# $\Lambda(1405)\ S_{01}$

$I(J^P) = 0(\frac{1}{2}^-)$ Status: ∗∗∗∗

## THE $\Lambda(1405)$

(by R.H. Dalitz, Oxford University)

It is generally accepted that the $\Lambda(1405)$ is a well-established $J^P = 1/2^-$ resonance. It is assigned to the lowest $L = 1$ supermultiplet of the 3-quark system and paired with the $J^P = 3/2^-$ $\Lambda(1520)$. Lying about 30 MeV below the $N\overline{K}$ threshold, the $\Lambda(1405)$ can be observed directly only as a resonance bump in the $(\Sigma\pi)^0$ subsystem in final states of production experiments. It was first reported by ALSTON 61B in the reaction $K^-p \to \Sigma\pi\pi\pi$ at 1.15 GeV/$c$ and has since been seen in at least eight other experiments. However, only two of them had enough events for a detailed analysis: THOMAS 73, with about 400 $\Sigma^\pm\pi^\mp$ events from $\pi^-p \to K^0(\Sigma\pi)^0$ at 1.69 GeV/$c$; and HEMINGWAY 85, with 766 $\Sigma^+\pi^-$ and 1106 $\Sigma^-\pi^+$ events from $K^-p \to (\Sigma\pi\pi)^+\pi^-$ at 4.2 GeV/$c$, after the selections $1600 \leq M(\Sigma\pi\pi)^+ \leq 1720$ MeV and momentum transfer $\leq 1.0$ (GeV/$c$)$^2$ to purify the $\Lambda(1405) \to (\Sigma\pi)^0$ sample. These experiments agree on a mass of about 1395–1400 MeV and a width of about 60 MeV. (Hemingway's mass of 1391 $\pm$ 1 MeV is from his best, but unacceptably poor, Breit-Wigner fit.)

The Byers-Fenster tests on these data allow any spin and either parity: neither $J$ nor $P$ has yet been determined *directly*. The early indications for $J^P = 1/2^-$ came from finding Re $A_{I=0}$ to be large and negative in a constant-scattering-length analysis of low-energy $N\overline{K}$ reaction data (see KIM 65, SAKITT 65, and earlier references cited therein). The first multichannel energy-dependent K-matrix analysis (KIM 67) strengthened the case for a resonance around 1400–1420 MeV strongly coupled to the $I = 0$ $S$-wave $N\overline{K}$ system.

THOMAS 73 and HEMINGWAY 85 both found the $\Lambda(1405)$ bump to be asymmetric and not well fitted by a Breit-Wigner resonance function with constant parameters. The asymmetry involves a rapid fall in intensity as the $N\overline{K}$ threshold energy is approached from below. This is readily understood as due to a strong coupling of the $\Lambda(1405)$ to the $S$-wave $N\overline{K}$ channel (see DALITZ 81). This striking $S$-shaped cusp behavior at a new threshold is characteristic of $S$-wave coupling; the other below-threshold hyperon, the $\Sigma(1385)$, has no such threshold distortion because its $N\overline{K}$ coupling is $P$-wave. For the $\Lambda(1405)$, this asymmetry is the *sole direct evidence* that $J^P = 1/2^-$.

Following the early work cited above, a considerable literature has developed on proper procedures for phenomenological extrapolation below the $N\overline{K}$ threshold, partly in order to strengthen the evidence for the spin-parity of the $\Lambda(1405)$, and partly to provide an estimate for the amplitude $f(N\overline{K})$ in the unphysical domain below the $N\overline{K}$ threshold; the latter is needed for the evaluation of the dispersion relation for $N\overline{K}$ and $NK$ forward scattering amplitudes. For recent reviews, see MILLER 84 and BARRETT 89. In most recent work, the $(\Sigma\pi)^0$ production spectrum is included in the data fitted (see, *e.g.*, CHAO 73, MARTIN 81).

It is now accepted that the data can be fitted only with an $S$-wave pole in the reaction amplitudes below $N\overline{K}$ threshold (see, however, FINK 90), but there is still controversy about the physical origin of this pole (for a review, see DALITZ 81 and DALITZ 82). Two extreme possibilities are: (a) an $L = 1$ SU(3)-singlet $uds$ state coupled with the $S$-wave meson-baryon systems; or (b) an unstable $N\overline{K}$ bound state, analogous to the (stable) deuteron in the $NN$ system. The problem with (a) is that the $\Lambda(1405)$ mass is so much lower than that of its partner, the $\Lambda(1520)$. This requires, in the QCD-inspired quark model, rather large spin-orbit couplings, whether or not one uses relativistic kinetic energies. ISGUR 80, CAPSTICK 86, and CAPSTICK 89 conclude that a proper QCD calculation leads only to small energy splittings, whereas LEINWEBER 90, using QCD sum rules, obtains a good fit to this splitting.

