

## Determination of the spin triplet $p\Lambda$ scattering length from the final state interaction in the $\vec{p}p \rightarrow pK^+\Lambda$ reaction

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The  $\vec{p}p \rightarrow pK^+\Lambda$  reaction has been measured with the COSY-TOF detector at a beam momentum of 2.7 GeV/c. The polarized proton beam enables the measurement of the beam analyzing power by the asymmetry of the produced kaon ( $A_N^K$ ). This observable allows the  $p\Lambda$  spin triplet scattering length to be extracted for the first time model independently from the final state interaction in the reaction. The obtained value is  $a_t = (-2.55^{+0.72}_{-1.39\text{stat.}} \pm 0.6_{\text{sys.}} \pm 0.3_{\text{theo.}})\text{fm}$ . This value is compatible with theoretical predictions and results from model-dependent analyses.

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The elementary hyperon-nucleon interaction is an essential ingredient for microscopic few-body or many-body calculations. This concerns investigations of light hypernuclei [1], like the hypertriton and  $^4_\Lambda\text{He}$  [2], as well as studies of neutron stars where hyperons are expected to be present in the core [3]. In particular, the interaction of the hyperons with the surrounding neutron matter has a crucial influence on the radius and mass of those stars.

Naturally, the reliability of pertinent calculations not only depends on the employed few-body or many-body approaches, but also crucially on the interaction that is used as input. Therefore, it is unfortunate that so far only the bulk properties of the hyperon-nucleon interaction are known from experiment. Specifically, with regard to the  $\Lambda N$  interaction, there are no data from elastic scattering that would allow us to pin down its spin dependence [4]. In addition, the chance is low for any pertinent low-energy scattering data in the future due to the short hyperon lifetime which makes it difficult to prepare a hyperon beam or target.

An alternative is to study the hyperon-nucleon interaction by the final state interaction (FSI) in high momentum transfer reactions such as  $pp \rightarrow pK^+\Lambda$  as pointed out in Ref. [5].

Indeed, the method developed and described in this reference allows the extraction of the  $S$ -wave  $p\Lambda$  scattering lengths from FSI effects with a definite theoretical uncertainty and without model assumptions. The scattering length is determined directly from the shape of the  $p\Lambda$  invariant mass spectrum. The spin dependence of the FSI and of the  $p\Lambda$  interaction can be disentangled by considering specific polarization states of the beam and/or target particles. For the spin-triplet component of the  $p\Lambda$  interaction this can be achieved by measuring the symmetric contribution of the beam analyzing power determined from the asymmetry of the produced kaon ( $A_N^K$ ), which is accessible in an experiment with a polarized beam. For the first time the results of a model-independent determination of the  $p\Lambda$  spin triplet scattering length are reported in the present paper.

The  $\vec{p}p \rightarrow pK^+\Lambda$  reaction has been exclusively measured with the COSY Time-of-Flight (COSY-TOF) detector using a polarized proton beam with a momentum of 2.7 GeV/c. The details of the detector system including the Straw-Tube-Tracker (STT) can be found in Refs. [6–9].

COSY-TOF covers the full phase space of the reaction. From Monte Carlo (MC) simulations the reconstruction efficiency times acceptance is determined to be about 15% and almost constant over the full kinematic range. The average  $p\Lambda$  invariant mass resolution is  $\sigma_m \approx 1.3$  MeV. At the kinematic borders the resolution improves to  $\sigma_m \approx 0.5$  MeV due to the kinematic fitting. Possible effects on the extraction procedure have been investigated by simulations and a dedicated analysis with a mass-dependent resolution. The results show negligible differences [10].

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The  $pK^+\Lambda \rightarrow pK^+p\pi^-$  events have a clear signature of four tracks in the final state where two tracks stem from the target and two tracks from the delayed weak decay of the  $\Lambda$  hyperon. After applying a geometric fit, a kinematic fit is performed on each event with two overconstraints.

The final event selection criteria consists of constraints on (i) the reduced  $\chi^2$  of the kinematic fit,  $\chi_{\text{kin}}^2/\text{ndf} < 5$ , (ii) the minimum distance  $d_\Lambda$  between the production and the decay of the  $\Lambda$ ,  $d_\Lambda > 3$  cm, and (iii) the minimum angle between the directions of the decay proton and the  $\Lambda$ ,  $\angle(\Lambda, p) > 2^\circ$ . Finally, 232 873 events are used for the further analysis.

