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Lineshape of the $\Lambda(1405)$ hyperon measured through its $\Sigma^0\pi^0$ decay

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Abstract

The $pp \to pK^+Y^0$ reaction has been studied for hyperon masses $m(Y^0) \leqslant 1540$ MeV/c^2 at COSY-Jülich by using a 3.65 GeV/c circulating proton beam incident on an internal hydrogen target. Final states comprising two protons, one positively charged kaon and one negatively charged pion have been identified with the ANKE spectrometer. Such configurations are sensitive to the production of the ground state Λ and Σ^0 hyperons as well as the $\Sigma^0(1385)$ and $\Lambda(1405)$ resonances. Applying invariant- and missing-mass techniques, the two overlapping excited states could be well separated, though with limited statistics. The shape and position of the $\Lambda(1405)$ distribution, reconstructed cleanly in the $\Sigma^0\pi^0$ channel, are similar to those found from other decay modes and there is no obvious mass shift. This finding constitutes a challenging test for models that predict $\Lambda(1405)$ to be a two-state resonance.

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The excited states of the nucleon are a topical field of research, since the full spectrum contains deep-rooted information about the underlying strong colour force acting between the quarks and gluons. In addition to searching for missing resonances predicted by quark models [1], it is important to understand the structure of certain well established states, such as the $\Lambda(1405)$ hyperon resonance.

Although a four-star resonance [2], and known already for many years, the dynamics of the $\Lambda(1405)$ are still not fully understood. Within the quark model it can be explained as a P-wave q^3 baryon [3]. It is also widely discussed as a candidate for a $\bar{K}N$ molecular state [4], or for one with a more intrinsic $q^4\bar{q}$ pentaquark structure [5]. If the $\Lambda(1405)$ is a dynamically generated resonance produced *via* $\bar{K}N$ rescattering within a coupled-channel formalism [6,7], it may consist of two overlapping $I = 0$ states [8–10]. Its decay spectrum would then depend upon the production reaction. Due to the opening of the $\bar{K}N$ channels, the $\Lambda(1405)$ lineshape is not represented satisfactorily by a Breit–Wigner resonance [4,11–13]. Nevertheless,

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if the $\Lambda(1405)$ were a single quantum state, as in the quark model or molecular pictures, its lineshape should be independent of the production method.

Part of the difficulty in elucidating the nature of the $\Lambda(1405)$ is due to it overlapping the nearby $\Sigma^0(1385)$. The interference between these two states can distort significantly the $\Sigma^+\pi^-$ and $\Sigma^-\pi^+$ spectra [6], for which there are experimental indications [14]. This interference can be eliminated by taking the average of $\Sigma^+\pi^-$ and $\Sigma^-\pi^+$ data [11] but the cleanest approach is through the measurement of the $\Sigma^0\pi^0$ channel, since isospin forbids this for $\Sigma^0(1385)$ decay. This is the technique that we want to develop here and, although our statistics are rather poor, these are already sufficient to yield promising results.

We have used data obtained during high statistics ϕ-production measurements with the ANKE spectrometer [15] to study the excitation and decay of low-lying hyperon resonances in pp collisions at a beam momentum of 3.65 GeV/c in an internal-ring experiment at COSY-Jülich. A dense hydrogen cluster-jet gas target was used and over a four-week period this yielded an integrated luminosity of $L = (69 \pm 10)\ \text{pb}^{-1}$, as determined from elastic pp scattering that was measured in parallel and compared with the SAID 2004 solution [16].

The detection systems of the magnetic three-dipole spectrometer ANKE simultaneously register and identify both negatively and positively charged particles [17]. Forward (Fd) and side-wall (Sd) counters were used for protons, telescopes and side-wall scintillators for K^+, and scintillators for π^-. Since the efficiencies of the detectors are constant to 2% (σ) across the momentum range of registered particles, any uncertainty in this can be neglected in the further analysis.

The basic principle of the experiment is the search for four-fold coincidences, comprising two protons, one positively charged kaon and one negatively charged pion, i.e., $pp \to pK^+p\pi^-X^0$. Such a configuration can correspond, e.g., to the following reaction chains involving the $\Sigma^0(1385)$ and $\Lambda(1405)$ as intermediate states:

$$pp \to pK^+\Sigma^0(1385) \to pK^+\Lambda\pi^0 \to pK^+p\pi^-\pi^0, \quad (1)$$

$$pp \to pK^+\Lambda(1405) \to pK^+\Sigma^0\pi^0 \to pK^+\Lambda\gamma\pi^0 \to pK^+p\pi^-\gamma\pi^0. \quad (2)$$

In the $\Sigma^0(1385)$ case, the residue is $X^0 = \pi^0$, while for the $\Lambda(1405)$, $X^0 = \pi^0\gamma$. The resonances overlap significantly because the widths of 36 MeV/c^2 for $\Sigma^0(1385)$ and 50 MeV/c^2 for $\Lambda(1405)$ are much larger than the mass difference [2]. The strategy to discriminate between them is to: (i) detect and identify four charged particles p_{Fd}, p_{Sd}, K^+ and π^- in coincidence, thereby drastically reducing the accidental background at the expense of statistics, (ii) select those events for which the mass of a $(p_{Sd}\pi^-)$ pair corresponds to that of the Λ, (iii) select the mass of the residue $m(X^0)$ to be that of the π^0 to tag the $\Sigma^0(1385)$, and $m(X^0) > m(\pi^0) + 55$ MeV/c^2 for the $\Lambda(1405)$.

