper, **Baryon-92**, #143.
- [28] P. Herczeg and N. C. Mukhopadhyay, "Theory of T-violation in muon capture process", contributed paper, Intl. Conf. on Weak and Electromagnetic Interaction in Nuclei (WEIN-92), Dubna, Russia 1992.

- [29] R. Davidson and N. C. Mukhopadhyay, Bull. Ann. Phys. Soc. **38**, 1017 (1993).
- [30] N. C. Mukhopadhyay and L. Zhang, Bull. Ann. Phys. Soc. **38**, 1016 (1993).
- [31] C. E. Carlson and N. C. Mukhopadhyay, "Leading-log effects in the resonance electroweak form factors", Contributed paper #1.8 to the Int. Conf. on Particles and Nuclei **PANIC-93**, Perugia, Italy.
- [32] M. Benmerrouche and N. C. Mukhopadhyay, "The electroproduction of eta mesons and the transition form factor of the $S_{11}(1535)$ excitation", Contributed paper #3.23, **PANIC-93**.
- [33] R. M. Davidson and N. C. Mukhopadhyay, "The $p(\vec{\gamma}, \pi^0)$ reaction in the $\Delta(1232)$ region", Contributed paper #9.32, **PANIC-93**.
- [34] N. C. Mukhopadhyay and L. Zhang, "Neutrino excitation of the Delta(1232) resonance and electroweak form factor", Contributed paper #16.7, **PANIC-93**.
- [35] Particle Data Group, K. Hikasa *et al.*, Phys. Rev. **D45**, June (1992).
- [36] S. Godfrey and N. Isgur, Phys. Rev. **D32**, 189 (1985).
- [37] J. Weinstein and N. Isgur, Phys. Rev. **D41**, 2236 (1990).
- [38] G. 't Hooft, Nucl. Phys. **B72**, 461 (1974); **B75**, 461 (1974).
- [39] P. Jain *et al.*, Phys. Rev. Phys. Rev. **D37**, 3253 (1988); U.-G. Meissner *et al.*, Phys. Rev. **D39**, 1956 (1989); (E)**D40**, 362 (1989).
- [40] E. Witten, Nucl. Phys. **B160**, 57 (1979); **B223**, 422, 433 (1983).
- [41] G. Blanpied *et al.*, Phys. Rev. Lett. **69**, 1880 (1992); A. M. Sandorfi and M. Khandaker, *ibid* **70**, 9835 (1993), and priv. comm. (1993).
- [42] D. B. Leinweber *et al.*, Phys. Rev. **D48**, 2230 (1993).
- [43] V. F. Grushin *et al.*, Sov. J. Nucl. Phys. **38**, 881 (1983).
- [44] R. A. Arndt *et al.*, Phys. Rev. **D32**, 1085 (1985), and latest phase shifts generated by the SAID program (priv. comm.).
- [45] W. Pfeil *et al.*, Nucl. Phys. **B73**, 166 (1974).
- [46] H. Genzel *et al.*, Z. Phys. **A279**, 399 (1976).
- [47] A. M. Nathan and D. M. Skopik, priv. comm. (1992).
- [48] T. A. Armstrong *et al.*, Phys. Rev. **D5**, 1640 (1972).

