Sign ambiguity in the $K\Sigma$ channel

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Abstract. Ambiguities of the signs of $N \rightarrow \Sigma K$ coupling constants are studied in a multichannel partial wave analysis of a large body of pion and photo-induced reactions. It is shown that the signs are not free from some ambiguities, and further experimental data are needed. Data on the reactions $\pi^{+}p \rightarrow \Sigma^{+}K^{+}$ and $\gamma p \rightarrow K^{+}\Sigma^{0}$ define rather well the isospin 3/2 contributions to these channels. However the lack of information on polarization observables for the reactions $\pi^{-}p \rightarrow \Sigma^{0}K^{0}$, $\pi^{-}p \rightarrow \Sigma^{-}K^{+}$ and $\gamma p \rightarrow K^{0}\Sigma^{+}$ does not allow us to fix uniquely the signs of $N \rightarrow \Sigma K$ coupling constants. As a consequence, also the contributions of nucleon resonances to these channels remain uncertain.

1 Introduction

The precision and diversity of data on photo-induced reactions off protons and neutrons studied experimentally has increased rapidly in the past, and significantly more data are expected in the near future. The data comprise high-resolution differential cross sections of various reactions and data in which the initial photons and/or the target nucleons are polarized, and data in which the polarization of final-state baryons is recorded. Recent reviews of ideas and results in baryon spectroscopy can be found in \cite{12}. Since then, important steps have been made by several groups analyzing pion and photo-induced reactions in coupled-channel frameworks. Here, we remind the reader of the recent developments.

The Giessen group has pioneered coupled-channel analyses of large data sets \cite{13,14,15,16,17,18}. Their most recent paper \cite{14} focusses on pion and photo-induced reactions of $\Sigma K$ final states with the aim to extract the couplings of known resonances to the $K\Sigma$ state.

The Bonn-Jülich group analyzed isospin $I = 3/2$ $\pi N$ elastic scattering amplitudes from the GWU/SAID analysis \cite{13} jointly with data on the $\pi^{+}p \rightarrow K^{+}\Sigma^{+}$ reaction \cite{14}. The analysis was extended to isospin-1/2 contributions by including all $\pi N$ elastic scattering amplitudes from \cite{13} and the reactions $\pi N \rightarrow N\eta$, $\Lambda K$, and $\Sigma K$ \cite{15}. A consistent treatment of the three $\pi p \rightarrow \Sigma K$ channels ($\pi^{-}p \rightarrow \Sigma^{+}K^{+}$, $\pi^{-}p \rightarrow \Sigma^{-}K^{+}$, and $\pi^{-}p \rightarrow \Sigma^{0}K^{0}$) was reached in \cite{15} but required - compared to \cite{14} - significant changes in the relative importance of the contributions to the total cross section from different partial waves. Photoproduction of single pions was included in a study presented in \cite{16}. It is shown that a good description of the data can be achieved.

The Osaka-Tokyo-Argonne group studies baryon resonances in a dynamical coupled-channels model by fitting a large body of pion and photo-induced reactions \cite{17,18,19,20,21}.

The Bonn-Gatchina group has published recently a comprehensive analysis of a large body of pion and photo-induced reactions \cite{22,23,24}. At present, this is the only group which systematically searched for new resonances in all partial waves. Mass, width, and partial decay widths of many resonances - including several new baryon resonances - were determined; their errors were evaluated by a systematic variation of the model parameters. The final results can be found in the latest RPP \cite{25}. The new resonances disfavor \cite{26} conventional diquark models in which one pair of quarks is frozen into a quasi-stable diquark \cite{27}. The observed pattern of resonances seems to occupy fully a limited number of SU(6) multiplets \cite{28} while other multiplets remain void. Interestingly, the new resonances can all be grouped naturally into spin-parity doublets. At present, there is an ongoing discussion if the occurrence of parity doublets in meson and baryon spectroscopy evidences a phase transition from broken to restored chiral symmetry \cite{27,28}.

