Evidence for $\Delta(2200)7/2^-$ from photoproduction and consequence for chiral-symmetry restoration at high mass

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**Abstract**

We report a partial-wave analysis of new data on the double-polarization variable $E$ for the reactions $\gamma p \to \pi^+ n$ and $\gamma p \to \pi^0 p$ and of further data published earlier. The analysis within the Bonn–Gatchina ($8nG$) formalism reveals evidence for a poorly known baryon resonance, the one-star $\Delta(2200)7/2^-$. This is the lowest-mass $\Delta^+ \pi$ resonance with spin-parity $J^P = 7/2^-$. Its mass is significantly higher than the mass of its parity partner $\Delta(1950)7/2^+$ which is the lowest-mass $\Delta^+ \pi$ resonance with spin-parity $J^P = 7/2^+$. It has been suggested that chiral symmetry might be restored in the high-mass region of hadron excitations, and that these two resonances should be degenerate in mass. Our findings are in conflict with this prediction.

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SU(3) symmetry and the conjecture that mesons and baryons are composed of constituent quarks [1,2] paved the path to an understanding of the particle zoo. A constituent light-quark mass of about 350 MeV was required to reproduce the masses of ground-state baryons; the $N^-(1535)$ mass splitting and the pattern of negative- and positive-parity excited baryons were interpreted as an effect of a QCD hyperfine interaction between these constituent quarks [3,4]. However, low-energy approximations of QCD [5] lead to the Gell–Mann–Oakes–Renner relation [6] which assigns a mass of a few MeV to light (current) quarks. The mass gap between current and constituent quarks is interpreted by spontaneous breaking of the chiral symmetry expected for nearly massless quarks [7,8]. An important consequence is the large mass gap between chiral partners: the masses of the $\rho(770)$ meson with spin-parity $J^P = 1^-$ and its chiral partner $a_1(1260)$ with $J^P = 1^+$ differ by about 500 MeV, those of the $J^P = 1/2^+$ nucleon and its negative-parity partner $N_{1/2}^- (1535)$ by about 600 MeV.

In spite of these large mass shifts between low-mass parity partners, mesons and baryons at higher masses are often observed in parity doublets, in pairs of resonances having the same total spin $J$, opposite parities, and about the same mass. There are, e.g., four positive-parity and four negative-parity $\Delta^+$ resonances at about 1900 MeV:

$\Delta(1910)1/2^+ \Delta(1920)3/2^+ \Delta(1905)5/2^+ \Delta(1950)7/2^+$

$\Delta(1900)1/2^- \Delta(1940)3/2^- \Delta(1930)5/2^- \Delta(2200)7/2^-.$

The resonances with $J^P = 1/2^+, 3/2^+, 5/2^\pm$ are nearly mass-degenerate, in particular when their natural widths of a few hundred MeV are considered. This example and similar observations in mesons and baryons have led to the conjecture that chiral symmetry might be effectively restored in highly excited hadrons [9,10] and has stimulated a vivid discussion; we quote here a few recent reviews [11–14]. Based on the hypothesis of chiral-symmetry restoration, the parity partner of $\Delta(1950)7/2^+$ with spin-parity $7/2^-$ should also have a mass of about 1900 or 1950 MeV while quark models [15] and AdS/QCD [16] predict $\approx 2200$ MeV. The Review of Particle Properties lists the one-star $\Delta(2200)7/2^-$ resonance and thus disfavors models assuming that chiral symmetry could be restored in high-mass baryons. But clearly, a resonance for which the evidence for its existence is estimated to be poor (the definition of the one-star rating) cannot decide on this important issue. It is essential to refute or confirm the existence of this state.

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The 250-MeV mass splitting between $\Delta(1950)/2^+$ and $\Delta(2200)/2^+$ -- unexpected when chiral symmetry is effectively restored in highly excited hadrons -- points to a more general concern: resonances falling onto a leading Regge trajectory (with $J = L + S$, $L$ intrinsic orbital angular momentum, $S$ total quark spin) have no mass-degenerate parity partner. We mention $f_2(1270)$, $f_0(2500)$, $f_0(2510)$, and $\Delta(1232)/2^+$. $\Delta(1530)/2^+$, $\Delta(2420)/1^+$. In [17] it is argued that formation of the spin-parity partners of mesons on the leading Regge trajectory could be suppressed by orbital angular momentum barrier factors. We give two examples: in $pp$ formation of $f_0(2500)$, $L = 3$ is required; formation of its (unobserved or non-existing) mass-degenerate parity partner $\eta_4$ requires $L = 4$. Likewise, $\Delta(1950)/2^+$ requires $L = 3$ in $\pi N$ scattering, and its $7/2^+$ parity partner $L = 4$. Their non-observation could be assigned to their suppression by the angular-momentum barrier. This is different in photoproduction: a $7/2^+$ resonance needs an amplitude with $L = 3$ between photon and nucleon, a $7/2^+$ resonance an amplitude with $L = 2$. Photoproduction hence provides the best and possibly the only chance to find a decisive support or an experimental argument against the hypothesized restoration of chiral symmetry.