Incorrectly reconstructed events with multiple primary tracks, i.e., from multipion production are effectively removed by the applied criteria (i)–(iii). The remaining physical background stems from the  $\bar{p}p \rightarrow pK^+\Sigma^0 \rightarrow pK^+\Lambda\gamma$  reaction, which has nearly the same topology. However, MC simulations show that at this beam momentum the contribution from the  $\Sigma^0$  production to the final event sample is below 1% [10]. Therefore, it is neglected in the following analysis.

The methods for the determination of the beam polarization and the analyzing power  $A_N^K$  are described in Refs. [6,10]. The beam polarization for the measurement at 2.7 GeV is  $(77.9 \pm 1.2)\%$ . It is determined from the asymmetry of elastic events and the  $pp$  analyzing power from the SAID partial wave analysis SP07 [11]. Systematic effects from different magnitudes of “up” and “down” beam polarization can be neglected in the following analysis as discussed in Ref. [6].

The observable  $A_N^K$  gives access to spin triplet  $p\Lambda$  states due to its particular dependence on interference terms of kaon partial waves. Expanding  $A_N^K$  in terms of associated Legendre polynomials  $P_l^m$  gives [6,12]

$$\frac{A_N^K(x, m_{p\Lambda})}{\Phi(s, m_{p\Lambda})} \frac{d^2\sigma}{d\Omega_K^* dm_{p\Lambda}} = \sum_{i=1}^N b_i(m_{p\Lambda}) P_i^1(x), \quad (1)$$

where  $\Phi(s, m_{p\Lambda})$  is a phase space factor and  $x = \cos\theta_K^*$ . The coefficients  $b_1, b_3, b_5, \dots$  result from an interference of odd and even kaon partial waves and in this case only the spin triplet  $p\Lambda$  final states can contribute (for details see Refs. [5,6,12]). It turns out that only the two leading terms of Eq. (1) are needed in the present analysis; hence  $b_1(m_{p\Lambda})$  can be used for the determination of the spin triplet scattering length.

Using the parametrization

$$|b_1(m_{p\Lambda})| = \exp \left[ C_0 + \frac{C_1}{m_{p\Lambda}^2 - C_2} \right], \quad (2)$$

the spin triplet scattering length  $a_t$  can be obtained by

$$a_t(C_1, C_2) = -\frac{\hbar c}{2} C_1 \sqrt{\frac{m_0^2}{m_p m_\Lambda}} \sqrt{\frac{(m_{\text{max}}^2 - m_0^2)}{(m_{\text{max}}^2 - C_2)(m_0^2 - C_2)^3}}, \quad (3)$$

where  $m_0 = m_\Lambda + m_p$  and  $m_{\text{max}} = m_0 + 40$  MeV. The latter value indicates the applied fit range as well as the upper limit of the dispersion integral from theory [5] to fulfill the requirement that the  $p\Lambda$  system is dominantly in the  $S$  wave. The dependence of the scattering length extraction on  $m_{\text{max}}$  is included in the estimated theoretical uncertainty of 0.3 fm [5].

The independence of Eq. (3) from  $C_0$  reflects the fact that only the shape of the FSI enhancement is important to determine the scattering length [5]. Therefore, the proportionality of  $|b_1(m_{p\Lambda})|$  to the spin triplet scattering amplitude is sufficient to determine  $a_t$ .

Since the kaon angular distribution is uniform [7],  $A_N^K$  is directly evaluated in terms of associated Legendre polynomials and bins of invariant mass  $m_{p\Lambda}$ , which gives

$$A_N^K(m_{p\Lambda}) = \alpha(m_{p\Lambda}) P_1^1 + \beta(m_{p\Lambda}) P_2^1. \quad (4)$$

Combining this expansion with Eq. (1) results in

$$b_1(m_{p\Lambda}) = \alpha(m_{p\Lambda}) |\tilde{A}(m_{p\Lambda})|^2 = \frac{\alpha(m_{p\Lambda})}{\Phi(s, m_{p\Lambda})} \frac{d\sigma}{dm_{p\Lambda}}. \quad (5)$$

The two equations correspond to Eqs. (5)–(7) in Ref. [6] with a different notation of the variables.

