

Problems with extraction of the nucleon to $\Delta(1232)$ photonic amplitudes

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We investigate the model dependence and the importance of choice of database in extracting the *physical* nucleon- $\Delta(1232)$ electromagnetic transition amplitudes, of interest to QCD and baryon structure, from the pion photoproduction observables. The model dependence is found to be much smaller than the range of values obtained when different datasets are fitted. In addition, some inconsistencies in the current database are discovered, and their affect on the extracted transition amplitudes is discussed. [S0556-2813(99)04202-8]

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The importance of electromagnetic amplitudes in the nucleon to $\Delta(1232)$ transition as a test of our understanding of the underlying hadron dynamics has been known for decades [1]. In the SU(6) symmetry limit of the quark model [2], the only surviving amplitude is the transverse magnetic dipole ($M1$). The other allowed electromagnetic transitions, the electric and scalar (longitudinal) quadrupole, $E2$ and $S2$ ($L2$) amplitudes, respectively, vanish identically in this symmetry limit. In more realistic quark models [3], the $M1$ amplitude for real photon transitions is predicted to be about 30% lower than what is extracted [4–6] from the data, while the $E2$ amplitude is considerably smaller in magnitude than the extracted value. Other models of hadrons, such as bags [7], Skyrmions [8], other solitons [9] and the more rigorous QCD approach on the lattice [10], all give varying values for these amplitudes, none in perfect agreement with the phenomenologically inferred values [4,6]. A relevant quantity that reflects this theoretical interest is the ratio of $E2$ to $M1$ at the K -matrix pole [where the πN phase shift in the $J=T=3/2$ (or $3,3$) channel goes through 90°]. At the real photon point, $Q^2=0$, this ratio is small and negative, while at large Q^2 , in the domain of perturbative QCD, this ratio is expected to be positive and unity [11].

Current research on this topic has theorists struggling to understand why theoretical predictions at the real photon point fall short of the values inferred from experiment. For example, introducing explicit pion degrees of freedom may be the solution to this long-standing problem. An early work [12] based on a simple pion emission model found that the $M1$ amplitude is largely unaffected by the pion cloud. More recent works on this topic are divided. The work of Sato and Lee [13], who use an effective Hamiltonian method, finds that the pion cloud is important for the $M1$ amplitude. On the other hand, a different work [14] in which the one-pion exchange potential is included in the quark model finds that the $M1$ amplitude is largely unaffected by the pionic degrees of freedom. This latter work also points out the importance of two-body currents in the $E2$ amplitude.

At the same time, a vigorous program has been launched by both experimentalists and phenomenologists to determine them more accurately by doing better experiments and analyses. Very recently, the Mainz [15] and the BNL LEGS [16] groups have released newly measured differential cross sec-

tion ($d\sigma/d\Omega$) and photon asymmetry (Σ) data in the $\Delta(1232)$ resonance region. These new data have caused tremendous interest among the phenomenologists, and the theorists from RPI [5], VPI [6], and Mainz [17] have produced their own analyses of these data. These analyses have found the $E2/M1$ ratio ranging from $-(1.5 \pm 0.5)\%$ [6] to $-(3.2 \pm 0.2)\%$ [5], a range of -1 to -3.4% . Given that $E2$ is so small compared to $M1$, it is quite satisfactory to have its value narrowed down to this range. However, it is not satisfactory that different analyses do not agree, within their quoted error bars, on the value of $E2/M1$. One reasonable explanation of this discrepancy is that the various authors have underestimated their errors. Are there any other explanations for the disagreement amongst the various analyses?

This brings us to the central issue of this work: finding the origin of this numerical spread of the $E2/M1$ ratio and what can be done to substantially reduce this spread. One might suspect [18] that this spread is coming from the theoretical model dependence of various analyses. However, we will show that the model dependence in extracting the *physical* photodecay amplitudes is *actually much smaller than the effect of different choices for the databases that various authors have made* [5,6,17]. Indeed, if a complete set of experiments were available at the K -matrix pole position, then the multipoles could be determined model independently, and thus there would be no model dependence in determining the K -matrix residues [19]. As a complete set of experiments does not yet exist, model dependence arises in the multipoles due to what one assumes about the structure of the photoproduction amplitude.

