$\bar{K}N \to \pi\Sigma$ scattering in the K^--induced reactions on deuteron and a hyperon resonance below the $\bar{K}N$ mass threshold

S. Aikawa, S. Ajimura, T. Akaishi, H. Asano, G. Beer, C. Berruct, M. Bragadireanu, L. Busso, M. Cargnelli, S. Choi, C. Curceanu, S. Enomoto, H. Fujioka, Y. Fujiwara, T. Fukuda, C. Guaraldo, T. Hashimoto, R. S. Hayano, T. Hiraiwa, M. Iio, M. Iliescu, K. Inoue, Y. Ishiguro, K. Itahashi, T. Ishikawa, M. Iwai, M. Iwasaki, S. Kanno, K. Kato, Y. Kato, S. Kawasaki, P. Kienle, Y. Komatsu, H. Kou, Y. Ma, J. Marton, Y. Matsuda, Y. Mizoi, O. Morra, T. Nagae, H. Noumi, H. Ohnishi, S. Okada, Z. Omar, H. Outa, K. Piscicchia, Y. Sada, A. Sakaguchi, F. Sakuma, M. Sato, A. Scordo, M. Sekimoto, H. Shi, K. Shirotori, D. Sirghi, F. Sirghi, K. Suzuki, S. Suzuki, T. Suzuki, K. Tanida, H. Tatsuno, A. O. Tokiyasu, M. Tokuda, D. Tomono, A. Toyoda, K. Tsukada, O. Vazquez-Doce, E. Widmann, T. Yamaga, T. Yamazaki, H. Yim, Q. Zhang, and and J. Zmeskal

Research Center for Nuclear Physics (RCNP), Osaka University, Ibaraki, 567-0047, Japan
Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK), Tsukuba, 305-0801, Japan
RIKEN, Wako, 351-0198, Japan
Department of Physics, Osaka University, Toyonaka, 560-0043, Japan
Department of Physics and Astronomy, University of Victoria, Victoria BC V8W 3P6, Canada
Stefan-Meyer-Institute für subatomare Physik, A-1090 Vienna, Austria
Department of Physics, Seoul National University, Seoul, 151-742, South Korea
National Institute of Physics and Uclear Engineering - IFINHH, Romania
INFN Sezione di Torino, Torino, Italy
Dipartimento di Fisica Generale, Universita'di Torino, Torino, Italy
Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy
Department of Physics, Kyoto University, Kyoto, 606-8502, Japan
Department of Physics, The University of Tokyo, 113-0033, Japan
Laboratory of Physics, Osaka Electro-Communication University, Neyagawa, 572-8530, Japan
Department of Physics, Tokyo Institute of Technology, Tokyo, 152-0551, Japan
Technische Universität München, D-85748, Garching, Germany
Craduate School of Arts and Sciences, The Univeristy of Tokyo, Tokyo, 153-8902, Japan
Department of Physics, Tohoku University, Sendai, 980-8578, Japan
Excellence Cluster University, Technische Universität München, D-85748, Garching, Germany
Korea Unstitute of Radiological and Medical Sciences (KIRAMS), Seoul, 139-706, South Korea
ASRC, Japan Atomic Energy Agency (JAEA), Ibaraki 319-1195, Japan
Department of Chemical Physics, Lund University, Lund, 221 00, Sweden and
Research Center for Electron Photon Science (ELPH), Tohoku University, Sendai, 982-0826, Japan

(J-PARC E31 Collaboration)

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We measured $\pi\Sigma$ invariant mass spectra in four different charged states in K^--induced reactions on deuteron. We deduced $\bar{K}N \to \pi\Sigma$ and $\bar{K}N \to \bar{K}N$ scattering amplitudes in the isospin I=0 channel within the $\bar{K}N$ and $\pi\Sigma$ coupled channel scattering matrix. We find a resonance pole located just below the $\bar{K}N$ mass threshold.

$\Lambda(1405)$ is a well-known hyperon resonance with strangeness -1, spin-parity $1/2^-$, and isospin I=0. It is classified as the first orbital excited state in the constituent quark model. However, the properties of $\Lambda(1405)$, such as its lightest mass among the negative parity baryons even if it contains a heavier strange quark and a large mass difference to the so-called spin-orbit partner state of $\Lambda(1520)$, are not straight-forwardly explained. Since $\Lambda(1405)$ is located just below the $\bar{K}N$ mass threshold, there is a long standing argument if it is a bound state of an anti-kaon ($\bar{K}$) and a nucleon (N).

