Strange baryon resonance results based on the Bonn-Gatchina-PWA

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$$\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} = \mathbf{10}_S \oplus \mathbf{8}_M \oplus \mathbf{8}_M \oplus \mathbf{1}_A$$

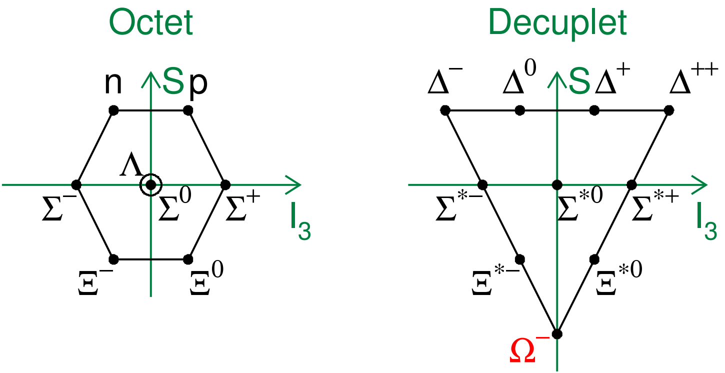


Table: **Λ-hyperons used in the first fit of the data.**

		J^P	Status	Mass	Width
$N(1535)$	$\Lambda(1670)$	$1/2^-$	****	$1660 - 1680$	$25 - 50$
$N(1650)$	$\Lambda(1800)$	$1/2^-$	***	$1720 - 1850$	$200 - 400$
singlet	$\Lambda(1520)$	$3/2^-$	****	1519.5 ± 1.0	15.6 ± 1.0
$N(1520)$	$\Lambda(1690)$	$3/2^-$	****	$1685 - 1695$	$50 - 70$
$N(1675)$	$\Lambda(1830)$	$5/2^-$	****	$1810 - 1830$	$60 - 110$
$N(2190)$	$\Lambda(2100)$	$7/2^-$	****	$2090 - 2110$	$100 - 250$
$N(1440)$	$\Lambda(1600)$	$1/2^+$	***	$1560 - 1700$	$50 - 250$
$N(1710)$	$\Lambda(1810)$	$1/2^+$	***	$1750 - 1850$	$50 - 250$
$N(1700)$	$\Lambda(1890)$	$3/2^+$	****	$1850 - 1910$	$60 - 200$
$N(1680)$	$\Lambda(1820)$	$5/2^+$	****	$1815 - 1825$	$70 - 90$
$N(2060)$	$\Lambda(2110)$	$5/2^+$	***	$2090 - 2140$	$150 - 250$

Table: **Σ-Hyperons used in the first fit of the data.**

		J^P	Status	Mass	Width
$N(1440)$	$\Sigma(1660)$	$1/2^+$	***	$1630-1690$	$40-200$
$\Delta(1230)$	$\Sigma(1385)$	$3/2^+$	****	1382.80 ± 0.35	36.0 ± 0.7
$N(1680)$, $\Delta(1905)$	$\Sigma(1915)$	$5/2^+$	****	$1900-1935$	$80-160$
$N(1990)$, $\Delta(1950)$	$\Sigma(2030)$	$7/2^+$	****	$2025-2040$	$150-200$
$N(1520)$	$\Sigma(1670)$	$3/2^-$	****	$1665-1685$	$40-80$
$N(1535)$, $\Delta(1620)$, $N(1650)$	$\Sigma(1750)$	$1/2^-$	***	$1730-1800$	$60-160$
$N(1675)$	$\Sigma(1775)$	$5/2^-$	****	$1770-1780$	$105-135$
$N(1700)$, $\Delta(1700)$	$\Sigma(1940)$	$3/2^-$	***	$1900-1950$	$150-300$

Many Σ states are missing, although there are number of "BUMPS"

Kaon beam motivation

There is a hope to observe the baryon multiplets and therefore to confirm the states observed in the Nucleon and Delta sector.

Table: **List of reactions used in the partial wave analysis.**

$K^- p \to K^0 n$	$K^- p \to K^- p$	$K^- p \to \pi^0 \Lambda$
$K^- p \to \pi^0 \Sigma^0$	$K^- p \to \pi^- \Sigma^+$	$K^- p \to \pi^+ \Sigma^-$
$K^- p \to \omega \Lambda$	$K^- p \to \eta \Lambda$	$K^- p \to \pi^0 \pi^0 \Lambda$
$K^- p \to K^+ \Xi^-$	$K^- p \to K^0 \Xi^0$	$K^- p \to \pi^0 \pi^0 \Sigma^0$
$K^- p \to \pi^0 \Lambda(1520)$	$K^- p \to K^- \Delta^+(1232)$	$K^- p \to \pi^\pm \Sigma^\mp(1385)$
$K^- p \to K^*(890) N$		

