Formation spectra of charmed meson-nucleus systems via pbarp reaction

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J. Yamagata-Sekihara, C. Garcia-Recio, J. Nieves,
L.L. Salcedo, L. Tolos, Phys. Lett. B754 (2016)26

Contents

Introduction

- **Meson-Nucleus systems**

  - Mesic atom : Coulomb Interaction

  - Mesic nucleus : Strong Interaction

Introduction

- **Meson-Nucleus systems**
  - Mesic atom : Coulomb Interaction
  - Mesic nucleus : Strong Interaction

π^-

- Most famous system
- Pion bounds on atomic orbit
- < qbar q > in nuclear medium
- Many works

η, η'

- $U_A(1)$ anomaly
- N*(1535) state

$D, \bar{D}$

- Charm quark
- High energy beam

$\bar{K}$

- Lightest meson with s quark
- Atomic states / Nuclear states
- Λ(1405) state
- Still controversial

ϕ

- Decay into K Kbar
- 3 % mass reduction ?

Introduction

- **Theoretical Works**

- Tsushima, Lu, Thomas, Saito, Landau, PRC59(99)2824
  Quark-meson coupling model, Dbar in ^{208}Pb.
- Yasui, Sudoh, PRD80(09)034008
- Yamaguchi, Yasui, Hosaka, NPA927(14)110
  Heavy Quark Symmetry. One pion exchange interaction.
  DbarN bound state, DbarNN bound state
- Garcia-Recio, Nieves, Tolos, PLB690(10)369
  D^0 in ^{12}C up to ^{208}Pb, D^+ in ^{12}C
- Garcia-Recio, Nieves, Salcedo, Tolos, PRC85(12)025203
  D^- in ^{12}C up to ^{208}Pb
- Ikeno, Nagahiro, Hirenzaki, JPS Meeting 2010
  Formation spectrum of D^0 in ^{12}C by Effective number approach
- Nagahiro at KEK workshop, Formation spectrum of D^- in ^{12}C

etc …

- **Experiments**

- New Facility FAIR @ GSI
  High intensity pbar beam up to 15 GeV/c.
- J-PARC

Introduction

- **In this work**

  - The possibility of the observation by the pbar beam at 8GeV/c

D ($c\bar{q}$) D^0 bound states by $^{12}\mathrm{C}(\bar{p}, \bar{D}^0)$ reaction

$\bar{D}$ ($\bar{c}q$) D^- bound states by $^{12}\mathrm{C}(\bar{p}, D^+)$ reaction

  - The structure of the formation spectrum

" Whether we can observe
the peak structure corresponding to the D^0(D^-)bound states"

  - Energy dependent optical potential
with the Green's function method

- Meson-nucleus Interaction

$\bar{D}$ ($\bar{c}$q)

D (c$\bar{q}$)

- Unitarized coupled-channel theory

-- Free space

Tolos, Garcia-Recio, J. Nieves, PRC80(09)065202
Garcia-Recio, Nieves, Salcedo, Tolos, PRC85(12)05203.

$$T^{\rho,IJ}(P) = \frac{1}{1 - V^{IJ}(\sqrt{s})\, G^{\rho,IJ}(P)} V^{IJ}(\sqrt{s}),$$

$$V_{ab}^{IJSC}(\sqrt{s}) = D_{ab}^{IJSC} \frac{2\sqrt{s} - M_a - M_b}{4 f_a f_b} \times \sqrt{\frac{E_a + M_a}{2M_a}} \sqrt{\frac{E_b + M_b}{2M_b}},$$

The effective interaction in free space is obtained by solving the on-shell Bethe-Salpeter equation in the coupled-channel space.

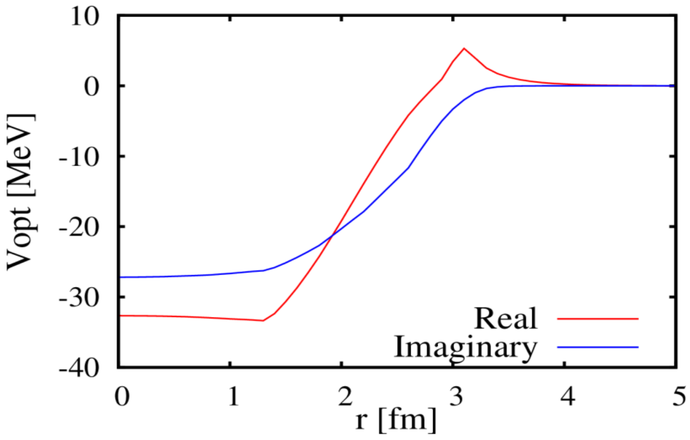
-- Medium effect (e.g. for D meson case)

$$\Pi_D(q^0, \vec{q}) = \int \frac{d^3p}{(2\pi)^3} n(\vec{p}) [T^{\rho(I=0,J=1/2)}_{DN}(P^0, \vec{P}) + 3T^{\rho(I=1,J=1/2)}_{DN}(P^0, \vec{P})],$$

