Analysis of Pion Photoproduction Data

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Abstract

A partial-wave analysis of single-pion photoproduction data has been completed. This study extends from threshold to 2 GeV in the laboratory photon energy, focusing mainly on the influence of new measurements and model-dependence in the choice of parameterization employed above the two-pion threshold. Results are used to evaluate sum rules and estimate resonance photo-decay amplitudes. These are compared to values obtained in the MAID analysis.

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I. INTRODUCTION

Meson-nucleon scattering, meson photoproduction, and meson electroproduction have been extensively studied within a comprehensive program exploring the spectroscopy of $N^*$ and $\Delta^*$ resonances. An objective of this program is the determination of all relevant characteristics of these resonances, \textit{i.e.} pole positions, widths, principal decay channels, and branching ratios. In order to compare directly with QCD-inspired models, there has also been a considerable effort to find “hidden” or “missing” resonances, predicted by quark models (see, for example, the states predicted by Capstick and Roberts [1]) but not yet confirmed.

Here we will give detailed results from an ongoing analysis of pion photoproduction data. This work complements our studies of pion-nucleon elastic scattering [2], both reactions having the same resonance content, and provides the real-photon limit for our pion-electroproduction fits [3]. Resonance characteristics are determined through a two-step procedure. The full database is initially fitted to determine the underlying multipole contributions. Those multipoles having resonant contributions are then fitted to a form containing both resonance and background terms.

The availability of multipole amplitudes greatly simplifies certain numerical aspects of coupled-channel analysis. The number of fitted multipole amplitudes, associated with a dataset, may be smaller (than the count of individual data) by one or two orders of magnitude, and can account for issues associated with statistical/systematic errors, data rejection, and incomplete sets of observables. In general, our partial-wave analyses (PWA) have been as model-independent as possible, so as to avoid bias when used in resonance extraction or coupled-channel analysis. However, in the absence of complete experimental information, all multipole analyses above the two-pion production threshold are model-dependent to some degree. This issue will be discussed in Section III.

The amplitudes from these analyses can be utilized in evaluating contributions to the Gerasimov-Drell-Hearn (GDH) sum rule [4] and sum rules related to the nucleon polarizability. We display our results for these and compare with recent Mainz experimental data and predictions.

In the next section, we summarize changes in the database since our last published analysis [5]. Results of our multipole analyses, as well as the photo-decay amplitudes for resonances within our energy region, are given in Section III. In Section IV, we summarize our findings and consider what improvements can be expected in the future.

II. DATABASE

Our three previous pion photoproduction analyses [5-7] extended to 1.0, 1.8, and 2.0 GeV, respectively. The present database [8] is considerably larger, due mainly to the addition of new data at low to intermediate (below 800 MeV) energies.

In 1994, bremsstrahlung data comprised over 85% of the existing measurements. These data often suffered from significant uncertainties in normalization that were not completely understood or not quoted. The available tagged-photon data were generally measured in low-statistics experiments, and hence were presented with large energy and angular binning. Much of the remaining dataset was comprised of excitation cross sections with no extensive
angular range. Inconsistencies were obvious almost everywhere that comparisons could be made.

The full database has increased by 30% since the publication of Ref. [5], and is about 40% larger than the set available for the analysis of Ref. [6]. The majority of these new data have come from tagged-photon facilities at MAMI (Mainz), GRAAL (Grenoble), and LEGS (Brookhaven.) [The total database has doubled over the last two decades (see Table 1).] The distribution of recent (post-1995) \( \pi^0 p \) and \( \pi^+ n \) data is given in Fig. 1 (there are no new \( \pi^- p \) and \( \pi^0 n \) data.)

As the full database contains conflicting results, some of these have been excluded from our fits. We have, however, retained all available data sets (and labeled these excluded data as “flagged”) so that comparisons can be made through our on-line facility 8. Data taken before 1960 were not analyzed, nor were those single-angle and single-energy points measured prior to 1970. Some individual data points were also removed from the analysis in order to resolve conflicts or upon authors’ requests (since our previous analysis 3, we have flagged 950 \( \pi^0 p \), 1060 \( \pi^+ n \), and 150 \( \pi^- p \) bremsstrahlung data taken prior to 1983.) Some of the data, listed as new, were available in unpublished form at the time of our previous analysis 3. A complete description of the database and those data not included in our fits is available from the authors.

Since 1995, 87% (21%) of all new \( \pi^0 p \) (\( \pi^+ n \)) data have been produced at Mainz using the MAMI facility 9–19. These measurements of total and differential cross sections, \( \Sigma \) beam asymmetry, and the GDH-related quantity \( \left( \sigma_{1/2} - \sigma_{3/2} \right) \) have increased the database by a factor of about two over the energy range from the threshold to 800 MeV. The angular range of cross sections extends from 10° to 170°, and thus increases the sensitivity to contributions from higher partial waves.

Results from other laboratories include low-energy unpolarized \( \pi^0 p \) total (47 data) and differential (198 data) cross sections measured at SAL 20,21, and \( \pi^+ n \) threshold data (45 points), covering a range of 2 MeV in \( E_\gamma \), produced by the TRIUMF–SAL Collaboration 22. At energies spanning the \( \Delta \) resonance, \( \Sigma \) (169 data) and differential cross section (157 data) for both \( \pi^0 p \) and \( \pi^+ n \) channels have been measured by the LEGS group at BNL 23.

In the medium-energy range, \( \pi^+ n \) \( \Sigma \) beam-asymmetry data between 600 and 1500 MeV (329 data) have been measured at GRAAL 24,25 and \( \pi^0 p \) \( \Sigma \) data between 500 and 1100 MeV (158 data) have been measured at the 4.5 GeV Yerevan Synchrotron 26. Target asymmetry \( T \) measurements between 220 and 800 MeV for both \( \pi^0 p \) (52 data) and \( \pi^+ n \) (210 data) have come from ELSA at Bonn 27,28. Excitation \( \pi^+ n \) differential cross sections for backward scattering between 290 and 2110 MeV, also from the Bonn facility, have been replaced by finalized data 29, with final versions of other \( \pi^+ n \) and \( \pi^0 p \) differential cross sections expected 30–33.