The Dalitz plot of the event sample is shown in Fig. 1. It has been corrected for acceptance and reconstruction efficiency by MC phase space generated events. The full kinematic acceptance of the COSY-TOF detector is evident. At low  $p\Lambda$  masses a strong enhancement from the final state interaction is clearly visible. The  $N^*$  resonances that would be visible as horizontal bands do not appear due to their width of about  $100 \text{ MeV}/c^2$ . However, they can distort the final state interaction because of interferences, which has been shown by means of a Dalitz plot analysis in Ref. [13]. Indeed, a deviation of about 1 fm on extracted scattering length values has been found in the analysis of a previous COSY-TOF at a higher beam momentum of  $2.95 \text{ GeV}/c$  [6]. In the data presented here this effect is very small, as discussed in detail later.

No pronounced enhancement at the  $N\Sigma$  thresholds from the  $N\Sigma - p\Lambda$  coupled channel effect can be observed in Fig. 1. However, the enhancement is clearly visible in the  $p\Lambda$  invariant mass spectrum which is shown in Fig. 2 but it is weaker than in measurements at higher beam momenta [6,13] due to the available phase space at higher beam momentum. The enhancement does not distort the results obtained from the fit of the final state interaction as it was shown in a previous analysis of COSY-TOF data at higher

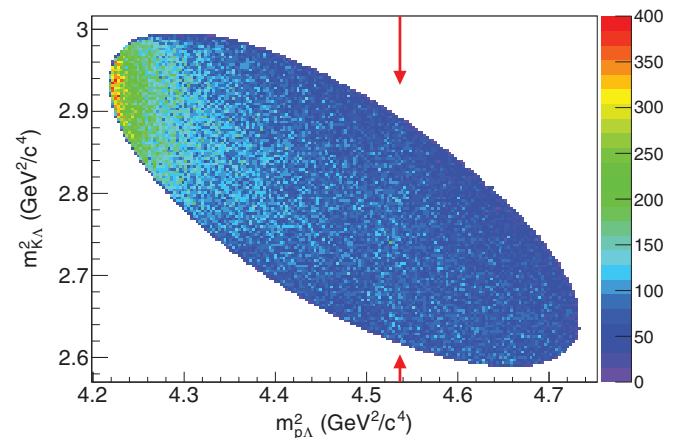


FIG. 1. Dalitz plot of the selected event sample at 2.7 GeV/c beam momentum corrected for acceptance and reconstruction efficiency. The red arrows indicate the region of the  $N\Sigma$  thresholds.

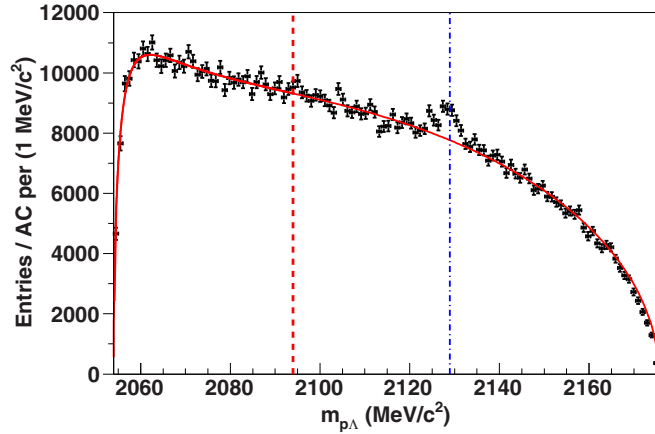


FIG. 2.  $p\Lambda$  invariant mass spectrum for the selected event sample at 2.7 GeV/c beam momentum corrected for acceptance and reconstruction efficiency (AC). The upper limit of the fit range is marked by the vertical dashed (red) line. The fit applied later (see Fig. 5) and its continuation over the whole spectrum is shown by the solid (red) line. The vertical dash-dotted (blue) line indicates the lower  $N\Sigma$  threshold ( $n\Sigma^+$ ).

beam momentum [7]. Furthermore, the fit of the final state interaction (see details below) extrapolated to the full  $m_{p\Lambda}$  range describes the spectrum well as shown by the solid line in Fig. 2.