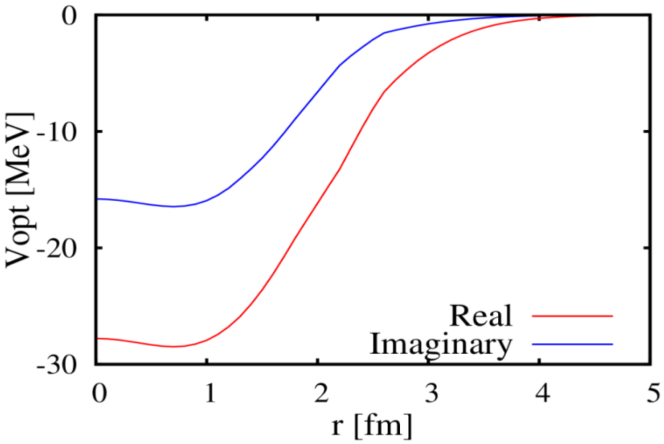
- Optical potential for ^{11}B at threshold energy

$$V_{\mathrm{opt}}(r, E) = \frac{1}{2\mu}\Pi_{D/\bar{D}}(r, E)$$

$\bar{D}$ ($\bar{c}$q)



D (c$\bar{q}$)



- Klein-Gordon equation

$$[-\nabla^2 + \mu^2 + 2\mu V_{\mathrm{opt}}(r, E)]\phi(r) = (E - V_{\mathrm{coul}}(r))^2\phi(r)$$

- Klein-Gordon equation

$$[-\nabla^2 + \mu^2 + 2\mu V_{\rm opt}(r, E)]\phi(r) = (E - V_{\rm coul}(r))^2\phi(r)$$

- Bound state for ^{11}B

Nuclear Sate : BE (Width) [MeV]

D^-	D^0
1s : 21.662 (0.458) 2p: 14.451(2.359)	1s : 6.525(10.78)

How can we observe these states ?

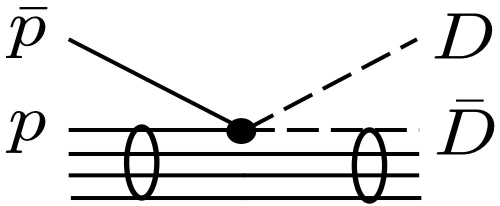
- Formation Reaction

  - Elementary reaction : $\bar{p}p \rightarrow \bar{D}D$

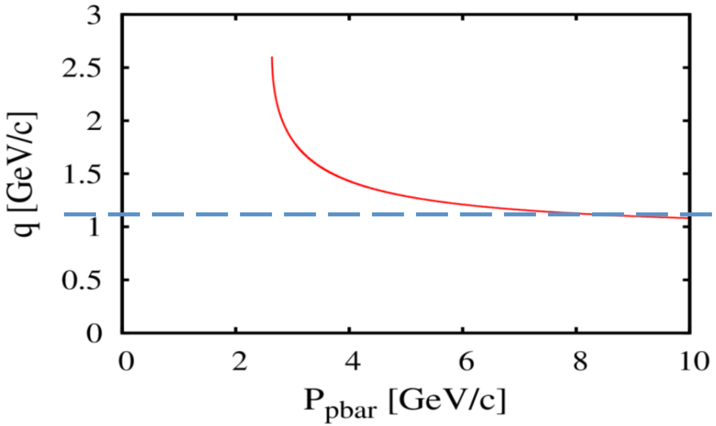
  - Target nucleus : ^{12}C

We choose the incident pbar beam as 8 GeV/c. This energy will be achieved in PANDA experiments at the future FAIR facility, and the future J-PARC facility.

D⁻ case



$$q \sim 1 \quad [\mathrm{GeV/c}]$$



- Formation Spectrum (${}^{12}\mathrm{C}(\bar{p}, D^+)$, ${}^{12}\mathrm{C}(\bar{p}, \bar{D}^0)$)

  - Green's function method :

$$\frac{d^2\sigma}{dEd\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\bar{p}p\to D\bar{D}} \sum_{\alpha} -\frac{1}{\pi}\mathrm{Im}\int d\vec{r}d\vec{r}' f^*_\alpha(\vec{r}\,')G(E;\vec{r}\,',\vec{r})\, f_\alpha(\vec{r})$$

Elementary Cross section (Theory)

J. Haidenbauer and G. Krein, PRC89(2014)114003

$$\left(\frac{d\sigma}{d\Omega}\right)^{\mathrm{Lab}}_{p\bar{p}\to D^0\bar{D}^0} = 37\ [nb/sr] \qquad \left(\frac{d\sigma}{d\Omega}\right)^{\mathrm{Lab}}_{p\bar{p}\to D^-D^+} = 756\ [nb/sr]$$

Distortion Factor F(r) (Theory)

$$f_\alpha(\vec{r}) = \exp(i\vec{q}\cdot\vec{r})F(\vec{r}) < \alpha|\psi_p(\vec{r})|i >$$

$$F(\vec{r}) = \exp\left(-\frac{1}{2}\bar{\sigma}\int \bar{\rho}(z',b)dz'\right)$$

