COLOR MAGNETISM IN PION PHOTOPRODUCTION AND RADIATIVE DELTA DECAY*†

Nimai C. Mukhopadhyay and R. Davidson
 Department of Physics, Rensselaer Polytechnic Institute
 Troy, New York 12180-3590

ABSTRACT

We use the extant multipole data base to extract the $\gamma N \rightarrow \Delta$ transition amplitudes, using the phenomenology of the effective Lagrangian approach. We find evidence for hadronic color magnetism in the radiative delta decay amplitudes.

INTRODUCTION

Quantum chromodynamics (QCD), believed to be the best candidate theory of strong interaction, indeed, the only one currently in the running, is expected to solve eventually the problem of non-perturbative color dynamics that leads to hadrons, which, in turn, form nuclei, and, finally, all hadronic matter of the universe. At present, however, it is far from doing so, even as considerable progress has been made in the lattice gauge theory techniques to study some implications of the QCD in the non-perturbative domain. In this note, we shall review the recent progress^{1,2} in the phenomenological extraction of the $\gamma N \Delta$ amplitude from the extant experimental data³ and their multipole analyses. Here N is the nucleon, and Δ is a special case of the baryon resonances N^* , the 1232 MeV $J^\pi = \frac{3}{2}^+$, $T = \frac{3}{2}$ isobar. It is a prototype of the three-point function γNN^* , of direct interest to the understanding of the quark-gluon structure of hadrons. We shall point out the relevance of this effort to the continuing search of color magnetism effects, arising from the one-gluon exchange⁴ between quarks, invoked in the context of quark shell model, and to other efforts in the hadronic model building inspired by the QCD.

Our review here draws heavily from the recent doctoral dissertations of Wittman⁵ and Davidson⁶. For a background of the current literature, we refer the reader to the recent reports of the photoproduction amplitudes in the survey by the Particle Data Group, and to many surveys at and contributions to the recent workshops⁷ organized by the Continuous Electron Beam Accelerator Facility (CEBAF).

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MASTER

COLOR MAGNETISM EFFECTS IN THE RADIATIVE DELTA DECAY

The quark shell model (QSM), a non-relativistic mean field approach to the hadron structure, has been quite successful in providing a phenomenological understanding⁸ of the observed properties of low-lying hadrons, in terms of a simple model Hamiltonian of the form $H = \sum_i H_i^{SP} + \sum_{i < j} H_{ij}$, where the terms of the right-hand side are constructed in a spirit analogous to that of the nuclear shell model. Thus, the two-body interaction consists of a harmonic confinement term and a color hyperfine term made of contact and tensor pieces. The color hyperfine interaction, due to one-gluon exchange between a pair of quarks, has been emphasized in the context of quark physics first by DeRujula et al.⁴ It has classical analogue in the interaction between two bar magnets (hence the name "color magnetism", in analogy to ordinary magnetism). It has quantum electrodynamic analogue in the Breit-Rabi interaction of the atomic physics, and quantum hadrodynamic analogue in the tensor force due to one-pion exchange between two nucleons in nuclear physics. The color magnetic tensor force, among other things, lifts the SU(6) degeneracy of the N and Δ . In direct analogy to the D-wave component admixture in the ground state wave function of the deuteron, it is responsible for the appropriate SU(6)-breaking admixtures⁹ in the wave functions of N and Δ .

Looking at the electromagnetic transition $N \rightarrow \Delta$, or the inverse radiative process $\Delta \rightarrow N\gamma$, the multipoles, allowed by the spin-parity selection rules, are M1 and E2. In the SU(6) limit, the QSM wave functions for N and Δ have L=0 components only. Thus, in the simplest SU(6) (and likewise SU(6)_w) model, $\langle \Delta | e_2 | N \rangle \equiv E2 = 0$, a result more than twenty years old¹⁰. Defining the ratio of the amplitudes E2/M1 as EMR, we get EMR = 0 in this limit. Thus, the non-vanishing resonant E2 amplitude, or equivalently, EMR $\neq$ 0, is a sensitive test for the hadronic color magnetism. Our recent work was triggered by the 1984 Particle Data Group Summary, implying the possibility of a non-zero E2 amplitude. Our analysis illuminates inconsistencies among extant multipole data bases and narrows somewhat the range of the EMR that can be extracted from the current data base. It also points out the difficulties of the theoretical approaches to extract resonant amplitudes from data, and provides an interesting bench mark to compare with, as attempts to extract γ_{NN^*} amplitudes for other N*'s continue. Finally, it provides with a unitarized impulse amplitude for use in nuclear applications¹¹.

