The helicity amplitudes $A_{1/2}$ and $A_{3/2}$ for the $D_{13}(1520)$ resonance obtained from the 
\( \gamma \vec{p} \rightarrow p \pi^0 \) reaction

J. Ahrens$^9$, S. Altieri$^{15,16}$, J.R.M. Annand$^6$, G. Anton$^3$, H.-J. Arends$^9$, K. Aulenbacher$^9$, R. Beck$^9$, C. Bradtke$^1$, A. Braghieri$^{15}$, N. Degrande$^4$, N. d’Hose$^5$, D. Drechsel$^9$, H. Dutz$^2$, S. Goertz$^1$, P. Grabmayr$^{17}$, K. Hansen$^8$, J. Harmsen$^1$, D. von Harrach$^9$, S. Hasegawa$^{13}$, T. Hasegawa$^{11}$, E. Heid$^9$, K. Helbing$^3$, H. Holvoet$^4$, L. Van Hoorebeke$^4$, N. Horikawa$^{14}$, T. Iwata$^{13}$, O. Jahn$^9$, P. Jennewein$^9$, T. Kageya$^{14}$, S. Kamalov$^{9\dagger}$, B. Kiel$^4$, F. Klein$^2$, R. Kondratiev$^{12}$, K. Kossert$^7$, J. Krümer$^{17}$, M. Lang$^9$, B. Lannoy$^9$, R. Leukel$^9$, V. Lisin$^{12}$, T. Matsuda$^{11}$, J.C. McGeorge$^6$, A. Meier$^1$, D. Menze$^2$, W. Meyer$^1$, T. Michel$^3$, J. Naumann$^3$, A. Panzer$^{15,16}$, P. Pedroni$^{15}$, T. Pinelli$^{15,16}$, I. Preobrajenski$^{9,12}$, E. Radtke$^1$, E. Reichert$^{10}$, G. Reicherz$^1$, Ch. Rohlf$^2$, G. Rosner$^6$, D. Ryckbosch$^4$, M. Sauer$^7$, B. Schoch$^2$, M. Schumacher$^7$, B. Seitz$^{17}$, T. Speckner$^3$, N. Takabayashi$^{13}$, G. Tanas$^9$, A. Thomas$^9$, L. Tiator$^9$, R. van de Vyver$^4$, A. Wakai$^{14}$, W. Weißhöfen$^7$, F. Wissmann$^7$, F. Zapadtkan$^5$, G. Zeitler$^3$

\( ^* \) corresponding author: e-mail address arends@kph.uni-mainz.de

\( ^\dagger \) present address: II. Physikalisches Institut, Universität Gießen

\( ^\ddagger \) permanent address: Laboratory of Theoretical Physics, JINR Dubna, Moscow, Russia

I. Introduction. – Over many years, measurements of the accessible observables in $\eta$ and single-pion photoproduction have been the basis of theoretical activity aiming to extract the properties of the baryon resonances beyond the $\Delta$. For example, the properties of the $S_{11}(1535)$ resonance, which dominates $\eta$ photoproduction near threshold, can be extracted from the measurements of total and differential cross sections$^{[1,2]}$ without strong model-dependence.

The situation is not so straightforward for the $D_{13}(1520)$ resonance, since in both single-pion and $\pi$ photoproduction other resonances also contribute. In fact, the photo-decay amplitudes $A_{1/2}$ and $A_{3/2}$ for this resonance, extracted using the VPI$^3$ and Glasgow$^4$ partial wave analyses of single-pion production, are significantly different from those evaluated by Mukhopadhyay \textit{et al.}$^5$ and Tiator \textit{et al.}$^6$ who used mainly $\eta$ production data. This discrepancy can be resolved by using the selectivity of polarization observables which allow the small, non-dominant resonances to be discerned via their interference with the dominant multipoles.

As is well-known, nine single and double polarization observables have to be measured to carry out a completely model-independent multipole analysis of single-pion photoproduction. However, as shown by Beck \textit{et al.}$^7$, some constraints can be applied in order to perform an almost model-independent analysis with fewer observables. A typical constraint is the low partial waves approximation, which can be applied only in a limited energy range. With increasing photon energy, the measurement of a more comprehensive set of single and double polarization data becomes very important. The sensitiv-
ity of an observable to small multipoles can reflect a corresponding sensitivity to the more weakly excited resonances. Figure 1 illustrates such sensitivity in the energy region from 450 MeV up to 1 GeV for the helicity dependent differential cross section \( (d\sigma/d\Omega)_{3/2} - (d\sigma/d\Omega)_{1/2} \) for the \( \gamma p \rightarrow p\pi^0 \) channel. This was obtained using circularly polarized photons and longitudinally polarized nucleons and the subscripts 3/2 and 1/2 indicate the relative nucleon-photon spin configurations, parallel and antiparallel, respectively. This cross section difference is plotted as a function of the photon energy at \( \theta^* = 90^\circ \), where \( \theta^* \) is the pion angle in the CM-system. The full curve represents the standard solution of the Unitary Isobar Model (UIM) \( b \), while the dotted, dashed and dashed-dotted curves represent solutions in which the coupling constant of the \( D_{13}(1520) \), the \( S_{11}(1535) \) and the \( P_{11}(1440) \) resonances, respectively, was set to zero. The difference between the standard and modified solutions indicates the sensitivity of this observable to the different resonances. As is clearly seen in Figure 1, the influence of the \( D_{13} \) resonance is rather strong as the cross section difference even changes sign. By contrast, the sensitivity to \( P_{11} \) is almost negligible and the sensitivity to \( S_{11} \) is not very pronounced. This observable is therefore well suited to extract the parameters of the \( D_{13} \) resonance.

