

$\Delta(1600) \ 3/2^+$ $I(J^P) = \frac{3}{2}(\frac{3}{2}^+)$ Status: ***

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, *Physics Letters* **111B** 1 (1982). Some further obsolete results published before 1984 were last included in our 2006 edition, *Journal of Physics, G* **33** 1 (2006).

The various analyses are not in good agreement.

$\Delta(1600)$ BREIT-WIGNER MASS

<u>VALUE (MeV)</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
1500 to 1700 (≈ 1600) OUR ESTIMATE			
1510 \pm 20	ANISOVICH	12A	DPWA Multichannel
1706 \pm 10	MANLEY	92	IPWA $\pi N \rightarrow \pi N$ & $N\pi\pi$
1600 \pm 50	CUTKOSKY	80	IPWA $\pi N \rightarrow \pi N$
1522 \pm 13	HOEHLER	79	IPWA $\pi N \rightarrow \pi N$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●			
1650 \pm 40	HORN	08A	DPWA Multichannel
1667 \pm 1	PENNER	02C	DPWA Multichannel
1687 \pm 44	VRANA	00	DPWA Multichannel
1672 \pm 15	ARNDT	96	IPWA $\gamma N \rightarrow \pi N$
1706	LI	93	IPWA $\gamma N \rightarrow \pi N$
1690	BARNHAM	80	IPWA $\pi N \rightarrow N\pi\pi$
1560	¹ LONGACRE	77	IPWA $\pi N \rightarrow N\pi\pi$
1640	² LONGACRE	75	IPWA $\pi N \rightarrow N\pi\pi$

$\Delta(1600)$ BREIT-WIGNER WIDTH

<u>VALUE (MeV)</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
220 to 420 (≈ 320) OUR ESTIMATE			
220 \pm 45	ANISOVICH	12A	DPWA Multichannel
430 \pm 73	MANLEY	92	IPWA $\pi N \rightarrow \pi N$ & $N\pi\pi$
300 \pm 100	CUTKOSKY	80	IPWA $\pi N \rightarrow \pi N$
220 \pm 40	HOEHLER	79	IPWA $\pi N \rightarrow \pi N$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●			
530 \pm 60	HORN	08A	DPWA Multichannel
397 \pm 10	PENNER	02C	DPWA Multichannel
493 \pm 75	VRANA	00	DPWA Multichannel
315 \pm 20	ARNDT	96	IPWA $\gamma N \rightarrow \pi N$
215	LI	93	IPWA $\gamma N \rightarrow \pi N$
250	BARNHAM	80	IPWA $\pi N \rightarrow N\pi\pi$
180	¹ LONGACRE	77	IPWA $\pi N \rightarrow N\pi\pi$
300	² LONGACRE	75	IPWA $\pi N \rightarrow N\pi\pi$

$\Delta(1600)$ POLE POSITION

REAL PART

<u>VALUE (MeV)</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
1460 to 1560 (≈ 1510) OUR ESTIMATE			
1498 \pm 25	ANISOVICH	12A	DPWA Multichannel
1457	ARNDT	06	DPWA $\pi N \rightarrow \pi N, \eta N$
1550	³ HOEHLER	93	SPED $\pi N \rightarrow \pi N$
1550 \pm 40	CUTKOSKY	80	IPWA $\pi N \rightarrow \pi N$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●			
1510 $^{+20}_{-50}$	HORN	08A	DPWA Multichannel
1599	VRANA	00	DPWA Multichannel
1675	ARNDT	95	DPWA $\pi N \rightarrow N\pi$
1612	ARNDT	91	DPWA $\pi N \rightarrow \pi N$ Soln SM90
1609 or 1610	⁴ LONGACRE	78	IPWA $\pi N \rightarrow N\pi\pi$
1541 or 1542	¹ LONGACRE	77	IPWA $\pi N \rightarrow N\pi\pi$

– 2×IMAGINARY PART

<u>VALUE (MeV)</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
200 to 350 (≈ 275) OUR ESTIMATE			
230 \pm 50	ANISOVICH	12A	DPWA Multichannel
400	ARNDT	06	DPWA $\pi N \rightarrow \pi N, \eta N$
200 \pm 60	CUTKOSKY	80	IPWA $\pi N \rightarrow \pi N$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●			
230 \pm 40	HORN	08A	DPWA Multichannel
312	VRANA	00	DPWA Multichannel
386	ARNDT	95	DPWA $\pi N \rightarrow N\pi$
230	ARNDT	91	DPWA $\pi N \rightarrow \pi N$ Soln SM90
323 or 325	⁴ LONGACRE	78	IPWA $\pi N \rightarrow N\pi\pi$
178 or 178	¹ LONGACRE	77	IPWA $\pi N \rightarrow N\pi\pi$