Energy dependent approach

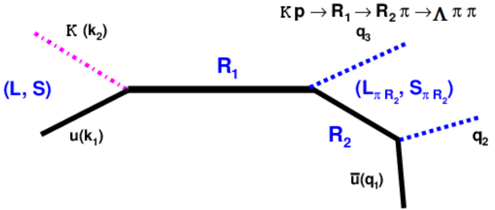
In many cases an unambiguous partial wave decomposition at fixed energies is impossible. Then the energy and angular parts should be analyzed together:

$$A(s,t) \quad = \quad \sum_{\beta\beta' n} A_n^{\beta\beta'}(s)\, Q^{(\beta)+}_{\mu_1\ldots\mu_n} F^{\mu_1\ldots\mu_n}_{\nu_1\ldots\nu_n} Q^{(\beta')}_{\nu_1\ldots\nu_n}$$

1. **Correlations between angular part and energy part are under control.**
2. **Unitarity and analyticity can be introduced from the beginning.**
3. **Parameters can be fixed from a combined fit of many reactions.**

1 C. Zemach, Phys. Rev. 140, B97 (1965); 140, B109 (1965)
2 S.U.Chung, Phys. Rev. D 57, 431 (1998)
3 A. V. Anisovich, V. V. Anisovich, V. N. Markov, M. A. Matveev and A. V. Sarantsev, J. Phys. G G 28, 15 (2002)
4 B. S. Zou and D. V. Bugg, Eur. Phys. J. A 16, 537 (2003)
5 A. Anisovich, E. Klempt, A. Sarantsev and U. Thoma, Eur. Phys. J. A 24, 111 (2005)
6 A. V. Anisovich and A. V. Sarantsev, Eur. Phys. J. A 30, 427 (2006)
7 A. V. Anisovich, V. V. Anisovich, E. Klempt, V. A. Nikonov and A. V. Sarantsev, Eur. Phys. J. A 34, 129 (2007).

Resonance amplitudes for meson photoproduction



General form of the angular dependent part of the amplitude:

$$\bar{u}(q_1)\tilde{N}^{\pm}_{\alpha_1\ldots\alpha_n}(R_2 \to K\Lambda)F^{\alpha_1\ldots\alpha_n}_{\beta_1\ldots\beta_n}(q_1+q_2)\tilde{N}^{(j\pm)\beta_1\ldots\beta_n}_{\gamma_1\ldots\gamma_m}(R_1 \to \pi R_2)\times$$

$$F^{\gamma_1\ldots\gamma_m}_{\xi_1\ldots\xi_m}(P)N^{\pm}_{\xi_1\ldots\xi_m}(R_1 \to Kp)u(k_1)BW_L(s)$$

$$F^{\mu_1\ldots\mu_L}_{\nu_1\ldots\nu_L}(p) = (m+\hat{p})O^{\mu_1\ldots\mu_L}_{\alpha_1\ldots\alpha_L}\frac{L+1}{2L+1}\left(g^{\perp}_{\alpha_1\beta_1} - \frac{L}{L+1}\sigma_{\alpha_1\beta_1}\right)\prod_{i=2}^{L} g_{\alpha_i\beta_i}O^{\beta_1\ldots\beta_L}_{\nu_1\ldots\nu_L}$$

$$\sigma_{\alpha_i\alpha_j} = \frac{1}{2}(\gamma_{\alpha_i}\gamma_{\alpha_j} - \gamma_{\alpha_j}\gamma_{\alpha_i})$$

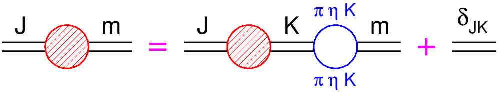
In c.m.s. of the reaction 2 particle→ 2 particle amplitude can be rewritten as:

$$A_{\pi N} = \omega^* \left[G(s,t) + H(s,t) i(\vec{\sigma}\vec{n})\right] \omega' \ ,$$
$$G(s,t) = \sum_L \left[(L+1)F_L^+(s) - LF_L^-(s)\right] P_L(z) \ ,$$
$$H(s,t) = \sum_L \left[F_L^+(s) + F_L^-(s)\right] P_L'(z) \ .$$

$$F_L^+ \quad = -(|\vec{k}||\vec{q}|)^L \sqrt{\chi_i \chi_f} \ \frac{\alpha(L)}{2L+1} BW_L^+(s) \ ,$$
$$F_L^- \quad = (|\vec{k}||\vec{q}|)^L \sqrt{\chi_i \chi_f} \ \frac{\alpha(L)}{L} BW_L^-(s) \ .$$

$$\chi_i = m_i + k_{i0} \qquad\qquad \alpha(L) = \prod_{l=1}^{L} \frac{2l-1}{l} = \frac{(2L-1)!!}{L!} \ .$$