Further experimental efforts will provide data in the intermediate energy region. Above 400 MeV, a large amount of new data is expected from CLAS at Hall B of Jefferson Lab 34. Differential cross sections associated with the Mainz GDH experiment 35 (related to the double-polarization quantity \( E \) 36) should also have an impact on the analysis when combined with 4° to 177° cross section (200 to 790 MeV) and 10° to 160° \( \Sigma \) beam asymmetry (250 to 440 MeV) measurements at MAMI 37. Beam asymmetry data for \( \pi^0 \) photoproduction below 1100 MeV will also be available from GRAAL 38. Of particular interest are the polarized \( \pi^0 \) photoproduction experiments (including the polarization transfers \( C_{x'} \).
and $C_\gamma$ from circularly polarized photons to recoil protons) above 800 MeV carried out in Hall A of JLab [39]. From Brookhaven, we expect final LEGS Σ beam asymmetries around the $\Delta$ resonance [40] and new radiative capture cross sections which have been taken at BNL–AGS using the Crystal Ball Spectrometer (E913/914) at $p_\pi$ from 400 to 750 MeV/c ($E_\gamma = 430 – 780$ MeV) [31].

### III. MULTIPOLAR AND PHOTO-DECAY AMPLITUDES

#### A. Analysis

Fits to the expanded database were first attempted within the formalism we have used and described previously [6,7,5]. Multipoles were parameterized using the form

$$M = (\text{Born} + A)(1 + iT_{\pi N}) + BT_{\pi N}$$  \hspace{1cm} (1)

with $T_{\pi N}$ being the associated elastic pion-nucleon $T$–matrix, and the terms $A$ and $B$ being purely phenomenological polynomials with the correct threshold properties. As in our most recent analysis [43], some multipoles were allowed an additional overall phase $e^{i\Phi}$, where the angle $\Phi$ was proportional to $(\text{Im} T_{\pi N} - T_{\pi N}^2)$. This form satisfied Watson’s theorem for elastic $\pi N$ amplitudes [42] while exploiting the undetermined phase for $\pi N$ inelastic amplitudes. For $T_{\pi N}$, we utilized our most recent fit (SM02) to elastic scattering data [43].

New and precise Σ measurements proved difficult to describe, using this choice of phenomenology. Searching for a more successful form, we found an improved description was possible if the dependence on $(\text{Im} T_{\pi N} - T_{\pi N}^2)$ was additive rather than multiplicative. As a result, we re-fitted the full database, removing the overall phase and instead added a term of the form

$$\left(C + iD\right)\left(\text{Im} T_{\pi N} - T_{\pi N}^2\right)$$  \hspace{1cm} (2)

with $C$ and $D$ again being energy-dependent polynomials.

The resulting energy-dependent solution (SM02) had a $\chi^2$ of 35296 for 17571 ($\pi^0 p$, $\pi^+ n$, $\pi^- p$, and $\pi^0 n$) data to 2 GeV. The overall $\chi^2$/data was significantly lower than that found in our previously published result ($\chi^2$/data = 2.4) [31]. This change is partly a reflection of the database changes discussed in Section [31]. Our present and previous energy-dependent solutions are compared in Table [31]. As in previous analyses, we used the systematic uncertainty as an overall normalization factor for angular distributions [31]. This renormalization freedom provided a significant improvement for our best fit results as shown in Table [31].

In order to see if the inclusion of the full existing database had resulted in a bias towards older and possibly outdated measurements, we compared the fit quality versus measurement date. Generally, we found no problem of bias, as illustrated in Table [31], where we have displayed our fit quality over the region covering the $N(1535)$ resonance. Except for

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1For total cross sections and excitation data, we combined statistical and systematic uncertainties in quadrature.
the above mentioned Σ measurements, over this energy region, our overall fit to the most recent measurements (1985–Present) is characterized by a χ²/data of about 1.3. For all data to 2 GeV, the date restriction yields a χ²/data near 1.5. Unfortunately, the modern measurements do not completely overlap older data. Much of the older data is required in an analysis extending over the full resonance region.

The very low energy region is complicated by different thresholds for π⁰p and π⁺n final states. While we have obtained a reasonable fit to the available π⁰p differential and total cross sections (we fit rather well the new threshold TRIUMF–SAL π⁺n cross sections [22], and Mainz π⁰p Σ at 160 MeV [19]), the multipole amplitudes have no cusp built into the π⁺n threshold region.

Both energy-dependent and single-energy solutions (SES) were obtained from fits to the combined π⁰p, π⁺n, π⁻p, and π⁰n databases to 2 GeV. In Table [IV], we compare the energy-dependent and single-energy results over the energy bins used in these single-energy analyses. Also listed are the number of parameters varied in each single-energy solution. A total of 148 parameters were varied in the energy-dependent analysis SM02. The extended database allowed an increase in the number of SES versus our previous result [5] over the same energy range to 2 GeV.

Fig. 2 is a plot of the energy dependent fits SM02 and SM95 over the full energy region. The SES are also shown with uncertainties coming from the error matrix. In the SES fits, initial values for the partial-wave amplitudes and their (fixed) energy derivatives were obtained from the energy-dependent solution. A comparison of global and single-energy solutions then serves as a check for structures that could have been “smoothed over” in the energy-dependent analysis. Partial waves with J < 4 are displayed, whereas the analysis fitted waves up to J = 5. Significant deviations from SM95 are visible in multipoles connected to the πN S- and P-waves, as well as D₃₅, F₃₅, and D₁₃ (for the neutron.)

As mentioned above, the parametrization used in our previous analysis SM95 [3] did not allow a good fit recent Yerevan π⁰p [26] and GRAAL π⁺n [24,25] Σ data (the critical range extends from 700 to 800 MeV.) For comparison purposes, in Table [V], we compare SM95, SM02, and SX99. The test fit SX99 retains the form used in previous fits (as in SM95) and is applied to the present full database. One can see that recent Mainz π⁺n (σ₁/₂ – σ₃/₂) [15] data are also problematic for the SX99 fit, with the most difficult region again covering the 700 to 800 MeV range. In Fig. 4, we display the energy dependence of a differential cross section measurement [15], at a fixed angle, displaying rapid variation over the region in question. These Mainz data from 560 to 780 MeV are reasonably well reproduced (χ² = 106/76), though not included in our analysis.