The Kent group \cite{29} has updated an older analysis \cite{30} of $\pi N$ elastic scattering amplitudes and (low-statistics) bubble chamber data on $\pi N \rightarrow N\pi\pi$. The group confirmed the existence of most resonances reported in \cite{29}. Some of them had already been seen in their 1983 analysis \cite{29}, even though the Particle Data Group did not open new entries for these resonances at that time.

Several groups studied particular aspects. The Gent group developed a Regge-plus-resonance (RPR) model \cite{31} in which the background is deduced from the high-energy Regge-trajectory exchange in the t-channel to which a few resonances are added. The coupled-channel model of the Groningen group \cite{32} \cite{33} was later extended at Giessen \cite{34}. The fit uses established resonances and derives decay coupling constants which are compared to SU(3) relations.

In the present paper we present the results of a systematic investigation of reactions with $K\Sigma$ final states within the Bonn-Gatchina partial wave analysis. All results were obtained in a combined analysis of data on $\pi N$, $\eta N$, $K\Lambda$, $K\Sigma$, $\pi\pi N$ and $\pi\eta N$ final states \cite{22,23,24} including recent measurements from the CBELSA/TAPS \cite{38} and MAMI-C \cite{39} collaborations. In total, 31,180 data points from two-body reactions are...
used which are described with a $\chi^2$ of 48.710, or $\chi^2/N_F = 1.6$. The fit is further constrained by a fraction of the events (≈ 500,000) from three-body final states which are included in an event-based likelihood fit.

### 2 Production of $K\Sigma$ final states

In Figs. [1] we demonstrate the quality of the fits to the reaction $\pi^- p \rightarrow K^0 \Sigma^0$ obtained with the solution BnGa2011-02M. The data on $\pi^- p \rightarrow K^+ \Sigma^-$ can be included in the fit rather easily: only a very small adjustment of the parameters is needed to describe them with a good quality (solution BnGa2011-02M). As mentioned in the introduction, the high precision photoproduction data from MAMI-C [39] are included in this analysis. Table 1 documents the quality for the description of the reactions with $K\Sigma$ final states.

![Differential cross section of the reaction $\pi^- p \rightarrow K^0 \Sigma^0$. Curves are from the solution BnGa2011-02M. Data: circles from Ref. [41]; up triangles from Ref. [42]; diamonds from Ref. [43].](image)

**Table 1.** Fit quality for fits with and without inclusion of data on the reaction $\pi^- p \rightarrow K^+ \Sigma^-$. 

| Obs. | BnGa 2011-02M | BnGa 2013-02 | $N_{data}$ | Ref. |
|------|---------------|---------------|------------|------|
| $\pi^- p \rightarrow K^0 \Sigma^0$ | | | | |
| $d\sigma/d\Omega$ | 1.02 | 0.69 | 220 | [43] (RAL) |
| $P$ | 1.53 | 1.21 | 85 | [43] (RAL) |
| $\gamma p \rightarrow K^+ \Sigma^0$ | | | | |
| $d\sigma/d\Omega$ | 1.46 | 1.35 | 743 | [44,45,46,47,48] (var.) |
| $P$ | 1.42 | 1.48 | 351 | [44,45,46,47,48] (var.) |
| $\beta$ | 2.09 | 1.89 | 7 | [49] (RAL) |
| $\pi^- p \rightarrow K^+ \Sigma^-$ | | | | |
| $d\sigma/d\Omega$ | 2.45 | 2.42 | 130 | [50,51,52,53] (var.) |
| $\gamma p \rightarrow K^0 \Sigma^0$ | | | | |
| $d\sigma/d\Omega$ | 1.30 | 1.49 | 1590 | [54] (CLAS) |
| $d\sigma/d\Omega$ | 1.45 | 1.40 | 1145 | [49] (MAMI) |
| $P$ | 2.43 | 2.17 | 351 | [44,45,46,47,48] (var.) |
| $\Sigma$ | 2.45 | 1.99 | 42 | [49] (MAMI) |
| $C_x$ | 2.13 | 2.56 | 94 | [49] (MAMI) |
| $C_z$ | 2.13 | 2.06 | 94 | [49] (MAMI) |
| $\gamma p \rightarrow K^0 \Sigma^+$ | | | | |
| $d\sigma/d\Omega$ | 3.25 | 4.00 | 48 | [57] (CLAS) |
| $d\sigma/d\Omega$ | 1.28 | 1.45 | 160 | [59] (SAPHIR) |
| $d\sigma/d\Omega$ | 0.87 | 0.94 | 72 | [59] (SAPHIR) |
| $P$ | 0.96 | 0.82 | 72 | [59] (SAPHIR) |
| $\Sigma$ | 2.04 | 1.68 | 15 | [59] (SAPHIR) |
Fig. 2. Differential cross section of the reaction $\pi^- p \rightarrow K^0 \Sigma^0$. Data: circles from Ref. [41]; up triangles from Ref. [42]; diamonds from Ref. [43]. Curves represent solution BnGa2013-02.
It can hence be expected that the $\pi^- p \rightarrow K^0 \Sigma^0$ reaction is sensitive to the interference between isospin $3/2$ and $1/2$ amplitudes. To check this interference we have changed the sign of the couplings of all nucleon resonances to the $K \Sigma$ channel. Let us note that the description of reactions in which nucleon or $\Delta$ resonances are dominant undergo little changes only. In those reactions, the interference is small and the $K \Sigma$ amplitudes contribute mostly quadratically.