N/D based (D-matrix) analysis of the data



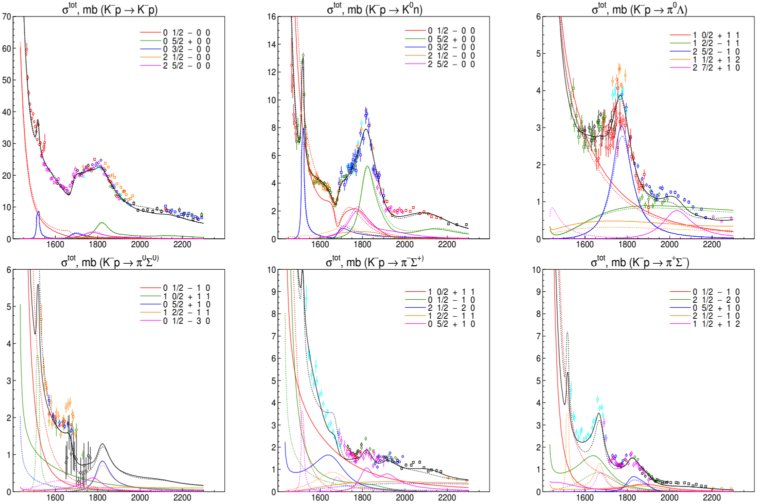
$$D_{jm} = D_{jk} \sum_{\alpha} B_{\alpha}^{km}(s) \frac{1}{M_m - s} + \frac{\delta_{jm}}{M_j^2 - s} \qquad \hat{D} = \hat{\kappa}(I - \hat{B}\hat{\kappa})^{-1}$$

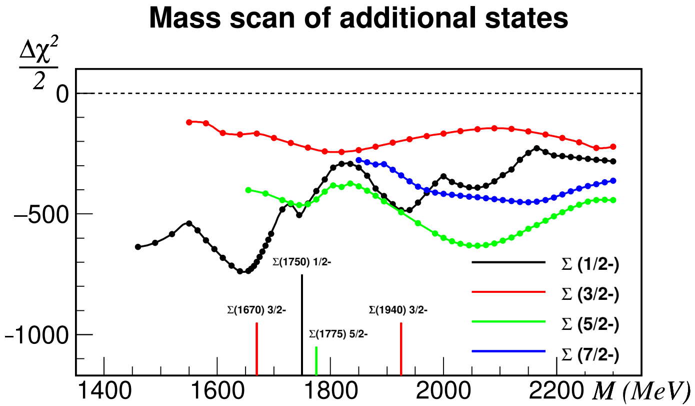
$$\hat{\kappa} = diag\left(\frac{1}{M_1^2 - s}, \frac{1}{M_2^2 - s}, \ldots, \frac{1}{M_N^2 - s}, R_1, R_2 \ldots\right)$$

$$\hat{B}_{ij} = \sum_{\alpha} B_{\alpha}^{ij} = \sum_{\alpha} \int \frac{ds'}{\pi} \frac{g_{\alpha}^{(R)i} \rho_{\alpha}(s', m_{1\alpha}, m_{2\alpha}) g_{\alpha}^{(L)j}}{s' - s - i0}$$

