HYP-X , Tokai, Japan, Sep. 17, 2009

^{3}He(in-flight K^-, n) spectrum and moving pole of a deeply-bound K^-pp state in complex energy plane

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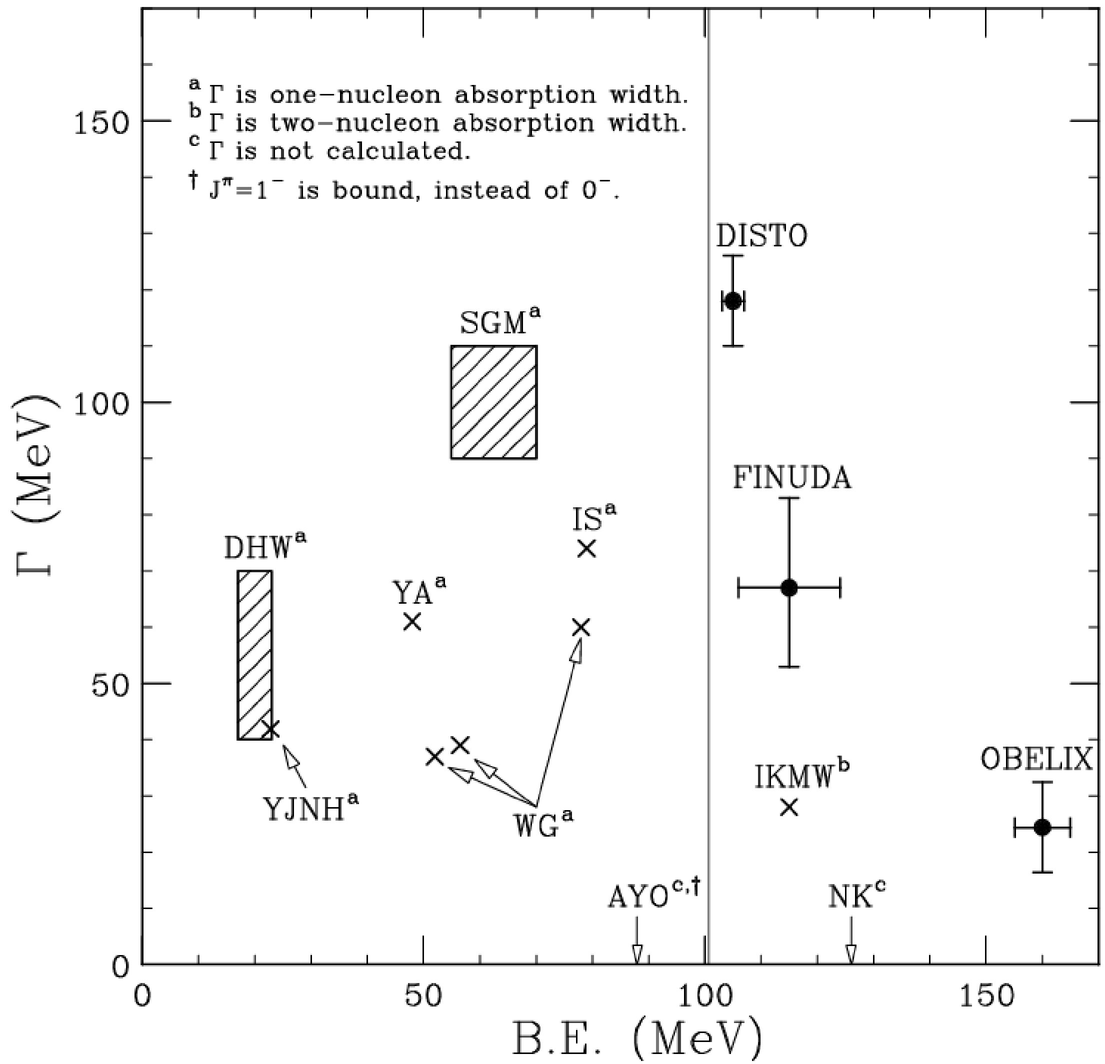
"K⁻pp" is suggested to be the lightest and most fundamental kaonic nuclei,

but the theoretically-calculated and experimentally-measured *B.E.* and *Γ* are not converged!



Theory

- **YA: Yamazaki, Akaishi**
- **SGM: Shevchenko, Gal, Mares**
- **IS: Ikeda, Sato**
- **DHW: Dote, Hyodo, Weise**
- **IKMW: Ivanov, Kienle *et al*.**
- **NK: Nishikawa & Kondo**
- **AYO: Arai, Yasui, Oka**
- **YJNH: Yamagata, Jido *et al*.**
- **WG: Wycech, Green,**

Experiment

- **FINUDA**
- **OBELIX**
- **DISTO**

◆ New measurement for searching "K$^-$pp"

★ M. Iwasaki, T. Nagae *et al.* , J-PARC E15 experiment

^{3}He(In-flight K$^-$, n) "K$^-$pp"
at p_{K^-} = 1 GeV/c and θ_n=0^o

missing-mass spectroscopy

+

Simultaneous mesurement

"K$^-$pp" →Λp □ π$^-$pp
detecting all charged particles from the decay of "K$^-$pp"

invariant-mass spectroscopy

Our purpose:

Theoretical calculation of ^{3}He(In-flight K$^-$, n) inclusive/ semi-exclusive spectra within the DWIA framework using Green's function method.

◆ Theoretical calculations of ^{3}He(In-flight K^-, n) reaction spectrum for J-PARC E15 experiment

- **Our approach:**

Phenomenological optical potential model using phase space factor

→ Examine a possible evidence for the various cases.

Refs. T. Koike & T. Harada, Phys. Lett. B652 (2007) 262-268.
T. Koike & T. Harada, Nucl. Phys. A804 (2008) 231-273.
T. Koike & T. Harada, arXiv: 0906.3659 [nucl-th].

- **Other approach within a similar framework:**

Optical potential model based on chiral unitary approach

Ref. J. Yamagata-Sekihara *et al.*, arXiv: 0812.4359 [nucl-th].