On the other hand, the problem with (b) is that then another $J^P = 1/2^- \Lambda$ is needed to replace the $\Lambda(1405)$ in the $L = 1$ supermultiplet, and it would have to lie close to the $\Lambda(1520)$, a region already well explored by $N\overline{K}$ experiments without result. Intermediate structures are possible; for example, the cloudy bag model allows the configurations (a) and (b) to mix and finds the intensity of (a) in the $\Lambda(1405)$ to be only 14% (VEIT 84, VEIT 85, JENNINGS 86). Such models naturally predict a second $1/2^-$ $\Lambda$ close to the $\Lambda(1520)$.

The determination of the mass and width of the resonance from $(\Sigma\pi)^0$ data is usually based on the "Watson approximation," which states that the production rate $R(\Sigma\pi)$ of the $(\Sigma\pi)^0$ state has a mass dependence proportional to $(\sin^2\delta_{\Sigma\pi})/q$, $q$ being the $\Sigma\pi$ c.m. momentum, in a $\Sigma\pi$ mass range where $\delta_{\Sigma\pi}$ is not far from $\pi/2$ and only the $\Sigma\pi$ channel is open, *i.e.*, between the $\Sigma\pi$ and the $N\overline{K}$ thresholds. Then $q\,R(\Sigma\pi)$ is proportional to $\sin^2\delta_{\Sigma\pi}$, and the mass $M$ may be defined as the energy at which $\sin^2\delta_{\Sigma\pi} = 1$. The width $\Gamma$ may be determined from the rate at which $\delta_{\Sigma\pi}$ goes through $\pi/2$, or from the FWHM; this is a matter of convention.

This determination of $M$ and $\Gamma$ from the data suffers from the following defects:

(i) The determination of $\sin^2\delta_{\Sigma\pi}$ requires that $R(\Sigma\pi)$ be scaled to give $\sin^2\delta_{\Sigma\pi} = 1$ at the peak for the best fit to the data; *i.e.*, the bump must be *assumed* to arise from a resonance. However, this assumption is supported by the analysis of the low-energy $N\overline{K}$ data and its extrapolation below threshold.

(ii) Owing to the nearby $N\overline{K}$ threshold, the shape of the best fit to the $M(\Sigma\pi)$ bump is uncertain. For energies below this threshold at $E_{N\overline{K}}$, the general form for $\delta_{\Sigma\pi}$ is

$$q \cot \delta_{\Sigma\pi} = \frac{1+\kappa\alpha}{\gamma + \kappa(\alpha\gamma - \beta^2)} \ .$$

Here $\alpha, \beta$, and $\gamma$ are the (generally energy-dependent) $NN$, $N\Sigma$, and $\Sigma\Sigma$ elements of the $I = 0$ $S$-wave K-matrix for the $(\Sigma\pi, N\overline{K})$ system, and $\kappa$ is the magnitude of the (imaginary) c.m. momentum $k_K$ for the $N\overline{K}$ system below threshold. The elements $\alpha, \beta, \gamma$ are real functions of $E$; they have no branch cuts at the $\Sigma\pi$ and $N\overline{K}$ thresholds, but they are permitted to have poles in $E$ along the real $E$ axis. The resonance asymmetry arises from the effect of $\kappa$ on $\delta_{\Sigma\pi}$. We note that $\delta_{\Sigma\pi} = \pi/2$ when $\kappa = -1/\alpha$.

