82. Λ and Σ Resonances

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82.1 Introduction

For several decades, there has been very little new experimental data bearing on the properties of Λ and Σ resonances. An exception was the study at JLab of the reactions $\gamma p \to K^+\Sigma^\pm\pi^\mp$ and $\gamma p \to K^+\Sigma^0\pi^0$ [1], which established the spin and parity of the $\Lambda(1405)$ [2]. There was also from BNL new data on the very low energy region of K^-p scattering [3–7]. Otherwise, the field is starved for data. Recent analyses (see below) have improved what we know about the *properties* of the known Λ and Σ resonances, but the *established* resonances are the same ones that were in our 1984 edition [8] except for the $\Sigma(2250)$ which we consider 2-star only due to its unkown spin-parity. The 1990 Review [9] gave a full report of the status then, and included Argand plots from the partial-wave analyses. The 2018 Review [10] has a short survey of the $\Sigma(1670)$-region.

In the last few years, four groups have re-analyzed K^-p reactions using fuller collections of the old data. These analyses make an update of the status of the Λ and Σ resonances appropriate. Although they have not established any new resonances, they have provided at least some evidence for new states and have given a better understanding of the old ones.

Tables I and II are our evaluation of the status, both over-all and channel by channel, of each Λ and Σ resonance in the Particle Listings. In making these evaluations, we considered, in addition to the four analyses just mentioned, the ratings that predated them. The ratings use a 1- to 4-star system. The main Summary Table includes only established states with an overall status of 3 or 4 stars; as has already been noted, they are the same fourteen Λ resonances (including $\Lambda(1116)$) and nine instead of the former ten Σ resonances (including $\Sigma(1193)3/2^+$, and $\Sigma(1385)3/2^+$) that have long been in the Table. In addition, there are seven 1-star and two 2-star Λ's, and fifteen 1-star and three 2-star Σ's in the Particle Listings.

82.2 New analyses

The new analysis progress was pioneered by the Kent group which collected a large fraction of the available data and performed a comprehensive partial wave analysis [11, 12]. K^-p scattering into a pseudoscalar meson and an octet baryon is governed by two complex amplitudes; hence four quantities need to be measured to construct fully the amplitudes (up to an arbitrary phase per energy and angular bin). Discussions of complete experiments also generally assume perfect data (no experimental errors); realistic errors further complicate the task of amplitude extraction. Here, the available data are limited to the differential cross section and the target or hyperon recoil polarization P; data on the polarization transfer do not exist. The authors of Ref. [11] overcame this difficulty by using start values for the partial wave amplitudes determined in [13] and/or from an energy-dependent fit and by freezing or releasing sets of amplitudes. The resulting amplitudes were fitted with a unitary multichannel parameterization [12].

The JPAC group presented a coupled-channel fit to the $\bar{K}N$ partial waves derived by the Kent group [14]. The JPAC approach was based on the K-matrix formalism. Special attention was paid to the analytical properties of the amplitudes determined by the square-root unitary branch points and the continuation to the complex angular momentum plane. The fit described the Kent partial waves reasonably well. However, when observables were calculated from their partial-wave amplitudes, significant discrepancies became apparent. The results were therefore not included in the RPP.

The ANL-Osaka group derived the energy-dependent amplitudes in fits to a large subset of the data collected in Ref. [11] and further data sets described in Ref. [15]. Their fits were based on a phenomenological SU(3) Lagrangian [15]. The two ANL-Osaka models agree on the leading contributions but differ significantly in cases with weaker candidates [16].

Table 82.1: The status of the Λ resonances. Only those with an overall status of $***$ or $****$ are included in the main Baryon Summary Table.