$$\bar{\sigma} = \frac{\sigma_{\bar{p}N} + \sigma_{\bar{D}^0N}}{2}$$

Theory : $\sigma_{\bar{D}^0N} = 10\ \mathrm{mb}$

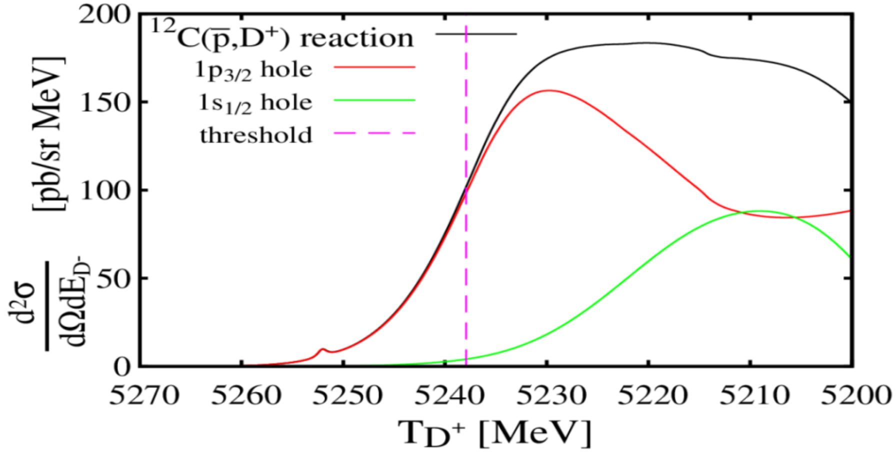
J. Haidenbauer et al., EPJA37(2008)55

- Formation Spectra

D^-

$^{12}C(\bar{p}, D^+)$

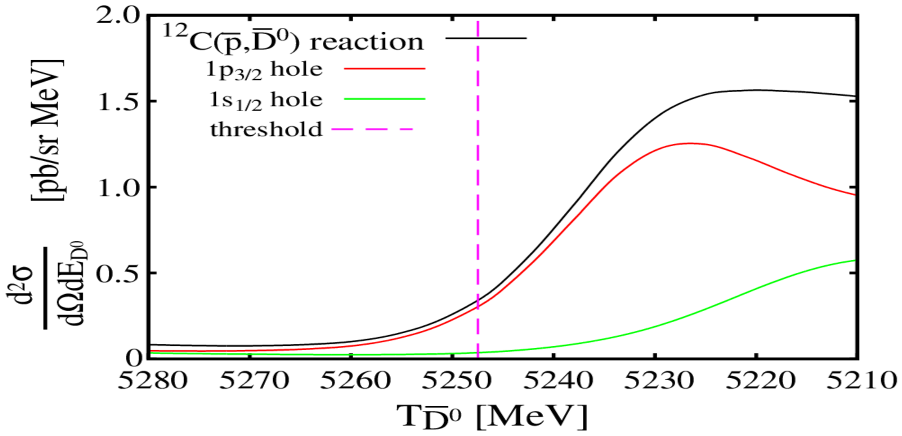
Nuclear Sate :
1s : 21.662 (0.458)
2p: 14.451(2.359)



D^0

$^{12}C(\bar{p}, \bar{D}^0)$

Nuclear Sate :
1s : 6.525(10.78)



- Formation Spectra

D^-

$^{12}\mathrm{C}(\bar{p}, D^+)$

Nuclear Sate :
1s : 21.662 (0.458)
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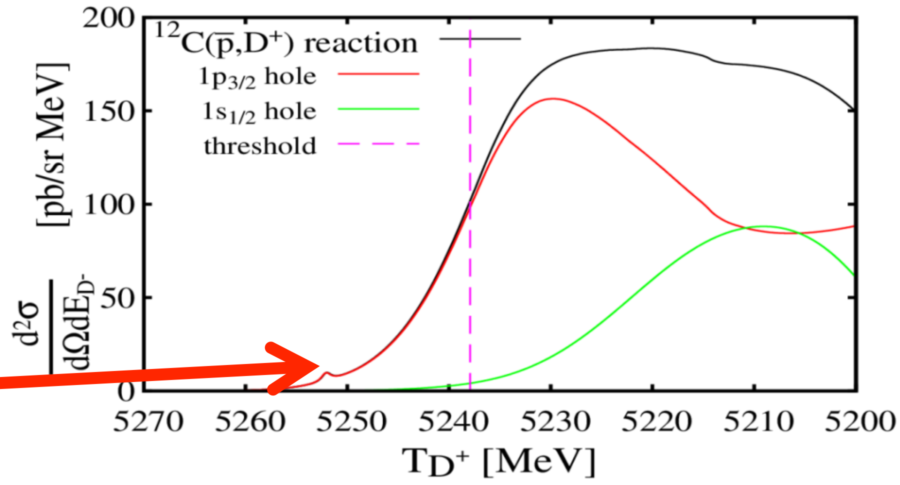

D^0

$^{12}\mathrm{C}(\bar{p}, \bar{D}^0)$

Nuclear Sate :
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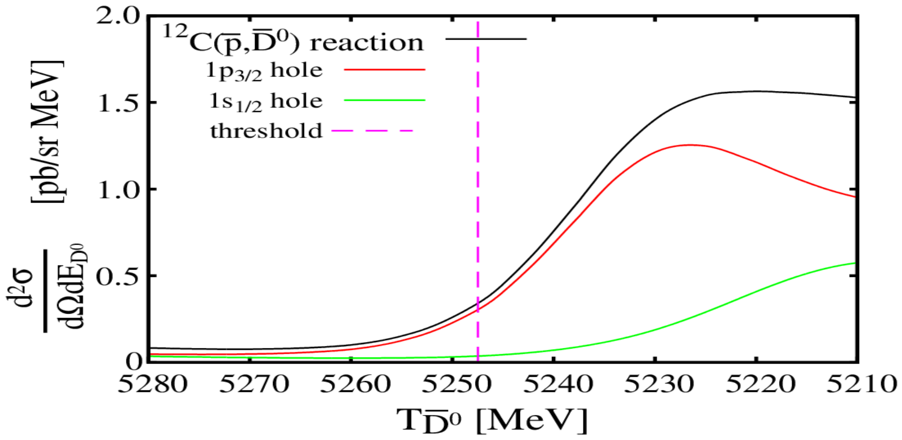