◆Distorted-Wave Impulse Approximation (DWIA)

$$\frac{d^2\sigma}{dE_n d\Omega_n} = \beta \left[\frac{d\sigma}{d\Omega_n}\right]^{(\mathrm{elem})} S(E)$$

Kinematical factor

Strength function

Fermi-averaged ementary cross-section

$K^- + n \rightarrow N + K^{bar}$ in lab. system

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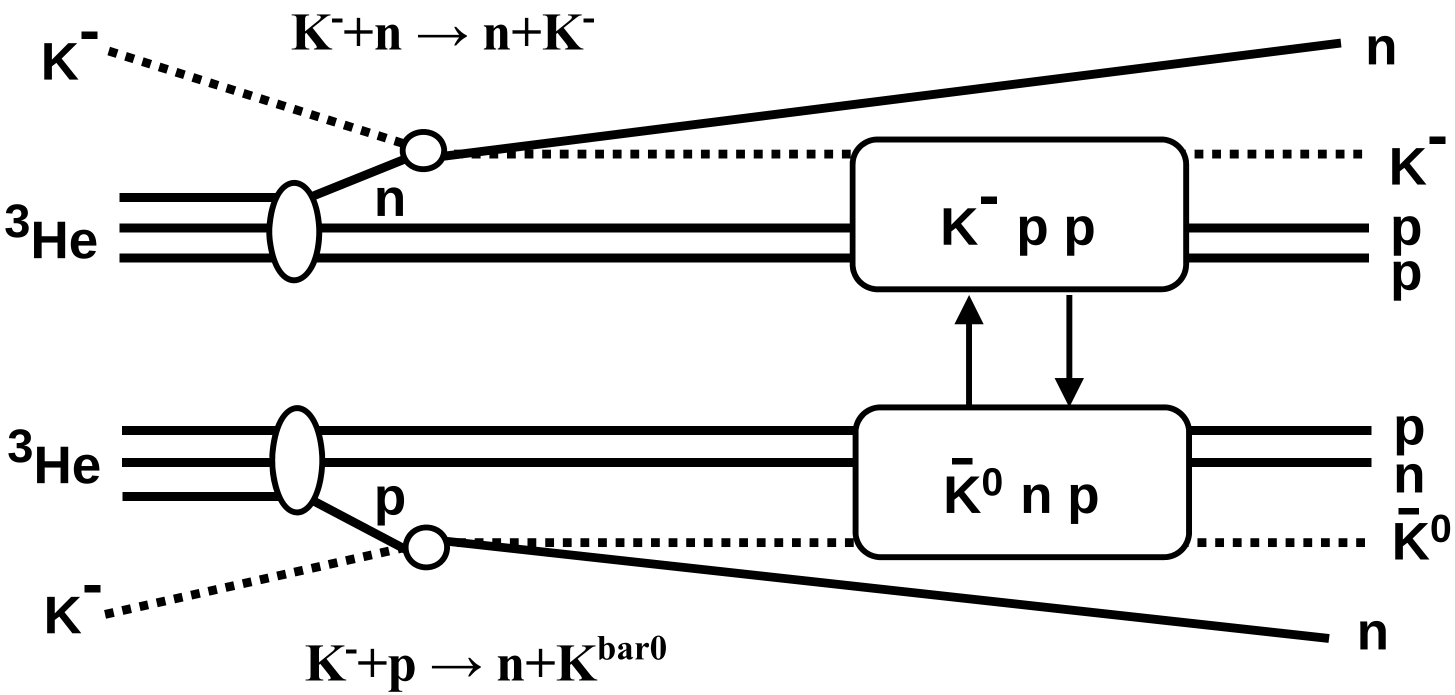
In charge basis,



◆Distorted-Wave Impulse Approximation (DWIA)

$$\frac{d^2\sigma}{dE_n d\Omega_n} = \beta \left[\frac{d\sigma}{d\Omega_n}\right]^{(\text{elem})} S(E)$$

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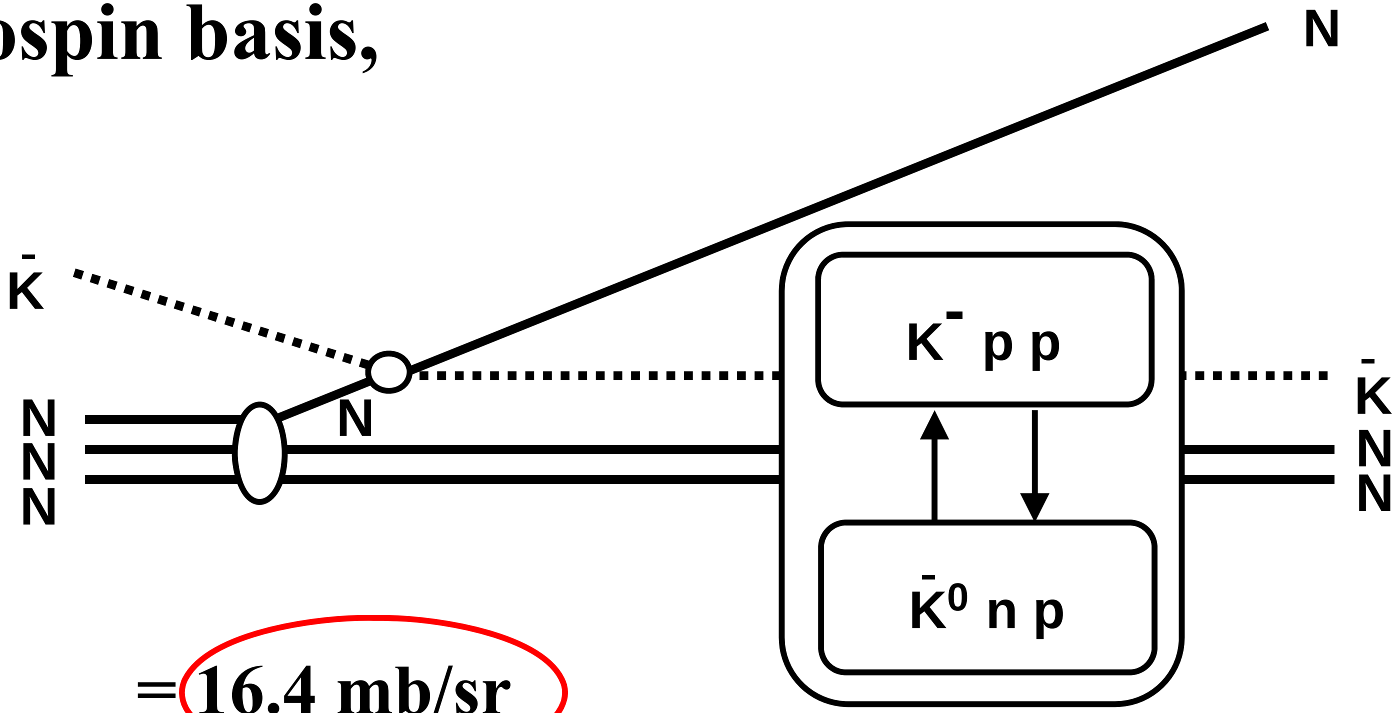
Strength function

Fermi-averaged ementary cross-section
$K^- + n \rightarrow N + K^{bar}$ in lab. system

In isospin basis,



$[\bar{K} \times \{NN\}_{I=1}]_{I=1/2}$

$$\left[\frac{d\sigma}{d\Omega_n}\right]_{\Delta I = 0} = 16.4 \text{ mb/sr}$$

now used

◆Distorted-Wave Impulse Approximation (DWIA)

$$\frac{d^2\sigma}{dE_n d\Omega_n} = \beta \left[\frac{d\sigma}{d\Omega_n}\right]^{(\mathrm{elem})} S(E)$$

