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

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We measured $\pi^\pm\Sigma^\mp$, $\pi^0\Sigma^0$, and $\pi^-\Sigma^0$ invariant mass spectra below and above the $\bar{K}N$ mass threshold in K^--induced reactions on deuteron. We deduced S-wave $\bar{K}N \to \pi\Sigma$ and $\bar{K}N \to \bar{K}N$ scattering amplitudes in the isospin I=0 channel in a framework of $\bar{K}N$ and $\pi\Sigma$ coupled channel. 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).

R. H. Dalitz and Tuan first predicted a possible quasi-bound state of $\bar{K}N$ with isospin I=0 in 1959, based on low-energy K^--proton scattering processes [1]. 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 was reported in 1961 [2]. Since then, several experimental data on $\Lambda(1405)$ have been reported [3–14]. 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 [6] based on the $\bar{K}N$ scattering theory [15]. The latest version of the Review of Particle Physics [16] refers the average value, $1405.1^{+1.3}_{-0.9}$ MeV and 50.5±2.0 MeV, including two later works [17, 18] which demonstrated that a so-called phenomenological approach giving the $\Lambda(1405)$ mass at $\sim$1405 MeV [19, 20] is favored.

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 [21–25], where the higher pole, coupled to $\bar{K}N$, is located at around 1420 MeV or greater. The chiral unitary approach is being debated with the phenomenological approach.

Experimental situation is controversial. Recent measurements of $(\pi\Sigma)^0$ mass spectra have been reported in photo-induced reactions on proton [9, 12–14] and proton-proton collisions [10, 11]. 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 [12, 13]. Theoretical analyses have been made for these data and reproduce the spectral shapes fairly well although many parameters [26] and/or reaction diagrams [27]are involved. The HADES collaboration reported invariant mass spectra of $\pi^-\Sigma^+$, $\pi^+\Sigma^-$, and their sum [11]. Their spectral shapes were different from those in the photo-productions. In particular, the peak is observed even below 1400 MeV. Theoretical analyses for their spectra have also been made [28, 29]. However, deduced locations of $\Lambda(1405)$ are not compatible between a chiral unitary model [29] and a phenomenological model [28]. 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 [30]. Here, we expect to measure a reaction sequence that an incident negative kaon of 1 GeV/c knocks out a neutron at a forward angle from a deuteron, and $\bar{K}$ recoiled backward reacts with a residual nucleon (N_2) to produce π and Σ, as a reaction diagram is shown in the inset of Fig. 1. In the second step of the reaction sequence, a $\bar{K}N_2 \to \pi\Sigma$ 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 [31] 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. A schematic layout of the experimental setup is illustrated in Fig. 1. 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. The kaon beam was defined a beam defining counters (DEF) placed just in front of 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 with a magnetic field of 0.715 Tesla. 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 a $d(K^-,n\pi^+\pi^-)$ missing mass spectrum. In these 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 the $d(K^-,n\pi^+\pi^-)$ missing mass spectrum. 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. 2-(a) and (b), respectively.

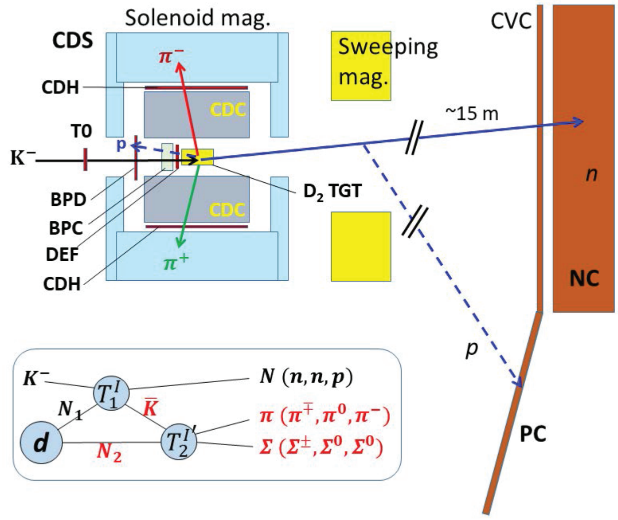

FIG. 1. Schematic illustration of the experimental setup. CDS: cylindrical detector system, CDH: cylindrical scintillator hodoscopes, CDC: cylindrical drift chamber, D_2 TGT: liquid deuterium target, T0: time zero counter, BPD: backward proton detector, BPC: backward proton drift chamber, DEF: beam defining counter, NC: neutron counter array, CVC: charged particle veto counter, and PC: proton counter array. A reaction diagram expected in $d(K^-,N)\pi\Sigma$ is shown in the inset.