Summary

- The formation spectra of $D/\bar{D}$ mesic nuclear states by the (pbar, $D/\bar{D}$) reaction at $P_{\bar{p}}$ = 8 GeV/c.
- For $\bar{D}$ meson : 2p bound state as small peak.
- For D meson : No clear peak
- The momentum transfer is large.

Future Work

- We consider different production reaction with small momentum transfer.

Back-up Slide

• Meson-nucleus Interaction

Tolos, Garcia-Recio, J. Nieves, PRC80(09)065202
Garcia-Recio, Nieves, Salcedo, Tolos, PRC85(12)05203.

$\bar{D}$ ($\bar{c}$q)

I=0	J=1/2	$\bar{D}N, \bar{D}^*N$
I=1	J=1/2	$\bar{D}N, \bar{D}^*N, \bar{D}^*\Delta$

D (c$\bar{q}$)

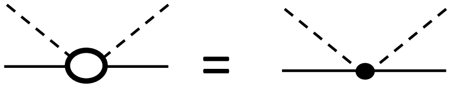
I=0	J=1/2	$\Sigma_c\pi,\ ND,\ \Lambda_c\eta,\ ND^*$ $\Xi_cK,\ \Lambda_c\omega,\ \Xi'_cK,\ \Lambda D_s$ $\Lambda D_s^*,\ \Sigma_c\rho,\ \Lambda_c\eta',\ \Sigma_c^*\rho$ $\Lambda_c\phi,\ \Xi_cK^*,\ \Xi'_cK^*,\ \Xi'_cK^*$
I=1	J=1/2	$\Lambda_c\pi,\ \Sigma_c\pi,\ ND,\ ND^*, \Xi_cK,\ \Sigma_c\eta$ $\Lambda_c\rho,\ \Xi'_cK,\ \Sigma D_s,\ \Sigma_c\rho,\ \Sigma_c\omega$ $\Delta D^*,\ \Sigma_c^*\rho,\ \Sigma_c^*\omega,\ \Sigma D_s^*,\ \Xi_cK^*$ $\Xi'_cK^*,\ \Sigma_c\phi,\ \Sigma^*D_s^*,\ \Sigma_c^*\phi,\ \Xi_c^*K^*$

SU(8) spin-flavor symmetry

- Meson-nucleus Interaction

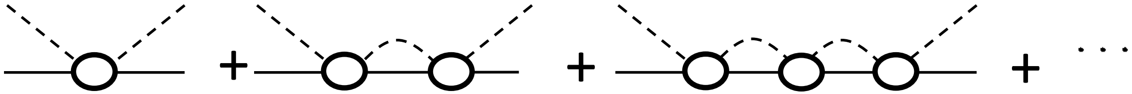
$\bar{D}$ ($\bar{c}$q) D (c$\bar{q}$)

-Winberg-Tomozawa Term



-Unitarized coupled-channel theory

$$T = V + VGT$$



-Medium effect

- Meson-nucleus Interaction

$\bar{D}$ ($\bar{c}$q) D (c$\bar{q}$)

- Unitarized coupled-channel theory

Tolos, Garcia-Recio, J. Nieves, PRC80(09)065202
Garcia-Recio, Nieves, Salcedo, Tolos, PRC85(12)05203.

-- Free

$$T^{\rho,IJ}(P) = \frac{1}{1 - V^{IJ}(\sqrt{s})\, G^{\rho,IJ}(P)}\, V^{IJ}(\sqrt{s}),$$

$$V^{IJSC}_{ab}(\sqrt{s}) = D^{IJSC}_{ab} \frac{2\sqrt{s} - M_a - M_b}{4 f_a f_b} \times \sqrt{\frac{E_a + M_a}{2M_a}} \sqrt{\frac{E_b + M_b}{2M_b}},$$

Pole position

X(2805) : I=0, J=1/2

Σc(2556): I=1, J=1/2
Λc(2595): I=0, J=1/2

- Meson-nucleus Interaction

$\bar{D}$ ($\bar{c}$q)

D (c$\bar{q}$)

- **Unitarized coupled-channel theory**

-- **Free space**

Tolos, Garcia-Recio, J. Nieves, PRC80(09)065202
Garcia-Recio, Nieves, Salcedo, Tolos, PRC85(12)05203.

$$T^{\rho,IJ}(P) = \frac{1}{1 - V^{IJ}(\sqrt{s})\, G^{\rho,IJ}(P)} V^{IJ}(\sqrt{s}),$$

$$V^{IJSC}_{ab}(\sqrt{s}) = D^{IJSC}_{ab} \frac{2\sqrt{s} - M_a - M_b}{4 f_a f_b} \times \sqrt{\frac{E_a + M_a}{2M_a}} \sqrt{\frac{E_b + M_b}{2M_b}},$$

The effective interaction in free space is obtained by solving the on-shell Bethe-Salpeter equation in the coupled-channel space.