Since the first observation of a hyperon resonance sitting just below the $\bar{K}N$ mass threshold in the $\pi^-\Sigma^+/\pi^+\Sigma^-$ invariant mass spectra in 1961 [1], several experimental data on $\Lambda(1405)$ have been reported [2–10]. R. H. Dalitz and A. Deloff have deduced a resonance energy and width as 1406.5±4.0 MeV and 50±2 MeV analyzing the measured $\pi^-\Sigma^+$ mass spectrum based on the $\bar{K}N$ scattering theory [11]. The latest version of the Review of Particle Physics [12] refers the average value, $1405.1^{+1.3}_{-0.9}$ MeV and 50.5±2.0 MeV, including two later works [13, 14].

In recent two decades, there have been intensive discussions based on a so-called chiral unitary approach, which is a coupled-channel meson-baryon scattering theory with employing chiral Lagrangians. Several calculations claim that there are two resonance poles between the $\pi\Sigma$ and $\bar{K}N$ mass thresholds [**?**], where the higher pole, coupled to $\bar{K}N$, is located around 1420 MeV or greater.

Experimental situation is controversial. Recent measurements of $(\pi\Sigma)^0$ mass spectra have been reported in photo-induced reactions on proton [7, 10**?**] and proton-

proton collisions [9?]. The CLAS collaboration reported precise data of $\pi^-\Sigma^+$, $\pi^+\Sigma^-$, and $\pi^0\Sigma^0$ spectra in a wide range of incident photon energy [10]. Theoretical analyses have been made for these data and reproduce the spectral shapes fairly well although many parameters [15] and/or reaction diagrams [16]are involved. The HADES collaboration reported invariant mass spectra of $\pi^-\Sigma^+$, $\pi^+\Sigma^-$, and their sum [9]. Their spectral shapes were different from those in the photoproductions. In particular, the peak is observed even below 1400 MeV. Theoretical analyses for their spectra have also been made [17, 18]. However, deduced locations of $\Lambda(1405)$ are not compatible between a chiral unitary model [18] and a phenomenological model [17]. Therefore, experimental data to directly access $\bar{K}N$ scattering amplitude coupled to $\Lambda(1405)$ are strongly desired.

We carried out an experimental study of kaon-induced $\pi\Sigma$ production via the $d(K^-,n)\pi\Sigma$ reactions [19]. In these reactions, an incident negative kaon of 1 GeV/c is knocked out a neutron at a forward angle, and $\bar{K}$ recoiled backward reacts with a residual nucleon to produce π and Σ.In the second step of the reaction sequence, a $\bar{K}N \to \pi\Sigma$ scattering takes place even below the $\bar{K}N$ mass threshold. Since a typical momentum of the recoiled $\bar{K}$ is as low as $\sim$250 MeV/c at a $\pi\Sigma$ invariant mass around 1405 MeV/c^2, an S-wave scattering is expected to be dominant. We measured the $\pi\Sigma$ invariant mass spectra, from which we deduced the $\bar{K}N$ scattering amplitude in the isospin I=0 channel.