A fit with all $(N \rightarrow K \Sigma)$ K-matrix coupling constants reversed cured the problems in the description of the angular distributions in Fig. 1. The solution also describes acceptably well all other reactions with $K \Sigma$ final states but introduces small changes of the properties like masses and widths of baryon resonances. As a result, the overall description of the data became worse.

These findings initiated a full systematic study of $N \rightarrow K \Sigma$ decay amplitudes changing the signs of all K-matrix coupling (resonances and background terms) in all possible combinations. The relative signs of coupling constants within a given partial wave turned out to be well defined; mostly, the signs of the full partial wave amplitudes needed to be changed. The optimum was found when the sign was changed for the $S_{11}$, $D_{13}$, and $F_{15}$ partial waves. This fit produced an overall likelihood value which was about 740 better than the one in solution BnGa2011-02M. We will denote this solution as BnGa2013-02. It describes the high energy $\pi^- p \rightarrow K^0 \Sigma^0$ data with the $\chi^2 = 0.69$. The description of the differential cross section with this solution is shown in Fig. 2.

The improvement in the description of the data with $K \Sigma$ final states is not very impressive but noticeable as can be seen in Table 1 and in a few figures. These show for $\pi^+ p \rightarrow K^+ \Sigma^+$ the differential cross section (Fig. 3), the recoil asymmetry (Fig. 4), and the spin rotation parameter (Fig. 5). For $\pi^- p \rightarrow K^- \Sigma^-$ we show the differential cross section (Fig. 6) and for $\pi^- p \rightarrow K^0 \Sigma^0$ the recoil asymmetry (Fig. 7). In the figures, solution BnGa2011-02M is shown with dashed lines and BnGa2013-02 with full lines. The solution BnGa2013-02 describes the backward structure in the $\pi^- p \rightarrow K^0 \Sigma^0$ reaction much better (see Fig. 3) and even provides a better description of the recoil asymmetry. However, the data are not really enforcing the changes which were introduced. The differential cross section for this reac-

![Fig. 3. Differential cross section for $\pi^+ p \rightarrow K^+ \Sigma^+$. The data are from [44-45,46,47,48]. Full curves: the solution BnGa2013-02 and dashed curves: BnGa2011-02M.](image1)

![Fig. 4. Recoil asymmetry from $\pi^+ p \rightarrow K^+ \Sigma^+$. The data are from [44-45,46,47,48,60]. Full curves: the solution BnGa2013-02 and dashed curves: BnGa2011-02M.](image2)

![Fig. 5. Spin-rotation parameter $\beta$ from the reaction $\pi^+ p \rightarrow K^+ \Sigma^+$. The data are from [49]. Full curves: the solution BnGa2013-02 and dashed curves: BnGa2011-02M. Note that $\beta$ is $2\pi$ cyclic.](image3)
Fig. 6. Differential cross section of the reaction $\pi^- p \rightarrow K^+ \Sigma^-$. Full curves: the solution BnGa2013-02 and dashed curves: BnGa2011-02M. The data are from [50] (circles); [51] (up triangles); [52] (squares); [53] (diamonds).