- [49] See, for example, Invited talks by A. M. Sandorff, B. Krusche, and M. Sanzone in PANIC-93 in contributed sessions.
- [50] See, for example, Invited talks by M. Benmerrouche and A. M. Nathan.
- [51] F. J. Federspiel *et al.*, Phys. Rev. Lett. **67**, 1511 (1991).
- [52] A. Zieger *et al.*, Phys. Lett. **B278**, 34 (1992).
- [53] We have used here the computation for $M1$ by N. Isgur *et al.*, Phys. Rev. **D25**, 2394 (1982).
- [54] R. P. Feynman *et al.*, Phys. Rev. **D3**, 2706 (1971); R. Koniuk and N. Isgur, *ibid.* **21**, 1868 (1980); F. E. Close and Z. Li, *ibid.* **42**, 2194, 2207 (1990); M. Warns *et al.* *ibid.* **42**, 2215 (1990).
- [55] E. D. Bloom and F. J. Gilman, Phys. Rev. Lett. **25**, 1140 (1970); A. de Rújula *et al.*, Ann. Phys. (N.Y.) **103**, 315 (1977); C. E. Carlson and N. C. Mukhopadhyay, Phys. Rev. **D41**, R2343 (1990).
- [56] e.g., T. Barnes and F. Close, Phys. Lett. **B116**, 365 (1982); Z. Li, Phys. Rev. **D44**, 2841 (1991).
- [57] e.g., C. E. Carlson and T. J. Havens, Phys. Rev. Lett. **91**, 261 (1983); E. J. Eichten *et al.*, Phys. Rev. **D45**, 2269 (1992).
- [58] L. Hambro and N. C. Mukhopadhyay, Lett. Nuovo Cim. **14**, 53 (1975); Phys. Lett. **B64**, 143 (1977); A. Hintermann and N. C. Mukhopadhyay, Phys. Rev. **A32**, 1985 (1985). See experimental tests in R. Kadano *et al.*, Phys. Rev. Lett. **57**, 1847 (1986); N. S. Newbury *et al.*, *ibid.* **67**, 3219 (1991); A. S. Barton *et al.*, *ibid.* **70**, 758 (1993).
- [59] N. C. Mukhopadhyay, H. Toki and W. Weise, Phys. Lett. **B84**, 35 (1979); E. G. Adelberger *et al.*, Phys. Rev. Lett. **67**, 3658 (1991); M. K. Banerjee, Phys. Rev. **C45**, 1358 (1992).
- [60] B. Doyle, Ph.D. Thesis in this program, RPI (1989).
- [61] B. Doyle, B. Goulard and N. C. Mukhopadhyay, Phys. Rev. **C42**, 1361 (1990).
- [62] J. Delorme, Ph.D. Thesis, Lyon (1970), unpublished.
- [63] J.P. Deutsch, *et al.*, Phys. Lett. **B26**, 315 (1968).
- [64] J.P. Deutsch, priv. comm. (1993).

4. PAPERS AND OTHER SCIENTIFIC COMMUNICATIONS IN THE CURRENT PROGRAM PERIOD

1. Journal and major research articles in proceedings of national and international conferences: *nineteen articles*. See Refs. [1-19].
2. Conference abstracts and short contributions: *thirteen*. See Refs. [22-34].
3. Book, Lab reports: seven.
See Refs. [5], [8], [10-11], [16-18].
4. M.S. and Ph.D. Dissertations by students: three (see Section 5).

5. M.S. AND Ph.D. DISSERTATIONS COMPLETED IN THE CURRENT PROGRAM PERIOD

1. M. Benmerrouche¹ : Ph.D. Thesis defended, June 1992.
Dissertation: "Photo- and Electroproduction of η Mesons in the $S_{11}(1535)$ Region."
2. L. Zhang^{1,2} : Ph.D. Thesis defended, June 1993.
Dissertation: "Baryon Physics from Mesons in the Realistic Chiral Soliton Model."
3. R. Schelp: M.S. Thesis defense, Dec 1993.
Thesis: "Axions".

¹Hillard B. Huntington Award from RPI for graduate research excellence.

²Submitted to the Division of Nuclear Physics, Am. Phys. Soc. for nationwide competition in excellence.

6. STUDENTS ASSOCIATED WITH THE CURRENT PROGRAM

1. M. Benmerrouche^{1,2}, Ph.D degree awarded in 1992.
2. L. Zhang^{1,2}, Ph.D. degree awarded in 1993.
3. K. C. Yeong^{1,2}, graduate student, associated with the program between 1991 and 1992.
4. E. Ulloa², graduate student, associated with the program in the academic year 1992 - 93.
5. R. Schelp, graduate student, associated with the program in the academic years 1991 - 93. M.S. degree, Dec. 1993.
6. Jun Liu², graduate student, associated with the program, summer 1993-present.

¹Research assistant supported by the DOE Grant.

²Summer partial support from the DOE Grant.

**7. EXTERNAL INSTITUTIONS HOSTING THE PRINCIPAL
INVESTIGATOR FOR SEMINARS, COLLOQUIA, AND OTHER
RESEARCH VISITS**

1991

1. Bhabha Atomic Research Center, Calcutta, India.
2. Tata Inst. of Fundamental Research, Bombay, India.
3. Saurashtra University, Rajkot, India.
4. Institute for Nuclear Theory, Seattle, WA.
Programs IV and V.
5. Theory Group, TRIUMF, Vancouver, Canada
6. Physics Colloquium, SUNY, Albany, NY.
7. Physics Colloquium, Union College, Schenectady, NY.