The prediction of electromagnetic transition moments in the QSM, in which the valence quark model space has been truncated for numerical convenience to a manageable size, has one important technical difficulty. It can produce a subtle, but numerically significant, violation of gauge invariance. Nuclear physicists are familiar¹² with this problem in the context of the Siegart theorem¹³. Thus, the gauge relation between longitudinal and scalar quadrupole transition amplitudes, L_{1+} and S_{1+} respectively, for the $\gamma_{N \rightarrow \Delta}$ transition (the suffix v standing for virtual or 'massive' photon),

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

where k and k_0 are momentum and energy of the virtual photon, has been found to be violated to varying degrees¹⁴ in the QSM, as is the Siegert theorem¹⁵

$$E_{1+}(0) \approx S_{1+}(0) , \quad (2)$$

the argument indicating real photon. Fortunately, the violation is mild¹⁴ in realistic models such as those of Isgur and Karl (IK). One important consequence of this is the following: a better model estimate of $L_{1+}(0)$ in the QSM can be made by computing the amplitude $S_{1+}(0)$. The EMR, thus calculated, will be called the "charge approach" estimate, in contrast to that in the "current approach", in which the non-relativistic interaction Hamiltonian is $H_{int} = \vec{J} \cdot \vec{A}$,

$\vec{J}$ is the transition current and $\vec{A}$ is the vector potential. In the IK model, the EMR is -0.4% and -0.6% respectively in the current⁸ and charge approaches.¹⁴

Finally, the limitations of the non-relativistic QSM calls for further investigations beyond this model. Many such models, all inspired to varying degrees by the QCD, predict the $\gamma N \rightarrow \Delta$ helicity amplitudes. The EMR predictions of some of these models are collected in Table I. One extension of the non-relativistic QSM is an attempt to "relativize" the problem, albeit not solving the full relativistic dynamics. A recent calculation, using the light-cone formalism, shows¹⁶ that the relativistic kinematics alone in the three-quark wave functions could be responsible for the EMR to be -0.2%, without introducing any color magnetic tensor force. Earlier, an attempt to estimate effects of one-pion exchange¹⁷ between quarks at large distance yielded a contribution about -0.4% to the EMR. Thus, these works warn us that a non-zero EMR may not be a straightforward signal for the hadronic color magnetism. One should add here that we are far from understanding relationships between these varying degrees of sophistication in hadronic model building or their intrinsic accuracies. When we refer below to the color magnetic effects, we shall mean it in the context of the non-relativistic QSM.

Before concluding this section, we draw attention to the fairly large negative values of the EMR obtained in the Skyrmon approach¹⁸. Non-topological soliton models¹⁹ also yield similar values, indicating this to be a generic property of soliton models, a fact that needs further theoretical clarification.

Table I: The $N \rightarrow \Delta$ transition amplitudes (in usual units) and comparison with selected theoretical models

Source	M1	E2	EMR%	$A_{1/2}$	$A_{3/2}$
A. Phenomenologically extracted amplitudes from expt.					
Particle Data Group	295	-4.27	-1.4	-141	-259
This Work	214 to 297	-6.05 to -0.60	-2.2 to -0.2	-142 to -104	-262 to -188
B. Theory					
Chiral Bag Model	290	-2.82	-0.9	-141	-254
Nonrelativistic Quark Model	206	-1.96	-0.4	-100	-180
Skyrme Model	284	-8.80	-2.9	-129	-254

DATA BASE FOR MULTIPOLES

The multipole data base that we have examined are compiled by many authors²⁰ based on a variety of experiments and are not always consistent with one another in the region of overlap. One motivation of our work is precisely to bring this point home, as new research gets underway in a number of laboratories such as Bates, Saclay, Mainz, to name a few, culminating in the availability of beams at CEBAF a few years down the line. We have made no attempt to examine this lack of consistency in the variety of multipole data sets, and have gone ahead to examine each set in its own right, to gather whatever conclusions we can. In our analysis, we have made a fit to the broad energy region, and then narrowed the fit to a smaller energy band around the "on-shell" production point for the delta resonance. In general, the narrower band produced smaller E2 resonance amplitude and a smaller absolute value of the EMR. The author codes for the multipole data base (see Table II) are²⁰: BD = Berends and Donnachie, PS = Pfeil and Schwela, GRU = Grushin et al., GET = Get'man et al., MIR = Miroshnichenko et al., SZ = Smith and Zagury.