$\Delta(1600)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

<u>VALUE (MeV)</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
11 \pm 6	ANISOVICH	12A	DPWA Multichannel
44	ARNDT	06	DPWA $\pi N \rightarrow \pi N, \eta N$
17 \pm 4	CUTKOSKY	80	IPWA $\pi N \rightarrow \pi N$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●			
52	ARNDT	95	DPWA $\pi N \rightarrow N\pi$
16	ARNDT	91	DPWA $\pi N \rightarrow \pi N$ Soln SM90

PHASE θ

<u>VALUE ($^\circ$)</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
– 160 \pm 33	ANISOVICH	12A	DPWA Multichannel
+ 147	ARNDT	06	DPWA $\pi N \rightarrow \pi N, \eta N$
– 150 \pm 30	CUTKOSKY	80	IPWA $\pi N \rightarrow \pi N$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●			
+ 14	ARNDT	95	DPWA $\pi N \rightarrow N\pi$
– 73	ARNDT	91	DPWA $\pi N \rightarrow \pi N$ Soln SM90

$\Delta(1600)$ INELASTIC POLE RESIDUE

The “normalized residue” is the residue divided by Γ_{pole} .

Normalized residue in $N\pi \rightarrow \Delta(1600) \rightarrow \Delta\pi$, *P*-wave

<u>MODULUS (%)</u>	<u>PHASE (°)</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
14±10	154 ± 40	ANISOVICH	12A DPWA	Multichannel

Normalized residue in $N\pi \rightarrow \Delta(1600) \rightarrow \Delta\pi$, *F*-wave

<u>MODULUS (%)</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
1.0±0.5	ANISOVICH	12A DPWA	Multichannel

$\Delta(1600)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

Mode	Fraction (Γ_i/Γ)
Γ_1 $N\pi$	10–25 %
Γ_2 ΣK	
Γ_3 $N\pi\pi$	75–90 %
Γ_4 $\Delta\pi$	40–70 %
Γ_5 $\Delta(1232)\pi$, <i>P</i> -wave	
Γ_6 $\Delta(1232)\pi$, <i>F</i> -wave	
Γ_7 $N\rho$	<25 %
Γ_8 $N\rho$, $S=1/2$, <i>P</i> -wave	
Γ_9 $N\rho$, $S=3/2$, <i>P</i> -wave	
Γ_{10} $N\rho$, $S=3/2$, <i>F</i> -wave	
Γ_{11} $N(1440)\pi$	10–35 %
Γ_{12} $N(1440)\pi$, <i>P</i> -wave	
Γ_{13} $N\gamma$	0.001–0.035 %
Γ_{14} $N\gamma$, helicity=1/2	0.0–0.02 %
Γ_{15} $N\gamma$, helicity=3/2	0.001–0.015 %

$\Delta(1600)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$	Γ_1/Γ		
<u>VALUE (%)</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
10 to 25 OUR ESTIMATE			
12±5	ANISOVICH	12A DPWA	Multichannel
12±2	MANLEY	92 IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
18±4	CUTKOSKY	80 IPWA	$\pi N \rightarrow \pi N$
21±6	HOEHLER	79 IPWA	$\pi N \rightarrow \pi N$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●			
10±3	HORN	08A DPWA	Multichannel
13±1	PENNER	02C DPWA	Multichannel
28±5	VRANA	00 DPWA	Multichannel

$(\Gamma_i \Gamma_f)^{1/2} / \Gamma_{\text{total}}$ in $N\pi \rightarrow \Delta(1600) \rightarrow \Sigma K$ $(\Gamma_1 \Gamma_2)^{1/2} / \Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
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-0.36 to -0.28 OUR ESTIMATE

• • • We do not use the following data for averages, fits, limits, etc. • • •

0.006 to 0.042 ⁵ DEANS 75 DPWA $\pi N \rightarrow \Sigma K$

Note: Signs of couplings from $\pi N \rightarrow N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620) S_{31}$ coupling to $\Delta(1232)\pi$.