B. Comparing SAID to MAID

While the SAID and MAID analyses are qualitatively similar from threshold to 1 GeV, some significant differences exist and these have been mentioned in a recent multi-analysis study which fitted to a benchmark dataset [46]. While some multipoles show significant differences, the photo-decay amplitudes from MAID and SM95 are quite similar, with larger differences between the MAID and SM02 solutions. The data fit quality shows greater variability and a few cases are given below.
The measurement of $\Sigma$ for $\pi^0 p$ at threshold (160 MeV) has been discussed in [47,48] and is particularly sensitive (Fig. 4). The plotted curves differ mainly in the P-wave multipoles. Our SES at 162 MeV, which covers $158 - 165$ MeV (see Table IV), fits the new Mainz data [13] rather well, while the energy-dependent MAID2000 and SM02 solutions are less successful.

At higher energies, close to the upper limit of MAID, new $\pi^+ n$ $\Sigma$ measurements, shown in Fig. 4, are clearly problematic. This has been used to suggest a change in the N(1650) photo-decay amplitude [24].

For the forward peaking in $\pi^+ n$ unpolarized differential cross sections, displayed in Fig. 6, the disagreement between SAID and MAID results reaches as much as 30%. In the SAID fits, some of these problems are resolved once systematic uncertainties are taken in account.

The double-polarization quantity $\vec{\gamma} \vec{p} \rightarrow \pi^0 p$, measured in the A2 Collaboration GDH experiment [13] and displayed in Fig. 2, is well described by both MAID2001 and SAID solution SM02. At higher energies, deviations become more apparent (as was also shown in Fig. 3) CLAS at JLab [56], ELSA at Bonn [57], SPring–8 at Hyogo [58], and LEGS at Brookhaven [59] have further programs underway to study this process.

In Fig. 8, we compare our results with the MAID analysis [44] where more substantial differences are seen for the $S_{11}pE$, $P_{33}pE$, $P_{31}pM$, and $D_{13}pE$ multipoles.

We have fitted our multipoles using a simple Breit-Wigner plus background function, as described in Ref. [6]. We have employed both single-energy and energy-dependent solutions over a variety of energy ranges in order to estimate uncertainties. A listing of our resonance couplings is given in Table VI. Here, values for the resonance mass ($W_R$), full width ($\Gamma$), and the decay width to $\pi N$ final states ($\Gamma_{\pi N}$) were taken from our elastic $\pi N$ analysis [43] and were not varied in the fits and error estimates.

We find that the $S_{11}pE$ ($E_{0+}^{1/2}$) multipole is very sensitive to both the database and parametrization in the range associated with the $N(1535)$. The range of variation, particularly large for the real part of $S_{11}pE$, is displayed in Fig. 2. This sensitivity is not surprising, as the quantity $(\text{Im} T_{\pi N} - T_{2\pi N}^2)$ has a very sharp structure at the $\eta N$ threshold. This variability in the multipole amplitude is reflected in the $N(1535)$ resonance coupling, which we feel is presently too uncertain to quote.

Other couplings significantly altered using the revised parameterization scheme include the $P_{11}(1710)$, which is still essentially undetermined, $P_{31}(1720)$, $S_{31}(1620)$, and $F_{35}(1905)$. The $F_{37}(1950)$ has an easily identifiable magnetic but, essentially no electric multipole. Multipoles associated with the $D_{35}(1930)$ show very little resonance signature.

We were particularly surprised to see a large change in the $\Delta(1232)$ photo-decay amplitudes. Comparison with our SM95 fit shows a significant decrease in cross section at the resonance position. This shift has resulted due to the inclusion of recent Mainz $\pi^0 p$ measurements [11], which are systematically lower (particularly at backward angles) than an older set of Bonn measurements. More recent Mainz fits for MAID2001 [61] give $-133 \pm 4$ and $-252 \pm 6$ (in $10^{-3} GeV^{-1/2}$ units) for $A_{1/2}$ and $A_{3/2}$, respectively. These results have also shifted lower and are consistent with our determination.

2This MAID solution is valid to $W = 1800$ MeV ($E_{\gamma} = 1250$ MeV) [60].
C. Sum Rules

The amplitudes obtained in our analyses can be used to evaluate the single-pion production component of several sum rules. The GDH integral \[ I_{GDH} = \int_{\nu_0}^{\infty} \frac{\sigma_{1/2} - \sigma_{3/2}}{\nu} d\nu = -\frac{\pi e^2}{2M^2} \kappa^2, \] (3)

where \( \sigma_{1/2} \) and \( \sigma_{3/2} \) are the photoabsorption cross sections for the helicity states \( 1/2 \) and \( 3/2 \), respectively, with \( \nu \) being the photon energy. For the proton (neutron) target, Eq. (3) predicts \( -205 \) \((-233) \) mb. The running GDH integrals for the proton and neutron are shown in Fig. 10, where a comparison with MAID is also given.

The Baldin sum rule \[ I_{Baldin} = \frac{1}{2\pi^2} \int_{\nu_0}^{\infty} \frac{\sigma_{tot}}{\nu^2} d\nu = \frac{1}{2\pi^2} \int_{\nu_0}^{\infty} \frac{\sigma_{1/2} + \sigma_{3/2}}{2\nu^2} d\nu. \] (4)

For the proton (neutron) target, the recent dispersion calculations by Levchuk and L’vov give \((14.0 \pm 0.3) \times 10^{-4} \text{fm}^3 \) \((15.2 \pm 0.5) \times 10^{-4} \text{fm}^3 \) [58]. For the proton, an independent Mainz determination gives \((13.8 \pm 0.4) \times 10^{-4} \text{fm}^3 \) [53] and the LEGS group quotes \((13.25 \pm 0.86^{+0.23}_{-0.58}) \times 10^{-4} \text{fm}^3 \) [23]. The isospin averaged nucleon polarizabilities determined by MAX-lab measurements of Compton scattering from the deuteron is \((16.4 \pm 3.6) \times 10^{-4} \text{fm}^3 \) [70]. Running Baldin integrals, with comparisons to MAID, are given in Fig. 11.