Accepting this close connection of $\delta_{\Sigma\pi}$ with the low-energy $N\overline{K}$ data, it is natural to analyze the two sets of data together (*e.g.*, MARTIN 81), and there is now a large body of accurate $N\overline{K}$ data for laboratory momenta between 100 and 300 MeV/$c$ (see MILLER 84). The two sets of data span c.m. energies from 1370 MeV to 1490 MeV, and the K-matrix elements will not be energy independent over such a broad range. For the $I = 0$ channels, a linear energy dependence for $\mathrm{K}^{-1}$ has been adopted routinely ever since the work of KIM 67, and it is essential when fitting the $q\,R(\Sigma\pi)$ and $N\overline{K}$ data together. However, $q\,R(\Sigma\pi)$ is not always well fitted in this procedure; the value obtained for the $\Lambda(1405)$ mass $M$ varies a good deal with the type of fit, not a surprising result when the $\Sigma\pi$ mass spectrum contributes only nine data points in a total of about 200. The value of $M$ obtained from an overall fit is not necessarily much better than from one using only the $q\,R(\Sigma\pi)$ data; and $M$ may be a function of the representation—K-matrix, $\mathrm{K}^{-1}$-matrix, relativistic-separable or nonseparable potentials, *etc.*— used in fitting over the full energy range. DALITZ 90 fitted the $qR(\Sigma^+\pi^-)$ Hemingway data with each of the first three representations just mentioned, constrained to the $I = 0$ $N\overline{K}$ threshold scattering length from low-energy $N\overline{K}$ data. The (nonseparable) meson-exchange potentials of MÜLLER-GROELING 90, fitted to the low-energy $N\overline{K}$ (and $NK$) data, predicted an unstable $N\overline{K}$ bound state with mass and width compatible with the $\Lambda(1405)$.

The present status of the $\Lambda(1405)$ thus depends heavily on theoretical arguments, a somewhat unsatisfactory basis for a four-star rating. Nevertheless, there is no known reason to doubt its existence or quantum numbers. A measurement of the energy-level shifts and widths for the atomic levels of kaonic hydrogen (and deuterium) would give a valuable check on analyses of the $(\Sigma\pi, N\overline{K})$ amplitudes, since the energy of the $K^-p$ atom lies roughly midway between those for the two sets of data. The three measurements of $(\Delta E - i\Gamma/2)$ for kaonic hydrogen are inconsistent with one another and require that the sign of $\mathrm{Re}(A_{I=0} + A_{I=1})$ be opposite that deduced from $N\overline{K}$ reaction data (see BATTY 89). Accurate measurements of $(\Delta E - i\Gamma/2)$ values for kaonic hydrogen are badly needed, but may not be possible until the KAON factory becomes operational.

To definitively settle the nature of the $\Lambda(1405)$ will require much further work, both experimental and theoretical. Higher-statistics experiments on the production and decay of the $\Lambda(1405)$ are needed, but suitable $K^-$ beams will not be available until KAON. The low-energy reaction cross sections, especially for the $\overline{K}^0 p$ interactions, last studied 25 years ago, need to be better determined.

# $\Lambda(1405)$ MASS

## PRODUCTION EXPERIMENTS

| VALUE (MeV) | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **1406.5±4.0** | | [1] DALITZ | 91 | | M-matrix fit |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 1391 ± 1 | 700 | [1] HEMINGWAY | 85 | HBC | $K^- p$ 4.2 GeV/$c$ |
| ~ 1405 | 400 | [2] THOMAS | 73 | HBC | $\pi^- p$ 1.69 GeV/$c$ |
| 1405 | 120 | BARBARO-... | 68B | DBC | $K^- d$ 2.1–2.7 GeV/$c$ |
| 1400 ± 5 | 67 | BIRMINGHAM | 66 | HBC | $K^- p$ 3.5 GeV/$c$ |
| 1382 ± 8 | | ENGLER | 65 | HDBC | $\pi^- p$, $\pi^+ d$ 1.68 GeV/$c$ |
| 1400 ±24 | | MUSGRAVE | 65 | HBC | $\overline{p}p$ 3–4 GeV/$c$ |
| 1410 | | ALEXANDER | 62 | HBC | $\pi^- p$ 2.1 GeV/$c$ |
| 1405 | | ALSTON | 62 | HBC | $K^- p$ 1.2–0.5 GeV/$c$ |
| 1405 | | ALSTON | 61B | HBC | $K^- p$ 1.15 GeV/$c$ |

## EXTRAPOLATIONS BELOW $N\overline{K}$ THRESHOLD

| VALUE (MeV) | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 1411 | [3] MARTIN | 81 | | K-matrix fit |
| 1406 | [4] CHAO | 73 | DPWA | 0–range fit (sol. B) |
| 1421 | MARTIN | 70 | RVUE | Constant K-matrix |
| 1416 ±4 | MARTIN | 69 | HBC | Constant K-matrix |
| 1403 ±3 | KIM | 67 | HBC | K-matrix fit |
| 1407.5±1.2 | [5] KITTEL | 66 | HBC | 0–effective-range fit |
| 1410.7±1.0 | KIM | 65 | HBC | 0–effective-range fit |
| 1409.6±1.7 | [5] SAKITT | 65 | HBC | 0–effective-range fit |