Kinematical factor

Fermi-averaged ementary cross-section

$K^- + n \to N + K^{bar}$ in lab. system

Strength function

Morimatsu & Yazaki's Green function method Prog.Part.Nucl.Phys.33(1994)679.

$$S(E) = -\frac{1}{\pi}\,\mathrm{Im}\left[\sum_{\alpha,\alpha'}\int d\boldsymbol{r}d\boldsymbol{r}' f_\alpha(\boldsymbol{r}) G_{\alpha,\alpha'}(E;\boldsymbol{r},\boldsymbol{r}') f_{\alpha'}(\boldsymbol{r}')\right]$$

Green's function K^-pp system

→ employing K^--"pp" optical potential

recoil effect

$$f_\alpha(\boldsymbol{r}) = \chi^{(-)*}\left(\boldsymbol{p}_n, \frac{M_{pp}}{M_{^3\mathrm{He}}}\boldsymbol{r}\right) \chi^{(+)}\left(\boldsymbol{p}_{K^-}, \frac{M_{pp}}{M_{^3\mathrm{He}}}\boldsymbol{r}\right) < \alpha\,|\psi_n(\boldsymbol{r})|\,i >$$

Distorted wave for incoming(+)/outgoing(-) particles

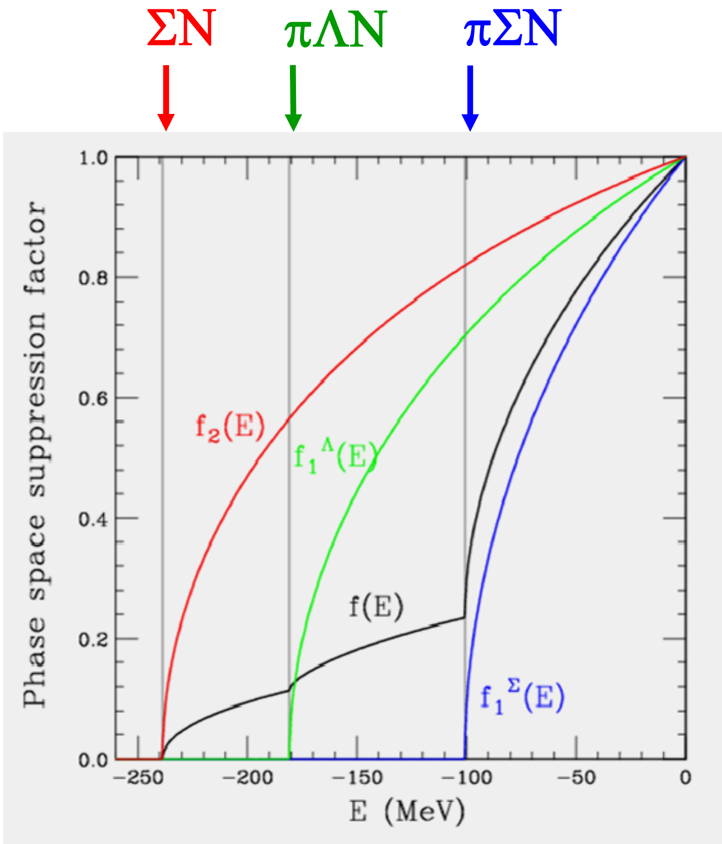
→ Eikonal approximation

neutron wave function

→ $(0s)^3$ harmonic oscillator model

◆ Phenomenological K^--"pp" optical potential

$$U^{\rm opt}(E;r) = (V_0 + i\,W_0 \underline{f(E)}\,)\exp[-(r/b)^2]$$



- **1-nucleon K^- absorption**

  $K^-pp \rightarrow$ "K^-p" + p $\rightarrow \pi + \Sigma + N$: $f_1^{\Sigma}(E)$
  $K^-pp \rightarrow$ "K^-p" + p $\rightarrow \pi + \Lambda + N$: $f_1^{\Lambda}(E)$

- **2-nucleon K^- absorption**

  $K^-pp \rightarrow K^-$ + "pp" $\rightarrow Y + N$: $f_2(E)$

- **Total phase space factor**

$$f(E) = \underbrace{B_1^{(\pi\Sigma N)}}_{=\,0.7}\, f_1^{\Sigma}(E) + \underbrace{B_1^{(\pi\Lambda N)}}_{=\,0.1}\, f_1^{\Lambda}(E) + \underbrace{B_2^{(YN)}}_{=\,0.2}\, f_2(E)$$

Refs. J. Mares, E. Friedman, A. Gal, PLB606 (2005) 295.
D. Gazda, E. Friedman, A. Gal and J. Mares, PRC76 (2007) 055204.
J. Yamagata, H. Nagahiro, S. Hirenzaki, PRC74 (2006) 014604.

◆ Single-channel Green's function

$$\{(E - V_{\rm Coul}(\boldsymbol{r}))^2 + \boldsymbol{\nabla}^2 - \mu^2 - 2\,\mu\, \underline{U^{\rm opt}(E;\boldsymbol{r})}\}\, G(E;\boldsymbol{r},\boldsymbol{r}') \;=\; \delta^3(\boldsymbol{r}-\boldsymbol{r}'),$$

Real

◆ Determing pole position

The Klein-Gordon equation is solved self-consistently in complex *E*-plane;

$$\{(\omega(E) - V_{\rm Coul}(\boldsymbol{r}))^2 + \boldsymbol{\nabla}^2 - \mu^2 - 2\,\mu\, \underline{U^{\rm opt}(E;\boldsymbol{r})}\}\, \Phi(E;\boldsymbol{r}) \;=\; 0,$$

Complex

$$\longrightarrow \begin{cases} {\rm Re}\ \omega(E) \;=\; -B.E. = E, \\ {\rm Im}\ \omega(E) \;=\; -\Gamma/2 \end{cases}$$