The experiment was performed at the K1.8BR beam line [20] of the Japan Proton Accelerator Research Complex (J-PARC). Negative-charged kaons delivered from K1.8BR were irradiated to a liquid deuterium (D_2) target of 125 mm (fiducial length of 105 mm) in thickness. A momentum of an incident kaon was analyzed by the K1.8BR-D5 magnetic spectrometer.Scattered neutrons were detected by neutron counters (NC), an array of 112 plastic scintillator slabs, placed at a distance of approximately 15 m from the D_2 target. Charged particles from the D_2 target were measured by a cylindrical detector system (CDS), which comprises a cylindrical drift chamber (CDC) and scintillator hodoscopes (CDH) surrounding the D_2 target. CDS was operated in a solenoid magnet of (0.715) T. We measured $\pi^\pm\Sigma^\mp$ productions associated with a knocked-out neutron detected by NC, where π^+ and π^- were detected by CDS and a missing neutron was identified in the missing mass spectrum of $d(K^-,n\pi^+\pi^-)$. In this modes, three kinds of background processes could be contaminated: (1) $K^-d \to n\bar{K}^0$"n", (2) $K^-d \to \pi^+\Sigma^-$ "n", and (3) $K^-d \to \pi^-\Sigma^+$"n" as all the processes are the same final state of $n\pi^+\pi^-$ "n", where "n" represents a neutron identified in missing mass. These processes could be removed since one can identify $\bar{K}^0$, Σ^-, and Σ^+ peaks in the invariant mass spectra of $\pi^+\pi^-$, $n\pi^-$, and $n\pi^+$, respectively. We obtained $\pi^\pm\Sigma^\mp$ missing mass spectra in the $d(K^-,n)\pi^\pm\Sigma^\mp$ reactions separately, as we will show them later. The production ratio of $\pi^+\Sigma^-$ to $\pi^-\Sigma^+$ in each mass bin in the $\pi^\pm\Sigma^\mp$ missing mass spectra was obtained by the missing mass spectra of $d(K^-,n\pi^\mp)$ decomposed with expected $\Sigma^\pm$ peak and $\Sigma^\mp$ continuum-like distributions. Decomposed missing $\Sigma^\pm$ spectra are shown in Fig. 1-(a)(b). In the $\pi^0\Sigma^0$ production, Σ^0 immediately decays into $\Lambda\gamma$ and the Λ hyperon decays into a proton and a pion. The pion is emitted in a wide angular region and could be detected by CDS. While, the proton is emitted rather backward due that most of a recoiled momentum of $\pi^0\Sigma^0$ produced in the $d(K^-,n)$ reaction at a neutron forward angle is carried by a heavier particle. We measured a time-of-flight of the backward proton detected by drift chambers (BPC) and scintillator hodoscopes (BPD) placed at distances of (100) mm and (550) mm before the D_2 target. We identified the decaying Λ in the invariant mass of the backward proton and the pion detected by CDS. Then, a missing mass spectrum of $d(K^-,np\pi^-)$ was decomposed into π^0, $\pi^0\gamma$, $(\pi\pi)^0$, and $(\pi\pi)^0\gamma$, as shown in Fig. 1-(c). Gating a mass window of 0.18 to 0.3 GeV/c^2 in the spectrum, we obtained the $\pi^0\Sigma^0$ mode with small contaminations from the $\pi^0\Lambda$, $(\pi\pi)^0\Lambda$, and $(\pi\pi)^0\Sigma^0$ modes. Contributions of the contaminations are subtracted in the measured $\pi^0\Sigma^0$ missing mass spectrum. Charged particles emitted at the forward angle, including the incident beams, were swept out by a dipole magnet placed behind the solenoid magnet. A proton knocked out from a deuteron by an incident kaon was bended by the sweeping magnet in an opposite direction of the beam. Proton counters (PC), hodoscopes of 27 scintillator slabs, were placed beside the charged-particle veto counters (CVC)

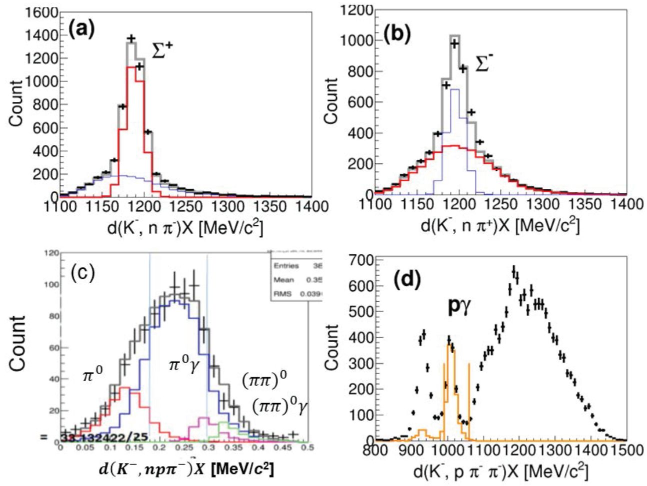

FIG. 1. (a)(b) Decomposed $\Sigma^\pm$ spectra. (c) Missing mass spectrum of $d(K^-,np\pi^-)$. Expected π^0, $\pi^0\gamma$, $(\pi\pi)^0$, and $(\pi\pi)^0\gamma$ components are overlaid. A $\pi^0\gamma$ region (0.18$\sim$0.3 GeV/c^2) was gated for $\pi^0\Sigma^0$ mode. (d) Missing mass spectra of $d(K^-,p\pi^-\pi^-)$ and $d(K^-,p\pi^-)$ to identify $\pi^-\Sigma^0$ mode ($p\gamma/\Sigma^0$ peaks) as well as $\pi^-\Lambda$ mode (p/Λ) peaks).