In Fig. 3 the beam analyzing power determined by the kaon asymmetry,  $A_N^K$ , is shown as a function of  $\cos(\theta_K^*)$  for the full  $m_{p\Lambda}$  range. The fit with the associated Legendre polynomials  $P_1^1$  and  $P_2^1$  (solid line) reproduces the data within their statistical errors. The individual contributions of  $P_1^1$  and  $P_2^1$  are shown by the dash-dotted and dotted lines, respectively. Including higher order contributions does not improve the fit. These contributions are compatible with zero.

In Fig. 4 the coefficients  $\alpha(m_{p\Lambda})$  (filled circles) and  $\beta(m_{p\Lambda})$  (open squares) from the fit of  $A_N^K$  are shown in 5 MeV/ $c^2$

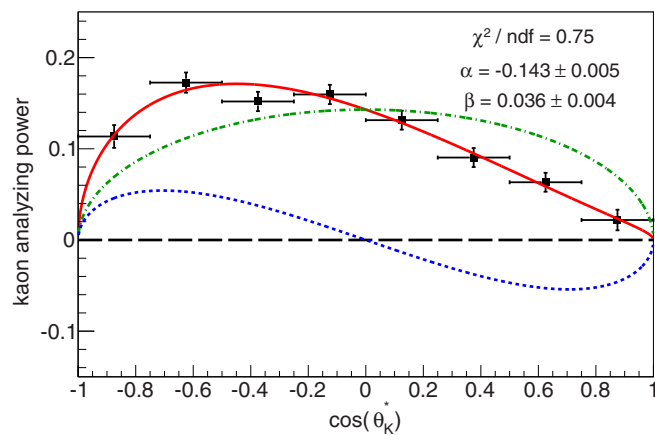


FIG. 3. The beam analyzing power determined by the kaon asymmetry,  $A_N^K$ , as a function of  $\cos(\theta_K^*)$  for the full  $m_{p\Lambda}$  range. The solid (red) line shows the fit with  $\alpha P_1^1 + \beta P_2^1$ . The individual contributions of the associated Legendre polynomials are shown by the dash-dotted (green) and dotted (blue) lines, respectively.

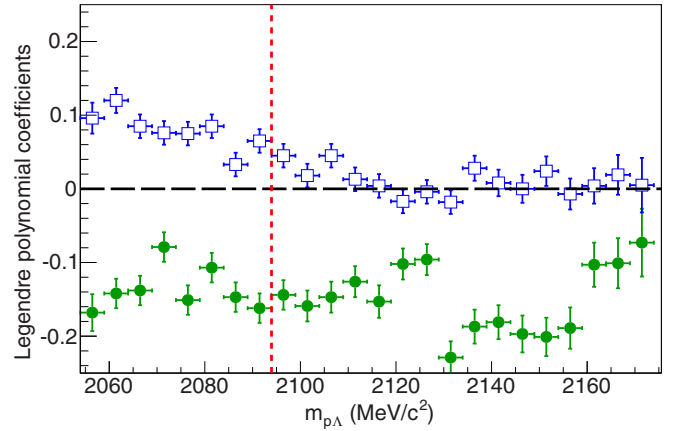


FIG. 4. The coefficients  $\alpha(m_{p\Lambda})$  (filled circles, green) and  $\beta(m_{p\Lambda})$  (open squares, blue) from the fit of  $A_N^K$  with associated Legendre polynomials as a function of  $p\Lambda$  invariant mass. The dashed (red) vertical line indicates the upper limit of the fitting range applied to the invariant mass spectrum.

wide bins of  $m_{p\Lambda}$ . The right end of the spectrum corresponds to the kinematic limit at this beam momentum. There, both contributions have to be zero since the kaon has vanishing momentum and hence it has to be purely in  $S$  wave without interference with higher order partial waves. It is interesting to note that  $\alpha(m_{p\Lambda})$  changes significantly at the  $N\Sigma$  thresholds at about 2130 MeV/ $c^2$  whereas  $\beta(m_{p\Lambda})$  does not change.