Contributions of the different partial waves to the total cross section

Analysis of the *Kp* collision reactions

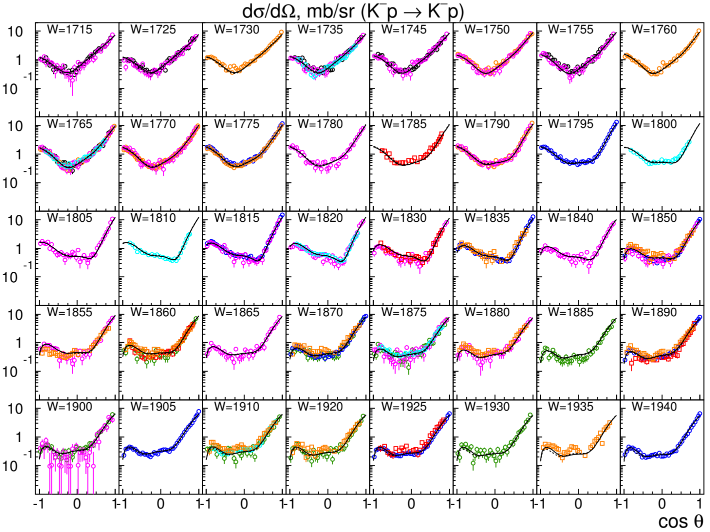




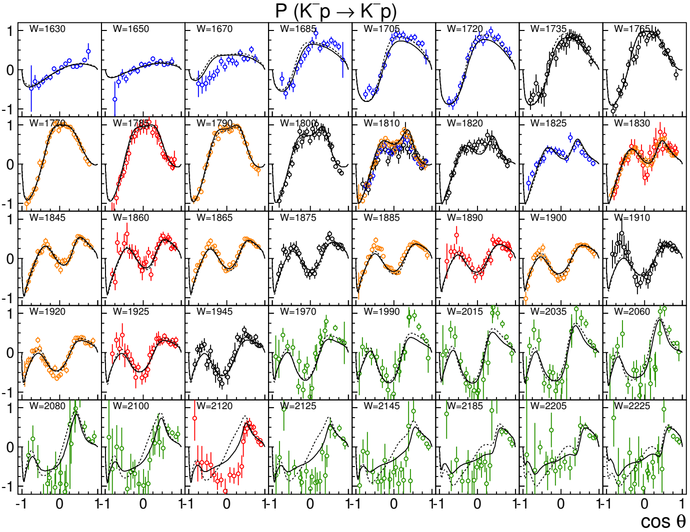
Mass scan of additional states
Δχ²/2
0
−500
-1000
1400
1600
1800
2000
2200
M (MeV)
Σ(1750) 1/2-
Σ(1670) 3/2-
Σ(1940) 3/2-
Σ(1775) 5/2-
Σ (1/2-)
Σ (3/2-)
Σ (5/2-)
Σ (7/2-)

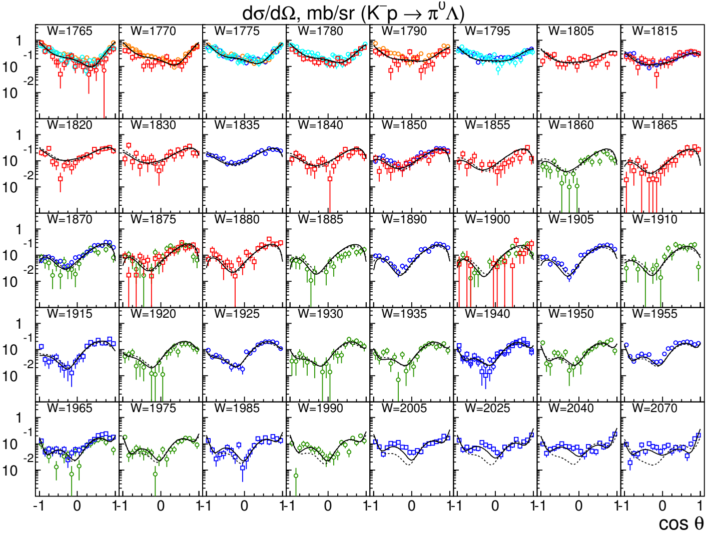
Table: **Σ-Hyperons Observed states**

J^P		Known state	New state	Mass
$1/2^+$	$N(1440)$	$\Sigma(1660)$		
$3/2^+$	$\Delta(1230)$	$\Sigma(1385)$		
$5/2^+$	$N(1680), \Delta(1905)$	$\Sigma(1915)$	????	
$7/2^+$	$N(1990), \Delta(1950)$	$\Sigma(2030)$	????	
$3/2^-$	$N(1520)$	$\Sigma(1670)$		
$1/2^-$	$N(1535), \Delta(1620), N(1650)$	$\Sigma(1750)$	$\Sigma(1620)$	1680 ± 8
			$\Sigma(1900)$	1936 ± 10
$5/2^-$	$N(1675)$	$\Sigma(1775)$		
$3/2^-$	$N(1700), \Delta(1700)$	$\Sigma(1940)$	$\Sigma(1860)$	1856 ± 10
$1/2^-$	$N(1895)$		$\Sigma(2120)$	2158 ± 25