Particle	J^P	Overall status	Status as seen in — $N\overline{K}$	$\Sigma\pi$	Other channels
$\Lambda(1116)$	$1/2^+$	$****$			$N\pi$ (weak decay)
$\Lambda(1380)$	$1/2^-$	$**$	$**$	$**$	
$\Lambda(1405)$	$1/2^-$	$****$	$****$	$****$	
$\Lambda(1520)$	$3/2^-$	$****$	$****$	$****$	$\Lambda\pi\pi, \Lambda\gamma$
$\Lambda(1600)$	$1/2^+$	$****$	$***$	$****$	$\Lambda\pi\pi, \Sigma(1385)\pi$
$\Lambda(1670)$	$1/2^-$	$****$	$****$	$****$	$\Lambda\eta$
$\Lambda(1690)$	$3/2^-$	$****$	$****$	$***$	$\Lambda\pi\pi, \Sigma(1385)\pi$
$\Lambda(1710)$	$1/2^+$	$*$	$*$	$*$	
$\Lambda(1800)$	$1/2^-$	$***$	$***$	$**$	$\Lambda\pi\pi, \Sigma(1385)\pi, N\overline{K}^*$
$\Lambda(1810)$	$1/2^+$	$***$	$**$	$**$	$N\overline{K}_2^*$
$\Lambda(1820)$	$5/2^+$	$****$	$****$	$****$	$\Sigma(1385)\pi$
$\Lambda(1830)$	$5/2^-$	$****$	$****$	$****$	$\Sigma(1385)\pi$
$\Lambda(1890)$	$3/2^+$	$****$	$****$	$**$	$\Sigma(1385)\pi, N\overline{K}^*$
$\Lambda(2000)$	$1/2^-$	$*$	$*$	$*$	
$\Lambda(2050)$	$3/2^-$	$*$	$*$	$*$	
$\Lambda(2070)$	$3/2^+$	$*$	$*$	$*$	
$\Lambda(2080)$	$5/2^-$	$*$	$*$	$*$	
$\Lambda(2085)$	$7/2^+$	$**$	$**$	$*$	
$\Lambda(2100)$	$7/2^-$	$****$	$****$	$**$	$N\overline{K}^*$
$\Lambda(2110)$	$5/2^+$	$***$	$**$	$**$	$N\overline{K}^*$
$\Lambda(2325)$	$3/2^-$	$*$	$*$		
$\Lambda(2350)$	$9/2^+$	$***$	$***$	$*$	
$\Lambda(2585)$		$*$	$*$		

The Bonn-Gatchina (BnGa) group added further (old) data to those analyzed in Ref. [11]. The data set was fitted in a modified K-matrix approach and the resulting amplitudes were compared with those from Refs. [11, 15]. New resonances were found, other states, mostly one and two-star states could not be confirmed; all resonances were tested for their statistical significance. Additional states with any set of quantum numbers were tested and were found to produce only small improvements in the fit [17]. In Ref. [18], properties of the full set of contributing hyperons were reported.

The star ratings of Λ and Σ resonances given in our earlier editions, and the new results from the Kent, ANL-Osaka and BnGa groups were used to update the star rating of the hyperon resonances. In [18], the overall star rating is directly estimated, for [12] we estimate the star rating from the

Table 82.2: The status of the Σ resonances. Only those with an overall status of $***$ or $****$ are included in the main Baryon Summary Table.

Particle	J^P	Overall status	Status as seen in — $N\overline{K}$	$\Lambda\pi$	$\Sigma\pi$	Other channels
$\Sigma(1193)$	$1/2^+$	****				$N\pi$ (weak decay)
$\Sigma(1385)$	$3/2^+$	****		****	****	
$\Sigma(1580)$	$3/2^-$	*	*	*		
$\Sigma(1620)$	$1/2^-$	*	*	*	*	
$\Sigma(1660)$	$1/2^+$	***	***	***	***	
$\Sigma(1670)$	$3/2^-$	****	****	****	****	
$\Sigma(1750)$	$1/2^-$	***	***	**	***	$\Sigma\eta$
$\Sigma(1775)$	$5/2^-$	****	****	****	**	
$\Sigma(1780)$	$3/2^+$	*	*	*	*	
$\Sigma(1880)$	$1/2^+$	**	**	*		
$\Sigma(1900)$	$1/2^-$	**	**	*	**	
$\Sigma(1910)$	$3/2^-$	***	*	*	*	
$\Sigma(1915)$	$5/2^+$	****	***	***	***	$\Sigma(1385)\pi$
$\Sigma(1940)$	$3/2^+$	*	*		*	
$\Sigma(2010)$	$3/2^-$	*	*	*		
$\Sigma(2030)$	$7/2^+$	****	****	****	**	$\Delta(1232)\overline{K}, N\overline{K}^*, \Sigma(1385)\pi$
$\Sigma(2070)$	$5/2^+$	*	*		*	
$\Sigma(2080)$	$3/2^+$	*		*		
$\Sigma(2100)$	$7/2^-$	*	*	*	*	
$\Sigma(2110)$	$1/2^-$	*	*	*	*	
$\Sigma(2230)$	$3/2^+$	*	*	*	*	
$\Sigma(2250)$		**	**	*	*	
$\Sigma(2455)$		*	*			
$\Sigma(2620)$		*	*			
$\Sigma(3000)$		*	*	*		
$\Sigma(3170)$		*				

branching-ratio errors. In [16], two solutions are given but no uncertainties for branching ratios. The overall star ratings are based on the evidence for the resonances in the new analyses as well as their consistency including also the results of earlier analyses given in [19].