The forward spin polarizability \( \gamma_0 \) [71] is

\[ \gamma_0 = \frac{1}{4\pi^2} \int_{\nu_0}^{\infty} \frac{\sigma_{1/2} - \sigma_{3/2}}{\nu^3} d\nu. \] (5)

A recent dressed K-matrix model approach for the proton gives \( \gamma_0 = -0.9 \times 10^{-4} \text{fm}^4 \) [72]. The LEGS analysis gives, for a proton target, \( \gamma_0 = (-1.55 \pm 0.15 \pm 0.003) \times 10^{-4} \text{fm}^4 \) [23]. The running integral is shown in Fig. 12.

For charge states \( \pi^+n \) and \( \pi^-p \), all three quantities are sensitive to the threshold energy range \((E_\gamma < 200 \text{ MeV})\), as shown in Table VII. From Figs. 10–12, one can see that each integral of the single-pion contribution, based upon the SM02 solution, has essentially converged by 2 GeV.

Experimental data for the GDH and \( \gamma_0 \) quantities have been obtained from measurements at MAMI, covering ranges from 200 to 450 MeV [15] and to 800 MeV [10]. In Tables VIII and IX we show SM02 and MAID results for the abovementioned quantities over energy ranges corresponding to measurements. Clearly, calculations above 450 MeV have to take into account contributions beyond single-pion photoproduction.

IV. SUMMARY AND CONCLUSION

The single-pion photoproduction database, for proton targets, has increased significantly since the publication of our fit SM95. The inclusion of these precise new measurements has
resulted in a fit with a lower overall $\chi^2$/data. However, some polarization quantities have been difficult to fit, and these difficulties have prompted an examination of the phenomenological forms we use. By changing the way we extrapolate beyond the two-pion threshold, an improved fit was obtained.

This new multipole solution was found to differ significantly from SM95 in a number of partial waves. The largest changes were associated with multipoles connected to $\pi N$ resonances with $\Gamma_\pi/\Gamma \lesssim 0.3$. Also quite different was the $S_{11}$ multipole, for which the associated $\pi N$ inelasticity has a sharp increase at the $\eta N$ threshold. As might be expected, states with large $\pi N$ branching fractions remained stable. This stability held for the $N(1520)$ as well, though investigations based upon $\eta N$ photoproduction, and quantities related to the GDH integral, have suggested a shift in its ratio of photo-decay amplitudes. Given the sensitivity of weaker resonances to the choice of phenomenology, we are now attempting to replace the dependence on $(\text{Im} T_{\pi N} - T_{\pi N}^2)$ with a form more directly connected to the opening of specific channels, such as $\eta N$ and $\pi \Delta$.

The evaluation of sum rules (GDH, Baldin, and forward spin polarizability) for a single-pion contribution exhibits convergence by 2 GeV. Agreement with Mainz is now good below 450 MeV, with larger deviations at higher energies.

In both $\pi N$ elastic scattering [73] and pion photoproduction [24,39], the measurements of precise new single- and double-polarization data have highlighted problems existing in the “standard” fits. Further polarization measurements will be required to test assumptions implicit in the SAID and MAID programs.

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### TABLE I. Comparison of present (SM02) and previous (SM95, SP93, and SP89) energy-dependent partial-wave analyses of charged and neutral pion photoproduction data. The $\chi^2$ values for the previous solutions correspond to our published results. $N_{prm}$ is the number parameters varied in the fit.

| Solution | Range (MeV) | $\chi^2/\pi^0p$ | $\chi^2/\pi^+n$ | $\chi^2/\pi^-p$ | $\chi^2/\pi^0n$ | $N_{prm}$ |
|----------|-------------|-----------------|-----------------|-----------------|-----------------|-----------|
| SM02     | 2000        | 18686/8092      | 12246/7279      | 4123/2080       | 241/120         | 148       |
| SM95     | 2000        | 13087/4711      | 12284/6359      | 6156/2225       | 282/120         | 135       |
| SP93     | 1800        | 14093/4015      | 22426/6019      | 8280/2312       | 275/120         | 134       |
| SP89     | 1000        | 13073/3241      | 11092/3847      | 4947/1728       | 461/120         | 97        |

### TABLE II. Comparison of $\chi^2$/data for normalized (Norm) and unnormalized (Unnorm) data for SM02 solution.

| Data     | Norm | Unnorm |
|----------|------|--------|
| $\pi^0p$ | 2.3  | 3.8    |
| $\pi^+n$ | 1.7  | 2.7    |
| $\pi^-p$ | 2.0  | 2.6    |
| $\pi^0n$ | 2.0  | 2.0    |

### TABLE III. Comparison of $\chi^2$/data for the SM02 solution over the 600–900 MeV range, associated with the N(1535), versus full database and more recent measurements.

| Reaction | Observable | All     | 1980–Present | 1985–Present |
|----------|------------|---------|--------------|--------------|
| $\pi^0p$ | $d\sigma/d\Omega$ | 3946/1644 | 1808/992 | 1211/903 |
|          | $\Sigma$   | 479/179 | 345/122 | 277/105 |
|          | $P$        | 361/181 | 177/103 | 56/33 |
|          | $T$        | 376/72  | 2/2     | 2/2     |
| $\pi^+n$ | $d\sigma/d\Omega$ | 1343/1407 | 768/930 | 349/596 |
|          | $\Sigma$   | 954/251 | 594/134 | 565/112 |
|          | $P$        | 158/62  | 5/5     | –       |
|          | $T$        | 437/228 | 44/60   | 44/60   |
TABLE IV. Single-energy (binned) fits of combined charge and neutral pion photoproduction data, with \( \chi^2 \) values. \( N_{prm} \) is the number parameters varied in the single-energy fits, and \( \chi^2_E \) is given by the energy-dependent fit, SM02, over the same energy interval.