Fig. 7. Recoil asymmetry in the reaction $\pi^- p \rightarrow K^0 \Sigma^0$. Full curves: the solution BnGa2013-02 and dashed curves: BnGa2011-02M. The data are from [53].

3 Total cross sections and partial wave contributions

The partial wave contributions to the total cross section for the three $\pi N \rightarrow K \Sigma$ reactions derived in fits BnGa2011-02M and BnGa2013-02, respectively, are shown in Fig. 8. The contributions of isospin $3/2$ partial waves hardly changed. Both solutions are well within the boundaries of the systematic error defined for solution BG2011-02. However, the contributions of nucleon resonances have undergone significant changes. In the solution BnGa2011-02M the dominant contribution to $\pi^- p \rightarrow K^0 \Sigma^0$ and $\pi^- p \rightarrow K^+ \Sigma^-$ comes from the $P_{13}$ partial wave while in the solution BnGa2013-02, this wave is very weak. The $S_{11}$ contribution has become stronger by a factor 2 in BnGa2013-02 and in the $\pi^- p \rightarrow K^+ \Sigma^-$ it is the dominant partial wave. Moreover, in BnGa2011-02M, destructive interference is observed in the region of $N(1895)S_{11}$. This destructive interference is compensated by a large intensity from the $P_{13}$ partial wave which reaches a maximum at 1800 MeV. In
4 Resolving the ambiguity in \( K\Sigma \) amplitudes

As mentioned above the present ambiguity is a consequence of the lack of data on polarization observables from pion and photo-induced reactions. In Fig. 10, we show predictions for the recoil asymmetry for \( \pi^- p \rightarrow K^+ \Sigma^- \). In the 1750-1900MeV region, the two solutions both predict large asymmetries but different in sign. An additional measurement of the spin rotation parameter would provide a full data base which would define the contributions from all leading partial waves unambiguously. Data on the recoil asymmetry for \( \pi^- p \rightarrow K^+ \Sigma^- \) could be measured at GSI by the HADES collaboration.

The data on the \( \gamma p \rightarrow K^0 \Sigma^+ \) is another important source of information which can resolve this ambiguity. The prediction for target asymmetry and double polarization observables are shown in Fig. 11. These data can be obtained by the CBELSA/TAPS and CLAS collaborations and will not only help to resolve this ambiguity but also to define resonances in the 2 GeV region more firmly.

5 Comparison with other work

Coupled channel analyses of pion and photo-induced production of the \( K\Sigma \) final states have been carried out by several groups. Here we discuss only recent results.
The largest contribution to the cross section is assigned to the partial wave contributions. In the Bonn-Jülich analysis [14], different answers concerning the magnitude of the most significant contributions at threshold, exceeds the π⁻p → K⁺Σ⁺ reaction near threshold, exceeds the leading partial waves of BnGa2011-02M (as well as in BnGa2013-02), the (3/2, 3/2⁺) contribution is by far dominant at 1900 MeV and falls off at higher energies. The (3/2, 1/2⁻) wave provides a significant but much smaller contribution. The (3/2, 7/2⁻) contribution rises slowly with energy, adopts the same height as the (3/2, 1/2⁻) contribution at 1.9 GeV, and becomes the largest contribution at the highest energy.

In the most recent analysis of the Bonn-Jülich group [15] a new solution was found. This solution uses a much larger data base and includes pion-induced reactions with different KΣ final states. For sake of convenience, we show in Fig. 12 the results of three analyses, BnGa2011-02M and BnGa2013-02, and of Bonn-Jülich 2012. In the isospin 3/2 sector, the three analyses identify the same partial waves, $F_{33}$, $S_{31}$, and $F_{37}$, as dominant contributions, even though in both Bonn-Gatchina analyses the $S_{31}$ falls off with energy while it very slowly rises in the Bonn-Jülich analysis. Only in the smaller contributions significant differences can be found: in particular the Bonn-Gatchina analysis does not find a significant contribution from the $D_{35}$ wave, and also possible contributions from the $G_{37}$ and $G_{39}$ waves are fitted to zero. Instead, more intensity is assigned to the leading $P_{33}$ wave.