-- **Medium effect** (e.g. for D meson case)

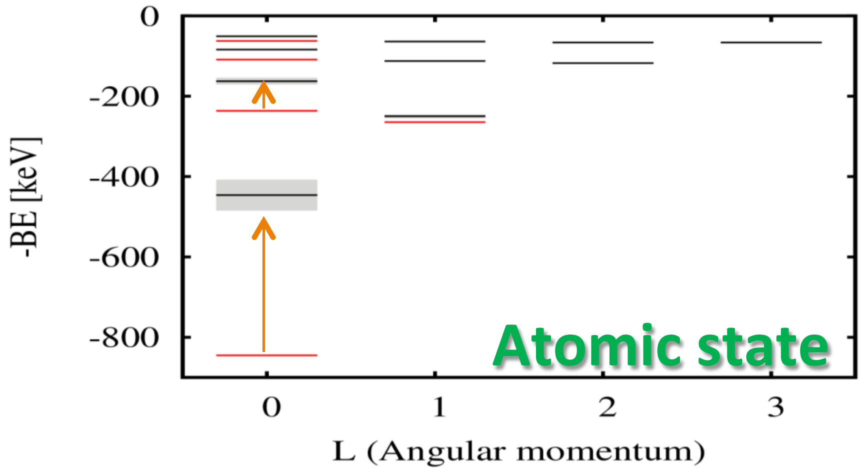
$$\Pi_D(q^0, \vec{q}) = \int \frac{d^3 p}{(2\pi)^3} n(\vec{p}) [T^{\rho(I=0,J=1/2)}_{DN}(P^0, \vec{P}) + 3T^{\rho(I=1,J=1/2)}_{DN}(P^0, \vec{P})],$$

- Klein-Gordon equation

$$[-\nabla^2 + \mu^2 + 2\mu V_{\mathrm{opt}}(r, E)]\phi(r) = (E - V_{\mathrm{coul}}(r))^2\phi(r)$$

D^- D^0

- Bound state for ^{11}B



The Coulomb Int.
is not included.
Atomic state does not exist.

- Klein-Gordon equation

$$[-\nabla^2 + \mu^2 + 2\mu V_{\mathrm{opt}}(r, E)]\phi(r) = (E - V_{\mathrm{coul}}(r))^2\phi(r)$$

D^- D^0

- Bound state for ^{11}B

Nuclear Sate : BE (Width) [MeV]

D^-

1s : 21.662 (0.458)
2p: 14.451(2.359)

Deeply bound Dbar mesic nuclear states exist with narrow width !!

How can we observe these states ?

D^0

1s : 6.525(10.78)

Deeply bound D^0 mesic nuclear state exist !!

This result is consistent with Ikeno's calculation

- D^0- nucleus bound states

State	^{11}B (BE, $\Gamma/2$) [MeV]
1s	(6.6, 5.2)

From Ikeno's slide @ JPS Meeting 2010

• Formation Reaction

- Green's function method :

$$\frac{d^2\sigma}{dEd\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\bar{p}p\to D\bar{D}} \sum_{\alpha} -\frac{1}{\pi}\mathrm{Im}\int d\vec{r}d\vec{r}' f_{\alpha}^{*}(\vec{r}\,')G(E;\vec{r}\,',\vec{r})f_{\alpha}(\vec{r})$$

- # Formation Reaction

- Green's function method :

$$\frac{d^2\sigma}{dEd\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\bar{p}p\to D\bar{D}} \sum_{\alpha} -\frac{1}{\pi}\mathrm{Im}\int d\vec{r}d\vec{r}' f_{\alpha}^{*}(\vec{r}\,')G(E;\vec{r}\,',\vec{r})f_{\alpha}(\vec{r})$$

Elementary Cross section (Theory)

J. Haidenbauer and G. Krein, PRC89(2014)114003

$$\sigma_{p\bar{p}\to D^0\bar{D}^0} = 0.01\ [\mu b]$$

$$\sigma_{p\bar{p}\to D^-D^+} = 0.2\ [\mu b]$$

Assumption : a flat angular distribution in CM.

$$\left(\frac{d\sigma}{d\Omega}\right)^{\mathrm{CM}}_{p\bar{p}\to D^0\bar{D}^0} = 0.80\ [nb/sr]$$

$$\left(\frac{d\sigma}{d\Omega}\right)^{\mathrm{CM}}_{p\bar{p}\to D^-D^+} = 16\ [nb/sr]$$

$$\left(\frac{d\sigma}{d\Omega}\right)^{\mathrm{Lab}}_{p\bar{p}\to D^0\bar{D}^0} = 37\ [nb/sr]$$

$$\left(\frac{d\sigma}{d\Omega}\right)^{\mathrm{Lab}}_{p\bar{p}\to D^-D^+} = 756\ [nb/sr]$$

• Formation Reaction

- Green's function method :

$$\frac{d^2\sigma}{dEd\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\bar{p}p\to D\bar{D}} \sum_{\alpha} -\frac{1}{\pi}\mathrm{Im}\int d\vec{r}d\vec{r}' f^*_\alpha(\vec{r}\,')G(E;\vec{r}\,',\vec{r})f_\alpha(\vec{r})$$