***B.E.* and *Γ* are determined from these relations.**

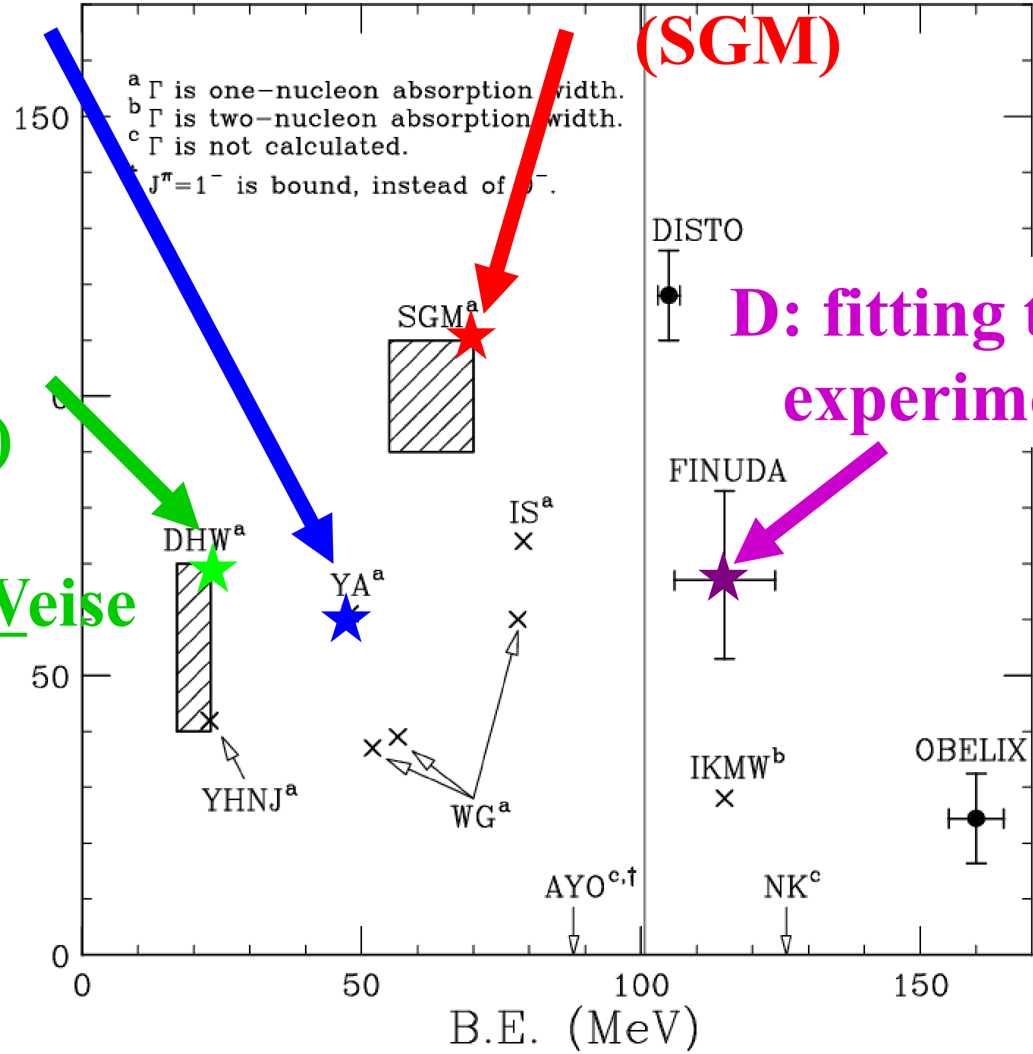
We consider the following 4 cases of the calculations/experiment;

B: variational cal. with phenomenological $K^{bar}N$ int. by Yamazaki-Akaishi (YA)

C: Faddeev cal. with phenomenological $K^{bar}N$ int. by Shevchenko-Gal-Mares (SGM)

A: variational cal. with Chiral SU(3) based $K^{bar}N$ int. by Dote-Hyodo-Weise (DHW)

D: fitting to FINUDA experimental data



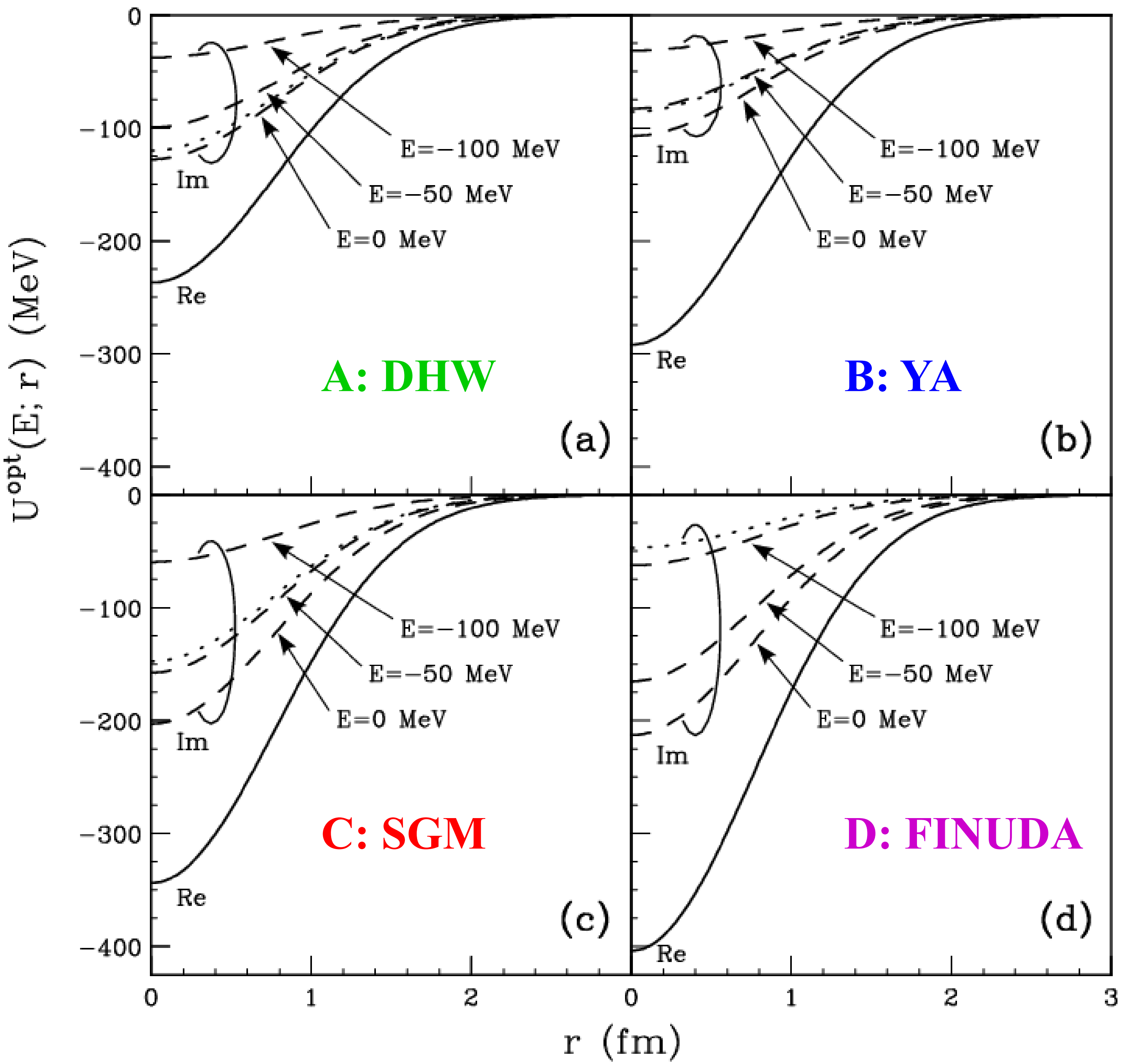
◆ Parameters of our optical potentials

	V_0 (MeV)	W_0 (MeV)	$B_2^{(YN)} = 0.0$ B.E. (MeV)	$B_2^{(YN)} = 0.0$ Γ (MeV)	$B_2^{(YN)} = 0.2$ B.E. (MeV)	$B_2^{(YN)} = 0.2$ Γ (MeV)
A	-237	-128	22	70	15	92
B	-292	-107	48	61	45	82
C	-344	-203	70	110	59	164
D	-404	-213	116	19	115	67