In this letter we report on a partial-wave analysis of the data on $p\gamma \rightarrow n\pi^+$ and $p\gamma \rightarrow p\pi^0$ covering differential cross sections $\sigma_d/\sigma_{\gamma p}$ [18–21], the beam asymmetry $\Sigma$ [22,23], and the double-polarization observables $T, P, H$ [24,25], $G$ [26], and $E$ from the CLAS [27] and CBELSA/TAPS [28] experiments. $T, P, H$ can be measured simultaneously when a transversely polarized target and a linearly polarized photon beam are used:

$$\frac{N(\phi)}{N_0} = 1 - p_T \Sigma \cos(2\phi) + p_T T \sin(\phi - \alpha)$$

$$+ p_T P \cos(2\phi) \sin(\phi - \alpha)$$

$$+ d p_T H \sin(2\phi) \cos(\phi - \alpha),$$

where $\phi$ is the azimuthal angle between the photon polarization plane and the scattering plane, and $\alpha$ is the azimuthal angle between the vector and the photon polarization plane. $G$ can be deduced from the correlation between the photon polarization plane and the scattering plane for protons polarized along the direction of the incoming photon; $E$ is defined by the (normalized) difference between the cross sections for parallel and anti-parallel photon and proton spin orientations. Data from older experiments [29] are also included in the partial-wave analysis. The data are fitted jointly with data on $N_0, A_K, \Sigma K, N_0^+\pi^0, 0, \pi^0\eta$ from both photo- and pion-induced reactions. Thus inelasticities in the meson–baryon system are constrained by real data. A list of the data used for the fit can be found in [30–33] and on our website (pwa.hiskp.uni-bonn.de).

We shortly outline the analysis technique and fit strategy. The helicity-dependent amplitude for photoproduction of the final state $b$ is cast into the form [34]

$$A_b^h = f_a^h (1 - i \rho K)_{ab}^{-1}$$

where

$$\rho = \sum \frac{A_\alpha^{a\alpha^*}}{M_\alpha^2 - s} + F_a.$$
When $\Delta (1950)/\Delta (2200)$: masses $M$, widths $\Gamma$, helicity amplitudes $A_{1/2}$, $A_{3/2}$ (in units of $10^{-3}$ GeV$^{-1/2}$), and branching ratios $BR = \Gamma_i/\Gamma_{tot}$. The RPP estimates [40] are given in parentheses. The fit yields the quantities $A_{1/2} \sqrt{BR}$ and $A_{3/2} \sqrt{BR}$. The branching ratio for $N\pi$ decays from a fit to the $\pi N$ elastic scattering amplitude $T$ [39] is used to determine the helicity amplitudes $A_{1/2}$, $A_{3/2}$. Also listed are the decay orbital angular momenta $L$.

| $\Delta (1950)/\Delta (2200)$ | $\Delta (2200)/\Delta (2200)$ |
|-----------------------------|-----------------------------|
| $M = 1917 \pm 4$ MeV        | $M = 2176 \pm 40$ MeV       |
| $\Gamma = 215 \pm 8$ MeV    | $\Gamma = 210 \pm 70$ MeV   |
| $A_{1/2} = -67 \pm 5$       | $A_{1/2} = 60 \pm 20$       |
| $A_{3/2} = -94 \pm 4$       | $A_{3/2} = -(20 \pm 8)$     |
| $N\pi, L = 1$: 46 ± 2%      | $N\pi, L = 4$: 11 ± 5       |
| $\Sigma K, L = 3$: 0.6 ± 0.2% | $\Sigma K, L = 4$: 12 ± 6   |
| $\Delta \pi, L = 3$: 5 ± 3% | $\Delta \pi, L = 2$: 50 ± 8 |
| $\Delta \pi, L = 5$: -      | $\Delta \pi, L = 4$: 23 ± 15|
| $\Delta \eta, L = 3$: 0.3 ± 0.3% | $\Delta \eta, L = 2$: -5     |
| $\Delta \eta, L = 5$: -     | $\Delta \eta, L = 4$: -     |