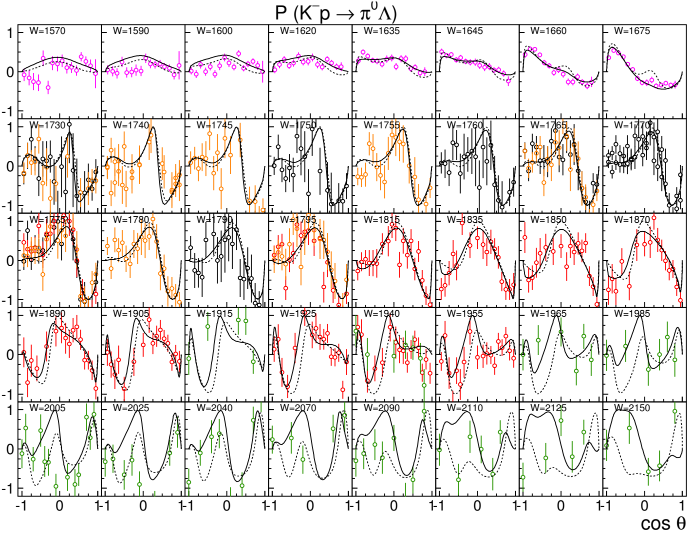


dσ/dΩ, mb/sr (K⁻p → K⁻p)
W=1715
W=1725
W=1730
W=1735
W=1745
W=1750
W=1755
W=1760
W=1765
W=1770
W=1775
W=1780
W=1785
W=1790
W=1795
W=1800
W=1805
W=1810
W=1815
W=1820
W=1830
W=1835
W=1840
W=1850
W=1855
W=1860
W=1865
W=1870
W=1875
W=1880
W=1885
W=1890
W=1900
W=1905
W=1910
W=1920
W=1925
W=1930
W=1935
W=1940
cos θ


P (K⁻p → K⁻p)
W=1630
W=1650
W=1670
W=1685
W=1705
W=1720
W=1735
W=1765
W=1770
W=1785
W=1790
W=1800
W=1810
W=1820
W=1825
W=1830
W=1845
W=1860
W=1865
W=1875
W=1885
W=1890
W=1900
W=1910
W=1920
W=1925
W=1945
W=1970
W=1990
W=2015
W=2035
W=2060
W=2080
W=2100
W=2120
W=2125
W=2145
W=2185
W=2205
W=2225
cos θ

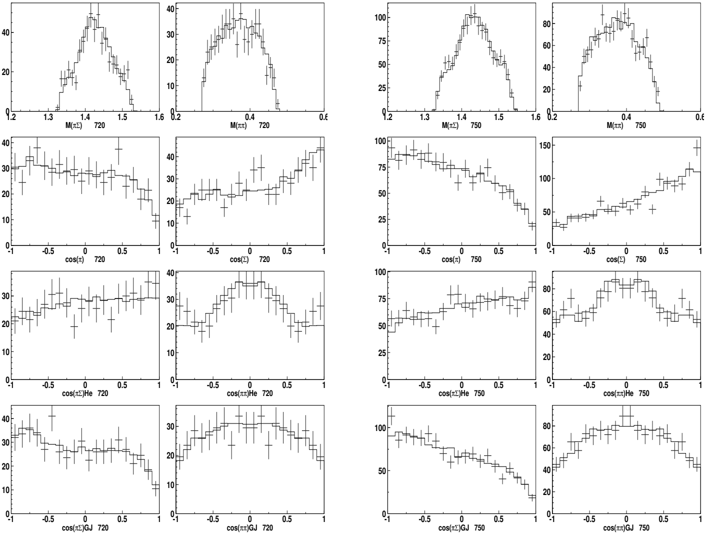


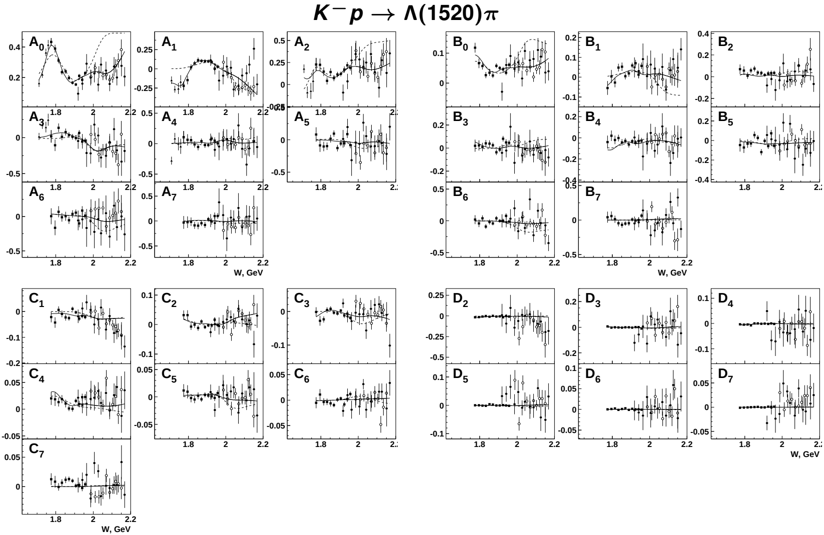
dσ/dΩ, mb/sr (K⁻p → π⁰Λ)
W=1765
W=1770
W=1775
W=1780
W=1790
W=1795
W=1805
W=1815
W=1820
W=1830
W=1835
W=1840
W=1850
W=1855
W=1860
W=1865
W=1870
W=1875
W=1880
W=1885
W=1890
W=1900
W=1905
W=1910
W=1915
W=1920
W=1925
W=1930
W=1935
W=1940
W=1950
W=1955
W=1965
W=1975
W=1985
W=1990
W=2005
W=2025
W=2040
W=2070
1
10⁻¹
10⁻²
-1
0
1
cos θ