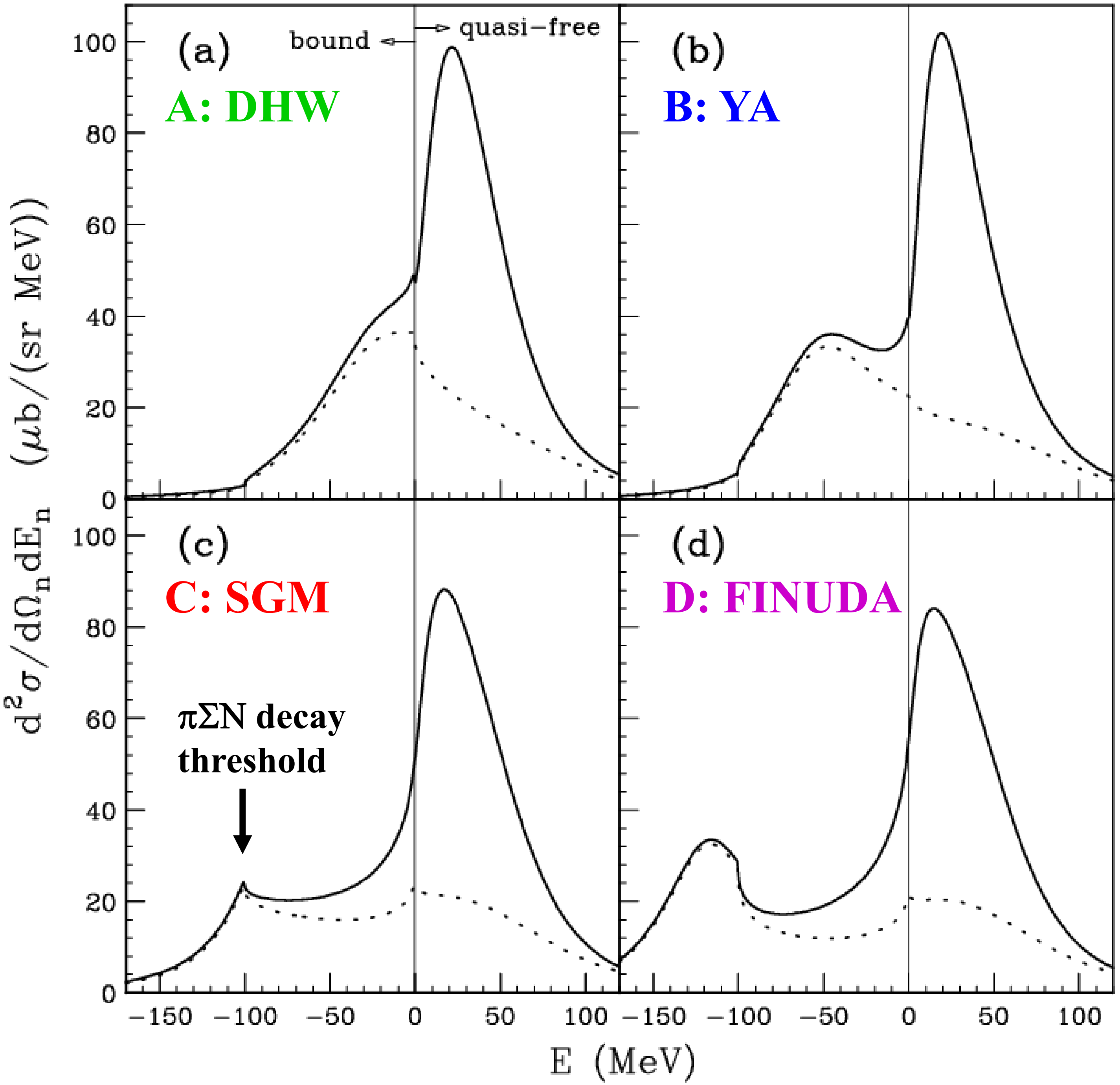
Fitted values

* *b* = 1.09 fm for all potentials; the range effect is small.

◆ Employed K$^-$-"pp" optical potentials



◆ Calculated results of inclusive spectrum



L = 0 compoment

◆ Decomposition of strength function into K^- escape / K^- conversion part

$$\mathrm{Im}\, G = (1 + G^\dagger U^\dagger)(\mathrm{Im}\, G_0)(1 + UG) + G^\dagger(\mathrm{Im}\, U)G,$$