We construct test datasets of pertinent observables in the energy region between the pion photoproduction threshold and the onset of the two pion threshold, beyond which implementation of unitarity is difficult. We then apply two distinct theoretical approaches of extracting the resonant amplitudes to the same dataset, to gauge the degree of model dependence in the extraction of the resonant amplitudes. Both of these approaches provide a generally good description of the photoproduction data, but differ significantly in their physics input. One of these two is the effective Lagrangian approach [4,5,20] which satisfies the constraints of chiral symmetry, unitarity and crossing symmetry. The other is a more phenomenological energy-dependent (global) multipole analysis [6].

The first approach, hereafter called the RPI analysis [4,5,20], is based on an effective Lagrangian [20] containing the pseudovector (PV) nucleon Born terms, s and u channel Δ exchange, and t -channel ρ and ω exchanges. It contains five parameters that are determined by fits to the data: two gauge couplings describing the $M1$ and $E2$ amplitudes and three off-shell parameters related to ambiguities in the relativistic spin-3/2 Lagrangian [21]. In this approach, the d and higher- l multipoles are dominated by the nucleon Born terms, i.e., effectively only the s and p wave multipoles are allowed to vary. In addition, not all the s and p wave multipoles are independent as the model contains only five parameters. While the resonance contribution is not *a priori* constrained, the background is. In fact, for the most part the background is dominated by the PV nucleon Born terms.

The second approach, which we call the VPI analysis [6], has the energy dependence of the s -, p -, and d -waves multipoles parametrized and unitarity is implemented via a K -matrix approach. The higher- l multipoles are assumed to be given by the nucleon Born terms, and the parameters, including $M1$ and $E2$, are determined by a fit to the data. Thus, apart from the $l > 2$ multipoles, the background and resonance contributions are not *a priori* constrained in this approach. We shall repeat our analysis for two different test databases to demonstrate the role of the choice of the database in extracting resonance parameters.

For this analysis, we need a standard set of definitions for resonance parameters [19,20]. For the K -matrix definition of the resonance photocouplings, we have [19]

$$\begin{aligned} M1 &= \text{Im } M_{1+}^3 A, \\ E2 &= \text{Im } E_{1+}^3 A, \end{aligned} \quad (1)$$

where

$$A = \sqrt{\frac{8\pi W q \Gamma_\Delta}{3MK}}, \quad (2)$$

and all kinematical quantities are evaluated at the cm energy where the phase shift in the isospin 3/2, spin 3/2 (3,3) channel is 90° . In Eq. (2), M is the nucleon mass, Γ_Δ is the Δ width at the K -matrix pole [19], q is the pion three-momentum, and K is the photon three-momentum.

At the T -matrix pole, we adopt a definition of the photocouplings which is similar to that used at the K -matrix pole. First, consider pion-nucleon elastic scattering in the 3,3 channel. Below energies where inelasticities become important, the T matrix is of the well-known elastic form

$$T = \sin \delta e^{i\delta}. \quad (3)$$

If we now define the energy dependence of the Δ width $\Gamma(W)$ to be given by

$$\tan \delta = \frac{\Gamma(W)/2}{W_R - W}, \quad (4)$$

then the T matrix in the 3,3 channel becomes, without loss of generality,

$$T = \frac{\Gamma(W)/2}{W_R - W - i\Gamma(W)/2}. \quad (5)$$

Note that in Eq. (5), W_R is the energy where the 3,3 phase shift is 90° . In the literature, one often finds the T matrix in the 3,3 channel written in the above form (5) *plus* an additional background contribution. However, the background contribution may be absorbed into the definition of $\Gamma(W)$.

