Dynamical coupled-channels study of hyperon resonances using anti-kaon induced reactions

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Background & Motivation

N* spectroscopy via global analysis of πN and γN reactions

- Based on Dynamical Coupled-Channels (DCC) approach

## Latest published analysis (ANL-Osaka):
**Fully combined analysis of** πN, γN → πN, ηN, KΛ, KΣ **up to**
W = 2.1 GeV. [HK, Nakamura, Lee, Sato, PRC88(2013)035209]

- Revealed role of **multichannel** meson-baryon reaction
  **dynamics** in understanding N* and Δ* resonances:

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Dynamical origin of P11 N* resonances
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Suzuki, Julia-Diaz, HK, Lee, Matsuyama, Sato
PRL104 065203 (2010)
```

```
G M(Q^2) for N → Δ(1232) M1 transition
```

```
Julia-Diaz, Lee, Sato, Smith
PRC75 015205 (2007)
```

**Reaction Data**
- πN → πN, ηN, ππN, KY, ωN...
- γ(0)N → πN, ηN, ππN, KY, ωN...

**Analysis Based on Reaction Theory**
- (Our approach)

**Hadron Models**

**Lattice QCD**

**QCD**

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BARE
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**Meson cloud effect**
Background & Motivation

**N* spectroscopy via global analysis of πN and γN reactions**

- Based on Dynamical Coupled-Channels (DCC) approach

  ## Latest published analysis (ANL-Osaka):
  *Fully combined analysis of πN, γN → πN, ηN, KΛ, KΣ up to W = 2.1 GeV.* [HK, Nakamura, Lee, Sato, PRC88(2013)035209]

Apply our DCC approach to the spectroscopy of hyperon resonances (Y* = Λ*, Σ*) !!

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**Reaction Data**

- πN → πN, ηN, ππN, KY, ωN...
- γ(α)N → πN, ηN, ππN, KY, ωN...

**Diagram**

- Graph showing dynamical origin of P11 N* resonances
- Q_2 dependence of G_\text{M}(Q^2) for N → Δ(1232) M1 transition
**Y* spectroscopy using anti-kaon beam**

- **The simplest reactions for studying Y* (= Λ*, Σ***).**

- Deuteron reactions allow one to directly access $\bar{K}N$ subthreshold region, and to study $YN$ and $YY$ interactions.

(Noumi et al., J-PARC E31)

(cf.) photon beam case:

(At least 3 particles appear in final state and process becomes complicated)

Necessary for studying Λ(1405) etc.
Dynamical coupled-channels (DCC) approach for $Y^*$ production reactions

HK, Nakamura, Lee, Sato, PRC90(2014)065204

Coupled-channels integral equations for partial-wave amplitudes of $a \rightarrow b$ reaction:

$$T_{b,a}^{(LSJ)}(p_b, p_a; E) = V_{b,a}^{(LSJ)}(p_b, p_a; E) + \sum_c \int_0^\infty q^2 dq V_{b,c}^{(LSJ)}(p_b, q; E) G_c(q; E) T_{c,a}^{(LSJ)}(q, p_a; E)$$

Reaction channels:

$$a, b, c = (\bar{K}N, \pi\Sigma, \pi\Lambda, \eta\Lambda, K\Xi, \pi\Sigma^*, \bar{K}^*N, \cdots)$$

quasi two-body channels

Transition Potentials:

$$V_{a,b} = v_{a,b} + \sum_{Y^*} \frac{\Gamma_{Y^*,a}^{\dagger} \Gamma_{Y^*,b}}{E - M_{Y^*}}$$

Exchange potentials

Bare $Y^*$ states
**Dynamical coupled-channels (DCC) approach for Y* production reactions**

HK, Nakamura, Lee, Sato, PRC90(2014)065204

Coupled-channels integral equations for partial-wave amplitudes of a → b reaction:

\[
T_{b,a}^{(LSJ)}(p_b, p_a; E) = V_{b,a}^{(LSJ)}(p_b, p_a; E) + \sum_c \int_0^\infty q^2 dq V_{b,c}^{(LSJ)}(p_b, q; E) G_c(q; E) T_{c,a}^{(LSJ)}(q, p_a; E)
\]

- **Meson-Baryon Green functions**
  \[ MB = \bar{K}N, \pi\Sigma, \pi\Lambda, \eta\Lambda, K\Xi \]
  **Stable channels**
  \[ MB = \pi\Sigma^*, \bar{K}^*N \]
  **Quasi 2-body channels**
  Produces three-body unitary cuts !!