where $G = G_0 + G_0\, U\, G$, G_0 ; **Free Green's function**

$$S = S^{\mathrm{esc}} + S^{\mathrm{con}}$$

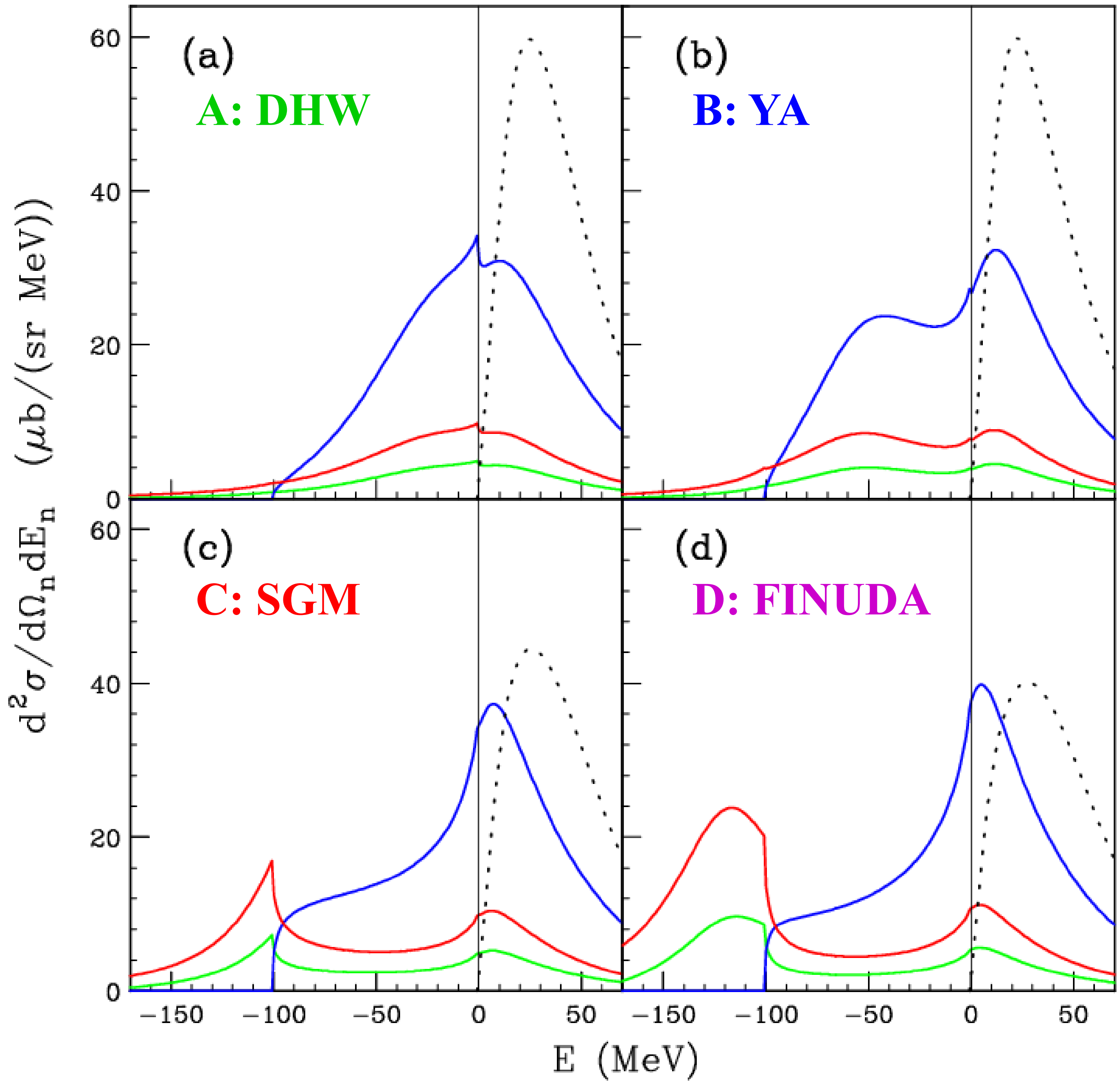
$$\begin{cases} S^{\mathrm{esc}} = -\dfrac{1}{\pi} F^\dagger(1 + G^\dagger U^\dagger)(\mathrm{Im}\, G_0)(1 + UG)F \\ S^{\mathrm{con}} = -\dfrac{1}{\pi} F^\dagger G^\dagger(\mathrm{Im}\, \underline{U})GF \end{cases}$$

S^{esc} ; **K^- escape**

S^{con} ; **K^- conversion** (U: optical potential)

★ **K^- conversion spectrum is actually measured in J-PARC experiment.**

◆ Decomposition into semi-exclusive spectra



π Σ N decay
via 1-nucleon K⁻ abs.

π Λ N decay
via 1-nucleon K⁻ abs.

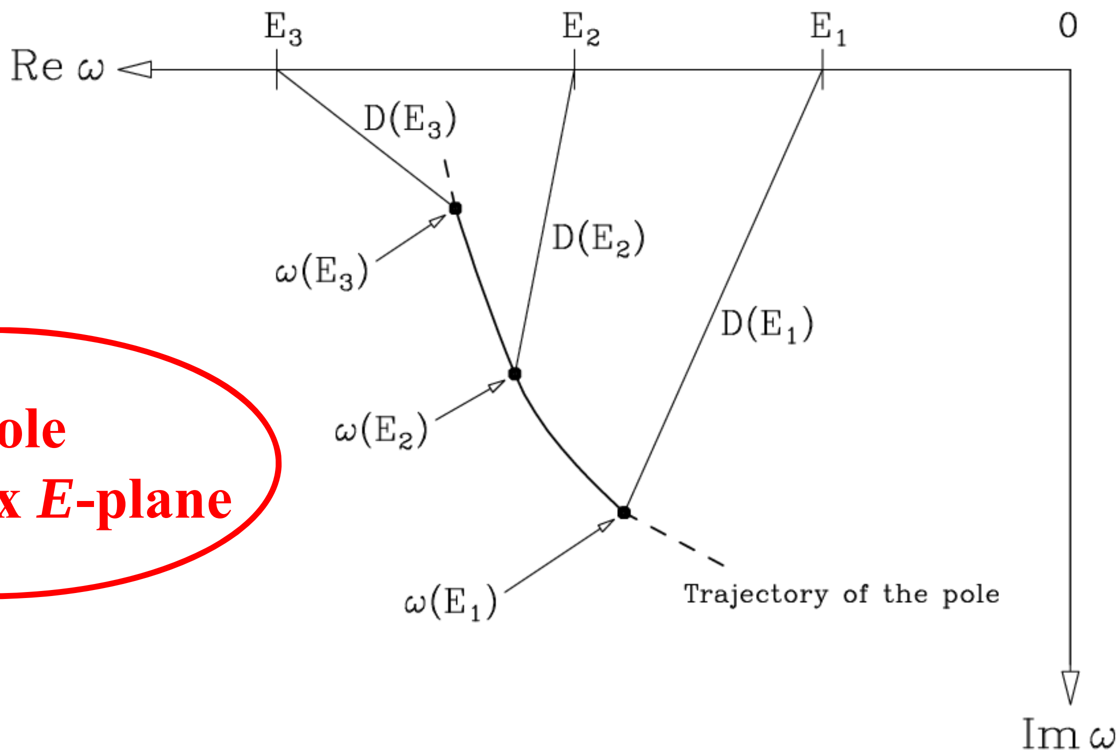
Y N decay
via 2-nucleon K⁻ abs.

K⁻ escape

◆ Definition of $D\,(E)$

$$\{(\omega(E)-V_{\rm Coul}(\boldsymbol{r}))^2+\boldsymbol{\nabla}^2-\mu^2-2\,\mu\,U^{\rm opt}(E;\boldsymbol{r})\}\,\Phi(E;\boldsymbol{r})\;=\;0,$$