In the vicinity of the T -matrix pole W_T we have

$$\Gamma(W) \approx \Gamma(W_T) + (W - W_T)\Gamma'(W_T) + \dots, \quad (6)$$

and by using the standard definition of W_T ,

$$W_T = W_R - i\Gamma(W_T)/2, \quad (7)$$

we obtain, in the vicinity of W_T ,

$$T \approx \frac{\Gamma(W_T)/2}{(W_T - W)[1 + i\Gamma'(W_T)/2]}. \quad (8)$$

Therefore, the residue at the T pole is

$$\text{Res } T \equiv R_S = \frac{\Gamma(W_T)/2}{1 + i\Gamma'(W_T)/2}. \quad (9)$$

From Eq. (7), one trivially obtains

$$\Gamma(W_T) = 2i(W_T - W_R), \quad (10)$$

and we also define the T -matrix width by $\Gamma_T = \text{Re}\{\Gamma(W_T)\}$.

Turning to photoproduction, the M_{1+} multipole in the $T = 3/2$ channel, M_{1+}^3 , may be written as

$$M_{1+}^3 = M1(W) \sqrt{\frac{3KM}{8\pi W q \Gamma(W)}} \frac{\Gamma(W)/2}{W_R - W - i\Gamma(W)/2}. \quad (11)$$

In terms of the residue of M_{1+}^3 at the T -matrix pole, we thus obtain

$$M1(W_T) = \frac{\text{Res } M_{1+}^3}{R_S} \sqrt{\frac{8\pi W_T q \Gamma(W_T)}{3KM}}, \quad (12)$$

where $\Gamma(W_T)$ is given by (10). The relevant expression for $E2(W_T)$ can be found from Eq. (12) by replacing $M1$ with $E2$ and M_{1+}^3 with E_{1+}^3 . To make connection with the quantity $re^{i\phi}$ introduced by the Mainz group [17], we obtain

$$\text{Res}(M_{1+}^3) = re^{i\phi} \Gamma_T. \quad (13)$$

In the RPI approach, $\text{Res}(M_{1+}^3)$ may be exactly calculated from Eq. (55) of Ref. [20] once the parameters have been fitted to the data. However, in other approaches it is necessary to fit some functional form to the multipoles and extrapolate to the T -matrix pole. Although countless extrapolation functions can be used, we expect, based on results from πN scattering [22], that the extrapolation is not very sensitive to the particular parametrization of the multipoles. Thus, we adopt the simple form

$$f(W) = \frac{\mu^2}{qK} \sin \delta e^{i\delta} (A + BX + CX^2), \quad (14)$$

where $X = (W - M_R)/M_R$, μ is the pion mass, and the constants A, B, C are determined from a fit to the multipole. This form (14) provides an accurate description of both the M_{1+}^3 and E_{1+}^3 multipoles in the W range from 1180 to 1250 MeV. The T -matrix residues are given by

$$\text{Res}(M_{1+}^3) = R_S \frac{\mu^2}{qK} (A + BX + CX^2), \quad (15)$$

where all kinematical quantities are evaluated at W_T . A similar equation holds for $\text{Res}(E_{1+}^3)$. For the RPI approach, the results obtained from the extrapolation function (14) agree with the exact results to within 1% for the M_{1+}^3 and within 5% for the E_{1+}^3 .

Let us now make our case that much of the difference in the extracted $M1$ and $E2$ values, and hence the $E2/M1$ ratios, can be traced back to the use of different databases in the various fits. Not surprisingly, the recent Mainz [17] and BNL [16] fits have been based largely on data produced at their own facilities. In order to investigate the implications of the Mainz data on the $M1$ and $E2$ amplitudes, the initial RPI fit [5] was restricted to the Mainz data [15] over the resonance. The initial VPI fits [6] were different in that they included the entire database. In order to investigate the model dependence and the dependence on the choice of dataset in extracting the values of the $M1$ and $E2$ amplitudes, we have performed several fits using different, but common, datasets. We have chosen to fit the data in the energy region of the recent Mainz experiment, i.e., from 270 to 420 MeV. This is partially dictated by the fact that RPI model [20] does not work outside the Δ region, and the VPI analysis [6] cannot be restricted to a narrow energy region. Furthermore, as we are primarily interested in the M_{1+}^3 and E_{1+}^3 multipoles, we have fitted only the proton data, which are sufficient to isolate the isospin 3/2 multipoles.

