The MAID Legacy and Future

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Abstract The MAID project is a collection of theoretical models for pseudoscalar meson photo- and electroproduction from nucleons. It is online available and produces results in real time calculations. In addition to kinematical variables also model parameters, especially for baryon resonances, can be online changed and investigated. Over 20 years MAID has become quite popular and the MAID web pages have been called more than 7.7 million times.

Keywords pion electroproduction · baryon resonances · transition form factors

1 Introduction

After the exploration of the baryonic spectrum with pion scattering in the 1980s, photo- and electroproduction of mesons, mainly at Mainz, Bonn and JLab have become the main source of further investigations of $N$ and $\Delta$ resonances. Among them, pion electroproduction is the main source for investigations of the transition form factors of the nucleon to excited $N$ and $\Delta$ baryons. In addition also two-pion and eta electroproduction have been very useful for studies of selected nucleon resonances. After early measurements of the $G_M^{\ast}$ form factor of the $N \rightarrow \Delta(1232)$ transition already in the 1960s, in the 1990s a large program was running at Mainz, Bonn, Bates and JLab in order to measure the very small $E/M$ ratio of the $N \rightarrow \Delta$ transition and the $Q^2$ dependence of the $E/M$ and $S/M$ ratios in order to get information on the internal quadrupole deformation of the nucleon and the $\Delta$. In parallel large progress was achieved in various kinds of quark models that gave predictions for $N \rightarrow N^*$ and $N \rightarrow \Delta^*$ transition form factors. Only at JLab both the energy and the photon virtuality were available to measure those form factors for a set of nucleon resonances up to $Q^2 \approx 5$ GeV$^2$. Two recent review articles on the electromagnetic excitation of nucleon resonances give a very good overview over experiment and theory and latest developments [1] [2].

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2 The MAID project

The first MAID program appeared in 1998 for pion photo- and electroproduction on the nucleon [3]. It was extended and updated with new data in the years 2000 and 2003. A major update was published in 2007 [4] and covers an energy range from threshold until $W = 2$ GeV and photon virtualities up to $Q^2 = 5$ GeV$^2$. A whole series of transition form factors was analyzed both as single-$Q^2$ data points and in a $Q^2$-dependent analysis with simple polynomial and exponential parameterizations [1]. Soon afterwards the Dubna-Mainz-Taipei (DMT) dynamical model [5] was going online. The DMT model has since proven an enormous predictive power for pion photo- and electroproduction from threshold up to the $\Delta(1232)$ resonance. Beyond the $\Delta(1232)$ the DMT model is very similar to the unitary isobar model MAID. At the same time also the isobar models KaonMAID [6] and EtaMAID [7] were developed. The online KaonMAID has not yet been updated, but extensions and updates have been published over the time until very recently [8]. The EtaMAID was extended in 2003 with a Regge background approach [9]. Also EtaprimeMAID2003 was established [9], but was not further updated until now. In 2007 the TwoPionMAID joined the project, an isobar model for two-pion photoproduction on the nucleon [10]. Finally, a chiral effective theory approach, ChiralMAID [11], where all low-energy constants were fitted to the world data of pion threshold production, was added, which is applicable for neutral and charged pion photo- and electroproduction in the threshold region until the onset of the $\Delta(1232)$ resonance and photon virtualities of $Q^2 \leq 0.15$ GeV$^2$.

The welcome page of the MAID programs on https://maid.kph.uni-mainz.de/ is

**Fig. 1** The MAID project on the Mainz web site https://maid.kph.uni-mainz.de/. Since the start of MAID98 in 1998, the programs have been called more than 7.7 million times.
shown in Fig. 1. In Fig. 2 a sketch of the nucleon response to space-like virtual photons is shown. Besides elastic scattering and real- and virtual Compton scattering, the meson production processes dominate the response. At low $Q^2$ the $\Delta(1232)$ is the major player, but its contribution drops faster than the dipole form factor, therefore other resonances are more pronounced at higher $Q^2$. In the time-like region meson production and transition form factors are also accessible by experiment via the Dalitz decays until the so-called pseudo-threshold, $Q^2_{pt} = -(M_{N^*} - M_N)^2$, which is at $\{-0.086, -0.252, -0.55\}$ GeV$^2$ at the resonance positions of the $\Delta(1232)3/2^+, N(1440)1/2^+, N(1680)5/2^+$ resonances, respectively. Beyond the pseudo-threshold, the time-like region becomes unphysical and opens again at $Q^2_{pt} = -(M_{N^*} + M_N)^2 < -4$ GeV$^2$.