Dynamical coupled-channels (DCC) approach for $Y^*$ production reactions

HK, Nakamura, Lee, Sato, PRC90(2014)065204

Coupled-channels integral equations for partial-wave amplitudes of a $\rightarrow b$ reaction:

$$
T_{b,a}^{(LSJ)}(p_b, p_a; E) = V_{b,a}^{(LSJ)}(p_b, p_a; E) + \sum_c \int_0^\infty q^2 dq V_{b,c}^{(LSJ)}(p_b, q; E) G_c(q; E) T_{c,a}^{(LSJ)}(q, p_a; E)
$$

Reaction channels:

- Transition Potentials:
  - Dynamical coupled-channels (DCC) approach for $Y^*$ production reactions

- CC effect
- off-shell effect

Summing up all possible transitions between reaction channels !!
(⇒ satisfies multichannel two- and three-body unitarity)

- e.g.) $\bar{K}N$ scattering

- Momentum integral takes into account off-shell rescattering effects in the intermediate processes.
Dynamical coupled-channels (DCC) approach for $Y^*$ production reactions

HK, Nakamura, Lee, Sato, PRC90(2014)065204

Coupled-channels integral equations for partial-wave amplitudes of $a \rightarrow b$ reaction:

Physical $Y^*$s will be a “mixture” of the two pictures:

- Baryon
- Meson
- Meson cloud
- Core

$$|Y^*\rangle = |MB\rangle$$

$$|Y^*\rangle = |qqq\rangle + |m.c.\rangle$$

Transition Potentials:

$$V_{a,b} = v_{a,b} + \sum_{Y^*} \frac{\Gamma_{Y^*,a}^{\dagger} \Gamma_{Y^*,b}}{E - M_{Y^*}}$$

Exchange potentials

Bare $Y^*$ states
What we have done so far

With the dynamical coupled-channels approach developed for the $S=-1$ sector, we made:

✓ Comprehensive analysis of all available data of $K^-p \rightarrow \bar{K}N, \pi\Sigma, \pi\Lambda, \eta\Lambda, K\Xi$ up to $W = 2.1$ GeV.

[HK, Nakamura, Lee, Sato, PRC90(2014)065204]

➢ Successfully determined the partial-wave amplitudes of $\bar{K}N \rightarrow \bar{K}N, \pi\Sigma, \pi\Lambda, \eta\Lambda, K\Xi$ for $S, P, D,$ and $F$ waves !!

✓ Extraction of $\Lambda^*$ and $\Sigma^*$ mass spectrum defined by poles of scattering amplitudes.

[HK, Nakamura, Sato, in preparation]
Issues in the availability of data:

✓ Most data are from 60-70’s.

✓ Kinematical coverage is rather scarce for most reactions.

✓ No data for spin rotations ($\beta$, $R$, $A$).

✓ No data near the threshold for $K^-p \rightarrow \bar{K}N$, $\pi\Sigma$, $\pi\Lambda$.

The $K^-p$ reaction data are far from “complete”!!

→ Need help of hadron beam facilities such as J-PARC !!
Results of the fits

\( K^- p \rightarrow MB \) total cross sections

**Red:** Model A

**Blue:** Model B

“Incompleteness” of the current database allows us to have two parameter sets that give similar quality of the fit.
Results of the fits

K⁻ p → K⁻ p scattering

\[ \frac{d\sigma}{d\Omega} \quad (1464 < W < 1831 \text{ MeV}) \]

\[ \frac{d\sigma}{d\Omega} \quad (1832 < W < 2100 \text{ MeV}) \]

Red: Model A  Blue: Model B

HK, Nakamura, Lee, Sato, PRC90(2014)065204
Comparison of extracted partial-wave amplitudes

Extracted $\bar{K}N$ scattering amplitudes

$S_{01}$, $P_{01}$, $D_{03}$, $D_{05}$, $F_{07}$, $S_{11}$, $P_{11}$, $D_{13}$, $D_{15}$, $F_{17}$

Red: Model A
Blue: Model B
Circles: KSU single-energy solution

HK, Nakamura, Lee, Sato, PRC90(2014)065204

$L_{1,2J} : L = S,P,..; I = \text{isospin}; J = \text{Total angular mom.}$

$[\text{PRC88(2013)035204}]$
Comparison of extracted partial-wave amplitudes

Extracted $\bar{K}N$ scattering amplitudes

On- and off-shell partial-wave amplitudes for $\bar{K}N \rightarrow \pi\Sigma$, $\bar{K}N \rightarrow \pi\Lambda$, $\bar{K}N \rightarrow \eta\Lambda$, $\bar{K}N \rightarrow K\Xi$

are also available for $S$, $P$, $D$, and $F$ waves !!