Fig. 2. Selected data and fits. Data: differential cross section $d\sigma/d\Omega$ [21,20]; target asymmetry $\Gamma$ [24,25,29]; beam asymmetry $\Sigma$ [23]; helicity dependence $E$ [28,27]. Best fit: solid curve, fit without $\Delta (2200)/\Delta (2200)$: dotted curve. The fit deteriorated by $\delta \chi^2 = 597$ when $\Delta (2200)/\Delta (2200)$ was removed. The mass ranges are given in MeV.

determinations will be discussed below. The $\Delta (2200)/\Delta (2200)$ mass is compatible with its nominal mass, we assign an uncertainty of ±40 MeV. The $\Delta (2200)/\Delta (2200)$ width is less well determined: several fits give $\Gamma \approx 140$ MeV, other fits return $\Gamma \approx 280$ MeV. Hence we quote $\Gamma = 210 \pm 70$ MeV.

The comparison of the $N\pi$ branching ratios of $\Delta (1950)/\Delta (2200)$ and $\Delta (2200)/\Delta (2200)$ shows why $\Delta (1950)/\Delta (2200)$ is a well-established resonance and $\Delta (2200)/\Delta (2200)$ not: in elastic $\pi N$ scattering, the $N\pi$ branching ratio enters in the entrance and the exit channel, and the signature of $\Delta (2200)/\Delta (2200)$ in elastic scattering is more than 100 times weaker than that of $\Delta (1950)/\Delta (2200)$. Due to the weakness of the $\Delta (2200)/\Delta (2200)$ signal in elastic scattering, the $\Delta (2200)/\Delta (2200)$ branching ratio has a sizable uncertainty. When this branching ratio is decreased by 20%, all other branching ratios are reduced by 20% while the squared helicity amplitudes increase by 20%.

In the next step, we removed $\Delta (2200)/\Delta (2200)$ from the list of resonances used in the PWA, and the fit deteriorated visibly, see Fig. 2. We tried to replace $\Delta (2200)/\Delta (2200)$ by other resonances or by a group of up to three additional resonances. Numerous combinations of different quantum numbers were tested, but even the best-suited three resonances do not lead to the same improvement of the fit quality as $\Delta (2200)/\Delta (2200)$. When $\Delta (2200)/\Delta (2200)$ was then admitted as fourth additional resonance, the fit still improved significantly. Further, we excluded individual data sets on the polarization variables $\Sigma$, $T$, and $E$ for $\gamma p \to \pi^0 p$ or $\gamma p \to \pi^- n$. All data sets contributed to the evidence for $\Delta (2200)/\Delta (2200)$. Most sensitive were the $\gamma p \to \pi^- n$ data on $E$ and $\Sigma$ and the $T$ and $E$ data on $\gamma p \to \pi^0 p$. Table 2 gives the change in $\chi^2$ which we observe and which we should expect ($N_{\text{events}} = 49044/32666$ with $N_{\text{events}}$ being the number of data points for a specified observable). The difference is assigned to the fractional evidence for the existence of $\Delta (2200)/\Delta (2200)$. Obviously, all data sets contributed to the evidence for $\Delta (2200)/\Delta (2200)$. The six masses obtained in these fits deviate by $-3 \pm 10$ MeV, the widths by $(1 \pm 13)$ MeV from the mean value. These differences are well covered by the spread of results obtained when different models were used to fit the data.

Next, we added data on three-body reactions, in particular $\gamma p \to \pi^0 \pi^0 p$ [32] and $\gamma p \to \pi^0 n p p$. The inclusion of three-body reactions did not lead to any significant changes in mass, width, or two-body couplings. Hence these values were frozen to their central values when the three-body reactions were included. Three-body decays were assumed to decay via intermediate meson or baryon resonances in an isobar ansatz. The three-body data were fitted in an event-based likelihood method; hence no $\chi^2$ value was returned by the fit. To quantify the improvement of a fit, we added to the change in $\chi^2$ – derived from the fit to two-body
The scans (Fig. 3) demonstrate clearly that the masses of Δ(1950)7/2⁺ and Δ(2200)7/2⁻ are different. The difference in squared masses of the two resonances is (1.06 ± 0.17) GeV², in excellent agreement with the slope of the leading Regge trajectory for Δ⁺’s of (1.08 ± 0.01) GeV².