Fig. 2  Meson electroproduction and space-like baryon resonance excitations.

3 The MAID ansatz

In the spirit of a dynamical approach to pion photo- and electroproduction, the $t$-matrix of the unitary isobar model MAID is set up by the ansatz

$$t_{\gamma\pi}(W) = t^B_{\gamma\pi}(W) + t^R_{\gamma\pi}(W),$$

with a background and a resonance $t$-matrix, each of them constructed in a unitary way. Of course, this ansatz is not unique. However, it is a very important prerequisite to clearly separate resonance and background amplitudes within a Breit-Wigner concept also for higher and overlapping resonances.

For a specific partial wave $\alpha = \{j, l, \ldots\}$, the background $t$-matrix is set up by a potential multiplied by the pion-nucleon scattering amplitude in accordance with
the K-matrix approximation,
\[ t^{B,\alpha}_{\gamma}(W, Q^2) = \nu^{B,\alpha}_{\gamma}(W, Q^2) [1 + i t^{\pi N}_{\gamma}(W)]. \]  
where only the on-shell part of pion-nucleon rescattering is maintained and the off-shell part from pion-loop contributions is neglected. Whereas this approximation would fail near the threshold for \( \gamma, \pi^0 \), it is well justified in the resonance region because the main contribution from pion-loop effects is absorbed by the nucleon resonance dressing.

The background potential \( v^{B,\alpha}_{\gamma}(W, Q^2) \) is described by Born terms obtained with an energy-dependent mixing of pseudovector-pseudoscalar \( \pi NN \) coupling and \( t \)-channel vector meson exchanges. The mixing parameters and coupling constants are determined by an analysis of non-resonant multipoles in the appropriate energy regions [3]. In the latest version MAID2007 [4], the \( S, P, D, F \) waves of the background contributions are unitarized as explained above, with the pion-nucleon elastic scattering amplitudes, \( t^{\pi N}_{\gamma} = [\eta_\alpha \exp(2i\delta_\alpha) - 1]/2i \), described by phase shifts \( \delta_\alpha \) and the inelasticity parameters \( \eta_\alpha \) taken from the GWU/SAID analysis [12].

For the resonance contributions Breit-Wigner forms for the resonance shape are assumed, following Ref. [3]
\[ t^{R,\alpha}_{\gamma}(W, Q^2) = A^{R}_{\alpha}(W, Q^2) \frac{f_{\gamma N}(W) \Gamma_{\text{tot}}(W) M_R f_{\pi N}(W)}{M_R^2 - W^2 - iM_R \Gamma_{\text{tot}}(W)} e^{i\phi_R(W)}, \]  
where \( f_{\pi N}(W) \) is the usual Breit-Wigner factor describing the decay of a resonance with total width \( \Gamma_{\text{tot}}(W) \), partial \( \pi N \) width \( \Gamma_{\pi N}(W) \), and spin \( j \),
\[ f_{\pi N}(W) = C_{\pi N} \left[ \frac{\kappa(W) M_N \Gamma_{\pi N}(W)}{(2j + 1) \pi q(W) M_R \Gamma_{\text{tot}}^2(W)} \right]^{1/2}. \]

The energy dependence of the partial widths and of the \( \gamma NN^* \) vertex can be found in Ref. [4]. The unitary phase \( \phi_R(W) \) in Eq. [3] is introduced to adjust the total phase such that the Fermi-Watson theorem is fulfilled below two-pion threshold. In the inelastic region above the two-pion threshold it can be considered as a free parameter.