1992

1. University of Kentucky, Lexington, KY.
2. University of Massachusetts, Amherst, MA.
3. Institute for Nuclear Theory, Seattle, WA.
4. Hadron Physics Workshop, Brookhaven, NY.
5. CEBAF Summer School, Newport News, VA.
6. University of Bonn, Germany.
7. J. Gutenberg Univ., Mainz, Germany.
8. NIKHEF-K, Holland.

9. Cyclotron Lab., Catholic Univ., Louvain-le-Neuve, Belgium.
10. Wroclaw Univ., Poland.
11. Physics Colloquium, University of Ohio, Athens, Ohio.
12. Virginia Polytech. Inst., Blacksburg, VA.
13. Univ. of Pittsburgh, Pittsburgh, PA.

1993

1. University of Pennsylvania, Philadelphia, PA.
2. Future Directions in Particles / Nuclei, Brookhaven, NY.
3. Low Energy Muon Science Conf., Santa Fe, NM.
4. Variable Energy Cyclotron Project, Calcutta, India.
5. Workshop on Exclusive Reactions, Elba, Italy.
6. Inst. Conf. on Particle and Nuclei, Perugia, Italy.
7. CEBAF Retreat, Snowshoe Resort, VA.
8. Theoretical Physics Seminar, Paul Scherrer Inst., Villigen, Switzerland.
9. Particle Physics Seminar, Univ. of Connecticut, Storrs, CT.
10. Indiana Univ. (visit as a member of the Program Advisory Comm., IUCF)

8. EXTERNAL PRESENTATIONS BY STUDENTS DURING THE PROGRAM PERIOD

1991

1. M. Benmerrouche, "Effective Lagrangian Approach", Saskatchewan Acc. Lab., Canada
2. M. Benmerrouche, "Eta Photoproduction Near Threshold and Beyond", Am. Phys. Soc. Spr. Meeting, Washington D.C.
3. L. Zhang, "Electroweak $N \rightarrow \Delta$ Transition in the Skyrme Model", Am. Phys. Soc. Spr. Meeting, Washington D.C.

1992

1. M. Benmerrouche, "Electromagnetic Transition Form Factor of the $\gamma p \rightarrow S_{11}(1535)$ Process from Eta Eletroproduction", Baryon 1992 Conf., Yale University, New Haven, CT.
2. L. Zhang, "Electroweak Nucleon to Delta Transition Properties in a Realistic Skyrme Model", Baryon 1992 Conf., Yale University, New Haven, CT.

1993

1. L. Zhang, "Baryon Physics from Mesons: a Realistic Skyrme Model", Ann. Phys. Soc. Spr. Meeting, Washington, D.C.
2. L. Zhang, "Neutrino excitation of the $\Delta(1232)$ resonance and eletroweak form factor",
Contributed paper #16.7, **PANIC-93**.

9. PERSONNEL

Principal Investigator:

Dr. Nimai C. Mukhopadhyay, Professor of Physics, Rensselaer Polytechnic Institute.

Other Personnel:

Postdoctoral associates:

1. Dr. J. Zhang, Research Associate¹.
2. Dr. L. Zhang, Research Associate¹.

Graduate Students:

1. M. Benmerrouche^{2,3}, associated with the program through Aug. 92.
2. L. Zhang^{2,3}, Ph.D., Aug. 93.
3. K. C. Yeong^{2,3}, associated with the program through Aug. 92.
4. E. Ulloa³, associated with the program through Aug. 93.
5. R. Schelp, associated with the program through Dec. 93.
6. Jun Liu³.

[In addition, there was one undergraduate associated with this program in the current program period.]

¹Part-time appointment from Fall, 1993

²Research assistant supported by the DOE Grant.

³Summer partial support from the DOE Grant.