Distortion Factor F(r) (Theory)

$$f_\alpha(\vec{r}) = \exp(i\vec{q}\cdot\vec{r})F(\vec{r}) < \alpha|\psi_p(\vec{r})|i >$$

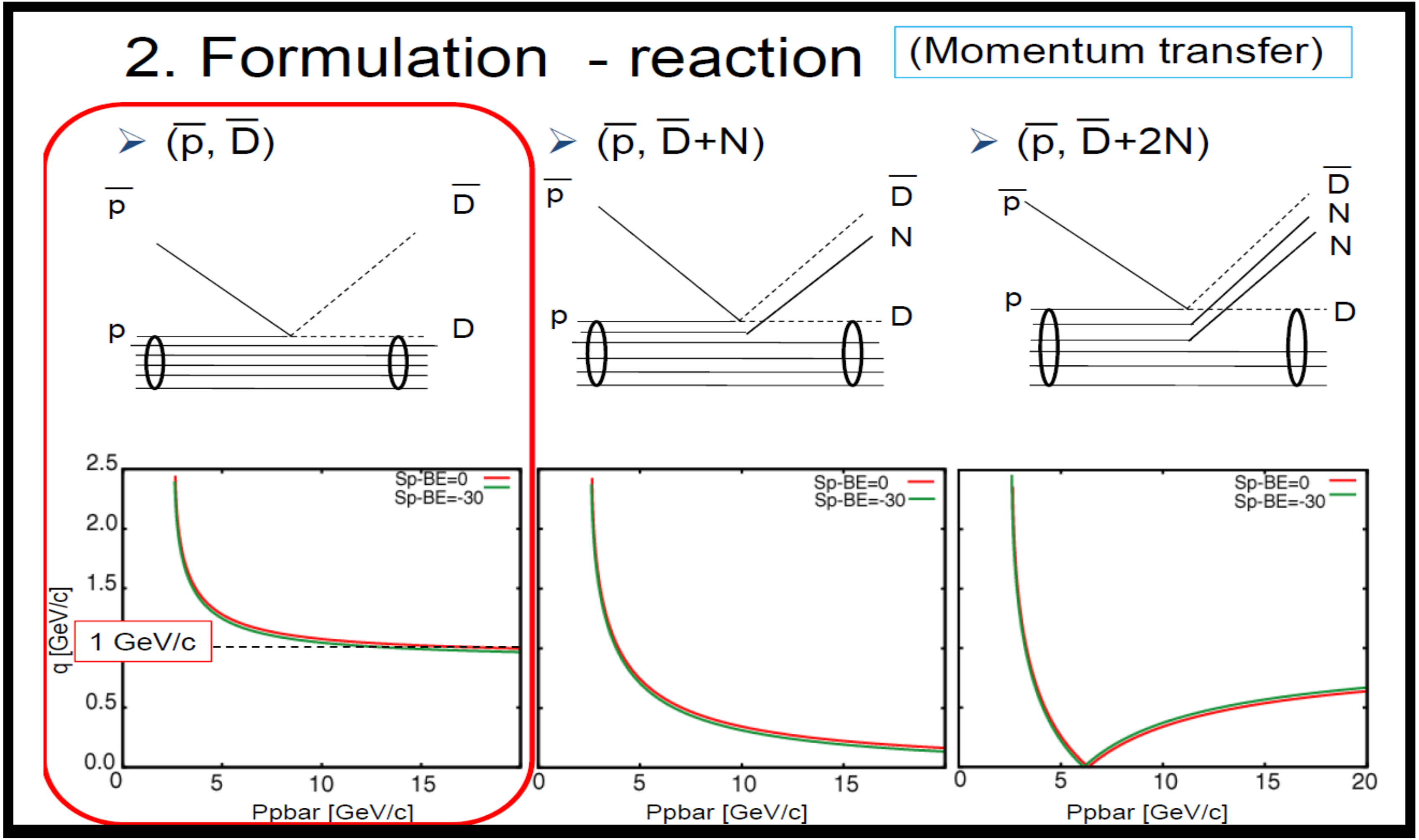
$$F(\vec{r}) = \exp\left(-\frac{1}{2}\bar{\sigma}\int\bar{\rho}(z',b)dz'\right)$$