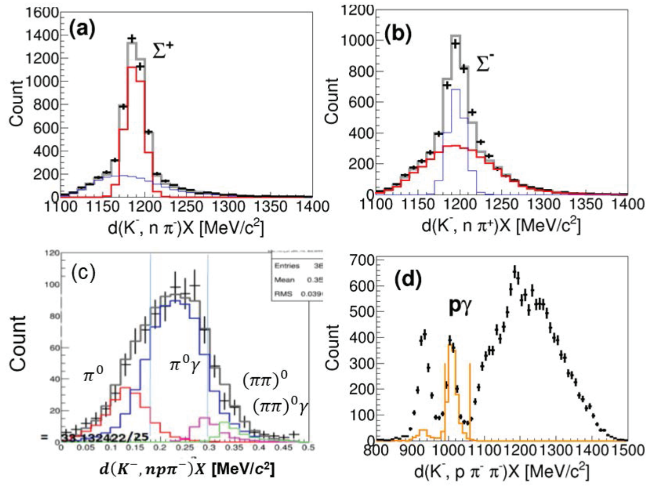

FIG. 2. (a) and (b) Decomposed $\Sigma^{\pm}$ peaks in the $d(K^-, n\pi^{\mp})$ missing mass spectra, respectively. (c) Missing mass spectrum of $d(K^-, np\pi^-)$. Expected π^0, $\pi^0\gamma$, $(\pi\pi)^0$, and $(\pi\pi)^0\gamma$ components are overlaid (histograms). A $\pi^0\gamma$ region (0.18$\sim$0.3 GeV/c^2) was gated for $\pi^0\Sigma^0$ mode. (d) A missing mass spectrum of $d(K^-, p\pi^-\pi^-)$ is ploted (cross points) and that selected Σ^0 in the $d(K^-, p\pi^-)$ missing mass (histogram). A $p\gamma$ peak was selected to identify the $\pi^-\Sigma^0$ mode (vertical lines).

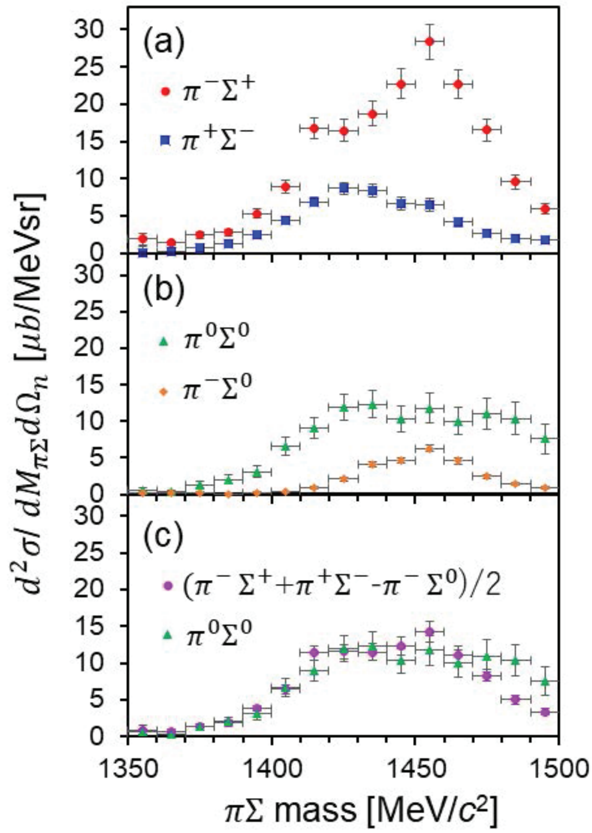

FIG. 3. Measured spectra of (a) $\pi^{\pm}\Sigma^{\mp}$, (b) $\pi^0\Sigma^0$ and $\pi^-\Sigma^0$, and (c) $\pi^0\Sigma^0$ and $(\pi^+\Sigma^- + \pi^-\Sigma^+ - \pi^-\Sigma^0)/2$ are plotted.

In the $\pi^0\Sigma^0$ production, Σ^0 immediately decays into $\Lambda\gamma$. 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 the momentum of $\pi^0\Sigma^0$ recoiled backward in the $d(K^-, n)$ reaction 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 143.2 mm and 482.5 mm upstream from the D_2 target center. We identified the decaying Λ in the invariant mass of the pion and proton detected by CDS and BPC/BPD, respectively. 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. 2-(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) 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 $p\gamma$ in the missing mass spectra of $d(K^-, p\pi^-\pi^-)$ and $d(K^-, p\pi^-)$, respectively, as shown in Fig. 2-(d).