10. CURRENT SUPPORT

CURRENT AND PENDING SUPPORT FOR: NIMAI C. MUKHOPADHYAY

CURRENT SUPPORT:

SOURCE: U.S. DEPARTMENT OF ENERGY
AWARD NO: DE-FG02-88ER40448
TITLE: ELECTROWEAK AND OTHER INTERACTIONS IN MEDIUM-ENERGY
NUCLEAR PHYSICS
BUDGET AMOUNT: \$80,000
BUDGET PERIOD: 04/01/93 - 03/31/94
PROJECT PERIOD: 04/01/91 - 03/31/94
EFFORT: [AS PRINCIPAL INV] ACADEMIC: NO CHARGE SUMMER: 8 WKS @ 100%
ASSOCIATES: NONE

SOURCE: RESEARCH CORPORATION
AWARD NO: 9917
TITLE: THEORETICAL ASPECTS OF ELECTROWEAK AND OTHER
INTERACTIONS IN MEDIUM-ENERGY NUCLEAR PHYSICS
BUDGET AMOUNT: \$4,200
BUDGET PERIOD: 11/01/82 - 01/01/99
PROJECT PERIOD: 11/01/82 - 01/01/99
EFFORT: [AS PRINCIPAL INV] ACADEMIC: 0% SUMMER: 0%
ASSOCIATES: NONE

PENDING PROPOSALS: NONE

NOTE: AMOUNTS SHOWN REPRESENT SPONSOR FUNDING ONLY
AND DO NOT INCLUDE COST SHARING.

11. BIOGRAPHICAL INFORMATION

NIMAI C. MUKHOPADHYAY

*Professor of Physics
School of Science
Physics Department*

Rensselaer Polytechnic Institute, Troy, NY 12180-3590

Phone: 518-276-6663, Fax: 518-276-6680, E-Mail: nimai@nimai.phys.rpi.edu

ACADEMIC DEGREES AND PREDOCTORAL RESEARCH EXPERIENCE:

B.Sc. University of Calcutta, India - 1963 (Physics)

1st Class Honors with distinction in subsidiaries

M.Sc. University of Calcutta, India - 1965 (Physics) 1st class

S.M. University of Chicago - 1970 (Physics)

Ph.D. University of Chicago - 1972 (Nuclear Theory)

1965-June 1966: Graduate Research at the Saha Institute of Nuclear Physics, India, at the Van de Graaf group

July 1966-Aug. 1968: Graduate Work and Research in Nuclear Physics, Tata Institute of Fundamental Research, Colabo, Bombay 5, India

Oct. 1968-July 1972: Research in Theoretical Nuclear Physics, Argonne National Laboratory, Argonne, IL

POSTDOCTORAL PROFESSIONAL RESEARCH/TEACHING EXPERIENCE:

1972-74: Fellow, Center for Theoretical Physics, University of Maryland

1974-75: Visiting Scientist, Theory Division, CERN, Geneva, Switzerland

1976-81: Physicist, Theory Group, Swiss Institute for Nuclear Research (SIN, now PSI), Switzerland;
1980-81, concurrent appointments with Swiss Federal Institute for Reactor Research (EIR)

1981-86: Associate Professor, Rensselaer Polytechnic Institute

1986-present: Professor, Rensselaer Polytechnic Institute

1975: Professor Invité, Université de Louvain, Belgium

1976: Visiting Lecturer, Scuola Ettore Majorana, Erice, Italy

1977: Visiting Scientist, Institute for Nuclear Research (IKO), Amsterdam, The Netherlands

1978: Visiting Professor, Joint Institute for Nuclear Research, Dubna, USSR

1978: Visiting Professor, Physical Research Laboratory, Ahmedabad, India

1979-80: Visiting Professor, Technion, Haifa, Israel

1981: Visiting Lecturer, U. of Fribourg, Switzerland

1985-present: Scientific Collaborator, Los Alamos National Laboratory

1986: Visiting Scientist, CEBAF

1987, 89, 93: Visiting Scientist, Paul Scherrer Institute, Villigen, Switzerland

1988-89: Visiting Professor, Institute of Nuclear and Particly Physics, University of Virginia

1989, 90: Visiting Scientist, T-5 Group, Los Alamos National Laboratory

1991, 92: Visiting Fellow, Institute for Nuclear Theory, University of Washington

1992 Summer: Visiting Professor, Inst. für Kernphysik, J. Gutenberg Univ., Mainz, Germany

PROFESSIONAL SOCIETIES:

Sigma Xi

American Physical Society: Fellow (1992)

RESEARCH INTERESTS:

Electroweak structure of hadrons, photo- and elctroproduction of mesions, search for effects beyond the standard model, theoretical interface between particle and nuclear physics.