While the original version of MAID included only the 7 most important nucleon resonances with only transverse e.m. couplings in most cases, MAID2007 describes all 13 four-star resonances below \( W = 2 \) GeV. In a forthcoming update of MAID, these list of dominant resonances is no more sufficient, due to the high accuracy of the data and the availability of many polarization observables with single and double polarization. With these data also the weaker three-star and two-star resonances can be analyzed and will be included in the model.

4 Transition form factors

In most cases, the resonance couplings \( A^{R}_{\alpha}(W, Q^2) \) are assumed to be independent of the total energy. However, an energy dependence may occur if the resonance is parameterized in terms of the virtual photon three-momentum \( k(W, Q^2) \), e.g., in MAID2007 for the \( \Delta(1232) \) resonance. For all other resonances a simple \( Q^2 \) dependence is assumed for \( A_{\alpha}(Q^2) \). These resonance couplings are taken as constants.
for a single-$Q^2$ analysis, e.g., for photoproduction ($Q^2 = 0$) but also at any fixed $Q^2 > 0$, whenever sufficient data with $W$ and $\theta$ variation are available. Independently from this single-$Q^2$ analysis, also a $Q^2$-dependent analysis, with a simple ansatz using polynomials and exponentials, was performed. In MAID2007 the $Q^2$ dependence of the e.m. $N \to \Delta(1232)$ transition form factors is parameterized as follows:

$$
G_{E,M}(Q^2) = g_{E,M}(1 + \beta_{E,M}Q^2)e^{-\gamma_{E,M}Q^2}G_D(Q^2),
$$

$$
G_C(Q^2) = g_C\frac{1 + \beta_CQ^2}{1 + \delta_CQ^2/(4M_N^2)}e^{-\gamma_CQ^2}G_D(Q^2),
$$

where $G_D(Q^2) = 1/(1 + Q^2/0.71\text{GeV}^2)^2$ is the dipole form factor and the parameters are given in Table 1.

|   | $g_{\alpha}$ | $\beta_{\alpha}$ | $\gamma_{\alpha}$ | $\delta_{\alpha}$ |
|---|-------------|-------------------|-------------------|-------------------|
| M1 | 3.0 | 0.0095 | 0.23 | |
| E2 | 0.0637 | -0.0206 | 0.16 | |
| C2 | 0.1240 | 0.120 | 0.23 | 4.9 |

For all other $N$ and $\Delta$ resonances the couplings are parameterized as functions of $Q^2$ by the ansatz

$$
\bar{A}_\alpha(Q^2) = \bar{A}_\alpha(0)(1 + a_1Q^2 + a_2Q^4 + a_4Q^8)e^{-b_1Q^2}.
$$

For such an ansatz the parameters $\bar{A}_\alpha(0)$ are determined in a fit to the world database of photoproduction, and the parameters $a_i$ and $b_1$ are obtained from a combined fit of all the electroproduction data at different $Q^2$. The latter procedure is called the $Q^2$-dependent fit. In MAID the photon couplings $\bar{A}_\alpha(0)$ are input parameters, directly related to the helicity couplings $A_{1/2}$, $A_{3/2}$, and $S_{1/2}$ of nucleon resonance excitation. Relations between these helicity form factors, Sachs form factors $G_M, G_E, G_C$ and Dirac form factors $F_1, F_2, F_3$ can be found in Refs. [4; 1].

In Fig. 3 the transverse and longitudinal helicity form factors for the transitions to the spin $1/2$ nucleon resonances $N(1440)1/2^+$ (P11, Roper) and $N(1535)1/2^-$ (S11) are shown. A comparison of the MAID parametrization according to Eq. (7) with the single-$Q^2$ analyses from MAID [4] and CLAS@JLab [13] shows a very good agreement. These transition form factors are well understood up to $Q^2 \approx 5\text{ GeV}^2$. Whereas the transverse form factors are constrained by photoproduction at $Q^2 = 0$, no such constraint is possible for longitudinal form factors. Therefore, in the right panels of Fig. 3 it remains unclear, whether the MAID extrapolation is realistic at the photon point.