***E*-dependent complex eigenvalue**

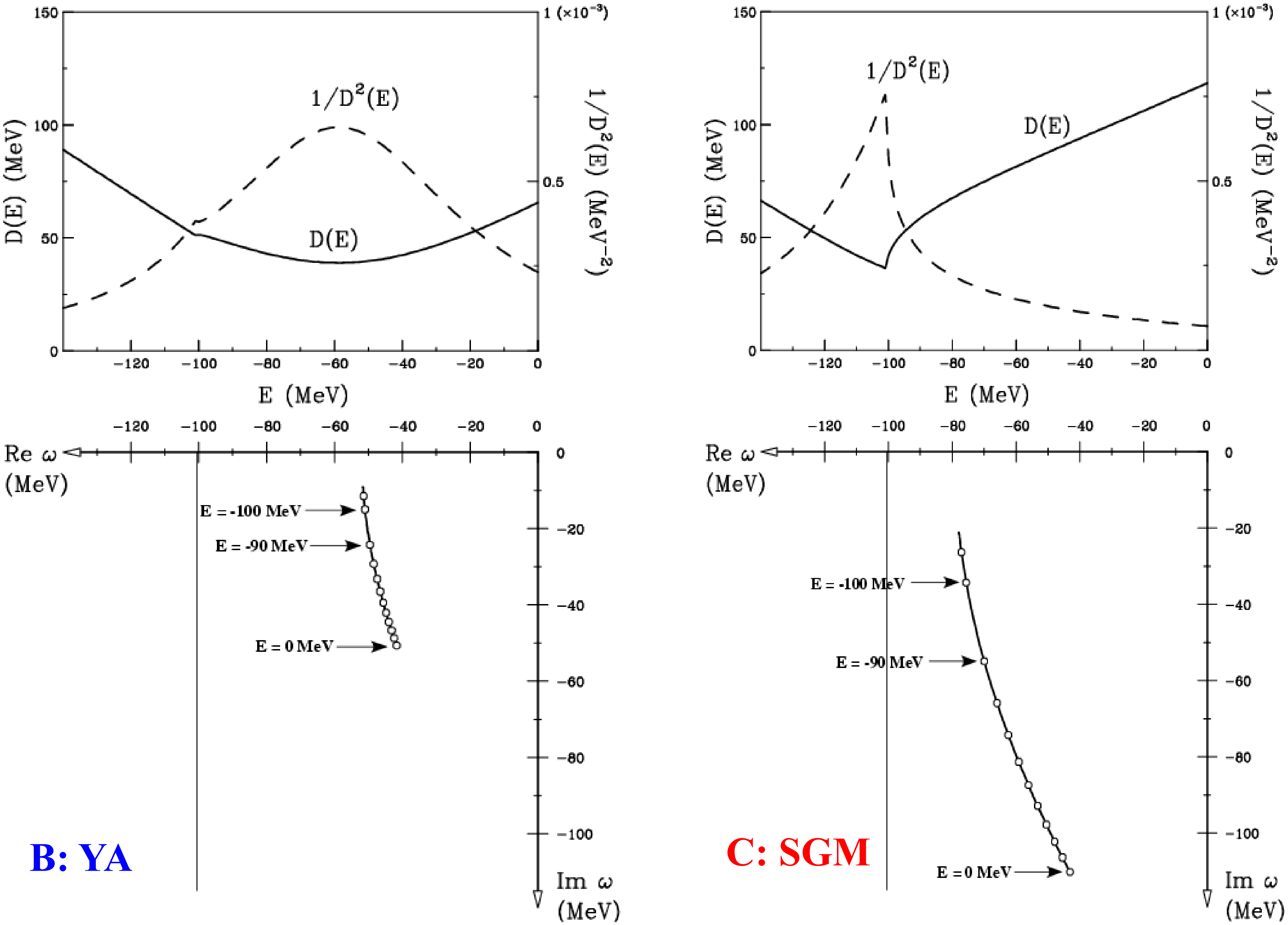


Moving-pole in complex *E*-plane

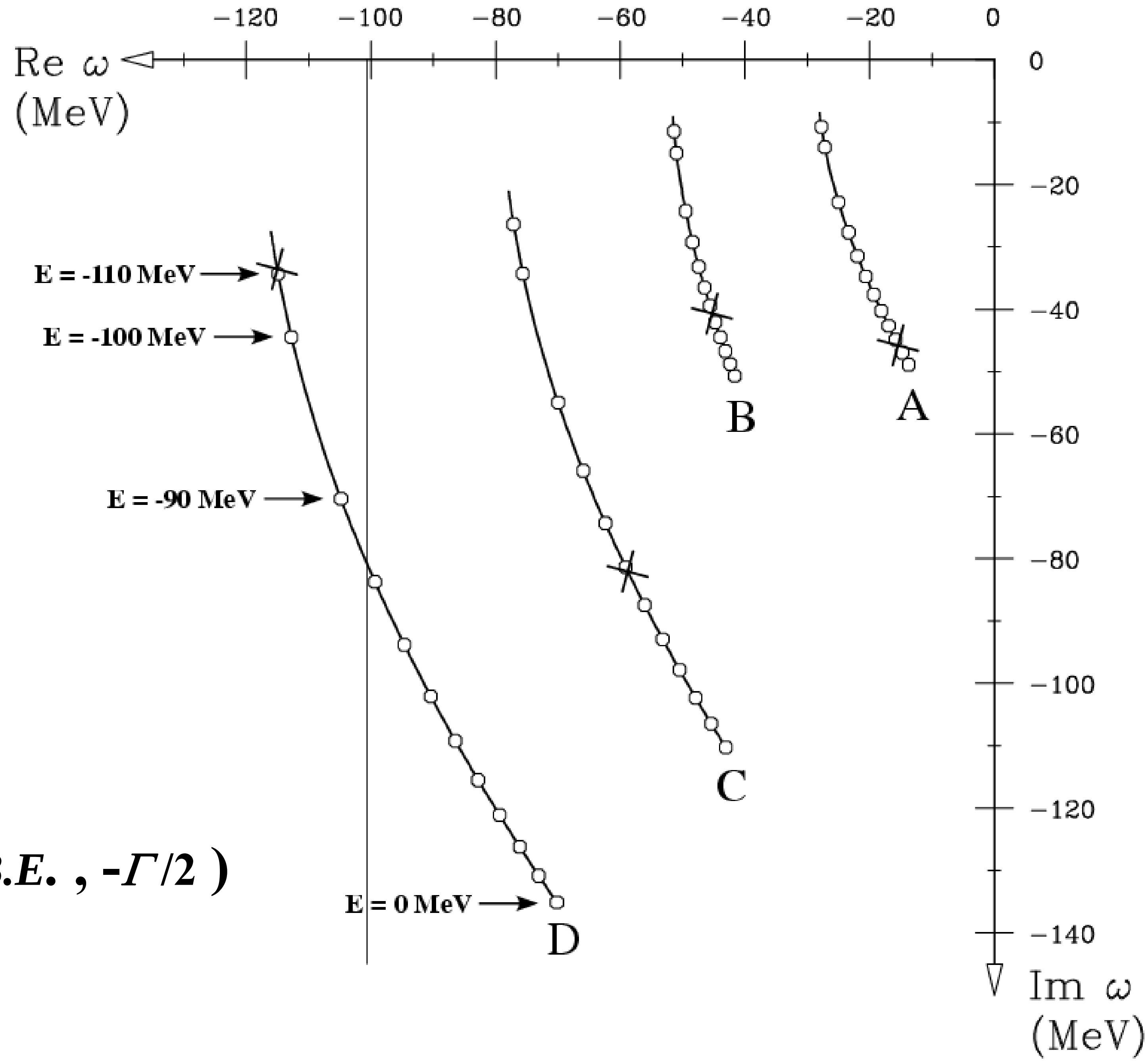
$$S_2^{\rm con}(E)\;\approx\;{\rm const.}\times\frac{f_2(E)}{D^2(E)}\;\approx\;{\rm const.}\times\frac{1}{D^2(E)}$$