| \( E_\gamma \) (MeV) | Range (MeV) | \( N_{prm} \) | \( \chi^2/\text{data} \) | \( \chi^2_E \) | \( E_\gamma \) (MeV) | Range (MeV) | \( N_{prm} \) | \( \chi^2/\text{data} \) | \( \chi^2_E \) |
|----------------------|-------------|----------------|----------------|-----------------|----------------------|-------------|----------------|----------------|----------------|
| \( \gamma \) | \( \gamma \) | \( \gamma \) | \( \gamma \) | \( \gamma \) | \( \gamma \) | \( \gamma \) | \( \gamma \) | \( \gamma \) | \( \gamma \) |
| Reaction | Observable    | SM95     | SM02     | SX99     | Data  |
|----------|--------------|----------|----------|----------|-------|
| \(\pi^0 p\) | \(d\sigma/d\Omega\) | 32235    | 12681    | 12745    | 5523  |
|          | \(\sigma_{tot}\) | 1577     | 1331     | 1681     | 713   |
|          | \(\sigma_{1/2} - \sigma_{3/2}\) | 7        | 10       | 10       | 13    |
|          | \(\Sigma\)  | 3238     | 1918     | 1975     | 772   |
|          | \(P\)       | 1269     | 1390     | 1393     | 576   |
|          | \(T\)       | 1499     | 1651     | 1678     | 389   |
| \(\pi^+ n\) | \(d\sigma/d\Omega\) | 7587     | 6364     | 6952     | 4995  |
|          | \(\sigma_{tot}\) | 132      | 70       | 84       | 76    |
|          | \(\sigma_{1/2} - \sigma_{3/2}\) | 147      | 29       | 67       | 13    |
|          | \(\Sigma\)  | 8672     | 2881     | 3780     | 1047  |
|          | \(P\)       | 512      | 471      | 430      | 250   |
|          | \(T\)       | 1678     | 1512     | 1854     | 694   |
| \(\pi^- p\) | \(d\sigma/d\Omega\) | 3702     | 3098     | 3118     | 1570  |
|          | \(\sigma_{tot}\) | 227      | 157      | 165      | 117   |
|          | \(\Sigma\)  | 541      | 600      | 576      | 216   |
|          | \(P\)       | 159      | 144      | 161      | 88    |
|          | \(T\)       | 117      | 157      | 129      | 96    |

TABLE V. Comparison of \(\chi^2\) for the SM95 [5], SM02, and SX99 solutions to 2 GeV versus the present database. Only a fraction of this database was used in generating SM95.
TABLE VI. Resonance couplings from a Breit-Wigner fit to the SM02 solution [GW] and SES [GWSES] (to illustrate the difference, we include $D_{35}(1930)$ and $D_{37}(1950)$ twice, once with the GWSES database and once with the GW (global fit) database), our previous solution SM95 [VPI], the analysis of Crawford and Morton [CM83], Crawford [CR01], Drechsel et al. [MAID98], an average from the Particle Data Group [PDG], and quark model predictions of Capstick [CAP92].

| Resonance State | Reference | $\gamma p(\text{GeV})^{-1/2} \times 10^{-3}$ | $\gamma n(\text{GeV})^{-1/2} \times 10^{-3}$ |
|-----------------|-----------|---------------------------------|---------------------------------|
| $S_{11}(1650)$  | GWSES     | $74 \pm 1$                      | $-28 \pm 4$                     |
| $\Gamma/\Gamma = 0.77$ | VPI       | $69 \pm 5$                      | $-15 \pm 5$                     |
| $\Gamma = 191 \text{ MeV}$ | CM83      | $33 \pm 15$                     | $-68 \pm 40$                    |
|                 | CR01      | $71$                            |                                 |
|                 | MAID98    | $39$                            | $-32$                           |
|                 | PDG       | $53 \pm 16$                     | $-15 \pm 21$                    |
|                 | CAP92     | $54$                            | $-35$                           |
| $P_{11}(1440)$  | GWSES     | $-67 \pm 2$                     | $47 \pm 5$                      |
| $\Gamma/\Gamma = 0.64$ | VPI       | $-63 \pm 5$                     | $45 \pm 15$                     |
| $\Gamma = 434 \text{ MeV}$ | CR01      | $-88$                           |                                 |
|                 | MAID98    | $-71$                           | $60$                            |
|                 | PDG       | $-65 \pm 4$                     | $40 \pm 10$                     |
|                 | CAP92     | $4$                             | $-6$                            |
| $D_{13}(1520)$  | GWSES     | $-24 \pm 2$                     | $135 \pm 2$                     |
| $\Gamma/\Gamma = 0.63$ | VPI       | $-20 \pm 7$                     | $167 \pm 5$                     |
| $\Gamma = 109 \text{ MeV}$ | CM83      | $-28 \pm 14$                    | $156 \pm 22$                    |
|                 | CR01      | $-15$                           | $162$                           |
|                 | MAID98    | $-17$                           | $164$                           |
|                 | PDG       | $-24 \pm 9$                     | $166 \pm 5$                     |
|                 | CAP92     | $-15$                           | $134$                           |
|                 |           | $9 \pm 3$                       | $-59 \pm 9$                     |
|                 |           | $-38$                           | $-139 \pm 11$                   |
| $D_{15}(1675)$  | GWSES     | $33 \pm 4$                      | $9 \pm 3$                       |
| $\Gamma/\Gamma = 0.39$ | VPI       | $15 \pm 10$                     | $10 \pm 7$                      |
| $\Gamma = 144 \text{ MeV}$ | CM83      | $21 \pm 11$                     | $15 \pm 9$                      |
|                 | CR01      | $13$                            | $38$                            |
|                 | MAID98    | $-$                             | $-40$                           |
|                 | PDG       | $19 \pm 8$                      | $15 \pm 9$                      |
|                 | CAP92     | $2$                             | $3$                             |
|                 |           | $-35$                           | $-58 \pm 13$                    |
| $F_{15}(1680)$  | GWSES     | $-13 \pm 2$                     | $129 \pm 2$                     |
| $\Gamma/\Gamma = 0.68$ | VPI       | $-10 \pm 4$                     | $145 \pm 5$                     |
| $\Gamma = 120 \text{ MeV}$ | CM83      | $-17 \pm 18$                    | $132 \pm 10$                    |
|                 | CR01      | $-14$                           | $135$                           |
|                 | MAID98    | $-10$                           | $138$                           |