In 2017 a new measurement of the A1@MAMI collaboration in Mainz was published [14], where the longitudinal transition form factor of the Roper resonance was measured at the lowest momentum transfer, $Q^2 = 0.1\text{ GeV}^2$, see Fig. 4.
Fig. 3 Transverse $pA_{1/2}$ and longitudinal $pS_{1/2}$ transition form factors of the Roper $N(1440)1/2^+$ and $S_{11} N(1535)1/2^-$ nucleon resonances. The red circles are single-$Q^2$ results from our MAID analyses and the black triangles from the JLab analysis [13]. For further details see Ref. [1].

Fig. 4 Longitudinal transition form factor $pS_{1/2}$ of the Roper $N(1440)1/2^+$ resonance. The red line shows the MAID2007 prediction constrained by the Siegert Theorem. The black squares are CLAS data [13] and the lowest data point (blue circle) is the new result of a beam-recoil polarization measurement of A1@MAMI in Mainz [14]. The gray shaded band shows the convolution of various model predictions, see Ref. [14].
A shaded area shows the immense range of predictions for this longitudinal transition form factor, and in Refs. [2; 14] various quark and meson-baryon models are mentioned, that predict quite different results. Most of them practically diverge in the $Q^2 \to 0$ region. However, the good agreement between MAID and the new data is not an accident, but it is due to a constraint from the Siegert Theorem in the MAID parametrization [4]. Principally, the Siegert theorem relates the longitudinal and electric form factors at pseudo-threshold, which is located in the time-like region at $Q^2_{pt} = -(M_{N^*} - M_N)^2$, and has a value of $-0.25 \text{ GeV}^2$ for the Roper transition. The Roper transition, however, does not have an electric form factor, but as a minimal constraint, all longitudinal helicity form factors $S_{1/2}(Q^2)$ must vanish at pseudo-threshold due to e.m. current conservation. And the new MAMI measurement very well shows this fundamental symmetry.

In Fig. 5 the transverse $pA_{1/2}(Q^2)$, $pA_{3/2}(Q^2)$ and the longitudinal $pS_{1/2}(Q^2)$ form factors for the transitions from the proton to the $N(1520)3/2^-$ (D13) and $N(1680)5/2^+$ (F15) resonances are shown. Besides the $\Delta(1232)3/2^+$ resonance transition, these two $N^*$ transitions are the most pronounced resonance structures in the electroexcitation of the proton. Again as before, the MAID parametrizations are in good agreement with the partial wave analyses of MAID and CLAS. The only remarkable deviation is found for the $pA_{1/2}$ form factor to the D13 resonance. There, however, a more recent analysis from $\pi^+\pi^-$ electroproduction [15] is partly in better agreement with our MAID analysis.

For both of these proton resonances the helicity non-conserving amplitude $A_{3/2}$ dominates for real photons but with increasing values of $Q^2$ it drops much faster than the helicity conserving amplitude $A_{1/2}$.

5 EtaMAID update 2017

With the advent of new polarization experiments in Mainz on eta photoproduction [16] and high precision differential cross sections for eta and etaprime photoproduction [17], the EtaMAID model is being updated since 2015 [18] but not yet online. The current version EtaMAID2017 is shown in Fig. 6 and Fig. 7 compared to the MAMI total cross section data [17]. In a Regge-plus-Resonance (RPR) approach, the contributions of $N^*$ resonances are added to a Regge background, which dominates the high-energy tail beyond the resonance region and becomes small near threshold. The new EtaMAID2017 model includes a non-resonant background, which consists of the vector ($\rho$ and $\omega$) and axial-vector ($b_1$) exchanges in the $t$ channel, and $s$-channel $N^*$ excitations. Regge trajectories for the meson exchange in the $t$ channel were used to provide the correct asymptotic behavior at high energies. In addition to the Regge trajectories, Regge cuts with natural and unnatural parity were also included [19].