$(\Gamma_i \Gamma_f)^{1/2} / \Gamma_{\text{total}}$ in $N\pi \rightarrow \Delta(1600) \rightarrow \Delta(1232)\pi$, *P-wave* $(\Gamma_1 \Gamma_5)^{1/2} / \Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
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+0.27 to +0.33 OUR ESTIMATE

+0.29 ± 0.02	MANLEY	92	IPWA $\pi N \rightarrow \pi N \& N\pi\pi$
+0.24 ± 0.05	BARNHAM	80	IPWA $\pi N \rightarrow N\pi\pi$
+0.34	^{1,6} LONGACRE	77	IPWA $\pi N \rightarrow N\pi\pi$
+0.30	² LONGACRE	75	IPWA $\pi N \rightarrow N\pi\pi$

$\Gamma(\Delta(1232)\pi, P\text{-wave}) / \Gamma_{\text{total}}$ Γ_5 / Γ

VALUE (%)	DOCUMENT ID	TECN	COMMENT
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78 ± 6	ANISOVICH	12A	DPWA Multichannel
59 ± 10	VRANA	00	DPWA Multichannel

$(\Gamma_i \Gamma_f)^{1/2} / \Gamma_{\text{total}}$ in $N\pi \rightarrow \Delta(1600) \rightarrow \Delta(1232)\pi$, *F-wave* $(\Gamma_1 \Gamma_6)^{1/2} / \Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
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-0.15 to -0.03 OUR ESTIMATE

-0.07 ^{1,6} LONGACRE 77 IPWA $\pi N \rightarrow N\pi\pi$

$(\Gamma_i \Gamma_f)^{1/2} / \Gamma_{\text{total}}$ in $N\pi \rightarrow \Delta(1600) \rightarrow N\rho, S=1/2$, *P-wave* $(\Gamma_1 \Gamma_8)^{1/2} / \Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
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+0.10 ^{1,6} LONGACRE 77 IPWA $\pi N \rightarrow N\pi\pi$

$(\Gamma_i \Gamma_f)^{1/2} / \Gamma_{\text{total}}$ in $N\pi \rightarrow \Delta(1600) \rightarrow N\rho, S=3/2$, *P-wave* $(\Gamma_1 \Gamma_9)^{1/2} / \Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
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+0.10 ^{1,6} LONGACRE 77 IPWA $\pi N \rightarrow N\pi\pi$

$(\Gamma_i \Gamma_f)^{1/2} / \Gamma_{\text{total}}$ in $N\pi \rightarrow \Delta(1600) \rightarrow N(1440)\pi$, *P-wave* $(\Gamma_1 \Gamma_{12})^{1/2} / \Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
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+0.15 to +0.23 OUR ESTIMATE

+0.16 ± 0.02	MANLEY	92	IPWA $\pi N \rightarrow \pi N \& N\pi\pi$
+0.23 ± 0.04	BARNHAM	80	IPWA $\pi N \rightarrow N\pi\pi$

$\Gamma(N(1440)\pi) / \Gamma_{\text{total}}$ Γ_{11} / Γ

VALUE (%)	DOCUMENT ID	TECN	COMMENT
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13 ± 4	VRANA	00	DPWA Multichannel
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$\Delta(1600)$ PHOTON DECAY AMPLITUDES

Papers on γN amplitudes predating 1981 may be found in our 2006 edition, *Journal of Physics*, G **33** 1 (2006).

$\Delta(1600) \rightarrow N\gamma$, helicity-1/2 amplitude $A_{1/2}$

<u>VALUE (GeV^{-1/2})</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
−0.023±0.020 OUR ESTIMATE			
−0.050±0.009	ANISOVICH	12A DPWA	Multichannel
−0.018±0.015	ARNDT	96 IPWA	$\gamma N \rightarrow \pi N$
−0.039±0.030	CRAWFORD	83 IPWA	$\gamma N \rightarrow \pi N$
−0.046±0.013	AWAJI	81 DPWA	$\gamma N \rightarrow \pi N$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●			
0.0	PENNER	02D DPWA	Multichannel
−0.026±0.002	LI	93 IPWA	$\gamma N \rightarrow \pi N$
−0.200	⁷ WADA	84 DPWA	Compton scattering
0.000±0.030	BARBOUR	78 DPWA	$\gamma N \rightarrow \pi N$