The behavior of  $\alpha(m_{p\Lambda})$  observed here is different from that in the measurement at higher beam momentum [6], where  $\alpha(m_{p\Lambda})$  was found to be compatible with zero at low invariant masses. In that case, the extraction of the spin triplet scattering length was not possible with sufficient precision. A simple explanation for the vanishing  $\alpha(m_{p\Lambda})$  value in that measurement [6] is a negligible production of the  $p\Lambda$  system in the spin triplet state. Indeed, such a conclusion has been drawn in a paper by the HIRES Collaboration [14] from a combined analysis of  $p\Lambda$  elastic scattering cross sections and data from the  $p\Lambda$  final state interaction in an inclusive  $pp \rightarrow K^+(\Lambda p)$  measurement at 2.735 GeV/c beam momentum. However, this explanation is definitely excluded by the result shown in Fig. 4.

In a first step of the analysis, the unpolarized invariant mass distribution divided by the phase space,  $|\tilde{A}(m_{p\Lambda})|^2$ , is fit using the parametrization (2). From the fit, the so-called effective  $p\Lambda$  scattering length  $a_{\text{eff}}$  is calculated by Eq. (3). The value is referred to as effective since the relative weights of the spin singlet and spin triplet final states are unknown for the unpolarized invariant mass distribution. It is not the spin averaged value determined in fits of  $p\Lambda$  elastic scattering data. Nevertheless, the effective value is determined for a comparison with previous analyses in Refs. [5,6] and for the study of the influence of  $N^*$  resonances on the scattering length value. Furthermore, systematic effects are studied for the effective scattering length due to the higher statistical precision in this case. It is assumed that the systematic effects are the same for the obtained spin triplet value.

Figure 5 shows  $|\tilde{A}(m_{p\Lambda})|^2$  and its fit (solid line). The fit parameters and its asymmetric errors are given in the

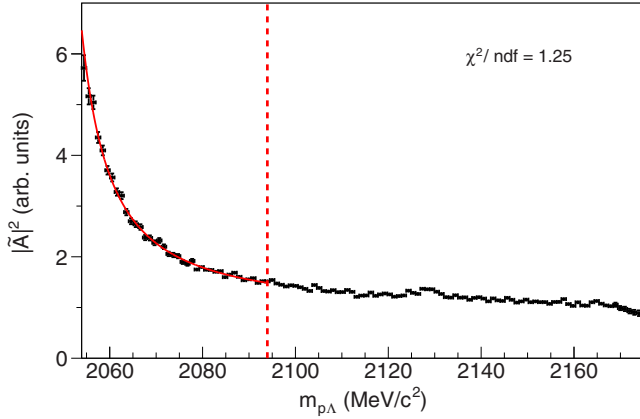


FIG. 5. The amplitude squared  $|\tilde{A}(m_{p\Lambda})|^2$  corresponding to the  $p\Lambda$  invariant mass distribution divided by the volume of available phase space. The solid (red) line shows a fit to the data by Eq. (2). The fit values are  $C_0 = -0.139^{+0.031}_{-0.033}$ ,  $C_1 = (0.121^{+0.008}_{-0.007})\text{GeV}/c^2$ , and  $C_2 = (4.158^{+0.003}_{-0.004})\text{GeV}/c^2$ . The vertical (red) dashed line marks the upper limit of the fitting range.

figure caption. The errors are calculated with the MINOS routine of the MINUIT2 library of the ROOT data analysis framework [15]. The dashed vertical line indicates the upper limit of the fit  $m_p + m_\Lambda + 40\text{ MeV}$ . To calculate the scattering length and its error from the highly correlated parameters  $C_i$  and their asymmetric errors, a bootstrapping method is used with 5 000 simulations [16,17]. From the scattering length distribution of the simulations, the value  $a_{\text{eff}} = (-1.38^{+0.04}_{-0.05\text{stat.}} \pm 0.22_{\text{syst.}} \pm 0.3_{\text{theo.}})\text{fm}$  is obtained. This value is in agreement with the previous analysis in Ref. [6] as well as the analysis of Ref. [5] in which the theoretical uncertainty is determined. The deviation to other methods of treating FSI effects with the effective range approximation or Jost function are in the order of 0.6 fm (see Table I in Ref. [18]).