We decided to remove the three so-called *bumps* $\Sigma(1480)$, $\Sigma(1560)$, $\Sigma(1670)$, and $\Sigma(1690)$ as well as $\Sigma(1620)$ from production experiments. The entries from $\Sigma(1770)1/2^+$ are now listed under $\Sigma(1660)1/2^+$ and $\Sigma(1880)1/2^+$, the entries from $\Sigma(1730)3/2^+$ and $\Sigma(1840)3/2^+$ are now combined to one $\Sigma(1780)3/2^+$. The one-star $\Sigma(2000)1/2^-$ is combined with a new one-star $\Sigma(2160)1/2^-$ to a single one-star $\Sigma(2110)1/2^-$. Apart from $\Lambda(1380)1/2^-$, four further new resonances were included in the Listings: $\Lambda(2070)3/2^+$, $\Lambda(2080)5/2^-$, $\Sigma(2010)3/2^-$, and $\Sigma(2230)3/2^+$, all with one star.

82.3 Sign conventions for resonance couplings

In terms of the isospin-0 and isospin-1 elastic scattering amplitudes A_0 and A_1, the amplitude for $K^-p \to \overline{K}^0 n$ scattering is $\pm(A_1 - A_0)/2$, where the sign depends on conventions used in conjunction with the Clebsch-Gordan coefficients (such as, is the baryon or the meson the "first" particle). If this reaction is partial-wave analyzed and if the overall phase is chosen so that, say, the $\Sigma(1775)D_{15}$ amplitude at resonance points along the positive imaginary axis (points "up"), then any Σ at resonance will point "up" and any Λ at resonance will point "down" (along the negative imaginary axis). Thus the phase at resonance determines the isospin. The above ignores background amplitudes in the resonating partial waves.

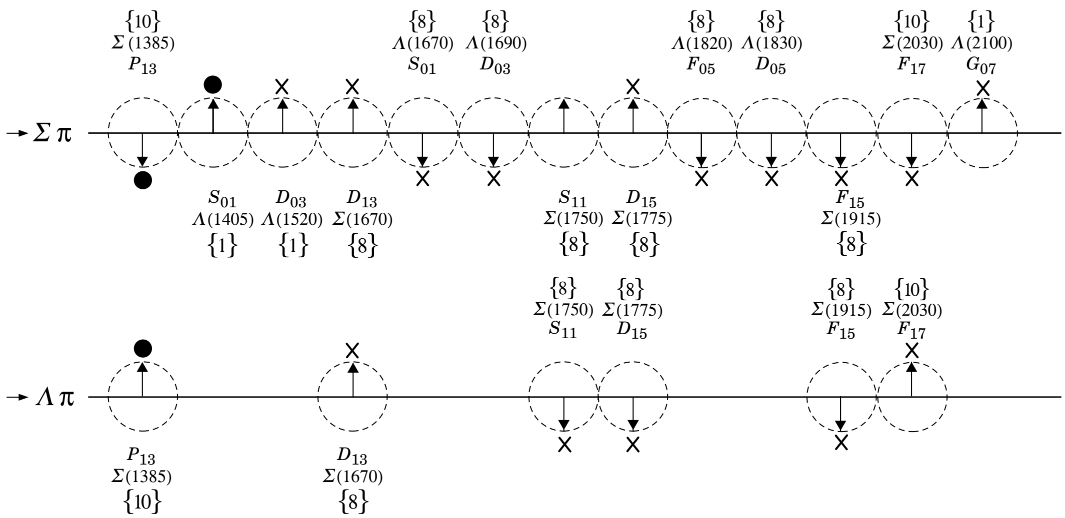

Figure 82.1: The signs of the imaginary parts of resonating amplitudes in the $\overline{K}N \to \Lambda\pi$ and $\Sigma\pi$ channels. The signs of the $\Sigma(1385)$ and $\Lambda(1405)$, marked with a $\bullet$, are set by convention, and then the others are determined relative to them. The signs required by the SU(3) assignments of the resonances are shown with an arrow, and the experimentally determined signs are shown with an $\times$.