$10^{-3}$
|        | PDG         | CAP92       | GWSES       | CM83       | CR01       | MAID98     | PDG         | CAP92       |
|--------|-------------|-------------|-------------|------------|------------|------------|-------------|-------------|
|        | $-15\pm6$  | $-38$       | $133\pm12$  | $29\pm10$  | $-33\pm9$  |            |             |             |
| $S_{31}(1620)$ |            |             |             |            |            |            |             |             |
| $W_R = 1612\ MeV$ |            |             | VPI $35\pm20$ |            |            |            |             |             |
| $\Gamma_\pi/\Gamma = 0.34$ |            |             | CM83 $35\pm10$ |            |            |            |             |             |
| $\Gamma = 117\ MeV$ |            |             | CR01 $17$ |            |            |            |             |             |
| $MAID98$ |            |             |             |            |            |            | PDG $27\pm11$ |             |
|        |            |             | GWSES $-13\pm3$ |            |            |            |             |             |
| $P_{33}(1232)$ |            |             | VPI $141\pm5$ | $-261\pm5$ |            |            |             |             |
| $W_R = 1235\ MeV$ |            |             | CM83 $-145\pm15$ | $-263\pm26$ |            |            |             |             |
| $\Gamma_\pi/\Gamma = 1.00$ |            |             | CR01 $-149$ | $-259$ |            |            |             |             |
| $\Gamma = 119\ MeV$ |            |             | VPI $-138$ | $-256$ |            |            |             |             |
| $MAID98$ |            |             | PDG $-135\pm6$ | $-255\pm8$ |            |            |             |             |
|        |            |             | GWSES $-129\pm1$ | $-243\pm1$ |            |            |             |             |
| $D_{33}(1700)$ |            |             | GWSES $92\pm7$ | $-243\pm1$ |            |            |             |             |
| $W_R = 1668\ MeV$ |            |             | VPI $90\pm25$ | $97\pm20$ |            |            |             |             |
| $\Gamma_\pi/\Gamma = 0.16$ |            |             | CM83 $111\pm17$ | $107\pm15$ |            |            |             |             |
| $\Gamma = 300\ MeV$ |            |             | CR01 $79$ | $90$ |            |            |             |             |
| $MAID98$ |            |             | GWSES $86$ | $85$ |            |            |             |             |
|        |            |             | CM83 $111\pm17$ | $107\pm15$ |            |            |             |             |
| $D_{35}(1930)$ |            |             | CR01 $8$ | $8$ |            |            |             |             |
| $F_{35}(1905)$ |            |             | VPI $-7\pm10$ | $5\pm10$ |            |            |             |             |
| $W_R = 2113\ MeV$ |            |             | CM83 $-38\pm47$ | $-23\pm80$ |            |            |             |             |
| $\Gamma_\pi/\Gamma = 0.14$ |            |             | CR01 $8$ | $8$ |            |            |             |             |
| $\Gamma = 524\ MeV$ |            |             |            |            |            |            | PDG $-9\pm28$ | $-18\pm28$ |
| $MAID98$ |            |             | GWSES $4\pm6$ | $-3\pm6$ |            |            |             |             |
|        |            |             |            |            |            |            | PDG $-9\pm28$ | $-18\pm28$ |
|        |            |             |            |            |            |            | CAP92 $-2$ | $-1$ |
| $F_{37}(1950)$ |            |             |            |            |            |            | PDG $26\pm11$ | $-45\pm20$ |
| $W_R = 1845\ MeV$ |            |             | VPI $22\pm5$ | $-45\pm5$ |            |            |             |             |
| $\Gamma_\pi/\Gamma = 0.13$ |            |             | CM83 $21\pm10$ | $-56\pm28$ |            |            |             |             |
| $\Gamma = 300\ MeV$ |            |             | CR01 $17$ | $-18$ |            |            |             |             |
| $MAID98$ |            |             |            |            |            |            | PDG $26\pm11$ | $-45\pm20$ |
|        |            |             |            |            |            |            | CAP92 $26$ | $-1$ |
| $F_{37}(1950)$ |            |             | GWSES $-62\pm4$ | $-80\pm3$ |            |            |             |             |
\[ W_R = 1929 \text{ MeV} \]
\[ \Gamma_\pi/\Gamma = 0.49 \]
\[ \Gamma = 274 \text{ MeV} \]

\begin{array}{lcc}
\text{GW} & -64 \pm 4 & -83 \pm 4 \\
\text{VPI} & -79 \pm 6 & -103 \pm 6 \\
\text{CM83} & -67 \pm 14 & -82 \pm 17 \\
\text{CR01} & -59 & -62 \\
\text{MAID98} & - & - \\
\text{PDG} & -76 \pm 12 & -97 \pm 10 \\
\text{CAP92} & -33 & -42 \\
\end{array}

\textbf{TABLE VII.} Comparison of the SM02 and recent MAID2000 \cite{44} calculations for the GDH and Baldin integrals and the forward spin polarizability from threshold to 2 GeV (for MAID to 1.25 GeV) [upper set] and from threshold to 200 MeV [lower set] displayed as SAID/MAID.

| Reaction | GDH \((\mu b)\) | Baldin \(10^{-4} fm^3\) | \(\gamma_0\) \(10^{-4} fm^4\) |
|---------|----------------|-----------------|----------------|
| \(\pi^0p\) | -142/-150 | 4.7/4.7 | -1.40/-1.47 |
| \(\pi^+n\) | -45/-18 | 6.8/6.9 | 0.55/ 0.79 |
| \(\pi^0n\) | -148/-153 | 4.6/4.6 | -1.44/-1.50 |
| \(\pi^-p\) | 11/ 33 | 8.3/8.8 | 1.36/ 1.64 |
| \(\pi^0p\) | -2/-1 | 0.1/0.1 | -0.05/-0.04 |
| \(\pi^+n\) | 30/ 32 | 1.2/1.2 | 0.99/ 1.02 |
| \(\pi^0n\) | -1/-1 | 0.1/0.1 | -0.04/-0.04 |
| \(\pi^-p\) | 42/ 47 | 1.7/1.8 | 1.39/ 1.53 |
TABLE VIII. Comparison of the SM02 and recent MAID2000 [44] calculations, and recent Mainz data [15] for the GDH and Baldin integrals and the forward spin polarizability for proton and neutron targets from 200 to 450 MeV. Units are $\mu b$, $10^{-4} fm^3$, and $10^{-4} fm^4$ for the GDH and Baldin integrals and polarizability, respectively.