The contributions in $I = 1/2$ sector are less well defined. Since both $N$ and $Σ$ resonances contribute with similar strengths to the reaction π⁻p → K⁺Σ⁺ and uncertainties on the sign of KΣ coupling constants of $N$ resonances play a large role. Thus, even the leading partial waves are different in BnGa2011-02M and BnGa2013-02. However, there is fair or even good agreement between the leading partial waves of BnGa2013-02 and Bonn-Jülich 2012: the $S_{11}$ wave is leading at low energies and $D_{15}$ and $P_{13}$ become important at the highest energy. $P_{13}$ is important in both analyses even though more pronounced in BnGa2013-02. Smaller contributions are present in both analyses even though their strengths may differ: Bonn-Gatchina assigns more intensity to the $F_{15}$ wave, Bonn-Jülich to $F_{17}$. There are significant $D_{13}$ contributions already at low energy in BnGa2013-02, a partial wave which gives a contribution that rises slowly with energy in the Bonn-Jülich analysis.

In general, the Bonn-Jülich solution varies more smoothly as a function of energy, the Bonn-Gatchina solution has more structure. The reason for this difference is due to the larger number of resonances used in the Bonn-Gatchina analysis which fits not only pion-induced reactions but also photo-induced reactions. They are of considerably higher statistical power and require introduction of more resonances.

In the comparison, one has to have in mind that the “area of uncertainty” or error bands are derived differently in the two approaches. The Bonn-Jülich group has used two different model assumptions yielding two sets of contributions to the cross section (solid and dashed curves). The Bonn-Gatchina
group has used in total eleven different parameterizations of partial waves and/or different weight factors (for BnGa2011-02M and BnGa2013) which all gave acceptable fits to the data. Errors are defined from the variance of the respective contributions.

6 Conclusion

The investigation of the reactions with $K\Sigma$ final state revealed a discrete ambiguity in the sign of the $K\Sigma$ coupling constants of leading nucleon partial wave amplitudes. While the isospin 3/2 amplitudes are firmly defined by the $\pi^+p \rightarrow K^+\Sigma^+$ and $\gamma p \rightarrow K^+\Sigma^0$ data (where isospin 3/2 contributions play a dominant role), the lack of polarization data in other reactions with $K\Sigma$ final states leads to two rather different solution. Both solutions provide a good overall description of the present data base. The solution BnGa2011-02M (which is very similar to the BaGa2011-02 solution) misses some structures in $\pi^-p \rightarrow K^0\Sigma^0$ data; the new solution BnGa2013-02 describes those data better but the overall fit is not really superior. Even though we give preference to the new solution, the decision which one of the two solution is closer to the truth can only be made when new data on polarization observables are available, either from reaction $\pi^-p \rightarrow K^+\Sigma^-$ or from $\gamma p \rightarrow K^0\Sigma^0$. For both reactions predictions were made how to discriminate the two solutions. It is shown that a measurement of the recoil polarization for the former reaction or a measurement of a polarization variable like $E$, $F$, $H$, or $T$ for the latter reaction will be sufficient to resolve the ambiguity.

The new solution compares favorably to the solution obtained by the Bonn-Jülich group. In the isospin 1/2 sector, the comparison shows even striking similarity of the leading waves. In the isospin 3/2 sector, the leading waves are similar even though minor waves differ in the magnitude of their contributions to the respective cross sections. The similarity of the results carries an important message: the Bonn-Gatchina and Bonn-Jülich groups use rather different analysis methods, but the leading waves are very similar. Obviously, the leading waves are defined by the data base, but not by the method. Differences in details are, however, important and ask for continued efforts, both in augmenting the data base and in the development of analysis techniques.

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