![Graph](image)

FIG. 1: Energy dependence of the helicity dependent differential cross section for \( \gamma p \rightarrow p\pi^0 \) at \( \theta^* = 90^\circ \) as described by the UIM model \( b \). The curves represent: standard solution (full), no \( D_{13}(1520) \) (dotted), no \( S_{11}(1535) \) (dashed), no \( P_{11}(1440) \) (dash-dotted).

In this letter, we present the first results for the helicity dependent differential cross section of the \( \gamma p \rightarrow p\pi^0 \) reaction in the energy range between 550 and 790 MeV. These data were obtained during the GDH experiment \( \beta \) \( \beta \) at the Mainz microtron MAMI, which studied the helicity structure of the partial cross sections and their contributions to the Gerasimov-Drell-Hearn sum rule.

**II. Experimental setup.** – The main characteristics of the experimental setup are summarized here, but more details may be found in Refs. \( \beta \) \( \beta \) and \( \beta \). The experiment was conducted with the tagged photon facility \( \beta \). at the MAMI accelerator in Mainz. Circularly polarized photons were produced by bremsstrahlung of longitudinally polarized electrons \( \beta \). The electron polarization (routinely about 75%) was monitored during the data taking by a Møller polarimeter.

Longitudinally polarized protons were provided by a frozen-spin butanol (\( C_4H_9OH \)) target \( \beta \). The proton polarization was measured using NMR techniques. Maximum polarization values close to 90% were obtained with a relaxation time of about 200 h.

Photoemitted hadrons were registered by the large acceptance detector DAPHNE \( \beta \). DAPHNE essentially is a charged particle tracking detector with cylindrical symmetry. It covers polar angles \( \theta_{lab} = 21^\circ \) to 159°.

**III. Data analysis.** – The identification methods for hadrons in DAPHNE have been described previously in detail \( \beta \) \( \beta \) and only the main features will be recalled here.

Protons were identified using the range method \( \beta \), making simultaneous use of all of the charged particle energy losses in the DAPHNE scintillator layers to discriminate between protons and \( \pi^\pm \) and to determine their kinetic energies. However, the range method can be applied only to particles stopped inside DAPHNE. This condition is satisfied by most of the protons stemming from the \( p\pi^0 \) channel; only protons emitted with \( \theta_{lab} < 25^\circ \) and at \( E_\gamma > 700 \) MeV cannot be identified.

The presence of a single charged track recognized as a proton was used as the signature for the \( p\pi^0 \) channel. The main background in this case originates from the \( p\pi^0\pi^0 \) and \( p\pi^+\pi^- \) channels. The separation between the single and double photoproduction channels was obtained from the analysis of the missing mass spectrum \( \gamma p \rightarrow pX \) \( \beta \).

The absolute efficiency of the \( p\pi^0 \) channel identification was evaluated using a GEANT based simulation and found to be between 85% and 95%.

Prior to the main experiment, data for detector calibration and for tests of the analysis methods were taken with the same apparatus using an unpolarized pure liquid hydrogen target. The total unpolarized cross sections for \( \gamma p \rightarrow n\pi^+ \) and \( \gamma p \rightarrow p\pi^0 \) in the \( \Delta \) region were found to be in a good agreement \( \beta \) with previously published data and with predictions of multipole analyses. This confirms that the detector response is well understood. Figure 2 shows the differential cross sections for \( \gamma p \rightarrow p\pi^0 \) in the energy range 550 MeV \( \beta \) \( \beta \) to 790 MeV \( \beta \), compared to the data of Ref. \( \beta \) \( \beta \) and to the results of the UIM \( \beta \) model and the SAID \( \beta \) multipole analysis. The agreement shows that the detector response is similarly well understood in this higher energy region.

As discussed previously \( \beta \), in the analysis of data taken using the butanol target, the background contribution of the reactions on C and O nuclei could not be fully separated event-by-event from the polarized H contribution. However, this background from spinless nuclei is not polarization dependent and cancels when the difference between events in the 3/2 and 1/2 states is taken. For this reason only the differential cross section
difference can be directly extracted from the measurement with the butanol target.

IV. Results and discussion. – By using the methods described above, the helicity dependent differential cross section \( \frac{d\sigma}{d\Omega} \) was obtained as a function of pion angle \( \theta^* \) in the CM-system in the photon energy region from 550 MeV up to 790 MeV \[18\]. The results are presented in Figure 3. The errors shown are statistical only. The systematic uncertainties contain contributions from charged particle identification (2.5%), photon flux normalization (2%), photon polarization (3%) and target polarization (1.6%). The addition of these errors in quadrature leads to a total systematic error of about 5%.