PUBLICATIONS:

1. "Particle Parameters for Conversion Electrons in ^{152}Sm , ^{152}Gd and ^{160}Dy ", Nucl. Phys. A127, 661 (1969) (with Y.K. Agaral and C.V.K. Baba).
2. "Transition Rate for Ground State to Ground State in the Capture of Negative Muons by ^{12}C ", Phys. Rev. Letts. 27, 1823 (1971) (with M.H. MacFarlane).
3. "On the Impulse Approximation Treatment of Allowed Muon Capture in ^8Li ", Phys. Lett. 40B, 157 (1972).
4. "Nuclear Structure Effects in Allowed Muon Capture in ^{14}N ", Phys. Lett. 44B, 33(1973).
5. "Interpretation of Weak and Electromagnetic Processes in ^{12}C in the Particle-Hole Model", Phys. Rev. C7, 1720 (1973).
6. "Roles of Weak Hadron Form Factors in the Allowed Muon Capture Processes in Light Nuclei", Lett. Nuovo Cimento 7, 460 (1973).
7. "Giant Magnetic Dipole Analogue Excitations by the Allowed Muon Capture in lp shell Nuclei", Phys. Letts. 45B, 309 (1973).
8. "Coulomb Corrections to the Induced Pseudoscalar Term in Nuclear Muon Capture", Phys. Letts. 47B, 115 (1973) (with L.P. Fulcher).
9. "Relativistic Corrections to Nuclear Matrix Elements in Mirror Decays", Phys. Letts 47B, 415 (1973).
10. "Mean Excitation Energies in the Nuclear Muon Capture", Phys. Rev. C10, 379 (1974) (with F. Cannata).
11. "The Persistence of Supermultiplet Selection Rules in Nuclear Weak and Electromagnetic Transitions", Phys. Letts. 51B, 225 (1974) (with F. Cannata).
12. "Remarks on the Nuon-Nucleon Interaction", in Report on the IKO Pion-Muon Study Week, eds. R. van Dantzig et al., Vol. I, Amsterdam (1974) pp. 49-60.
13. "Low Energy Muon Physics - Long-term Prospects", ibid. Vol. II, (1975) pp. 315-320.
14. "Coulomb Renormalization of the Nuclear Pion Propagator", Nuovo Cimento 28A, 487 (1975) (with L.P. Fulcher).
15. "An Open-Shell Finite Fermi System Approach to the Structure of $A=12$ Nuclei", Phys. Letts. 56B, 13 (1975).
16. "Effects of Nonstatistical Hyperfine Populations in Muon Capture by Polarized Nuclei", Lett. Nuovo Cimento 14, 53 (1975) (with L. Hambro).
17. "Studies of the Muon-Nucleon Weak Interaction by Nuclear Muon Capture", Invited paper at the Zuoz Conference on the Intermediate Energy Physics, in the Proceedings of the Conference, ed. M. Locher, SIN, Vol. I, (1976) pp. 25-39.