Fig. 1(a) shows the two-dimensional distribution of the four-particle missing mass $MM(pK^+\pi^-p)$ of the $p_{Sd}\pi^-$ pairs *versus* the invariant mass $M(p_{Sd}\pi^-)$. A vertical band corresponding to the Λ, is visible around a mass of 1116 MeV/c^2.

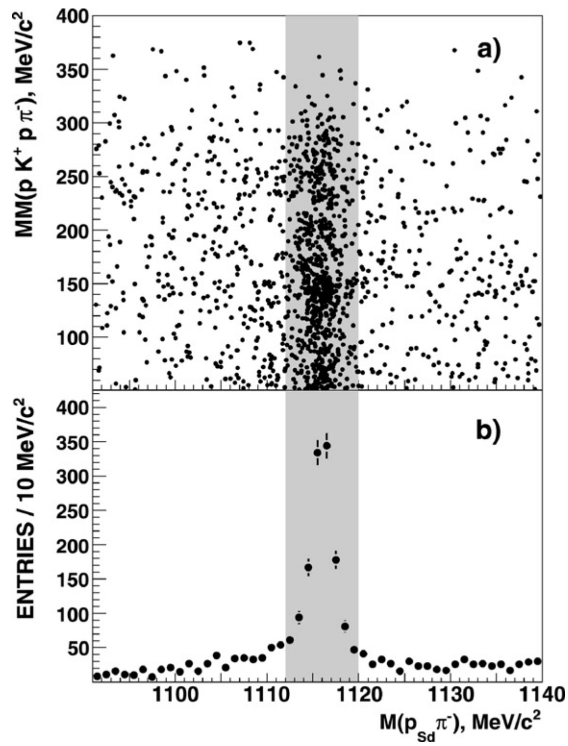

Fig. 1. (a) Missing mass $MM(pK^+p\pi^-)$ *versus* invariant mass $M(p_{Sd}\pi^-)$. The shaded vertical box shows the band used to select the Λ. (b) The projection of all the events from panel (a) onto the $M(p_{Sd}\pi^-)$ axis shows a clear Λ peak with a FWHM projection of ~ 5 MeV/c^2 and a slowly varying background.

The features of this band are illustrated clearly in the projection onto the $M(p_{Sd}\pi^-)$ axis shown in Fig. 1(b). The Λ peak, with a FWHM of ~ 5 MeV/c^2, sits on a slowly varying background, much of which arises from a false $p\pi^-$ association (the combinatorial background).

Data within the invariant-mass window 1112–1120 MeV/c^2 were retained for further analysis and, in Fig. 2, $MM(p_{Fd}K^+)$ is plotted against $MM(pK^+p\pi^-)$ for these events. The triangular-shaped domain arises from the constraint $MM(p_{Fd}K^+) \geqslant MM(pK^+p\pi^-) + m(\Lambda)$. Despite the lower limit of 50 MeV/c^2 on $MM(pK^+p\pi^-)$, there is a background from Σ^0 production at the bottom of the triangle, but this can be easily cut away. The enhancement for $MM(p_{Fd}K^+) \sim 1400$ MeV/c^2 corresponds to $\Sigma^0(1385)$ and $\Lambda(1405)$ production. The two vertical bands show the four-particle missing-mass $MM(pK^+p\pi^-)$ criteria used to separate the $\Sigma^0(1385)$ from the $\Lambda(1405)$. The left band is optimised to identify a π^0 whereas, in view of the missing-mass resolution, the right one selects masses significantly greater than $m(\pi^0)$.

Since the properties of the $\Sigma^0(1385)$ are undisputed [2], we first present and discuss results for this hyperon as a test case for the $\Lambda(1405)$ analysis. In Fig. 3 we show the experimental missing-mass $MM(p_{Fd}K^+)$ spectrum for events within the π^0-band of Fig. 2. When this is fit with a Breit–Wigner distribution plus a linear background, a mass of $M = (1384 \pm 10)$ MeV/c^2 and a width of $\Gamma \sim 40$ MeV/c^2 are obtained, in good agreement with the PDG values [2]. The resonance is located half way between the $\Sigma\pi$ and $\bar{K}N$ thresholds, indicated