| Integral | Reaction | SAID | MAID  | Mainz       |
|----------|----------|------|-------|-------------|
| GDH      | $\pi^0p$ | −129 | −136  | $-144\pm7\pm9$ |
|          | $\pi^+n$ | −42  | −25   | $-32\pm3\pm2$ |
|          | proton   | −171 | −161  | $-176\pm8\pm11$ |
|          | $\pi^-p$ | −14  | −1    |             |
|          | $\pi^0n$ | −135 | −139  |             |
|          | neutron  | −149 | −140  |             |
| Baldin   | $\pi^0p$ | 4.0  | 4.0   |             |
|          | $\pi^+n$ | 4.5  | 4.6   |             |
|          | proton   | 8.5  | 8.6   |             |
|          | $\pi^-p$ | 5.5  | 5.9   |             |
|          | $\pi^0n$ | 3.9  | 4.0   |             |
|          | neutron  | 9.5  | 9.8   |             |
| $\gamma_0$ | $\pi^0p$ | −1.31 | −1.39 | $-1.45\pm0.09\pm0.09$ |
|          | $\pi^+n$ | −0.39 | −0.21 | $-0.23\pm0.04\pm0.01$ |
|          | proton   | −1.71 | −1.61 | $-1.68\pm0.10\pm0.10$ |
|          | $\pi^-p$ | −0.05 | 0.11  |             |
|          | $\pi^0n$ | −1.35 | −1.40 |             |
|          | neutron  | −1.41 | −1.29 |             |

TABLE IX. Comparison of the SM02 and recent MAID2000 [44] calculations, and recent Mainz data [16] for the GDH and Baldin integrals and the forward spin polarizability for proton and neutron targets from 200 to 800 MeV. Units are $\mu b$, $10^{-4} fm^3$, and $10^{-4} fm^4$ for the GDH and Baldin integrals and polarizability, respectively.

| Integral | Reaction | SAID | MAID  | Mainz       |
|----------|----------|------|-------|-------------|
| GDH      | proton   | −193 | −175  | $-226\pm5\pm12$ |
|          | neutron  | −167 | −160  |             |
| Baldin   | proton   | 9.8  | 9.9   |             |
|          | neutron  | 10.9 | 11.3  |             |
| $\gamma_0$ | proton | −1.76 | −1.63 | $-1.87\pm0.08\pm0.10$ |
|          | neutron  | −1.46 | −1.34 |             |
Figure captions

Figure 1. Energy-angle distribution of recent (post-1995) data: (a) unpolarized $\pi^0p$, (b) polarized $\pi^0p$, (c) unpolarized $\pi^+n$, (d) polarized $\pi^+n$. (a,c) total cross sections and (b,d) $(\sigma_{1/2} - \sigma_{3/2})$ are plotted at zero degrees.

Figure 2. Partial-wave amplitudes ($L_{2f,2f}$) from threshold to $E_\gamma = 2$ GeV. Solid (dashed) curves give the real (imaginary) parts of amplitudes corresponding to the SM02 solution. The real (imaginary) parts of single-energy solutions are plotted as filled (open) circles. The previous SM95 solution \[44\] is plotted with long dash-dotted (real part) and short dash-dotted (imaginary part) lines. Plotted are the multipole amplitudes (a) $pE_{1/2}^0$, (b) $nE_{0+}^1$, (c) $pE_{1/2}^3$, (d) $pM_{1/2}^1$, (e) $nM_{1/2}^1$, (f) $pE_{1+}^1$, (g) $pM_{1/2}^1$, (h) $nE_{1/2}^1$, (i) $nM_{1/2}^1$, (j) $pM_{1/2}^3$, (k) $pE_{1+}^3$, (l) $pM_{1+}^3$, (m) $pM_{2-}^3$, (n) $pM_{1/2}^3$, (o) $nE_{2-}^3$, (p) $nM_{2-}^3$, (q) $pE_{2-}^3$, (r) $pE_{2+}^3$, (s) $pE_{3-}^3$, (t) $pM_{3-}^3$, (u) $nE_{3-}^3$, (v) $nM_{3-}^3$, (w) $pE_{3+}^3$, and (x) $pM_{3+}^3$. The subscript p (n) denotes a proton (neutron) target.

Figure 3. Differential cross section ($d\sigma/d\Omega_{1/2} - d\sigma/d\Omega_{3/2}$) for $\gamma\vec{p}\rightarrow \pi^0p$ at $\theta = 85 \pm 4^\circ$. The solid (dash-dotted) line plots the SM02 (MAID2001 [44]) solution. Experimental data are from Mainz [15].

Figure 4. Photon asymmetry for $\pi^0$ photoproduction on the proton at 159.5 MeV. Data are from Mainz (solid circles) [19]. Plotted are the SM02 (solid line), the 162 MeV-SES (158 – 165 MeV) fit associated with SM02 (dotted lines represent uncertainties of the SES fit) and the MAID2000 results (dash-dotted) [44].

Figure 5. $\Sigma$ beam asymmetry for $\pi^+n$ at 1100 MeV. Black circles show GRAAL results [23], open circles indicate the results of the Daresbury group [49], open triangles indicate the results from Saclay [50]. The solid (dash-dotted) line represents the SM02 (MAID2001 [44]) solution.

Figure 6. Forward ($5^\circ$) differential cross section for $\gamma p \rightarrow \pi^+n$ as a function of energy. Experimental data for the range of $5 \pm 2^\circ$ are from Orsay [21] (black circles), SLAC [52] (open circles), [53] (open triangles), [54] (black square), and DESY [55] (black diamonds.) The solid (dash-dotted) line represents the SM02 (MAID2001 [44]) solution.

Figure 7. Difference of the total cross sections for the helicity states 1/2 and 3/2. (a) $\vec{\gamma}\vec{p}\rightarrow \pi^0p$ and (b) $\vec{\gamma}\vec{p}\rightarrow \pi^+n$. The solid (dash-dotted) line represents the SM02 (MAID2001 [44]) solution. Experimental data are from Mainz [15].