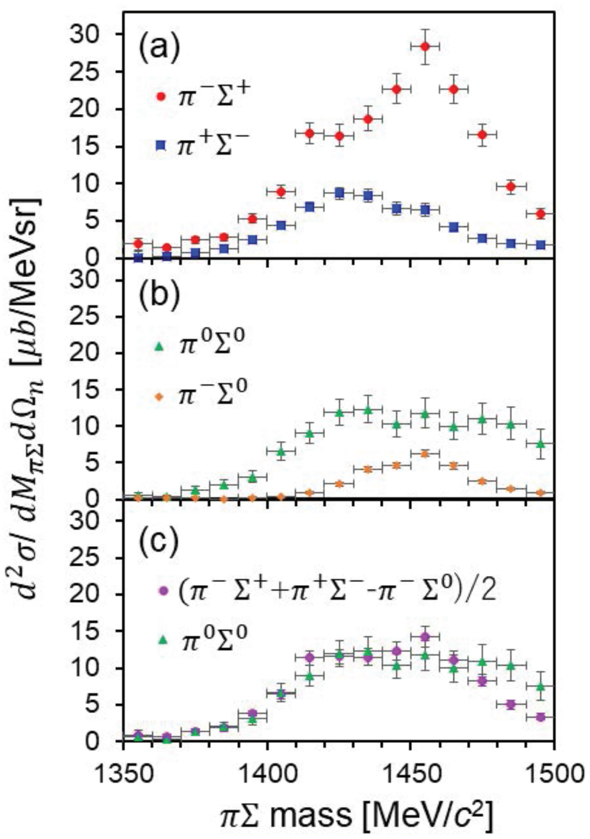

FIG. 2. Measured spectra of (a) $\pi^\pm\Sigma^\mp$, (b) $\pi^0\Sigma^0$ and $\pi^-\Sigma^0$, and (c) $\pi^0\Sigma^0$ and $(\pi^+\Sigma^- + \pi^-\Sigma^+ - \pi^-\Sigma^0)/2$ are plotted.

placed in front of NC in order to measure a time-of-flight of the knocked-out proton. We measured $\pi^-\Sigma^0$ productions associated with a proton detected by PC, where two negative pions in the final states of the $\pi^-\Sigma^0$, identifying the Σ^0 and γ-proton in the missing mass spectra of $d(K^-, p\pi^-\pi^-)$ and $d(K^-, p\pi^-)$, respectively, as shown in Fig. 1-(d).

Mass spectra of $\pi^\pm\Sigma^\mp$, $\pi^0\Sigma^0$, and $\pi^-\Sigma^0$ are shown in Fig. 2. We observed different line shapes in the $\pi^\pm\Sigma^\mp$ modes (Fig. 2-(a)). Since both isospin I=0 and 1 amplitudes are to be contributed, the difference is due to interference between the two amplitudes. In the $\pi^-\Sigma^+$ mode, one finds a bump around 1450 MeV/c^2 with a small shoulder below the K^-p mass threshold. On the other hand, the $\pi^+\Sigma^-$ spectrum shows a broad distribution with a maximum strength just below the K^-p mass threshold. The $\pi^0\Sigma^0$ and $\pi^-\Sigma^0$ mode (Fig. 2-(b)) contain only the I=0 and 1 amplitude, respectively. The $\pi^0\Sigma^0$ spectrum has a similar shape to the average of the $\pi^\pm\Sigma^\mp$ spectra. The strength of the $\pi^-\Sigma^0$ spectrum is smaller than that of the $\pi^0\Sigma^0$ spectrum. We find that the I=0 amplitude is dominant, in particular, below the K^-p mass threshold. We find no structure at around 1385 MeV/c^2 in the $\pi^-\Sigma^0$, where one may expect a structure of the $\Sigma^*(1385)$ resonance. This fact suggests dominance of S-wave $\pi\Sigma$ productions in the present reactions. We expect isospin independence among the 4 reactions. Namely, the average of the $\pi^\pm\Sigma^\mp$ spectra minus a half of the $\pi^-\Sigma^0$ spectrum coincides the $\pi^0\Sigma^0$, as demonstrated in Fig. 2-(c).