Our first test of model dependence is a fit which arbitrarily rejects all pre-1980 cross section data, but keeps all single-polarization observables. This dataset contains 836 datum points, of which 353 correspond to $p\pi^0$ observables. In particular, there are 140 photon asymmetry points, 91 differential cross section points, 68 target asymmetry points, and 54 recoil polarization points. Of the 483 $n\pi^+$ datum points, 164 are photon asymmetry points, 144 are differential cross section points, 121 are target asymmetry points, and 54 are recoil polarization points. The effect of the few double polarization points available in this energy region was found to be negligible.

The results for the resonant amplitudes, $M1$ and $E2$, in standard units of $10^{-3}\text{GeV}^{-1/2}$, and the $E2/M1$ ratio are shown in Table I at the K matrix pole and in Table II at the T -matrix pole (labeled by fit 1). The results from the RPI and VPI approaches for the dominant $M1$ amplitude are in excellent agreement at both the K - and T -matrix poles. Somewhat surprising is how well the RPI and VPI analyses agree on the value of $E2$ and hence the $E2/M1$ ratio. For example, at the K -matrix pole, the RPI analysis gives $E2/M1 = -2.1\%$ while the VPI analysis gives $E2/M1 = -1.9\%$.

TABLE I. Results of the K -matrix residues obtained from fitting selected databases on pion photoproduction observables in the $\Delta(1232)$ region by the RPI and VPI analyses. Selection of the databases and these analyses are discussed in the text. The K -matrix residues are in the standard units of $10^{-3} \text{ GeV}^{-1/2}$.

		K-matrix pole		
		M1	E2	E2/M1
Fit 1	RPI	289	-6.0	-2.1%
	VPI	290	-5.6	-1.9%
Fit 2	RPI	290	-1.3	-0.45%
	VPI	291	-1.1	-0.38%

Based solely on the quoted systematic errors on the data, the RPI analysis gives an error of about 0.2% for this ratio. It is quite satisfactory that these *two rather different ways of analyzing the data agree so well on the extracted values of these amplitudes*.

Comparing the results of these two solutions with the excluded differential cross sections, general agreement is found with two main exceptions: two sets of $\pi^0 p$ differential cross sections from Bonn [23], containing a total of 587 datum points. Thus, the $p\pi^0$ dataset in this energy region is dominated by the Bonn datasets. Therefore, as an additional test of model dependence, and to determine the influence of the Bonn data on the $M1$ and $E2$ amplitudes, we have performed fits which include these Bonn data, but still exclude all other pre-1980 differential cross sections. The results, labeled as fit 2 are also shown in Tables I and II. Again, the results from RPI and VPI approaches are in excellent agreement. In fact, *this is a very stringent test of model dependence on the extracted $E2$ amplitude*, since the $E2$ amplitude is so small in this case. Although at the T -matrix pole the real and imaginary parts of this ratio have shifted compared to the fit without the Bonn data, the magnitude is quite similar in both fits.

Although the $M1$ amplitude is almost identical in the two fits, the $E2/M1$ ratio is quite sensitive to the chosen data set. This is particularly surprising since the Mainz and Bonn π^0 differential cross sections are in agreement. The influence of these Bonn data on the extracted value of the $E2/M1$ ratio has also been confirmed by the BNL group [16]. In that work, as a test, the BNL cross sections are removed and replaced by the Bonn cross sections. The value of the extracted EMR drops from -3.0 to -1.3% . Similar results have also been found by the Mainz group [24]. In the RPI fits, the raw data have been fitted, that is, any systematic differences between different datasets has not been taken into account. On the other hand, in the VPI fits, the data were allowed to “float” in an attempt to take into account systematic differences. As the effect of the Bonn data on the $E2/M1$ ratio is found in both approaches, it seems to be a shape effect rather than a scale effect.

Although the Mainz [15] and Bonn [23] cross sections agree over their common angular range, their implications for the $E2$ amplitude are quite different. Let us try to understand this. Near the resonance energy, the Bonn cross sections [23] range from 10° to 160° while the Mainz cross sections [15] go from 75° to 125° . Thus, it is apparently the Bonn data at forward and backward angles that are respon-

TABLE II. Results of T -matrix residues, in the standard units of $10^{-3} \text{ GeV}^{-1/2}$, obtained from the RPI and VPI analyses. For comparison with the Mainz group [17], we also give $re^{i\phi}$ at the T -matrix pole, where r is in units of $10^{-3}/\mu$ and ϕ is in degrees.