Input for elementary processes of nuclear target reactions (hypernuclei, kaonic nuclei...).

$\text{Red : Model A} \quad \text{Blue: Model B} \quad \text{Circles: KSU single-energy solution}$

[PRC88(2013)035204]

HK, Nakamura, Lee, Sato, PRC90(2014)065204

$L_{1,2J} : L = S,P,.. ; I = \text{isospin}; J = \text{Total angular mom.}$
S-wave contributions in the threshold region

$K^- p \rightarrow MB$ total cross sections

Higher partial waves can be significant at the region even close to the threshold!!

HK, Nakamura, Lee, Sato, PRC90(2014)065204
Predicted spin-rotation angle $\beta$

\[ \beta \text{ is modulo } 2\pi \]

Analysis dependence is clearly seen in observables that are not yet measured.

Measurement of spin-rotation $\beta$ will give strong constraints on the $Y^*$ spectrum!!

Red: Model A
Blue: Model B
Black: KSU

The KSU results are computed by us using their amplitudes in PRC88(2013)035204.

## NOTE:
Predicted $\pi \Sigma$ scattering total cross section at low energies

Predicted total cross section $\sigma$ of $\pi$-$\Sigma^+$ scattering from the threshold up to $W = 1.55$ GeV.

Contribution from higher partial waves can be sizable in the $K\bar{N}$ subthreshold region !!
Extracting $Y^*$ resonance parameters

**Definitions of**

- $Y^*$ masses (spectrum)
- $Y^* \rightarrow MB$ coupling constants

$\Rightarrow$ Pole positions of the amplitudes

$\Rightarrow$ Residues$^{1/2}$ at the pole

$$\langle p_a | \hat{T}(E)| p_b \rangle \bigg|_{E \rightarrow E_0} \rightarrow \frac{\Gamma(E_0, p_a) \tilde{\Gamma}(E_0, p_b)}{E - E_0} + \text{(regular terms)}$$

$Y^* \rightarrow b$ coupling constant

$Y^*$ pole position ($\text{Im}(E_0) < 0$)

**(Multichannel) unitarity** is a key to making "correct" analytic continuation!!

Extracting $Y^*$ resonance parameters

**Definitions of**

- $Y^*$ masses (spectrum) ➔ Pole positions of the amplitudes
- $Y^* \rightarrow$ MB coupling constants ➔ Residues$^{1/2}$ at the pole

Consistent with the resonance theory based on **Gamow vectors**

G. Gamow (1928), R. E. Peierls (1959), …
For a brief introduction of Gamow vectors, see, e.g., de la Madrid et al, quant-ph/0201091

- Resonances are (**complex-energy**) eigenstates of the Hamiltonian of the underlying fundamental theory with the purely outgoing boundary condition !!

$$(\text{complex)} \text{ energy eigenvalues} = \text{pole values}$$

$$(\text{transition matrix elements}) = (\text{residue})^{1/2} \text{ of the poles}$$
Comparison of $\Lambda^*$ spectrum between multichannel analyses

### Here only $Y^*$s ABOVE $KN$ threshold are presented.

**J^P(L_{12}J)**

<table>
<thead>
<tr>
<th>$1/2^+$ ($P_{01}$)</th>
<th>$3/2^+$ ($P_{03}$)</th>
<th>$5/2^+$ ($F_{05}$)</th>
<th>$7/2^+$ ($F_{07}$)</th>
</tr>
</thead>
</table>

**“$\Lambda$” resonance (I=0)**

- $-2\text{Im}(M_R)$ ("total width")
  - $\text{Re}(M_R)$
- $M_R$: (resonance pole mass (complex))

**Preliminary**

Comparison of Λ* spectrum between multichannel analyses

### Here only Λ*s ABOVE K̅N threshold are presented.

- **Red**: Model A
- **Blue**: Model B
- **Green**: KSU [on-shell K-matrix, PRC88(2013)035205]
- **Black**: PDG (Breit-Wigner)

HK, Nakamura, Sato, in preparation

preliminary
Comparison of $\Lambda^*$ spectrum between multichannel analyses

### Here only Y*'s ABOVE $\bar{K}N$ threshold are presented.

- **$1/2^+ (P_{01})$**
- **$3/2^+ (P_{03})$**
- **$5/2^+ (F_{05})$**
- **$7/2^+ (F_{07})$**


**$\Lambda(1/2^-)$ resonance**

Sharp peak near threshold require the existence of $\Lambda(1/2^-)$ resonance.