18. "Nuclear Muon Capture", Phys. Reports 30C, 1 (1977).
19. "Repolarization of Muons in Muonic Atoms with Polarized Nuclei", Phys. Letts., 68B, 143 (1977).
20. "An Improved Impulse Approximation Treatment of the Allowed Weak and Analogue Electromagnetic Transitions in ^{12}C ", Nucl. Phys. A296, 461 (1978) (with J. Martorell).
21. "Particle and Nuclear Physics with Muon Capture", Invited paper at the Erice International School of Mesonic Interface between Particles and Nuclei, in Progress in Particle and Nuclear Physics, ed. D.H. Wilkinson, Pergamon Press, Vol. I (1978) pp. 253-278.
22. "Theory of Nuclear Fission by Stopped Pions", Nucl. Phys. A319, 448 (1979) (with J. Hadermann and K. Junker).
23. "Atomic Repolarization of Muons by Polarized Nuclei of Arbitrary Spin", Phys. Lett. 86B, 137 (1979).
24. "Phenomenology of Inclusive Fast-Nucleon Spectra in Weak, Electromagnetic and Strong Nuclear Processes", Phys. Rev. Lett. 42, 162 (1979) (with P. Singer and R.D. Amado).
25. "Pion Photoproduction and the "Anomalous" Transition $^{14}\text{N}_{\text{g.s.}} \longleftrightarrow ^{14}\text{C}_{\text{g.s.}}$ ", Nucl. Phys. A338, 514 (1980) (with A. Figureau).
26. "Muon Physics with Polarized Nuclear Targets", Invited paper at the IKO Pion/Muon School, SIN preprint PR-79-002, March (1979), published in the proceedings of the school, J. Bailey, ed., IKO (1980).
27. "Theory of Intrinsic State Density Calculations for Intermediate and High Energies", Invited paper presented at IAEA Conference (Julich, May 1980) IAEA-SM-241/c.10 (1980) (with K. Junker and J. Hadermann).
28. "Spin-Isospin Polarizability of Nuclear Matter and Renormalization of Weak Currents", Phys. Letts. 84B, 35 (1980) (with H. Toki and W. Weise).
29. "Final-State Interaction in Quasi-Elastic Electron Scattering", Phys. Rev. C22, 1680 (1980) (with Y. Horikawa and F. Lenz).
30. "Nuclear Muon Capture", Invited paper at the 8th Intl. Conf. on High Energy Physics and Nuclear Structure, Vancouver (August 1979), Nucl. Phys. A335, 111 (1980).
31. "Study of Nuclear Response Tail by High Threshold Reactions in Muon Capture", Phys. Rev. Letts. 44, 1653 (1980) (with J. Hadermann and P. Singer).
32. "Physics with Muons Stopped in Polarized Nuclear Targets", Invited paper, 5th Intl. Symposium on Polarization Phenomena in Nuclear Physics, Santa Fe (1980) SIN Preprint PR-80-014) published in the Proceedings on FISP, Am. Inst. Phys., New York (1981) (with A. Hintermann).
33. "Polarization Dynamics for Spin 1/2 - Spin I Systems with the Breit-Rabi Interaction", Phys. Lett. 82A, 327 (1981) (with A. Hintermann).

34. "Axions: to be or not to be?", Phys. Lett. 106B, 91 (1981) (with A. Barroso).
35. "Nuclear Axion Decay", Phys. Rev. C24, 2382 (1981) (with A. Barroso).
36. "Muon Repolarization", Hyperfine Int. 8, 827 (1981) (with A. Hintermann).
37. "On the Fundamental Continuity Equation of Transport in Fractured Media and Retention Factors for a System of Joints", Nucl. Sci. Eng. 80, 26 (1982) (with J. Hadermann).
38. "Inclusive Neutron Spectra from the Absorption of Stopped Negative Pions in Heavy Nuclei", Nucl. Phys. A392, 368 (1983) (with H.P. Isaak, R. Engfer, H.K. Walter, et al.).
39. "On the Theory of Transport of Fluids in Fractured Media for the Safety Analysis of a Nuclear Waste Repository", Nucl. Sci. Eng. 85, 233 (1983).
40. "Continuum RPA with Finite Range Interaction", Nuova Cimento 76, 220 (1983) (with A. Dellafiore and F. Lenz).
41. "Bounds on Light Scalar Particles from Nuclear Decays", Phys. Rev. D29, 565 (1984) (with P.F.A. Goudsmit and A. Barroso).
42. "Watson's Theorems and Resonant Pion Photoproduction Amplitude in the Delta Channel", Phys. Lett. 142B, 336 (1984) (with R. Wittman and R. Davidson).
43. "Muonic Atoms with Vacant Electron Shells", Phys. Rev. Lett. 54, 2057 (1985) (with P. Bacher, et al.).
44. "Polarization Dynamics for the Muon-Nuclear Breit-Rabi Interaction", Inst. for Intermediate Energy Physics, ETH-Zurich, ETHZ-IMP-P84/6, Phys. Rev. A32 (1985) (with A. Hintermann).
45. "Are Hadrons Deformed? An Examination of the E2/M1 Amplitude Ratio in the $N \leftarrow \rightarrow \Delta$ Transition" in Hadronic Probes and Nuclear Interactions (edited by J.R. Confert et al.), Am. Inst. of Phys., New York (1985) (with R. Davidson and R. Wittman).
46. "Theory of Photo- and Electroproduction of Mesons: Problems and Prospects", Invited Paper, CEBAF Summer Study Proceedings, F. Gross, ed. (1985) (with R. Davidson, R. Wittman, M. Bourdeau and S. Nergiz).
47. "Are Axions Visible?", Phys. Rev. Lett. 56, 206 (1986) (with A. Zehnder).
48. "Ratio of Electric Quadrupole to Magnetic Dipole Amplitudes in the Nucleon Delta Transition", Phys. Rev. Lett. 56, 804 (1986) (with R. Davidson and R. Wittman).
49. "Are Nucleons and Delta Deformed?", Invited paper in Intersections Between Particle and Nuclear Physics, D.F. Geesaman, ed., Am. Inst. of Phys., New York (1986) (with M. Bourdeau and R. Davidson).
50. "A Precise Test for the Unitarized Pion Photoproduction Impulse Amplitude in Exclusive Nuclear Reactions", Phys. Rev. Lett. 57, 1113 (1986) (with R. Wittman).