To search for a mass-degenerate parity partner of Δ(50)7/2⁺, we did a series of fits trying to impose a Δ(1950)7/2⁻ with a mass restricted in the range 1920 to 1980 MeV in addition to Δ(2200)7/2⁻. In all fits, both helicity amplitudes converged to zero: there is no mass-degenerate parity partner of Δ(1950)7/2⁺ in the data.

Evidence for the Δ(2200)7/2⁻ resonance has been reported before, see Table 3. The Review of Particle Properties lists it as a one-star resonance, the evidence was considered as poor. Δ(2200)7/2⁻ is not seen in the elastic πN scattering analysis of the GWU group [41]; in the recent Bonn–GWU–Jülich analysis it is included in the fits but the authors state that they cannot claim much evidence either [46].

Finally, we discuss the helicity couplings. The Δ(50)7/2⁺ resonance can be excited by the E₃⁺ and M₃⁺ multipoles, Δ(2200)7/2⁻ by the E₄⁻ and M₄⁻ multipoles. The multipoles are related to the helicity amplitudes by [47]

\[
A^{1/2}_3 = -\frac{1}{2} (5E_3 + 3M_3);
A^{3/2}_3 = \frac{1}{2} \sqrt{15} (E_3 - M_3)
\]

\[
A^{1/2}_4 = -\frac{1}{2} (4E_4 - 6M_4);
A^{3/2}_4 = -\frac{1}{2} \sqrt{24} (E_4 + M_4)
\]

from which we deduce

\[
\Delta(1950)7/2^+ \quad E_3 = -(1.5 \pm 1.5) \times 10^{-3} \text{ GeV}^{-1/2}
M_3 = (47.1 \pm 1.8) \times 10^{-3} \text{ GeV}^{-1/2}
\]

\[
\Delta(2200)7/2^- \quad E_4 = -(7.1 \pm 4.5) \times 10^{-3} \text{ GeV}^{-1/2}
M_4 = (15.3 \pm 4.2) \times 10^{-3} \text{ GeV}^{-1/2}
\]

Table 3

| Mass (MeV) | Width (MeV) | BR % | Ref. |
|------------|-------------|------|------|
| 2280 ± 80  | 400 ± 150   | 9 ± 2% | [42] |
| 2115 ± 60  | 400 ± 100   | 5 ± 2% | [43] |
| 2200 ± 80  | 450 ± 100   | 6 ± 2% | [44] |
| 2280 ± 40  | 400 ± 50    |      | [45] |
| 2157       | 477         |      |      |
| 2176 ± 40  | 210 ± 70    | 3.5 ± 1.5% | this work |

The scans (Fig. 3) show the change in log likelihood multiplied by 2. This number is referred to as pseudo-χ². Since the absolute value of the log-likelihood function is meaningless, we give only changes of the pseudo-χ².

With these data included, we performed mass scans in the J^P = 7/2⁺ and J^P = 7/2⁻ partial waves. In the mass scans, the J^P = 7/2⁺ and J^P = 7/2⁻ partial waves were not described by K-matrix poles but represented by multichannel Breit–Wigner amplitudes, hence the optimal parameters for mass and width can differ. Fig. 3 (top) shows the change of the resulting pseudo-χ² as a function of the imposed mass of the J^P = 7/2⁺ or the J^P = 7/2⁻ resonance. The total pseudo-χ² has clear minima at a mass of 1917 MeV for J^P = 7/2⁺ and 2176 MeV for J^P = 7/2⁻. When the masses are detuned from the best values, the widths of the resonances become wide.

Fig. 3 also shows a breakdown of the total pseudo-χ² into contributions from specific reactions. Clear minima are observed in γp → π⁺p, π⁺n, η, η', p, and even in π⁺n+p (due to Δ(1232)η). The minima are found at 1913, 1917, 1922, 1904, 1942 MeV, respectively at 2186, 2155, 2193, 2115, 2200 MeV, consistent with the overall minima at 1917 and 2176 MeV. It is remarkable that the same minima which are found for Δ⁺ decays into πN are as well seen in the other allowed decay channels.

In spite of the small Δ(2200)7/2⁻ → πN coupling, the largest evidence stems from photoproduction of single pions. There are two reasons: first, the highly constraining polarization data and their statistical power define the angular-momentum decomposition very well. Second, the sequential decays in 2γ⁰ photoproduction allow for a large flexibility in describing the data; hence the statistical significance of such data is reduced.
that the photoproduction multipoles with low orbital angular momenta might be determined in an energy-independent (and thus model-independent) analysis when further polarization data become available. This would be the basis to derive the \(\Delta(2200)\) properties exploiting different model assumptions.

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