$K^- p \rightarrow \eta \Lambda$

$\pi^- p \rightarrow \eta n$

$N^*(1535)1/2^-$

$-2\text{Im}(M_R)$ ("total width")

$M_R :$ (resonance pole mass)
Comparison of $\Lambda^*$ spectrum between multichannel analyses

### Here only $\Upsilon$'s ABOVE $KN$ threshold are presented.

$J^P(L_{12j})$ \hspace{1cm} “$\Lambda$” resonance ($I=0$)

<table>
<thead>
<tr>
<th>$J^P$</th>
<th>$1/2^+$ ($P_{01}$)</th>
<th>$3/2^+$ ($P_{03}$)</th>
<th>$5/2^+$ ($F_{05}$)</th>
<th>$7/2^+$ ($F_{07}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{12j}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

-2Im($M_R$) ("total width") \hspace{1cm} Re($M_R$)

$M_R$ : resonance pole mass (complex)

HK, Nakamura, Sato, in preparation


Comes from P03 resonance

Preliminary
P03 resonance just above the $\eta\Lambda$ threshold

$\frac{d\sigma}{d\Omega}$ of $K^- p \rightarrow \eta\Lambda$ @ $W=1672$ MeV (just 8 MeV above the threshold)

- Even in the region very close to the threshold, the $\frac{d\sigma}{d\Omega}$ data show a clear angular dependence.

Model A
(S01 wave ~99%)

- Concave-up behavior of the data is not reproduced.

Model B
(S01 wave ~60%, P03 wave ~40%)

- NEW narrow P03 resonance is responsible for reproducing the angular dependence of $\frac{d\sigma}{d\Omega}$ !!
Comparison of $\Sigma^*$ spectrum between multichannel analyses

### Here only $Y^*$s ABOVE $\bar{K}N$ threshold are presented.

$J^P(L_{12}J)$

"$\Sigma$" resonance ($I=1$)

$\Sigma$ resonance (I=1)

$\Sigma^*$: Resonance pole mass (complex)

-2Im($M_R$)

(“total width”)

$M_R$ : Resonance pole mass (complex)

### Here only Y*s ABOVE \( \bar{K}N \) threshold are presented.

A number of low-lying resonances are found !! (corresponds to 1* and 2* states in PDG ???)

**Comparison of \( \Sigma^* \) spectrum between multichannel analyses**

**“\( \Sigma \)” resonance (\( I=1 \))**

<table>
<thead>
<tr>
<th>( J^P(L_{12}I) )</th>
<th>( 1/2^+ (P_{11}) )</th>
<th>( 3/2^+ (P_{13}) )</th>
<th>( 5/2^+ (F_{15}) )</th>
<th>( 7/2^+ (F_{17}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDG(BW) A</td>
<td>Red: Model A</td>
<td>Blue: Model B</td>
<td>Green: KSU</td>
<td>Black: PDG</td>
</tr>
<tr>
<td></td>
<td>Red: Model A</td>
<td>Blue: Model B</td>
<td>Green: KSU</td>
<td>Black: PDG</td>
</tr>
</tbody>
</table>

\( \Sigma \) resonance (I=1)

-2Im(\( M_R \))

(“total width”)

\( M_R \): Resonance pole mass (complex)


Low-lying \( \Sigma^* \) resonances(PDG)

\[
\begin{align*}
\Sigma(1193) & \quad 1/2^+ \quad **** \\
\Sigma(1385) & \quad 3/2^+ \quad **** \\
\Sigma(1480) & \quad * \\
\Sigma(1560) & \quad ** \\
\Sigma(1580) & \quad 3/2^- \quad * \\
\Sigma(1620) & \quad 1/2^- \quad ** \\
\Sigma(1660) & \quad 1/2^+ \quad **** \\
\Sigma(1670) & \quad 3/2^- \quad ****
\end{align*}
\]
Summary & Future works

✓ Comprehensive analysis of $K^- p \rightarrow \bar{K}N, \pi\Sigma, \pi\Lambda, \eta\Lambda, K\Xi$ up to $W = 2.1$ GeV has been accomplished for the first time within a dynamical coupled-channels approach.