Mass spectra of $\pi^{\pm}\Sigma^{\mp}$, $\pi^0\Sigma^0$, and $\pi^-\Sigma^0$ were measured, as shown in Fig. 3. We observed different line shapes in the $\pi^{\pm}\Sigma^{\mp}$ modes (Fig. 3-(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. 3-(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 since $\Sigma^*(1385)$ decays into a P-wave $\pi\Sigma$ state. We confirm a relation with respect to the isospin states among the four 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. 3-(c).

As many authors discussed the $\pi\Sigma$ productions associated with a nucleon emission in the kaon induced reactions on deuteron [32–36], we describe the $\pi\Sigma$ spectral shape assuming that the two-step reaction is dominant in the case that the knocked-out nucleon is emitted at a forward angle. We neglect a direct production of $\pi\Sigma$ by a collision of incident K^- with a nucleon in a 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. [32, 34, 36]. The cross section can be simplified by factorization approximation as follows.

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

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

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 a partial wave analysis [37] and the deuteron wave function Φ_d [38], 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. [39].

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

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

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. Here, k_2 becomes a pure imaginary number below the $\bar{K}N$ mass threshold.

We demonstrate a fitting result for the $\pi\Sigma$ (I=0) channel, as shown in Fig. 4-(b). 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 constant number was introduced to adjust the vertical scale and an experimental resolution function (Fig. 4-(a)) 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 $T_2^0(\bar{K}N \to \bar{K}N)$ are shown in Fig. 4-(c). 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 $1416.7^{+21.8}_{-5.0}-26.9^{+10.1}_{-12.1}i$ 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 $\Lambda(1405)$ region based on chiral unitary approaches with constraint from a kaonic hydrogen atom X-ray data by the SIDDHARTA collaboration [40] in the recent Review of Particle Physics [41]. 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

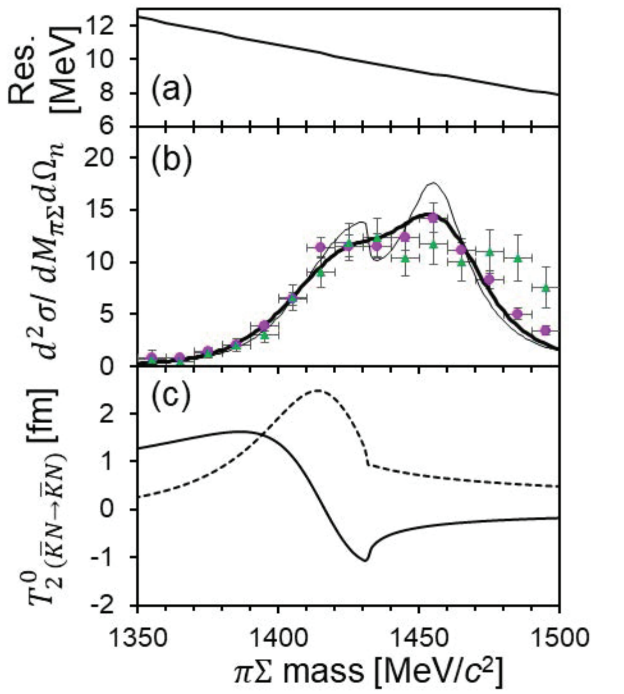

FIG. 4. (a) Experimental resolution as a function of the $\pi\Sigma$ mass. (b) Calculated $\pi\Sigma$ spectrum so as to fit the measured spectra in I=0 channel. Solid thick (thin) line is the spectrum with (without) the resolution function convoluted. (c) Deduced scattering amplitude of $\bar{K}N \to \bar{K}N$ in I=0 channel. Its real (imaginary) part is shown in a solid (dashed) line.

(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∼1434 MeV in the real axis and 10∼26 MeV in the imaginary axis in the complex energy plane. Compared to these values, the present experiment gives 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 a forward angle of N knocked out by the incident kaon momentum of 1 GeV/c. We obtained decomposed $\pi\Sigma$ spectra in terms of I=0 and 1 and confirmed a relation among the four reactions with respect to the isospin states. 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 $1416.7^{+21.8}_{-5.0} - 26.9^{+10.1}_{-12.1}i$ 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 [42].

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