Figure 8. Selected partial-wave amplitudes to $E_\gamma = 1250$ MeV. Solid (dashed) curves give the real (imaginary) parts of amplitudes corresponding to the SM02 solution. The recent MAID2001 solution [44] is plotted with long dash-dotted (real part) and short dash-dotted (imaginary part) lines. Plotted are the multipole amplitudes (a) $S_{11}pE_{1/2}^0$, (b) $P_{13}pE_{1+}^1$, (c) $P_{31}pM_{1/2}^3$, and (d) $D_{13}pE_{2+}^3$. The subscript p (n) denotes a proton (neutron) target.
Figure 9. $S_{11pE}$ multipole for 600 to 1200 MeV. Plotted are (a) real part and (b) imaginary part. The SM02 (SX99) solution is plotted with a solid (dashed) line and previous SM95 solution [5] with a dash-dotted line.

Figure 10. Running GDH integral. (a) for proton and (b) neutron targets. The solid (dash-dotted) line represents the SM02 (MAID2000 [44]) solution.

Figure 11. Running Baldin integral. (a) for proton and (b) neutron targets. The solid (dash-dotted) line represents the SM02 (MAID2000 [44]) solution.

Figure 12. Forward spin polarizability $\gamma_0$. (a) for proton and (b) neutron targets. The solid (dash-dotted) line represents the SM02 (MAID2000 [44]) solution.
FIG. 1. Energy-angle distribution of recent (post-1995) data: (a) unpolarized $\pi^0 p$, (b) polarized $\pi^0 p$, (c) unpolarized $\pi^+ n$, (d) polarized $\pi^+ n$. (a,c) total cross sections and (b,d) $(\sigma_{1/2} - \sigma_{3/2})$ are plotted at zero degrees.
FIG. 2. Partial-wave amplitudes \((L_{2f,2f})\) from threshold to \(E_\gamma = 2\) GeV. Solid (dashed) curves give the real (imaginary) parts of amplitudes corresponding to the SM02 solution. The real (imaginary) parts of single-energy solutions are plotted as filled (open) circles. The previous SM95 solution is plotted with long dash-dotted (real part) and short dash-dotted (imaginary part) lines. Plotted are the multipole amplitudes (a) \(pE_{1/2}^0\), (b) \(nE_{1/2}^0\), (c) \(pE_{3/2}^0\), (d) \(pM_{1/2}^1\), (e) \(nM_{1/2}^1\), (f) \(pE_{1/2}^1\), (g) \(pM_{1/2}^1\), (h) \(nE_{1/2}^1\), (i) \(nM_{1/2}^1\), (j) \(pM_{3/2}^1\), (k) \(pE_{1/2}^3\), (l) \(pM_{1/2}^3\), (m) \(pE_{3/2}^3\), (n) \(pM_{2/2}^3\), (o) \(nE_{2/2}^3\), (p) \(nM_{2/2}^3\), (q) \(pE_{3/2}^3\), (r) \(pE_{2/2}^3\), (s) \(pE_{3/2}^3\), (t) \(pM_{3/2}^3\), (u) \(nE_{3/2}^3\), (v) \(nM_{3/2}^3\), (w) \(pE_{3/2}^3\), and (x) \(pM_{3/2}^3\). The subscript \(p\) (n) denotes a proton (neutron) target.
FIG. 3. Differential cross section \((d\sigma/d\Omega_{1/2} - d\sigma/d\Omega_{3/2})\) for \(\gamma p \rightarrow \pi^0 p\) at \(\theta = 85 \pm 4^\circ\). The solid (dash-dotted) line plots the SM02 (MAID2001 [44]) solution. Experimental data are from Mainz [45].

FIG. 4. Photon asymmetry for \(\pi^0\) photoproduction on the proton at 159.5 MeV. Data are from Mainz (solid circles) [19]. Plotted are the SM02 (solid line), the 162 MeV-SES (158 – 165 MeV) fit associated with SM02 (dotted lines represent uncertainties of the SES fit) and the MAID2000 results (dash-dotted) [44].
FIG. 5. $\Sigma$ beam asymmetry for $\pi^+n$ at 1100 MeV. Black circles show GRAAL results [25], open circles indicate the results of the Daresbury group [49], open triangles indicate the results from Saclay [50]. The solid (dash-dotted) line represents the SM02 (MAID2001 [44]) solution.

FIG. 6. Forward (5°) differential cross section for $\gamma p \rightarrow \pi^+n$ as a function of energy. Experimental data for the range of $5\pm 2^\circ$ are from Orsay [51] (black circles), SLAC [52] (open circles), [53] (open triangles), [54] (black square), and DESY [55] (black diamonds.) The solid (dash-dotted) line represents the SM02 (MAID2001 [44]) solution.
FIG. 7. Difference of the total cross sections for the helicity states 1/2 and 3/2. (a) $\gamma p \rightarrow \pi^0 p$ and (b) $\gamma p \rightarrow \pi^+ n$. The solid (dash-dotted) line represents the SM02 (MAID2001 [44]) solution. Experimental data are from Mainz [15].
FIG. 8. Selected partial-wave amplitudes to $E_\gamma = 1250$ MeV. Solid (dashed) curves give the real (imaginary) parts of amplitudes corresponding to the SM02 solution. The recent MAID2001 solution [44] is plotted with long dash-dotted (real part) and short dash-dotted (imaginary part) lines. Plotted are the multipole amplitudes (a) $S_{11}pE \left[ pE_{1/2}^{0+} \right]$, (b) $P_{13}pE \left[ pE_{1/2}^{1+} \right]$, (c) $P_{31}pM \left[ pM_{3/2}^{1-} \right]$, and (d) $D_{13}pE \left[ pE_{2-}^{1/2} \right]$. The subscript $p$ ($n$) denotes a proton (neutron) target.

FIG. 9. $S_{11}pE$ multipole for 600 to 1200 MeV. Plotted are (a) real part and (b) imaginary part. The SM02 (SX99) solution is plotted with a solid (dashed) line and previous SM95 solution [5] with a dash-dotted line.
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FIG. 11. Running Baldin integral. (a) for proton and (b) neutron targets. The solid (dash-dotted) line represents the SM02 (MAID2000 [44]) solution.

FIG. 12. Forward spin polarizability $\gamma_0$. (a) for proton and (b) neutron targets. The solid (dash-dotted) line represents the SM02 (MAID2000 [44]) solution.