$$\bar{\sigma} = \frac{\sigma_{\bar{p}N} + \sigma_{\bar{D}^0N}}{2}$$

Theory : $\sigma_{\bar{D}^0N} = 10\ \mathrm{mb}$

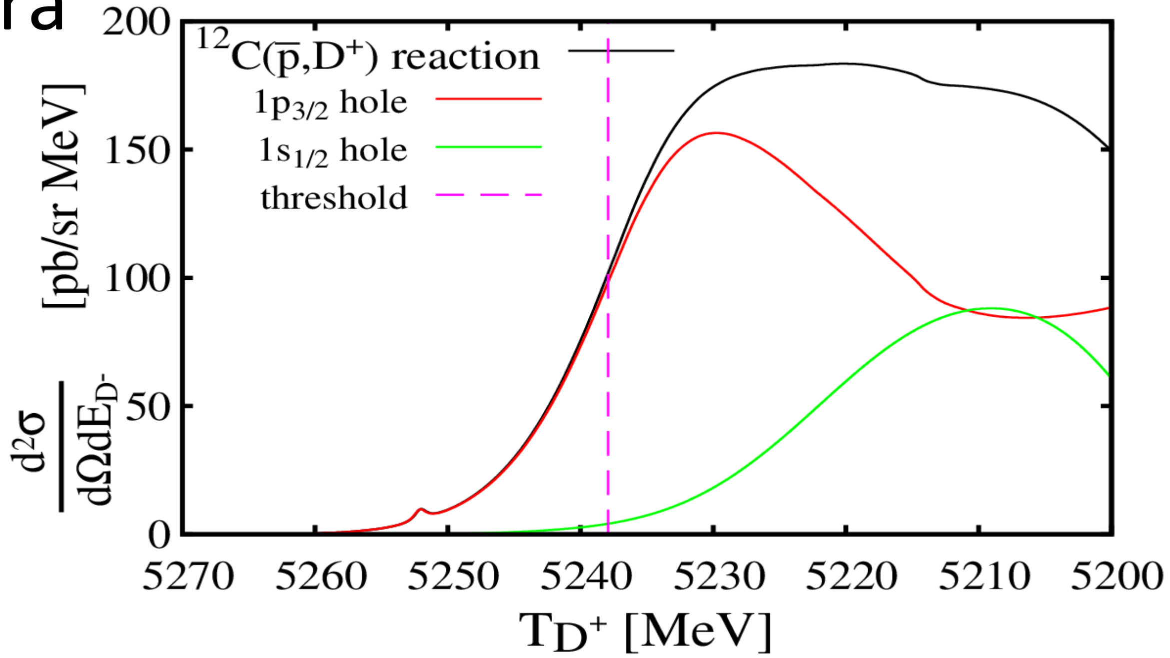
J. Haidenbauer et al., EPJA37(08)55

Ikeno’s slide @ JPS Meeting 2010



• Formation Spectra

D^-



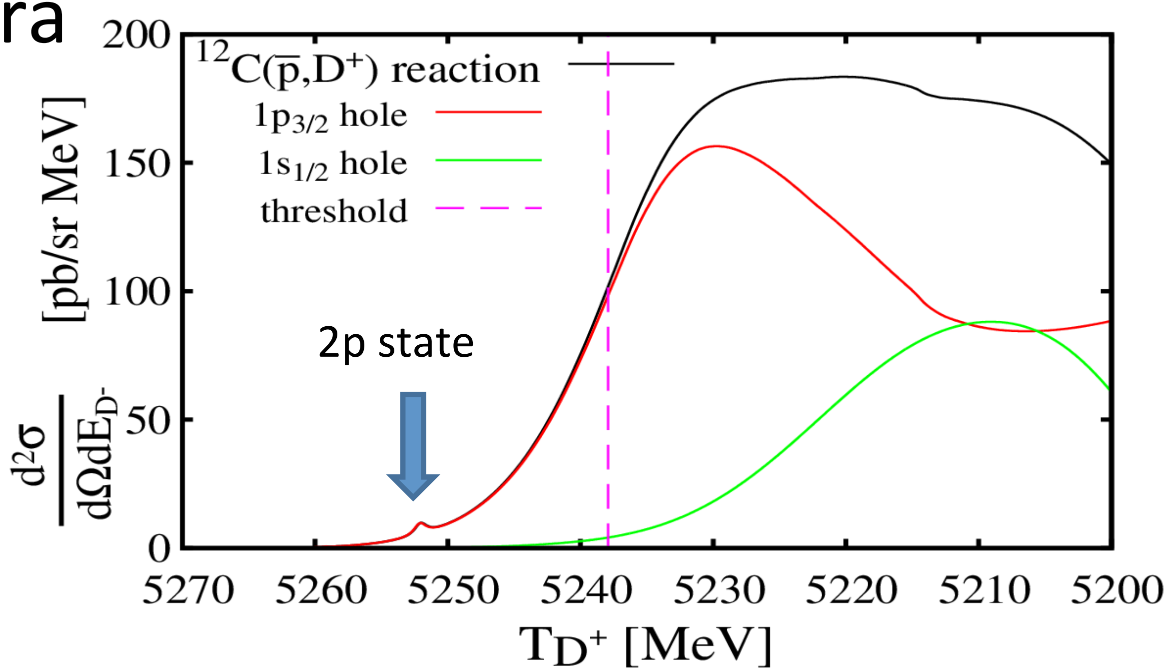
Nuclear Sate :

1s : 21.662 (0.458)

2p: 14.451(2.359)