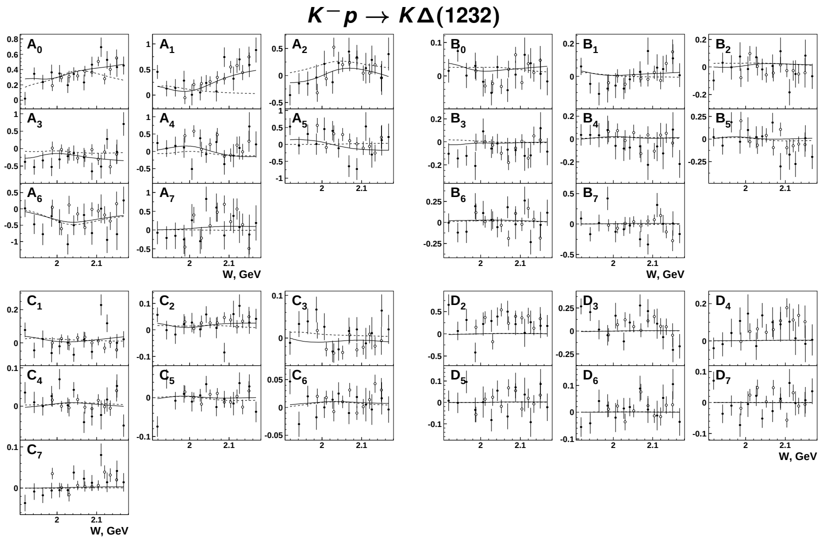


P (K⁻p → π⁰Λ)
W=1570
W=1590
W=1600
W=1620
W=1635
W=1645
W=1660
W=1675
W=1730
W=1740
W=1745
W=1750
W=1755
W=1760
W=1765
W=1770
W=1775
W=1780
W=1790
W=1795
W=1815
W=1835
W=1850
W=1870
W=1890
W=1905
W=1915
W=1925
W=1940
W=1955
W=1965
W=1985
W=2005
W=2025
W=2040
W=2070
W=2090
W=2110
W=2125
W=2150
cos θ

$K^- p \to \pi^0 \pi^0 \Sigma^0$ (beam momenta 720 and 750 MeV/c)




$K^- p \to \Lambda(1520)\pi$
A_0
A_1
A_2
A_3
A_4
A_5
A_6
A_7
B_0
B_1
B_2
B_3
B_4
B_5
B_6
B_7
C_1
C_2
C_3
C_4
C_5
C_6
C_7
D_2
D_3
D_4
D_5
D_6
D_7
W, GeV

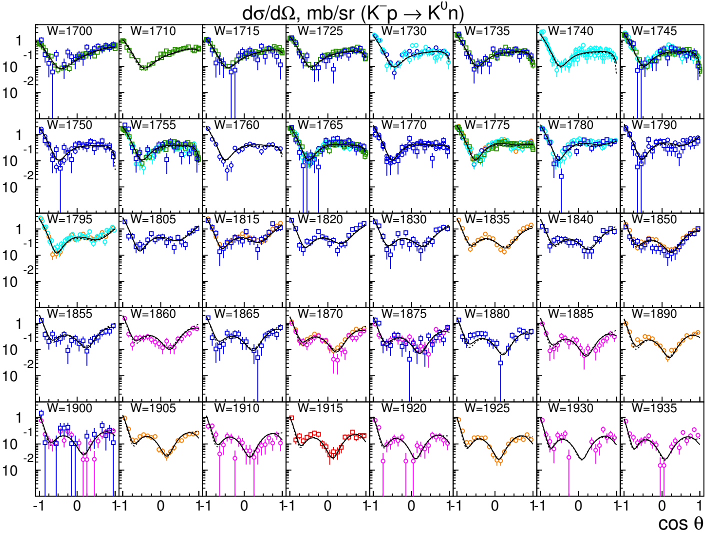


$K^- p \to K\Delta(1232)$
A_0
A_1
A_2
A_3
A_4
A_5
A_6
A_7
B_0
B_1
B_2
B_3
B_4
B_5
B_6
B_7
C_1
C_2
C_3
C_4
C_5
C_6
C_7
D_2
D_3
D_4
D_5
D_6
D_7
W, GeV