Several systematic checks have been performed. The upper limit of the fit was varied between 35 and 60 MeV above threshold, which gives similar results within the statistical error. Additionally, acceptance corrections were varied and binning issues were checked. Their contributions to the systematic error are 0.2 and 0.02 fm, respectively.

Another systematic error results from the influence of  $N^*$  resonances, in particular the non- $S$ -wave resonances  $N^*(1710)$  and  $N^*(1720)$ . To study the resonance effect, the Dalitz plot is sliced in four ranges of the  $p\Lambda$  helicity angle  $\cos\theta_{pK}^{R_{p\Lambda}}$ . Each slice occupies the full  $m_{p\Lambda}$  range, and the invariant mass spectra for each slice would be practical identical without any  $N^*$  contributions. For each invariant mass spectrum a value for  $a_{\text{eff}}$  is determined. The root mean square deviation of these values is 0.1 fm and gives the error from the influence of  $N^*$  resonances [10].

In order to determine the spin triplet scattering length,  $|\tilde{A}(m_{p\Lambda})|^2$  is combined with  $|\alpha(m_{p\Lambda})|$  to obtain  $|b_1(m_{p\Lambda})|$ . In this case the spectrum,  $|\tilde{A}(m_{p\Lambda})|^2$ , is rebinned to have sufficient statistics for the analyzing power in each  $m_{p\Lambda}$  bin. The resulting distribution for  $|b_1(m_{p\Lambda})|$  is depicted in Fig. 6. The distribution is fitted according to Eq. (2), and the fit parameters and errors are given in the figure caption. They

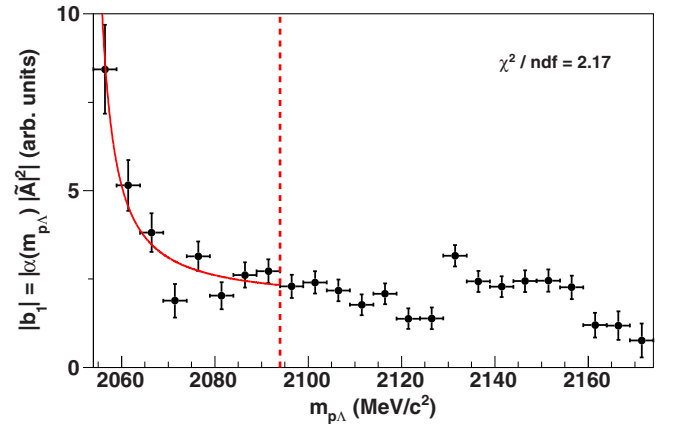


FIG. 6. The  $|b_1(m_{p\Lambda})|$  distribution determined from  $|\tilde{A}(m_{p\Lambda})|^2$  and  $|\alpha(m_{p\Lambda})|$ . The solid (red) line shows the fit with the parametrization (2) from which the spin triplet  $p\Lambda$  scattering length is determined. The fit values are  $C_0 = 0.599^{+0.171}_{-0.233}$ ,  $C_1 = (0.046^{+0.035}_{-0.020})\text{GeV}/c^2$ , and  $C_2 = (4.200^{+0.010}_{-0.017})\text{GeV}/c^2$ . The vertical (red) dashed line marks the upper limit of the fitting range.

are calculated as before with the MINOS routine of the ROOT data analysis framework [15]. A bootstrapping method with 100 000 simulations is used to determine the value for the spin triplet scattering length and its statistical error [16,17]. The result is  $a_t = (-2.55^{+0.72}_{-1.39\text{stat.}} \pm 0.6_{\text{syst.}} \pm 0.3_{\text{theo.}})\text{fm}$ . The larger systematic error stems from stronger binning effects compared to the determination of the effective scattering length.

Results for the spin triplet scattering length from experiments and theoretical predictions are shown in Table I. The determined scattering length in this paper is compatible within  $1\sigma$  of the statistical and theoretical uncertainty to the theoretical calculation from next-to-leading order chiral effective field theory ( $\chi\text{EFT}$ ) [21] and from meson-exchange based models, Jülich 04 [22] and Nijmegen NSC97f [23]. All of these calculations reproduce the measured hypertriton binding energy [2].