At lower photon energies, the data are in a good agreement with model predictions, but there is a clear systematic discrepancy when the \( D_{13} \) (1520) resonance is approached. In order to extract information about this resonance, a fit of our unpolarized and polarized differential cross sections, based on the UIM \[8\], has been performed.

Since our data cover only the angular region around \( \theta^* = 90^\circ \), additional cross sections were included in the fit to reduce the model dependence of this procedure. These were the \( p\pi^0 \) data from \[20\], which contain unpolarized and target polarization (1.6%). The addition of these contributions from charged particle identification (2.5%), photon flux normalization (2%), photon polarization (3%) and target polarization (1.6%) leads to a total systematic error of about 5%.

The \( D_{13} \) partial wave amplitudes up to a photon energy of 800 MeV could be simultaneously determined in the fit.

Within the UIM framework, seven free parameters have been used in our fit: six resonance couplings and the pseudoscalar-pseudovector mixing parameter (PS/PV), which mostly affects the amplitudes \( E_0^{1/2} \) and \( M_1^{1/2} \), see Ref. \[8\]. A modification of the resonance couplings only affects the imaginary part of the resonance amplitude in the corresponding partial wave. The resulting modification factors for the \( D_{13} \) resonance compared to the standard UIM couplings have been found to be \( 1.11^{+0.06}_{-0.07} \) and \( 0.81^{+0.08}_{-0.07} \) while the other parameters remained unchanged within the fitting errors. This modified UIM solution is shown in Figures 2 and 3 by the dotted curves.

The \( D_{13} \) \( \rightarrow \gamma p \) helicity amplitudes \( A_{1/2} \) and \( A_{3/2} \) were then evaluated from the modified UIM solution. In principle, the transition from the electric and magnetic representation to helicity amplitudes is model dependent since a separation between resonant and background multipole components has to be performed. Once the separation is done, the standard recipe described in Ref. \[22\] can be used. Since the \( D_{13} \) partial wave am-
amplitudes are almost purely imaginary at the resonance position, the model dependence is weak. Because the background is real, only the imaginary partial wave amplitudes are required to calculate the helicity couplings from electric and magnetic partial waves. This situation is related to the nearly perfect Breit-Wigner shape of the $D_{13}(1520)$. Taking a resonance position of 1520 MeV, a resonance width of 120 MeV, and a pion branching ratio of 0.55 (from PDG [24]), the helicity amplitudes $A_{1/2}$ and $A_{3/2}$ were found to be $-0.038 \pm 0.003$ GeV$^{-1/2}$ and $0.147 \pm 0.010$ GeV$^{-1/2}$, respectively. The errors are a combination of the statistical fitting errors and the estimated model errors due to the uncertainties in the $D_{13}$ resonance parameters. Using the same method, the helicity amplitudes were extracted from the standard UIM (MAID2000) solution and from the SAID (SM01) solution. These results are summarized in Table 1 together with the latest PDG estimate [25].

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
Solution & $A_{1/2}$ & $A_{3/2}$ \\
\hline
standard UIM & -0.017 & 0.164 \\
SAID & -0.016 & 0.167 \\
PDG estimate & -0.024 $\pm$ 0.009 & 0.166 $\pm$ 0.005 \\
modified UIM & -0.038 $\pm$ 0.003 & 0.147 $\pm$ 0.010 \\
\hline
\end{tabular}
\caption{The $D_{13}$ helicity amplitudes $A_{1/2}$, $A_{3/2}$ for the proton (in units of GeV$^{-1/2}$) estimated from the modified UIM analysis, are compared to the standard UIM (MAID2000) solution, SAID (SM01) analysis and PDG, see text.}
\end{table}

As pointed out by Workman \textit{et al.} [21], the photon asymmetry $\Sigma$ is also quite sensitive to the parameters of the $D_{13}(1520)$ resonance. This observable has been recently measured for the $\gamma p \rightarrow p\pi^0$ channel in Yerevan [25] and for the $\gamma p \rightarrow n\pi^+$ channel at GRAAL [24]. A comparison has therefore been made between our modified UIM solution and these new data, as shown in Figure 4. In the same figure, the results of the standard UIM and SAID solutions are also plotted. The modified UIM solution is in satisfactory agreement with the $n\pi^+$ data, but tends to disagree with the $p\pi^0$ data. However, preliminary data from GRAAL for this latter channel [25] agree better with the theories and in this case the sensitivity to the parameters of the $D_{13}$ resonance is small.

In conclusion, our first data on the helicity dependent cross sections for $\pi^0$ photoproduction can be used to determine the photo coupling parameters of the $D_{13}$ resonance, due to the almost exclusive sensitivity of the helicity difference to this resonance. However, other data are needed to reconstruct a sufficient number of partial waves. Existing unpolarized cross sections and photon asymmetry data for the $\gamma p \rightarrow n\pi^+$ channel seem to be good candidates for this purpose. Our data imply that $A_{1/2}$ is larger (in absolute value) by about 60% and $A_{3/2}$ is smaller by about 12% compared to the standard PDG values.

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