		ANL-Osaca	Bn-Ga	Model A	Model B	Bn-Ga
$K^- p \to K^- p$	$d\sigma/d\Omega$	3962	5495	3.07	2.98	2.28
	P	510	859	2.04	2.08	1.79
$K^- p \to \bar{K}^0 n$	$d\sigma/d\Omega$	2950	3445	2.67	2.75	1.62
$K^- p \to \pi^- \Sigma^+$	$d\sigma/d\Omega$	1792	2095	3.37	3.49	3.17
	P	418	578	1.30	1.28	2.06
$K^- p \to \pi^0 \Sigma^0$	$d\sigma/d\Omega$	580	581	3.68	3.50	3.57
	P	196	124	6.39	5.80	1.51
$K^- p \to \pi^+ \Sigma^-$	$d\sigma/d\Omega$	1786	2082	2.56	2.18	1.80
$K^- p \to \pi^0 \Lambda$	$d\sigma/d\Omega$	2178	2478	2.59	3.71	1.82
	P	693	732	1.41	1.73	1.73
$K^- p \to \eta \Lambda$	$d\sigma/d\Omega$	160	160	2.69	2.03	1.52
	P	18	—	0.94	3.83	—
$K^- p \to K^0 \Xi^0$	$d\sigma/d\Omega$	33	67	1.24	1.61	1.20
$K^- p \to K^+ \Xi^-$	$d\sigma/d\Omega$	92	193	2.05	1.74	1.38
$K^- p \to \Lambda \omega$	$d\sigma/d\Omega$	–	300	—	—	0.88
$K^- p \to \Lambda \omega$	DM	–	627	—	—	1.30
$K^- p \to K \Delta(1232)$	DM	–	667	—	—	1.29
$K^- p \to \pi \Lambda(1520)$	DM	–	168	—	—	1.94
$K^- p \to \pi \Sigma(1380)$	DM	–	899	—	—	1.71
$K^- p \to K^*(890) N$	DM	–	834	—	—	2.30

Λ and Σ resonances seen in early analyses (PDG)and by the BnGa group.

$\Lambda(1380)\ 1/2^-$		$\Sigma(1580)\ 3/2^-$	
$\Lambda(1405)\ 1/2^-$		$\Sigma(1620)\ 1/2^-$	
$\Lambda(1520)\ 3/2^-$		$\Sigma(1660)\ 1/2^+$	
$\Lambda(1600)\ 1/2^+$		$\Sigma(1670)\ 3/2^-$	
$\Lambda(1670)\ 1/2^-$		$\Sigma(1750) 1/2^-$	
$\Lambda(1690)\ 3/2^-$		$\Sigma(1775)\ 5/2^-$	
$\Lambda(1710)\ 1/2^+$	Not seen	$\Sigma(1780)\ 3/2^+$	Not seen
$\Lambda(1800)\ 1/2^-$		$\Sigma(1880)\ 1/2^+$	Not seen
$\Lambda(1810)\ 1/2^+$		$\Sigma(1900)\ 1/2^-$	
$\Lambda(1820)\ 5/2^+$		$\Sigma(1910)\ 3/2^-$	
$\Lambda(1830)\ 5/2^-$		$\Sigma(1915)\ 5/2^+$	
$\Lambda(1890)\ 3/2^+$		$\Sigma(1940)\ 3/2^+$	Not seen
$\Lambda(2000)\ 1/2^-$	Not seen	$\Sigma(2010)\ 3/2^-$	New
$\Lambda(2050)\ 3/2^-$	Not seen	$\Sigma(2030)\ 7/2^+$	
$\Lambda(2070)\ 3/2^+$	New	$\Sigma(2070)\ 5/2^+$	Not seen
$\Lambda(2080)\ 5/2^-$		$\Sigma(2080)\ 3/2^+$	Not seen
$\Lambda(2085)\ 7/2^+$	Not seen	$\Sigma(2100)\ 7/2^-$	
$\Lambda(2100)\ 7/2^-$		$\Sigma(2110)\ 1/2^-$	New
$\Lambda(2110)\ 5/2^+$		$\Sigma(2230)\ 3/2^+$	
$\Lambda(2325)\ 3/2^-$	Not seen		
$\Lambda(2350)\ 9/2^+$	Not seen		



dσ/dΩ, mb/sr (K⁻p → K⁰n)
W=1700
W=1710
W=1715
W=1725
W=1730
W=1735
W=1740
W=1745
W=1750
W=1755
W=1760
W=1765
W=1770
W=1775
W=1780
W=1790
W=1795
W=1805
W=1815
W=1820
W=1830
W=1835
W=1840
W=1850
W=1855
W=1860
W=1865
W=1870
W=1875
W=1880
W=1885
W=1890
W=1900
W=1905
W=1910
W=1915
W=1920
W=1925
W=1930
W=1935
cos θ