The major role for the description of $\eta$ and $\eta'$ photoproduction is played by three $s$-wave resonances: $N(1535)1/2^-$, $N(1650)1/2^-$, and $N(1895)1/2^-$, the latter of which plays the key role in the features observed at the $\eta'$ threshold. Both the exact shape of the cusp in the $\eta$ photoproduction and the steepness of $\eta'$ photoproduction at threshold are strongly correlated with the properties of $N(1895)1/2^-$, allowing their extraction with good accuracy. Mainly due to these data, a two-star
status in PDG [20] has now been raised to 4-star, the status for well established nucleon resonances.

6 Applications

The MAID programs have been used in many different ways.

The first group are applications, where the theoretical results can be obtained directly from the MAID web pages:

- comparison of cross sections and polarization observables with experiment
- predictions for new measurements and for experimental proposals
Fig. 6 Total cross section for $\gamma p \rightarrow \eta p$ obtained with EtaMAID2017 in a Regge-plus-Resonance approach. The separately shown Regge contribution (lower red line) contains trajectory and cuts with natural and un-natural parity. The black data points are the recent MAMI data [17] and the red points show the Bonn data of 2009 [21]. The blue data points, reaching to the highest energies, are obtained from a Legendre fit of the angular distributions of the 2009 CLAS data [22].

Fig. 7 Total cross section for $\gamma p \rightarrow \eta p$ (left panel) and $\gamma p \rightarrow \eta' p$ (right panel) obtained with EtaMAID2017 in a Regge-plus-Resonance approach. The black data points are the recent MAMI data [17] and the red points show the Bonn data of 2009 [21]. The separately shown Regge contribution (lower blue lines) contain trajectory and cuts with natural and un-natural parity.

- comparison with different theoretical models and partial wave analysis (PWA)
- investigations of CGLN, helicity and invariant amplitudes
- PWA with electric, magnetic and charge multipoles
- nucleon resonances $N^*$ and $\Delta^*$ in Breit-Wigner parametrization
- transverse and longitudinal transition form factors

The second group are indirect applications, where numerical results of the MAID programs are used for further calculations:

- T-matrix pole positions and residues of nucleon resonances [23] [24]
7 Summary and Outlook

The MAID project is a collection of online programs that perform real-time calculations for pseudoscalar meson photo- and electroproduction. It started in 1998 with pion photo- and electroproduction, and kaon, eta, etaprime and 2-pion production followed soon. The most recent part is a chiral effective field theory approach, where all free low-energy constants are fitted to the world data of pion production in the threshold region. MAID has been used in many different ways, for data analysis, experimental proposals, for sum rules, dispersion theoretical calculations, in particular for real, virtual and double-virtual Compton processes. A lot of PhD students profitted very much from the easily available MAID programs, and this gave us a lot of positive feedback.

Besides cross sections, the programs also provide all possible polarization observables, including beam, target and recoil polarization. For detailed investigations and partial wave analyses, the programs also provide full sets of CGLN, helicity and invariant amplitudes and electromagnetic multipoles, the partial waves of photoproduction.

MAID has been updated only a few times, nevertheless it often has proven predictive power after new experimental data became available. However, with high statistics of recent data, especially with MAMI cross section data \cite{33; 17}, and with a lot of new double-polarization observables from Mainz and Bonn, the limitations of the MAID models became obvious, as can be seen in a recent comparison of PWA from different data analysis groups \cite{34}.

In 2015 an EtaMAID update for $\gamma, \eta$ and $\gamma, \eta'$ was started with a much improved high-energy region, described by Regge approaches \cite{19} and a resonance region that now contains up to about 20 $N^*$ resonances \cite{13; 17}. This part will soon become online available.

The next updates are planned for kaon photoproduction, where a lot of new and high-quality data became available during the last decade. Furthermore, we also plan to update the pion photo- and electroproduction MAID with new data and a series of new $N^*$ and $\Delta^*$ resonances. So far, MAID2007 was limited to only 13 resonances, the full set of 4-star resonances below 2 GeV in 2007.

The pion electroproduction process has the biggest impact in theoretical applications and will certainly be needed for a long time. Whether the MAID service can be much longer provided is currently unclear. Probably for another few years, but afterwards it may become frozen for the future.

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