51. "Introducing the Working Group on Excited Baryons in the CEBAF-1986 Workshop: Son et Lumiere", Invited Paper, CEBAF-1986 Workshop Proceedings, CEBAF, Newport News, VA, eds. F. Gross, et al. (1986).
52. "Workshop Summary: Excited Baryons", Invited Paper, CEBAF-1986 Workshop Proceedings, CEBAF, Newport News, VA, eds. F. Gross, et al. (1986).
53. "Excited Baryons", Invited Summary Paper, CEBAF-1986 Workshop Proceedings, ed. F. Gross (1986).
54. "Color Magnetism, Hadronic Deformation and the Helicity Zero ($\gamma N \rightarrow \Delta$) Transition Amplitude", Invited Paper, Research Program at CEBAF (II), CEBAF, Newport News, VA, ed. F. Gross, (1987) (with M. Bourdeau).
55. "Color Magnetism and Helicity Zero ($\gamma N \rightarrow \Delta$) Transition Amplitude", Phys. Rev. Lett. 58, 976 (1987) (with M. Bourdeau).
56. "A Precise Test for the Unitarized Pion Photoproduction Amplitude in Exclusive Nuclear Reactions", Invited Paper, Research Program at CEBAF (II), CEBAF, Newport News, VA (1987) (with R. Wittman).
57. "Color Magnetism and Radiative Delta Decay", The Proceedings of the 2nd Intl. 1987 Workshop on Pion-Nucleon Interaction, eds. W. Gibbs et al., Los Alamos, NM (1988) (with R. Davidson).
58. "Neutral-pion Photoproduction on Proton Near Threshold", Phys. Rev. Lett. 60, 748 (1988) (with R. Davidson).
59. "Color Magnetism in Pion Photoproduction and Radiative Delta Decay", Research Program at CEBAF (II), CEBAF (1988) (with R. Davidson).
60. "Background-free Determination of the Residues at the K-matrix Pole: The Example of the Delta (1232) Excitation", Proc. of 1988 CEBAF Summer Workshop, eds. F. Gross, J. Lightbody, CEBAF (January 1989) (with M. Benmerrouche).
61. "Effective Lagrangian Approach to the S_{11} Excitation", Proc. of the Int. Conf. on Particle-Nucl. Interface, APS, New York (1989) (with M. Benmerrouche).
62. "Color Magnetism and Delta Photoproduction", Invited Paper in Excited Baryons 1988, eds. G. Adams, N. Mukhopadhyay, P. Stoler, World Scientific, Singapore (1989).
63. "Problems of Describing Spin - 3/2 Baryon Resonances in the Effective Lagrangian Theory", Phys. Rev. C39, 2339 (1989) (with M. Benmerrouche and R.M. Davidson).
64. "Eta Photoproduction in the S_{11} Region", Excited Baryons 1988, World Scientific Singapore (1989) (with M. Benmerrouche).
65. "Bourdeau and Mukhopadhyay Reply to the Comment by A. Abbas", Phys. Rev. Lett. 63, 335 (1989) (with M. Bourdeau).
66. "A Quantum Chromodynamic Explanation of the Bloom-Gilman Duality", Phys. Rev. D, Rapid Communications D41, 2343 (1990) (with C. Carlson).