✓ Partial-wave ($S$, $P$, $D$, and $F$) amplitudes & $\Lambda^*$ and $\Sigma^*$ mass spectrum have been successfully extracted.

Future works:

- $Y^*$ spectroscopy below $\bar{K}N$ threshold with $K$-d reactions (J-PARC E31).
- Multi-strange baryon ($\Xi^*$ and $\Omega^*$) spectroscopy.
- Application to production reactions of hypernuclei and kaonic nuclei.
Results of the fits

K⁻ p → K⁰ n reaction

d\sigma/d\Omega (1466 < W < 1796 MeV)

Red: Model A Blue: Model B

d\sigma/d\Omega (1804 < W < 1992 MeV)

HK, Nakamura, Lee, Sato, PRC90(2014)065204
Results of the fits

$K^- p \rightarrow \pi^- \Sigma^+$ reaction

$\frac{d\sigma}{d\Omega}$

$P \times \frac{d\sigma}{d\Omega}$

HK, Nakamura, Lee, Sato, PRC90(2014)065204

Red: Model A  Blue: Model B
Results of the fits

$K^- p \rightarrow \pi^0 \Sigma^0$ reaction

HK, Nakamura, Lee, Sato, PRC90(2014)065204

Red: Model A  Blue: Model B
Results of the fits

\[ \frac{d\sigma}{d\Omega} \]

\( K^- p \rightarrow \pi^+ \Sigma^- \) reaction

HK, Nakamura, Lee, Sato, PRC90(2014)065204

Red: Model A  Blue: Model B
Results of the fits

K⁻ p → π⁰ Λ reaction

\[ \frac{d\sigma}{d\Omega} \, (1536 < W < 1870 \text{ MeV}) \]

\[ \frac{d\sigma}{d\Omega} \, (1875 < W < 2088 \text{ MeV}) \]

HK, Nakamura, Lee, Sato, PRC90(2014)065204

Red: Model A  Blue: Model B
Results of the fits

$K^- p \rightarrow \pi^0 \Lambda$ reaction (cont’d)

HK, Nakamura, Lee, Sato, PRC90(2014)065204

Red: Model A  Blue: Model B
Results of the fits

$K^-$ $p \rightarrow \eta \Lambda$ reaction

$K^-$ $p \rightarrow K^0 \Xi^0$ reaction

$K^-$ $p \rightarrow K^+ \Xi^-$ reaction

HK, Nakamura, Lee, Sato, PRC90(2014)065204

Red: Model A  Blue: Model B
Comparison of extracted partial-wave amplitudes

Extracted $\bar{K}N \rightarrow \pi\Sigma$ amplitudes

Red : Model A
Blue: Model B
Circles: KSU single-energy solution

$\text{L}_{12J} : L = S, P, \ldots ; I = \text{isospin}; J = \text{Total angular mom.}$

HK, Nakamura, Lee, Sato, PRC90(2014)065204

[PRC88(2013)035204]
Comparison of extracted partial-wave amplitudes

Extracted $\bar{K}N \rightarrow \pi\Lambda$ amplitudes

HK, Nakamura, Lee, Sato, PRC90(2014)065204

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[PRC88(2013)035204]
Comparison of extracted partial-wave amplitudes

HK, Nakamura, Lee, Sato, PRC90(2014)065204

$\bar{K}N \rightarrow \eta\Lambda$ amplitudes

$L_{12J} : L = S, P, \ldots ; I = \text{isospin}; J = \text{Total angular mom.}$

Red : Model A
Blue: Model B
Comparison of extracted partial-wave amplitudes

Extracted $\bar{K}N \rightarrow K\Xi$ amplitudes

Red: Model A
Blue: Model B

HK, Nakamura, Lee, Sato, PRC90(2014)065204

$L_{1,2,3} : L = S,P,.. ; I = \text{isospin}; J = \text{Total angular mom.}$
### Extracted scattering lengths and effective ranges

**HK, Nakamura, Lee, Sato, PRC90(2014)065204**

#### Scattering length and effective range

<table>
<thead>
<tr>
<th></th>
<th>$I = 0$</th>
<th>$I = 1$</th>