The result from this paper is also compatible with the model-dependent analyses using the effective range

TABLE I. Comparison of the spin triplet values from this paper with results from other experiments and theoretical predictions.

	$a_t$ (fm)	Stat. (fm)	Sys. (fm)	Theo. (fm)
This paper	-2.55	$^{+0.72}_{-1.39}$	$\pm 0.6$	$\pm 0.3$
$pp \rightarrow K^+(\Lambda p)$ [14] <sup>a</sup>	-1.56	$^{+0.19}_{-0.22}$		$\pm 0.4$
$p\Lambda$ scattering [19]	-1.6	$^{+1.1}_{-0.8}$		
$K^-d \rightarrow \pi^- p\Lambda$ [20]	-2.0	$\pm 0.5$		
$\chi\text{EFT NLO (500)}$ [21]	-1.61			
$\chi\text{EFT NLO (700)}$ [21]	-1.48			
Jülich 04 model [22]	-1.66			
Nijmegen NSC97f [23]	-1.75			

<sup>a</sup>Here, the inclusive data are fit together with the data from Ref. [19] in a combined, model-dependent procedure with the result from Ref. [20] as a constraint.

approximation from Refs. [19,20]. As mentioned in the context of the analyzing power, the result from the HIRES Collaboration [14] stems from a combined fit of  $p\Lambda$  elastic scattering data and an inclusively measured  $p\Lambda$  invariant mass spectrum with the result of Ref. [20] as a constraint. In this way a value for the spin triplet scattering length has been obtained, although the authors of Ref. [14] conclude a negligible production of spin triplet  $p\Lambda$  states which is excluded by the results for the analyzing power shown in Fig. 4. Therefore, the result from this paper cannot be compared with their result.

In summary, the  $\bar{p}p \rightarrow pK^+\Lambda$  reaction has been measured with the COSY-TOF detector at a beam momentum of 2.7 GeV/c. Optimized selection criteria give a data sample of 232 873 kinematically fitted events.

For the determination of the spin triplet  $p\Lambda$  scattering length from the final state interaction the beam analyzing power determined from the kaon asymmetry is evaluated in terms of associated Legendre polynomials ( $P_1^1$  and  $P_2^1$ ) and the  $p\Lambda$  invariant mass. The symmetric contribution  $\alpha(m_{p\Lambda})$  to the analyzing power is nearly constant and nonzero for low invariant masses. Therefore, the extraction of the spin triplet scattering length is possible by the model-independent method from Gasparyan *et al.* [5]. Furthermore, this result excludes the explanation of a dominant production of  $p\Lambda$  spin singlet states in  $pp \rightarrow pK^+\Lambda$  given in an analysis of an inclusive measurement at a similar beam momentum [14].

The spin triplet  $p\Lambda$  scattering length is obtained to be  $a_t = (-2.55^{+0.72}_{-1.39\text{stat.}} \pm 0.6_{\text{syst.}} \pm 0.3_{\text{theo.}})$  fm. This is the first direct determination of this parameter without relying on

model assumptions or  $p\Lambda$  elastic scattering data with mixed spin states [14,19]. The systematic error from the influences of  $N^*$  resonances has been studied by analyzing different Dalitz plot slices. The error is of the order of 0.1 fm which is a factor ten smaller compared to a measurement at  $p_{\text{beam}} = 2.95$  GeV/c [6]. This is in agreement with the expectation of a weaker influence of the non-S-wave  $N^*$  resonances,  $N^*(1710)$  and  $N^*(1720)$ , on the production mechanism at lower beam momenta as has been determined by a previous Dalitz plot analysis [13]. In addition, we want to point out that results from a combined partial wave analysis of several  $pp \rightarrow pK\Lambda$  data sets will be published soon. This partial wave analysis addresses especially the influence of the different  $N^*$  resonances in the production.

It is also necessary to investigate the effect of other polarization observables, e.g., the  $\Lambda$  polarization, in order to put further constraints on the production mechanism of associated strangeness as well as on the creation of  $p\Lambda$  spin triplet states. These results are published in Ref. [24] but further theoretical considerations are necessary to set other constraints.

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