- # Formation Spectra

D^-

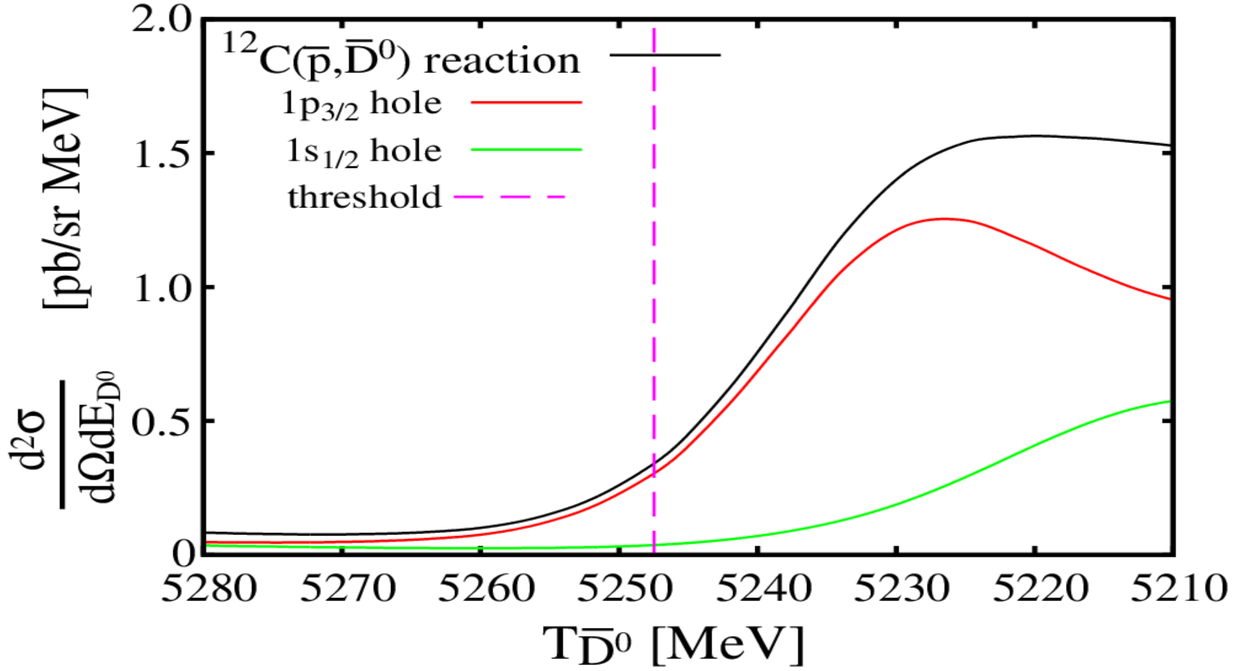


Nuclear Sate :
1s : 21.662 (0.458)
2p: 14.451(2.359)

The peak corresponding to the 2p state might appear, and very small.
One of the reason of that is the momentum transfer is very large.
In this calculation, we included Dbar state up to L=15.
➔ Different formation reaction with small q may get clearer peak structure.

- Formation Spectra

D^0



Nuclear Sate :
1s : 6.525(10.78)

The peak corresponding to the 1s state doesn't appear.
The momentum transfer is very large.

Dbar meson nucleus potential

Garcia-Recio, Nieves, Salcedo, Tolos, PRC85(12)05203.

I=0	**J=1/2**	$\bar{D}N, \bar{D}^{*}N$
I=1	**J=1/2**	$\bar{D}N, \bar{D}^{*}N, \bar{D}^{*}\Delta$

- SU(8) spin-flavor symmetry
- The optical potential is obtained by Tρ approximation.

Amplitude T has a pole X(2805) state : I=0, J=1/2

- Decay mode :

For atomic states, a bound Dbar meson may falls to lower level.

For nuclear states, the decay width comes from the existence of X(2805) state, which appears around threshold energy.

D meson nucleus potential

Tolos, Garcia-Recio, Nieves, PRC80(09)065202.

Garcia-Recio, Nieves, Tolos, PLB690(10)369

$I = 0,\ J = 1/2$

$\Sigma_c \pi$	$N D$	$\Lambda_c \eta$	$N D^*$	$\Xi_c K$	$\Lambda_c \omega$	$\Xi'_c K$	ΛD_s
2591.6	2806.15	2833.97	2947.54	2965.11	3069.11	3072.51	3084.18
ΛD_s^*	$\Sigma_c \rho$	$\Lambda_c \eta'$	$\Sigma_c^* \rho$	$\Lambda_c \phi$	$\Xi_c K^*$	$\Xi'_c K^*$	$\Xi_c^* K^*$
3227.98	3229.05	3244.24	3293.46	3305.92	3361.11	3468.51	3538.01

$I = 1,\ J = 1/2$

$\Lambda_c \pi$	$\Sigma_c \pi$	$N D$	$N D^*$	$\Xi_c K$	$\Sigma_c \eta$	$\Lambda_c \rho$	$\Xi'_c K$	ΣD_s	$\Sigma_c \rho$	$\Sigma_c \omega$
2424.5	2591.6	2806.15	2947.54	2965.12	3001.07	3061.95	3072.52	3161.64	3229.05	3236.21
ΔD^*	$\Sigma_c^* \rho$	$\Sigma_c^* \omega$	ΣD_s^*	$\Xi_c K^*$	$\Sigma_c \eta'$	$\Xi'_c K^*$	$\Sigma_c \phi$	$\Sigma^* D_s^*$	$\Sigma_c^* \phi$	$\Xi_c^* K^*$
3240.62	3293.46	3300.62	3305.45	3361.11	3411.34	3468.51	3473.01	3496.87	3537.42	3538.01

- SU(8) spin-flavor symmetry
- Optical potential is obtained by T ρ approximation.
- Amplitude T has a pole of Σc(2556) state (I=1, J=1/2) and Λc(2595) state (I=0, J=1/2).