MAIN POINTS OF OUR ANALYSIS

We extend the approach of Olsson and collaborators²¹, attempting to compute the background and resonance contributions by the effective Lagrangian theory. Main points of our analysis are as follows: (1) All significant non-resonant contributions at the tree level are included. Among them are relatively small contributions of vector mesons and the u-channel Δ exchange contribution. (2) We include both electromagnetic gauge couplings at the $\gamma N \Delta$ vertex, a feature essential for the extraction of the E2 amplitude from the multipole data. This introduces a role of these couplings in the non-resonant channels through the u-channel Δ exchange. (3) We examine the ambiguities of the massive spin $\frac{3}{2}$ field. This brings in three extra parameters, one each for the electromagnetic couplings and one for the strong vertex. This allows us, as in the work of Olsson et al., to go beyond the Breit-Wigner form of delta propagator. (4) Unitarity is constrained via Watson's theorem. The ambiguity of unitarization procedures is explored in our work through the use of Olsson's²² and Noelle's ansatz²³ and through the use of K-matrix methods, appropriately abbreviated in Table II. (5) Finally, we use all relevant multipoles in the fit to see if poor quality of one or a combination of them can influence the extraction of resonant amplitudes.

Details of our analysis will be published elsewhere.

RESULTS OF OUR ANALYSIS

In Table II, we show the results of our analysis in extracting the $N\Delta$ electromagnetic transition amplitudes. The multipole data base and method of unitarization of resonant multipoles are appropriately abbreviated in the column "analysis", in which the last number indicates the number of data points used in the fit of M_1+ and E_1+ multipoles. All the amplitudes, multipole or helicity, are in units of $10^{-3} \text{ GeV}^{-1/2}$. The EMR is expressed in %. Combining best fits to all data sets, the extracted amplitudes, in appropriate units, are

$$A_{1/2} = -127 \pm 15,$$

$$A_{3/2} = -231 \pm 25,$$

$$M1 = 263 \pm 30,$$

$$E2 = 3.2 \pm 2.5,$$

giving a range of $\text{EMR} = (-1.3 \pm 0.7)\%$.

Table II: Summary of $N \rightarrow \Delta$ Electromagnetic Transition Amplitudes

Analysis	M1	E2	EMR%	$A_{1/2}$	$A_{3/2}$
BD OL 22	250.0	-2.20	-0.88	-121.7	-218.4
BD OL 7	251.4	-0.80	-0.32	-124.5	-218.4
BD N 22	287.7	-4.05	-1.41	-137.8	-252.7
BD N 7	286.3	-0.97	-0.35	-141.7	-248.8
BD K 22	285.7	-2.22	-0.78	-139.5	-249.3
BD K 7	286.2	-0.61	-0.21	-142.2	-248.4
PS OL 11	254.7	-3.63	-1.43	-121.9	-223.7
PS OL 5	255.3	-1.71	-0.81	-125.1	-222.6
PS N 11	297.4	-5.47	-1.84	-140.5	-262.3
PS N 5	291.4	-3.35	-1.15	-140.7	-255.3
GET OL 10	252.7	-3.51	-1.41	-121.1	-221.9
GET OL 5	254.2	-2.99	-1.17	-122.6	-222.7
MIR OL 11	220.7	-3.89	-1.76	-104.5	-194.5
MIR OL 5	214.5	-2.43	-1.17	-103.5	-187.9
SZ OL 22	256.8	-5.62	-2.19	-120.0	-227.3
SZ OL 7	259.4	-5.52	-2.12	-121.4	-229.4
GRU OL 6	269.2	-6.05	-2.25	-125.2	-237.8

CONCLUSIONS

We believe our analysis safely yields the conclusion that the ratio of electric quadrupole to magnetic dipole amplitude or the EMR, is negative. Its range is not easily narrowed, from our conservative analysis, $EMR = (-1.3 \pm 0.7)\%$, given the present state of multipole data. This is consistent with our previous² results, in which we claimed a narrower range of the EMR based on a more restricted data base. We do not understand the energy dependence of the fit (i.e., changing of resonant amplitudes and hence the EMR, when the region of fit is varied). It may just be from the poor quality of multipole

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data, or it might indicate a deeper problem with the phenomenological Lagrangian approach used in the extraction of the multipoles. We may be getting a hint of the latter²³ from the recently extracted value²⁴ of the E_0^+ multipole from π^0 photoproduction on protons, but its implications on the resonance region are unclear. Given our present answer, the chromomagnetic effects in the radiative delta decay are still consistent with experiment. We need further theoretical and experimental confirmation to clinch the issue. Study of higher resonances is clearly aided by our current and future understanding of the delta (1232 MeV) resonance.

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