$\Delta(1600) \rightarrow N\gamma$, helicity-3/2 amplitude $A_{3/2}$

<u>VALUE (GeV^{-1/2})</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
−0.009±0.021 OUR ESTIMATE			
−0.040±0.012	ANISOVICH	12A DPWA	Multichannel
−0.025±0.015	ARNDT	96 IPWA	$\gamma N \rightarrow \pi N$
−0.013±0.014	CRAWFORD	83 IPWA	$\gamma N \rightarrow \pi N$
0.025±0.031	AWAJI	81 DPWA	$\gamma N \rightarrow \pi N$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●			
−0.024	PENNER	02D DPWA	Multichannel
−0.016±0.002	LI	93 IPWA	$\gamma N \rightarrow \pi N$
0.023	WADA	84 DPWA	Compton scattering
0.000±0.045	BARBOUR	78 DPWA	$\gamma N \rightarrow \pi N$

$\Delta(1600)$ FOOTNOTES

¹ LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

² From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

³ See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

⁴ LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

⁵ The range given is from the four best solutions. DEANS 75 disagrees with $\pi^+ p \rightarrow \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

⁶ LONGACRE 77 considers this coupling to be well determined.

⁷ WADA 84 is inconsistent with other analyses — see the Note on N and Δ Resonances.

Δ(1600) REFERENCES

For early references, see Physics Letters **111B** 1 (1982).

ANISOVICH	12A	EPJ A48 15	A.V. Anisovich <i>et al.</i>	(BONN, PNPI)
HORN	08A	EPJ A38 173	I. Horn <i>et al.</i>	(CB-ELSA Collab.)
Also		PRL 101 202002	I. Horn <i>et al.</i>	(CB-ELSA Collab.)
ARNDT	06	PR C74 045205	R.A. Arndt <i>et al.</i>	(GWU)
PDG	06	JPG 33 1	W.-M. Yao <i>et al.</i>	(PDG Collab.)
PENNER	02C	PR C66 055211	G. Penner, U. Mosel	(GIES)
PENNER	02D	PR C66 055212	G. Penner, U. Mosel	(GIES)
VRANA	00	PRPL 328 181	T.P. Vrana, S.A. Dytman,, T.-S.H. Lee	(PITT+)
ARNDT	96	PR C53 430	R.A. Arndt, I.I. Strakovsky, R.L. Workman	(VPI)
ARNDT	95	PR C52 2120	R.A. Arndt <i>et al.</i>	(VPI, BRCO)
HOEHLER	93	πN Newsletter 9 1	G. Hohler	(KARL)
LI	93	PR C47 2759	Z.J. Li <i>et al.</i>	(VPI)
MANLEY	92	PR D45 4002	D.M. Manley, E.M. Saleski	(KENT) IJP
Also		PR D30 904	D.M. Manley <i>et al.</i>	(VPI)
ARNDT	91	PR D43 2131	R.A. Arndt <i>et al.</i>	(VPI, TELE) IJP
WADA	84	NP B247 313	Y. Wada <i>et al.</i>	(INUS)
CRAWFORD	83	NP B211 1	R.L. Crawford, W.T. Morton	(GLAS)
PDG	82	PL 111B 1	M. Roos <i>et al.</i>	(HELSE, CIT, CERN)
AWAJI	81	Bonn Conf. 352	N. Awaji, R. Kajikawa	(NAGO)
Also		NP B197 365	K. Fujii <i>et al.</i>	(NAGO)
BARNHAM	80	NP B168 243	K.W.J. Barnham <i>et al.</i>	(LOIC)
CUTKOSKY	80	Toronto Conf. 19	R.E. Cutkosky <i>et al.</i>	(CMU, LBL) IJP
Also		PR D20 2839	R.E. Cutkosky <i>et al.</i>	(CMU, LBL) IJP
HOEHLER	79	PDAT 12-1	G. Hohler <i>et al.</i>	(KARLT) IJP
Also		Toronto Conf. 3	R. Koch	(KARLT) IJP
BARBOUR	78	NP B141 253	I.M. Barbour, R.L. Crawford, N.H. Parsons	(GLAS)
LONGACRE	78	PR D17 1795	R.S. Longacre <i>et al.</i>	(LBL, SLAC)
LONGACRE	77	NP B122 493	R.S. Longacre, J. Dolbeau	(SACL) IJP
Also		NP B108 365	J. Dolbeau <i>et al.</i>	(SACL) IJP
WINNIK	77	NP B128 66	M. Winnik <i>et al.</i>	(HAIF) I
DEANS	75	NP B96 90	S.R. Deans <i>et al.</i>	(SFLA, ALAH) IJP
LONGACRE	75	PL 55B 415	R.S. Longacre <i>et al.</i>	(LBL, SLAC) IJP