67. "Model-independent Determination of K-matrix Pole and Residues in the Δ (1232) Region from the Multipole Data for Pion Photoproduction", Phys. Rev. D42, 20 (1990) (with R.M. Davidson).
68. "Effective Lagrangian Theory of Photopion Production", Phys. Rev. D43, 71 (1991) (with R.M. Davidson and R. Wittman).
69. "Study of Fundamental Interactions with Nuclear Muon Capture", Invited Paper, in Proc. Int. Conf. on Weak and Electromagnetic Interactions in Nuclei. P. Depommier, ed. Editions Frontieres, Gif-sur-Yvette, France (1990).
70. "Meson Exchange Current in the Beta Decay of ${}^6\text{He}_{g.s.}$ ", Phys. Rev. C42, 1361 (1990) (with B. Doyle and B. Goulard).
71. "Spectrum Generating Algebra for Stringlike Mesons: Mass Formula for $q\bar{q}$ Mesons", Phys. Lett. B256, 295 (1991) (with F. Iachello and L. Zhang).
72. "Vibrational Regge Trajectories for Heavy Quarkonia", Phys. Rev. D44, 2085 (1991) (with L. Zhang).
73. "Spectrum Generating Algebra for String-like Mesons: Mass formula for $q\bar{q}$ Mesons", Phys. Rev. D 44, 898 (1991) (with F. Iachello and L. Zhang).
74. "Eta Photoproduction near Threshold", Proceedings on Int. Conf. on Particle Production near Threshold, Indiana Univ., Am. Inst. of Phys. (New York, 1991) (with M. Benmerrouche). Invited Paper.
75. "Eta Photoproduction from Threshold through the S11 (1535) Resonance", Physical Review Letters 67, 1070 (1991) (with M. Benmerrouche).
76. "Perturbative QCD Signatures of Hybrid Hadrons in Electroproduction at High Q^2 ", Phys. Rev. Lett. 67, 3745 (1991) (with C.E. Carlson).
77. "Compton Scattering and Delta Excitations", Invited Paper, Conference on Medium and High Energy Nuclear Physics, Calcutta, India (with M. Benmerrouche). In press.
78. "Connections between Compton Scattering and Pion Photoproduction", Invited Paper, Workshop on Hadron structure, Brookhaven National Lab., Report #BNL 47972, pp. 117 (1992) (with M. Benmerrouche).
79. "Model-independent Connections Between Pion-photoproduction and Compton Scattering in the Delta (1232) Region", Phys. Rev. D46, 101 (1992) (with M. Benmerrouche).
80. "Recent Progress in Baryon Spectroscopy", Invited Paper, CBAF Summer Workshop, Mainz Report #MKPT-T-92-14 (1992).
81. "Nucleon Magnetic Polarizability and the Excitation of the Delta Resonance", Phys. Rev. D, Rapid Comm., January issue (1993) (with A. Nathan and L. Zhang).
82. "Duality in the Inelastic Structure Function and the Disappearing Delta Resonance", Rapid Communications, Phys. Rev. D47, R7 (1993) (with C. Carlson).

83. • "Dynamic Symmetry in Hadron Physics: A Mesonic Puzzle for the $U(4) \supset SU(4)$ Chain", Invited paper for the Book "Symmetries in Science VI: from the Rotation Group to Quantum Algebras" (editor B. Gruber), Plenum, New York (with L. Zhang). In press.
84. "Visionsloses Paul Scherrer Institut", Letter to the Neue Zürcher Zeitung, January 12, 1993.
85. "Delta Contribution to the Paramagnetic Polarizability of Protons", Rapid Comm., Phys. Rev. D47, R7 (1993) (with A.M. Nathan and L. Zhang).
86. "Pi-Zero Photoproduction from Protons with Polarized Photons in the Delta Region", Phys. Rev. Letters 70, 3834 (1993) (with R.M. Davidson).
87. "Nuclear Muon Capture", Proceedings of LEMS-93 Conference. In press.
88. "Test of Standard Model in Nuclear Muon Capture", Proceedings of PANIC-93 Conference. In press.
89. "Complementarity Between Electromagnetic and Hadronic Production of Eta Mesons". Proceedings of Workshop on Future Directions in Particles and Nuclear Physics. (with M. Benmerrouche). In press.

12. APPENDIX: A SAMPLE OF PAPERS AND OTHER
SCIENTIFIC COMMUNICATIONS

*Preprints & reprints
removed & cycled separately*

**DATE
FILMED**

2 / 2 / 94

END