That is the basic idea. In a similar but somewhat more complicated way, the phases of the $\overline{K}N \to \Lambda\pi$ and $\overline{K}N \to \Sigma\pi$ amplitudes for a resonating wave help determine the SU(3) multiplet to which the resonance belongs. Again, a convention has to be adopted for some overall arbitrary phases: which way is "up"? Our convention is that of Levi-Setti [20] and is shown in Fig. 82.1, which also compares experimental results with theoretical predictions for the signs of several resonances. In the Listings, a + or − sign in front of a measurement of an inelastic resonance coupling indicates the sign (the *absence* of a sign means that the sign is not determined, *not* that it is positive). Also other decay modes can be used to assign a hyperon to a SU(3) multiplet [21, 22]. Modern analyses determine properties of resonances at the pole position. In these analyses, the + or − sign is replaced by a phase. Background amplitudes can lead to significant phase shifts, and an additional phase shift due to rescattering is admitted in some analyses. In comparison to quark model predictions [18, 23], three Λ spin doublets can be identified as being mainly SU(3) singlets: the well-known ($\Lambda(1405)1/2^-$, $\Lambda(1520)3/2^-$), the ($\Lambda(2080)5/2^-$, $\Lambda(2100)7/2^-$), and ($\Lambda(2070)3/2^+$, $\Lambda(2110)5/2^+$).

82.4 The Λ(1405)

In coupled-channels calculations based on the chiral SU(3) effective field theory, the strongly attractive forces between $N\overline{K}$ and $\Sigma\pi$ generate five poles, one SU(3) singlet pole, two Λ octet poles and two (or one) octet Σ poles (see Section 100). In quark models, these five states are $\Lambda(1405)$, $\Lambda(1670)$, $\Lambda(1800)$, $\Sigma(1620)$, and $\Sigma(1750)$. The octet states are found 100 to 150 MeV above the corresponding nucleon resonances. In chiral SU(3) effective field theories, at least three of these states are seen in the 1300 to 1600 MeV mass range. The appearance of two Λ poles in this mass range, a narrow SU(3) octet at ∼1420 MeV and a wider SU(3) singlet at ∼1380 MeV, was unexpected. This approach has been pursued by a number of groups; for a summary of the results see our Review 100, "Pole Structure of the $\Lambda(1405)$ Region". In the Listings, we have introduced the $\Lambda(1380)$ as a new candidate resonance (with two stars), named in accordance with its approximate pole position. The second SU(3) octet Λ state is the well-known $\Lambda(1670)$. The masses of the two associated Σ states are uncertain so far, and no new entries are introduced in the Listings.

In traditional approaches only one resonance was seen in this mass region, the narrow state at 1405 MeV. It was reported to be the SU(3) singlet state a long time ago in Ref. [24], in agreement with the quark-model expectations but in contrast to the findings based on coupled-channels calculations within chiral SU(3) effective field theories. In the Listings, the $\Lambda(1405)$ has been retained with its traditional name. In quark models, this state is identified with the SU(3) singlet state, the two Λ octet states with $\Lambda(1670)$ and $\Lambda(1800)$, and the two Σ states with $\Sigma(1620)$ and $\Sigma(1750)$.

82.5 Errors on masses and widths

The errors quoted on resonance parameters from partial-wave analyses are often only statistical, and the parameters can change by more than these errors when a different parametrization of the waves is used. Furthermore, the different analyses use more or less the same data, so it is not really appropriate to treat the different determinations of the resonance parameters as independent or to average them together. In any case, the spread of the masses, widths, and branching fractions from the different analyses is certainly a better indication of the uncertainties than are the quoted errors. In the Listings, we usually give a range reflecting the spread of the values rather than a particular value with error.

82.6 Production experiments

Partial-wave analyses of course separate partial waves, whereas a peak in a cross section or an invariant mass distribution usually cannot be disentangled from background and analyzed for its quantum numbers; and more than one resonance may be contributing to the peak. The $\Sigma(1385)$ and $\Lambda(1405)$ lie below the $\overline{K}N$ threshold and nearly everything about $\Sigma(1385)$ is learned from production experiments. Our knowledge on $\Lambda(1405)$ benefits greatly from photoproduction of the three $\Sigma\pi$ charge states [1, 2] and from the precise measurement of the energy shift and width of the kaonic hydrogen atom [25].

Production and formation experiments agree quite well in the case of $\Lambda(1520)$ and results have been combined. Above this mass, no new results on peak hunting have been reported for about 40 years. For these early results, we refer the reader to our earlier editions. In photoproduction with energetic photons [26, 27] or at LHCb [28], hyperons are produced abundantly. So far, no attempt has been made to extract hyperon properties from these data. New data on hyperon spectroscopy can be expected from J-PARC [29], JLAB [30], and the forthcoming PANDA experiment [31].

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