		$M1$		$E2$		T -matrix pole			
		$M1$	$E2$	$E2/M1$	r_M	ϕ_M	r_E	ϕ_E	
Fit 1	RPI	$300+i27$	$-8.7-i13.2$	$-(3.3+i4.1)\%$	22.3	-26.7	1.17	-155.2	
	VPI	$297+i19$	$-6.5-i15.9$	$-(2.5+i5.2)\%$	22.0	-28.1	1.27	-144.1	
Fit 2	RPI	$301+i26$	$-4.8-i14.8$	$-(2.0+i4.7)\%$	22.3	-26.9	1.15	-139.8	
	VPI	$301+i14$	$-1.1-i15.0$	$-(0.6+i4.9)\%$	22.3	-29.1	1.11	-126.0	

sible for bringing the $E2/M1$ ratio down in magnitude. As a check on this, we have truncated the Bonn data to the same angular range as the Mainz data and have redone the fit using the RPI approach. The result for the $E2/M1$ ratio is -1.4% , which accounts for much of the discrepancy between the fits with and without the Bonn data. It is also worth noting that the fit to the π^0 photon asymmetry data is significantly worsened when the Bonn data are included in the fit, while the fit to all other observables remains largely unchanged. Therefore, viewed from our two approaches, *there is an inconsistency between the π^0 photon asymmetry data and the Bonn cross section data at forward and backward angles.*

It is natural to ask how these two distinct observables could be in disagreement. This is difficult to pin down quantitatively, because the other multipoles, with the possible exception of the M_{1+}^3 , will differ if different datasets are fit. Qualitatively, however, the problem seems to arise from the interference term between the M_{1+} and E_{1+} multipoles, which appears both in the differential cross section and the polarized photon asymmetry [25]. The Bonn π^0 differential cross section favors a small interference term, while the polarized photon asymmetry favors a significantly larger value. The role of $E2$ in these two observables can be judged by comparing the results of our two fits, which are shown in

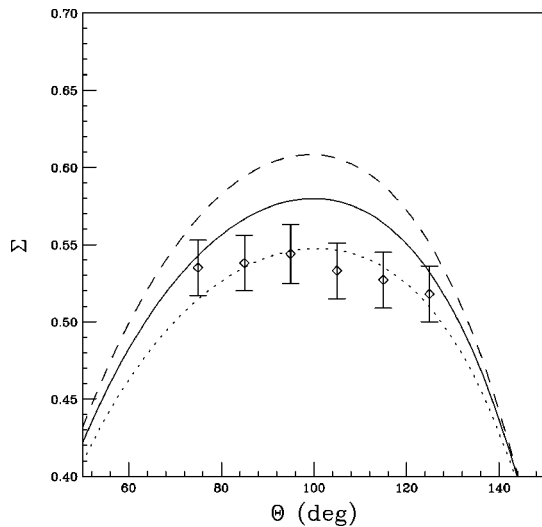


FIG. 1. A comparison of the RPI results of fit 1 (solid line) and fit 2 (dashed line), discussed in the text, with the recent Mainz Σ data [15] at a photon lab-energy of 340 MeV. The dotted line is obtained from fit 2 by rescaling the $E2$ amplitude such that the $E2/M1$ ratio is -3.2% , everything else held fixed.

Figs. 1 and 2 at 340 MeV. The solid line is the result from fit 1, while the dashed line is obtained from fit 2. For the photon asymmetry (Fig. 1), fit 1, which has the larger $E2$ amplitude, is clearly favored, while for the differential cross section (Fig. 2), the backward angle data from Bonn favor fit 2. We can further investigate the role of the $E2$ amplitude in these two observables by scaling the $E2$ amplitude in fit 2 such that the $E2/M1$ ratio is -3.2% with everything else held fixed. As is shown by the dotted line, the agreement with the photon asymmetry is greatly improved when this scaling is done, while the fit to the cross section becomes poorer. Finally, it should be emphasized that the d waves are allowed to vary in the VPI approach, and therefore the discrepancy cannot be accounted for by *these* multipoles.