<th>$I = 0$</th>
<th>$I = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_{KN}$ (fm)</td>
<td>$-1.37 + i0.67$</td>
<td>$0.07 + i0.81$</td>
<td>$-1.62 + i1.02$</td>
<td>$0.33 + i0.49$</td>
</tr>
<tr>
<td>$a_{\eta\Lambda}$ (fm)</td>
<td>$1.35 + i0.36$</td>
<td>-</td>
<td>$0.97 + i0.51$</td>
<td>-</td>
</tr>
<tr>
<td>$a_{K\Xi}$ (fm)</td>
<td>$-0.81 + i0.14$</td>
<td>$-0.68 + i0.09$</td>
<td>$-0.89 + i0.13$</td>
<td>$-0.83 + i0.03$</td>
</tr>
<tr>
<td>$r_{KN}$ (fm)</td>
<td>$0.67 - i0.25$</td>
<td>$1.01 - i0.20$</td>
<td>$0.74 - i0.25$</td>
<td>$-1.03 + i0.19$</td>
</tr>
<tr>
<td>$r_{\eta\Lambda}$ (fm)</td>
<td>$-5.67 - i2.24$</td>
<td>-</td>
<td>$-5.82 - i3.32$</td>
<td>-</td>
</tr>
<tr>
<td>$r_{K\Xi}$ (fm)</td>
<td>$-0.01 - i0.33$</td>
<td>$-0.42 - i0.49$</td>
<td>$0.13 - i0.20$</td>
<td>$-0.22 - i0.11$</td>
</tr>
</tbody>
</table>

\[ a_{K-p} = -0.65 + i0.74 \text{ fm (Model A)} \]
\[ a_{K-p} = -0.65 + i0.76 \text{ fm (Model B)} \]
Polarization observables for spin-0 + spin-1/2 → spin-0 + spin-1/2 reactions

Suppose target nucleon polarization points z-axis (parallel to pion momentum):

\[ \vec{P}_{NT} = P_{NT} \hat{z} \]

Polarization of the recoil nucleon is then expressed as

\[ \vec{P}_{NR} = P \hat{y} + P_{NT} \sqrt{1 - P^2} \sin \beta \hat{x} + P_{NT} \sqrt{1 - P^2} \cos \beta \hat{z} \]

\[ R = \sqrt{1 - P^2} \sin \beta, \quad A = \sqrt{1 - P^2 \cos \beta} \]

Note: Various conventions are taken for \( \beta, R, A \) in literatures.

e.g.) \( \pi N \) scattering (in c.m. frame)

Wolfenstein, Phys. Rev. 96(1954)1654
Kelly, Sandusky, Cutkosky, PRD10(1974)2309
Supek et al., PRD47(1993)1762
Extraction of resonance parameters

1. Construct model (determine amplitudes) by fitting data

2. Analytic continuation of determined amplitudes to complex energy plane !!

3. Resonances are obtained as poles of amplitudes in complex energy plane !!

\[
\text{mass \ & \ width} = \text{pole value} \\
\text{coupling constants} = (\text{residue})^{1/2} \text{ at the pole}
\]

Suzuki et al PRC79(2009)025205
PRC82(2010)045206
$\Lambda(1/2^-)$ resonance near the $\eta\Lambda$ threshold

$\Lambda(1/2^-)$ pole at $1669 - i9$ MeV (Model A) (would correspond to $\Lambda(1670)$ in PDG)

- Next higher excited states of $\Lambda(1405)$.
- $K^- p \rightarrow \eta\Lambda$ data make the existence of this $\Lambda(1/2^-)$ stable and model-independent.
- Dip at $W \sim 1670$ MeV seen in $K^- p \rightarrow MB$ total cross sections is produced by this $\Lambda(1/2^-)$. [$\eta\Lambda$ cusp effect is hindered by the large contribution from $\Lambda(1/2^-)$.]

$\eta\Lambda$ cut (rotated from real $W$ axis)

$\eta\Lambda$ physical sheet

$\eta\Lambda$ unphysical sheet

$K^- p \rightarrow \eta\Lambda$

Sharp peak near threshold requires the existence of $\Lambda(1/2^-)$ resonance.

Peaks due to $1^{st} \Lambda(3/2^-)$ [known as $\Lambda(1520)$]

Dip due to $\Lambda(1/2^-)$ near $\eta\Lambda$ threshold