As many authors discussed the $\pi\Sigma$ productions associated with a nucleon emission in the kaon induced reactions on deuteron [21–25], we describe the $\pi\Sigma$ spectral shape assuming that the two-step reactionis dominant at a forward angle of the knocked-out nucleon. We neglect a direct production of $\pi\Sigma$ by a collision of incident K^- with a nucleon in deuteron. Then, the $\pi\Sigma$ production cross section can be described as

$$\frac{d^2\sigma}{dM_{\pi\Sigma}d\Omega_n}| \sim |\langle n\pi\Sigma|T_2 G_0(\bar{K}, N_2)T_1|K^-\Phi_d\rangle|^2, \quad (1)$$

$$T_2 = T_2^{I'}(\bar{K}N_2, \pi\Sigma), \quad (2)$$

$$T_1 = T_1^{I}(K^-N_1, \bar{K}N), \quad (3)$$

where $|K^-\Phi_d\rangle$ and $|n\pi\Sigma\rangle$ denote initial K^- and deuteron and final $n\pi\Sigma$ wave functions, respectively. $T_1^I(T_2^{I'})$ represents scattering amplitude of the first-step (second-step) two body $K^-N_1 \to \bar{K}N$ ($\bar{K}N_2 \to \pi\Sigma$) reaction with isospin $I(I')$. $G_0(\bar{K}, N_2)$ is a Green's function which describes an intermediate $\bar{K}$ propagation between the two vertices. More detailed expressions can be found in Refs. [21, 23, 25]. The cross section can be simplified by factorization approximation as follows.

$$\frac{d^2\sigma}{dM_{\pi\Sigma}d\Omega_n} \approx |T_2^{I'}|^2 F_{res}(M_{\pi\Sigma}), \quad (4)$$

$$F_{res}(M_{\pi\Sigma}) = \left|\int G_0 T_1^I \Phi_d(q_{N_2}) d^3q_{N_2}\right|^2. \quad (5)$$

Here, q_{N_2} is a momentum of the recidual nucleon. In this way, the $\pi\Sigma$ spectrum can be decomposed into $T_2^{I'}$ and a response function F_{res}. Employing the $K^-N \to \bar{K}N$ scattering amplitudes based on partial wave analysis [26] and the deuteron wave function [27], we evaluate F_{res} as a function of the $\pi\Sigma$ mass $M_{\pi\Sigma}$. For S-wave $T_2^{I'}$, we consider $\bar{K}N$-$\pi\Sigma$ coupled channel T matrix. Diagonal and off-diagonal matrix elements can be parametrized as is the case similar to Ref. [28].

$$T_2^{I'}(\bar{K}N, \bar{K}N) = \frac{A^{I'}}{1 - iA^{I'}k_2 + \frac{1}{2}A^{I'}R^{I'}k_2^2}, \quad (6)$$

$$T_2^{I'}(\bar{K}N, \pi\Sigma) = \frac{e^{i\delta^{I'}}}{\sqrt{k_1}} \frac{\sqrt{\mathrm{Im}A^{I'} - \frac{1}{2}|A^{I'}|^2 \mathrm{Im}R^{I'}k_2^2}}{1 - iA^{I'}k_2 + \frac{1}{2}A^{I'}R^{I'}k_2^2}, \quad (7)$$

where $A^{I'}$, $R^{I'}$, and $\delta^{I'}$ are a scattering length, an effective range, and a phase. They are complex numbers and a real number, respectively. k_1 and k_2 are respectively momenta of π and $\bar{K}$ in the center of mass frame. k_2 becomes a pure imaginary number below the $\bar{K}N$ mass threshold.