# $\Lambda(1405)$ WIDTH

## PRODUCTION EXPERIMENTS

| VALUE (MeV) | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **50 ± 2** | | [1] DALITZ | 91 | | M-matrix fit |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 32 ± 1 | 700 | [1] HEMINGWAY | 85 | HBC | $K^- p$ 4.2 GeV/$c$ |
| 45 to 55 | 400 | [2] THOMAS | 73 | HBC | $\pi^- p$ 1.69 GeV/$c$ |
| 35 | 120 | BARBARO-... | 68B | DBC | $K^- d$ 2.1–2.7 GeV/$c$ |
| 50 ±10 | 67 | BIRMINGHAM | 66 | HBC | $K^- p$ 3.5 GeV/$c$ |
| 89 ±20 | | ENGLER | 65 | HDBC | |
| 60 ±20 | | MUSGRAVE | 65 | HBC | |
| 35 ± 5 | | ALEXANDER | 62 | HBC | |
| 50 | | ALSTON | 62 | HBC | |
| 20 | | ALSTON | 61B | HBC | |

## EXTRAPOLATIONS BELOW $N\overline{K}$ THRESHOLD

| VALUE (MeV) | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 30 | [3] MARTIN | 81 | | K-matrix fit |
| 55 | [4,6] CHAO | 73 | DPWA | 0–range fit (sol. B) |
| 20 | MARTIN | 70 | RVUE | Constant K-matrix |
| 29 ±6 | MARTIN | 69 | HBC | Constant K-matrix |
| 50 ±5 | KIM | 67 | HBC | K-matrix fit |
| 34.1±4.1 | [5] KITTEL | 66 | HBC | |
| 37.0±3.2 | KIM | 65 | HBC | |
| 28.2±4.1 | [5] SAKITT | 65 | HBC | |

# $\Lambda(1405)$ DECAY MODES

| | Mode | Fraction ($\Gamma_i/\Gamma$) |
|---|---|---|
| $\Gamma_1$ | $\Sigma\pi$ | 100 % |
| $\Gamma_2$ | $\Lambda\gamma$ | |
| $\Gamma_3$ | $\Sigma^0\gamma$ | |
| $\Gamma_4$ | $N\overline{K}$ | |

## $\Lambda(1405)$ PARTIAL WIDTHS

### $\Gamma(\Lambda\gamma)$ — $\Gamma_2$

| *VALUE* (keV) | *DOCUMENT ID* | *COMMENT* |
|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | |
| $27 \pm 8$ | BURKHARDT 91 | Isobar model fit |

### $\Gamma(\Sigma^0\gamma)$ — $\Gamma_3$

| *VALUE* (keV) | *DOCUMENT ID* | *COMMENT* |
|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | |
| $10 \pm 4$ or $23 \pm 7$ | BURKHARDT 91 | Isobar model fit |

## $\Lambda(1405)$ BRANCHING RATIOS

### $\Gamma(N\overline{K})/\Gamma(\Sigma\pi)$ — $\Gamma_4/\Gamma_1$

| *VALUE* | *CL%* | *DOCUMENT ID* | *TECN* | *COMMENT* |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $<3$ | 95 | HEMINGWAY 85 | HBC | $K^- p$ 4.2 GeV/$c$ |

## $\Lambda(1405)$ FOOTNOTES

[1] DALITZ 91 fits the HEMINGWAY 85 data.
[2] THOMAS 73 data is fit by CHAO 73 (see next section).
[3] The MARTIN 81 fit includes the $K^{\pm}p$ forward scattering amplitudes and the dispersion relations they must satisify.
[4] See also the accompanying paper of THOMAS 73.
[5] Data of SAKITT 65 are used in the fit by KITTEL 66.
[6] An asymmetric shape, with $\Gamma/2$ = 41 MeV below resonance, 14 MeV above.

## $\Lambda(1405)$ REFERENCES


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| MARTIN | 81 | NP B179 33 | | (DURH) |
| CHAO | 73 | NP B56 46 | +Kraemer, Thomas, Martin | (RHEL, CMU, LOUC) |
| THOMAS | 73 | NP B56 15 | +Engler, Fisk, Kraemer | (CMU) J |
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