In conclusion, we have demonstrated that the RPI and VPI approaches give very similar results for both the $M1$ and $E2$ amplitudes in the case where all pre-1980 differential cross sections are removed. These very different methods of analysis also agree on the effect of adding two sets [23] of $\pi^0 p$ differential cross sections measured at Bonn in the 1970's. The agreement between these two different approaches suggests that the model dependence in extracting the *physical* resonant amplitudes is much smaller than the range of $E2/M1$ values obtained from fitting different databases. As our two approaches do not exhaust all the theoretical methods used to analyze these data, a benchmark dataset, available to all groups, would be useful for a broader

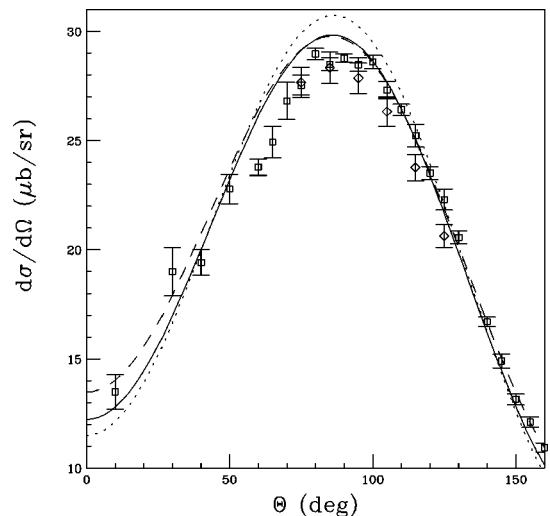


FIG. 2. A comparison of the RPI results with the differential cross sections from Mainz (diamonds) [15] and Bonn (squares) [23]. Curves as in Fig. 1.

investigation of the model dependence in the extraction of the $M1$ and $E2$ amplitudes.

Looked at from our approaches, there is an inconsistency between the Bonn $\pi^0 p$ differential cross section data at forward and backward angles and the Mainz Σ data. As the recent BNL Σ data [16] are consistent with the Mainz Σ data, it is vitally important to verify the forward and backward Bonn cross sections for neutral pion photoproduction. Given this, the wider angle measurements of the differential cross section for $\pi^0 p$ photoproduction from Mainz [26], not yet available in the current database, could be crucial to a more definitive resolution of the $E2/M1$ problem, of great topical interest to the understanding of baryon structure [1].

Although our main goal has been to investigate the model dependence in the extraction of the $M1$ and $E2$ resonant amplitudes, some comments on the preferred values of these amplitudes is in order. Of the datasets considered here, the extracted value of the $M1$ amplitude is quite stable with a value of about $290 \times 10^{-3} \text{ GeV}^{-1/2}$, which is roughly 30% larger than most quark model predictions [3]. On the other hand, the recent BNL differential cross sections [16] are larger than the previous Bonn and Mainz cross section measurements, presenting yet another problem in the database. As the BNL cross sections imply an $M1$ amplitude of about 310 in the same units, a resolution of the discrepancy between these cross sections is urgently needed. Presently, a

conservative estimate of the $M1$ amplitude is 300 ± 20 , where the error is almost entirely systematic. For the $E2$ amplitude, or the $E2/M1$ ratio, a reasonable estimate can be found by examining the fit to the Σ data at a photon lab energy of 340 MeV, close to the K -matrix pole. Although most analyses have very similar global chi-squares per degree of freedom, the quality of fit to these particular data vary widely. Comparing the results of various multipole solutions with these data and discarding those that give poor fits to these data, chi-squared per datum point greater than 2, one finds an $E2/M1$ range of about -2.5 to -3.2% . Thus, if we adopt the Σ data at 340 MeV as a benchmark, then we have $E2/M1 = -(2.8 \pm 0.4)\%$. An accurate and consistent *complete set* of measurements is needed to resolve the issues of the $M1$ and $E2$ nucleon to $\Delta(1232)$ transition amplitudes once for all.

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