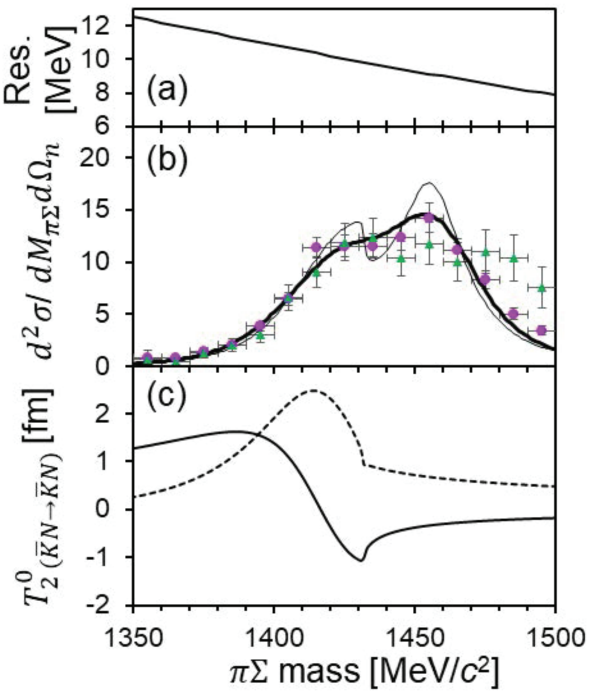

FIG. 3. (a) Experimental resolution as a function of the $\pi\Sigma$ mass. (b) Calculated $\pi\Sigma$ spectrum so as to fit the measured spectra in I=0 channel. Solid thick (thin) line is the spectrum with (without) the resolution function convoluted. (c) Deduced scattering amplitude of $\bar{K}N \to \bar{K}N$ in I=0 channel. Its real (imaginary) part is shown in a solid (dashed) line.

We demonstrate fitting result for the $\pi\Sigma$ (I=0) channel, as shown in Fig. 3. A^0 and R^0 are determined so as to fit the measured $\pi^0\Sigma^0$ and $(\pi^+\Sigma^- + \pi^-\Sigma^+ - \pi^-\Sigma^0)/2$ spectra. In the fitting, an additional parameter was introduced to adjust the vertical scale and an experimental resolution function is convoluted to the calculated spectrum. We obtained A^0=-1.04(0.09)+0.93(0.11)i and R^0=-0.25(0.26)-0.53(0.13)i. Here, the numbers in parentheses are fitting errors. The thick (thin) solid line in the figure shows the resolution-convoluted (no-resolution-convoluted) spectrum calculated with the fitted A^0 and R^0. Energy dependences of deduced $T^0_2(\bar{K}N \to \bar{K}N)$ are shown in Fig. **??**. One finds a zero-crossing in real part and a bump peak in imaginary part at a same place. This is a typical structure of a resonance. We find a resonance pole at 1416.7()-26.9()i MeV/c^2 in the I=0 channel of $\bar{K}N \to \bar{K}N$ scattering. The deduced pole position is closer to the K^-p mass threshold than the so-called PDG value of 1405 MeV/c^2. U.-G. Meissner and T. Hyodo have reviewed and discussed the pole structure of the Λ(1405) region based on chiral unitary approaches with constraint from a kaonic hydrogen atom X-ray data by the SIDDHARTA collaboration [29] in the recent Review of Particle Physics [30]. In their article, four sets of two poles deduced by several authors in the relevant region are collected. Pole 1 (2) is the so-called higher (lower) pole which is thought to be coupled to $\bar{K}N(\pi\Sigma)$. The suggested higher poles are located at the region of 1421$\sim$1434 MeV in the real axis and 10$\sim$26 MeV in the imaginary axis in the complex energy plane. Compared to these values, the present experiment provides a slightly smaller and larger value in real and imaginary part, respectively.

In summary, we measured $\pi^\pm\Sigma^\mp$, $\pi^0\Sigma^0$, $\pi^-\Sigma^0$ mass spectra below and above the K^-p mass threshold in the $d(K^-,N)\pi\Sigma$ reactions at the incident kaon momentum of 1 GeV/c. We obtained decomposed $\pi\Sigma$ spectra in terms of I=0 and 1 and their isospin independence. We find that the I=0 amplitude is dominant. We demonstrated that the $\pi\Sigma$ spectral shape in I=0 channel is well reproduced by the two step reaction of a neutron knocked out at the forward angle by an incident negative kaon and a recoiled $\bar{K}$ reacting with a residual nucleon in deuteron to produce $\pi\Sigma$ in the I=0 state. We deduced two-body $\bar{K}N$ scattering amplitudes in I=0 channel, from which we find a resonance pole at 1416.7()-26.9()i MeV/c^2.

The present data figure out a hyperon resonant state with I=0 coupled to $\bar{K}N$ 15 MeV below the K^-p mass threshold, which provide fundamental information on the $\bar{K}N$ interaction and kaonic nuclei [31].

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