Let us consider the decay of the isospin 0 and isospin 1 states into $K^- p$ and $K^0 n$

$$
\begin{aligned}
|A(K^- p)|^2 &= \left(A_1 \frac{1}{\sqrt{2}} + A_0 \frac{1}{\sqrt{2}}\right)^2 = \frac{1}{2}\left(|A_1|^2 + |A_0|^2 + 2Re(A_1 A_0^*)\right) \\
|A(K^0 n)|^2 &= \left(A_1 \frac{1}{\sqrt{2}} - A_0 \frac{1}{\sqrt{2}}\right)^2 = \frac{1}{2}\left(|A_1|^2 + |A_0|^2 - 2Re(A_1 A_0^*)\right)
\end{aligned}
$$

$$
A_{KN} = \omega^* \left[G(s,t) + H(s,t) i(\vec{\sigma}\vec{n})\right] \omega' \qquad \vec{n}_j = \varepsilon_{\mu\nu j} \frac{q_\mu k_\nu}{|\vec{k}||\vec{q}|} \, .
$$

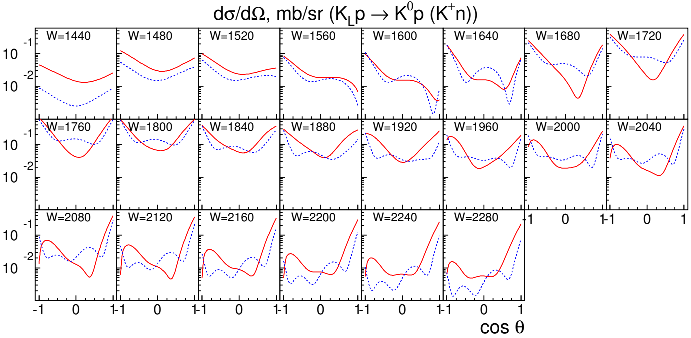
Differential cross section in c.m.s. of the reaction

$$
|A|^2 = \frac{1}{2} \mathrm{Tr}\, [A^*_{\pi N} A_{\pi N}] = |G(s,t)|^2 + |H(s,t)|^2 (1 - z^2)
$$

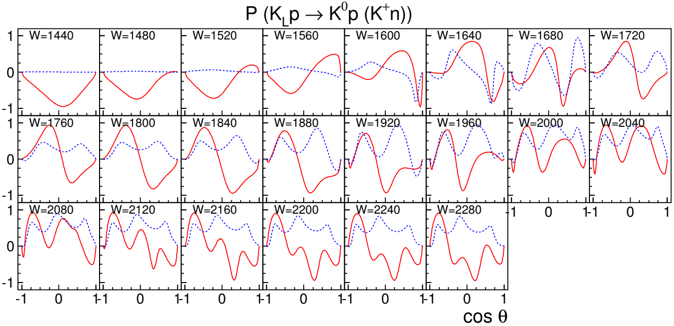
the recoil asymmetry:

$$
P = \frac{\mathrm{Tr}\left[A^*_{\pi N} \sigma_2 A_{\pi N}\right]}{2|A|^2 \cos\phi} = \sin\Theta \frac{2Im\,(H^*(s,t) G(s,t))}{|A|^2} \, .
$$

Prediction for $\frac{d\sigma}{d\Omega}(K_L p \to K^0 p(K^+ n))$



Prediction for the recoil asymmetry $K_L p \to K^0 p(K^+ n)$



SUMMARY

- The analysis of the data on the $K^- p \to KN, \pi\Lambda, \pi\Sigma$ reactions is notably improved after adding to 4-star and 3-star resonances 5 states. three of these states are Σ-hyperons with $J^P = \frac{1}{2}^-$
- The data on the $Kp \to \pi\pi\Lambda$ and $Kp \to \pi\pi\Sigma$ are well described by the solution found in the analysis of the reactions with two particle final states.
- The analysis of the data on the production of the vector mesons and baryons with the spin 3/2 solidly confirmes the found solution.
- The 11 states observed in earlier analyses was not confirmed by the combined analysis.
- The planned $K_L p$ experiment provides a unique possibility to perform the full amplitude decomposition of the observables measured in the $K^- p$ collision reactions and to determine the spectrum and properties of Σ hyperons.