$$D(E)\;\equiv\;\sqrt{(E-{\rm Re}\,\omega(E))^2+({\rm Im}\,\omega(E))^2}$$

◆ Examples of the relation between $D(E)$ and $\omega(E)$



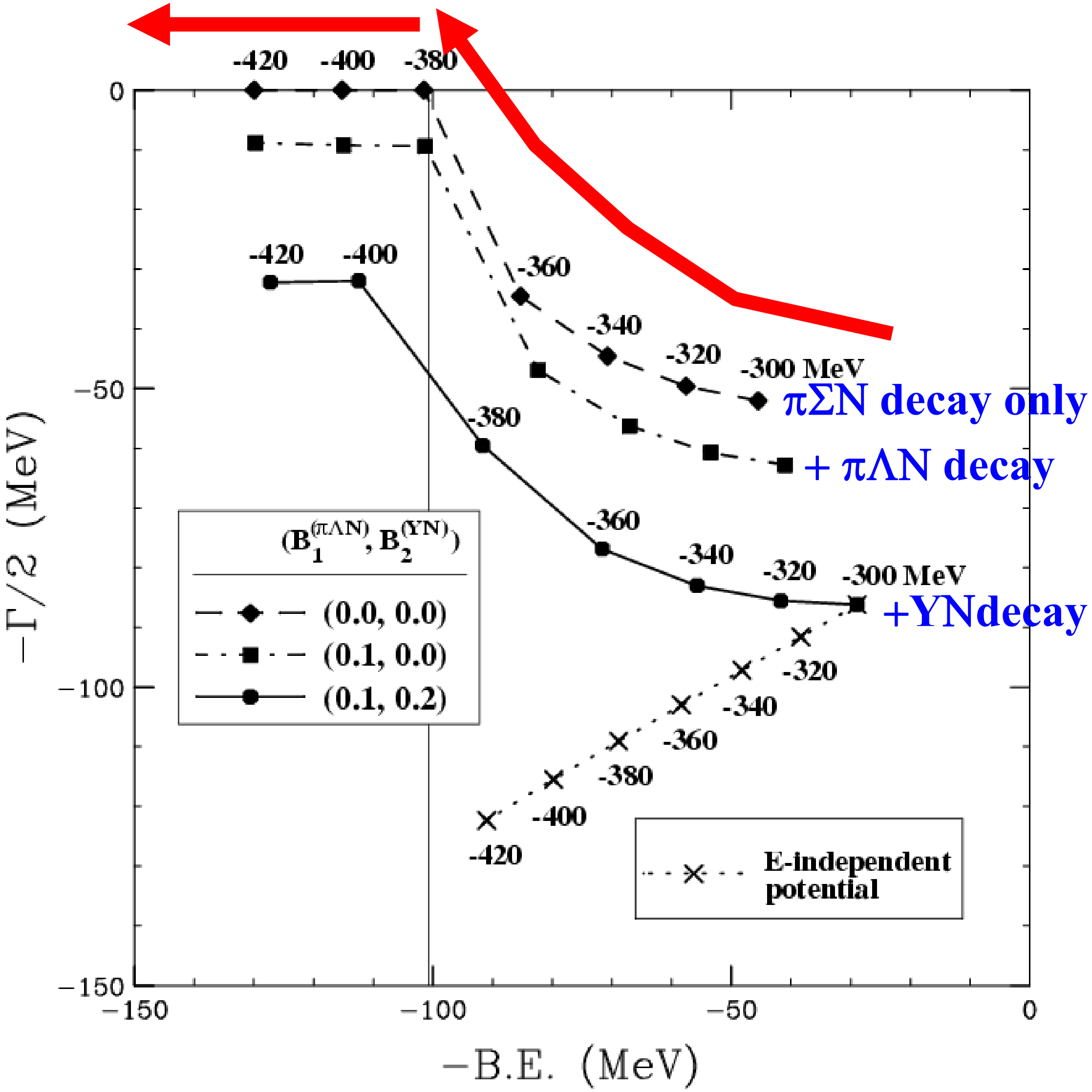
◆ Pole trajectory $\omega(E)$ in complex E-plane



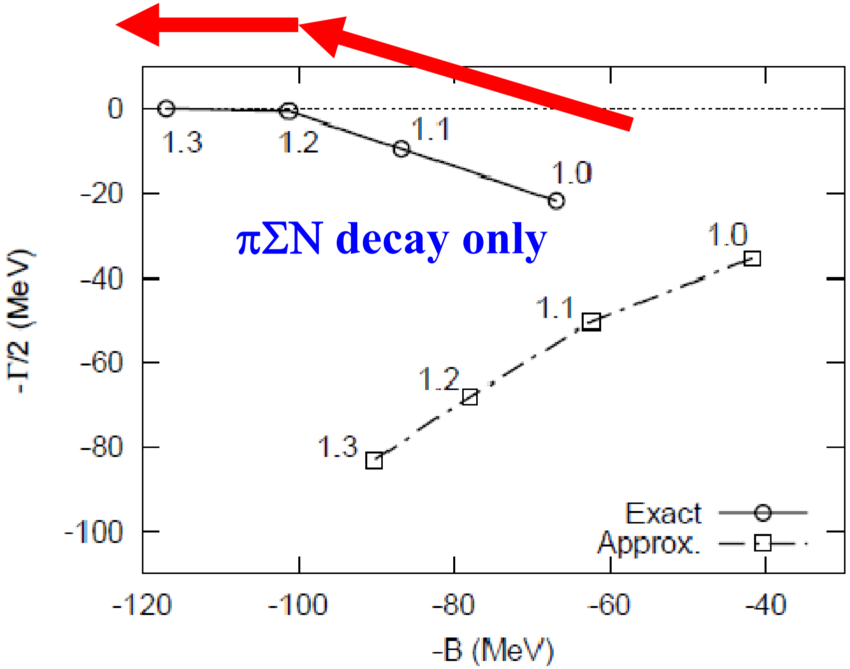
× = (-*B.E.* , -*Γ*/2)

◆ Validity of *E*-dependence of our optical potential

V_0 is made deeper in our optical potential model.



$K^{bar}N$ attraction is artificially enhanced in Faddeev calculation.



Ikeda&Sato, Phys. Rev. C79 (2009) 035201.

◆ Summary

- **Within the $K^{bar}NN$ single channel picture, the spectrum shape can be understood by relating to the trajectory of the moving pole in the complex *E*-plane, rather than the static values of *B.E.* and Γ.**

- **The *E*-dependence of the optical potential determines the trajectory of the moving pole.**

- **The *E*-dependence of our phenomenological potential is qualitatively agree with that in the $K^{bar}N\,N - \pi\,\Sigma\,N$ Faddeev calculation.**