Formation of kaon bound states by kaon beam

J. Yamagata (Nara Women's Univ.)
H. Nagahiro (RCNP, Osaka Univ.)
S. Hirenzaki (Nara Women's Univ.)

J. Yamagata, H. Nagahiro, Y. Okumura and S. Hirenzaki,
Prog. Theor. Phys. 114, 301 (2005)

J. Yamagata, H. Nagahiro and S. Hirenzaki, Phys. Rev. C 74, 014604 (2006)

Introduction

R. Seki, C. E. Wiegand Ann. Rev. Nucl. Part. Sci. 25(75)241.
C. J. Batty, E. Friedman and A. Gal, Phys. Rep. 287(97)385.
S. Hirenzaki et al., Phys. Rev. C61(00)055205.
many others…….

- Study of Kaonic Atoms … for long time
  - To know the kaon properties at finite density, K-A interaction
  - X-ray spectroscopy

    Deeply bound state were not observed

➢Deeply bound pionic atoms observed with (d,^{3}He) reactions
➢New facility J-PARC … coming soon!!

- We can expect kaonic bound states formation

  by using the (K^-,p) reactions
- Theoretical (K-,p) spectra

  ⟹ Important!! Before experiment.

Introduction

Kishimoto Group, Iwasaki, Suzuki Group, FINUDA Group
Akaishi, Yamazaki, Dote
Oset, Toki --- Recent activities on kaonic nuclei studies.

- Our Studies
  - Theoretical Comprehensive Spectra

→ We can also check the contributions
from Kaonic Nuclear states in the calculated spectra

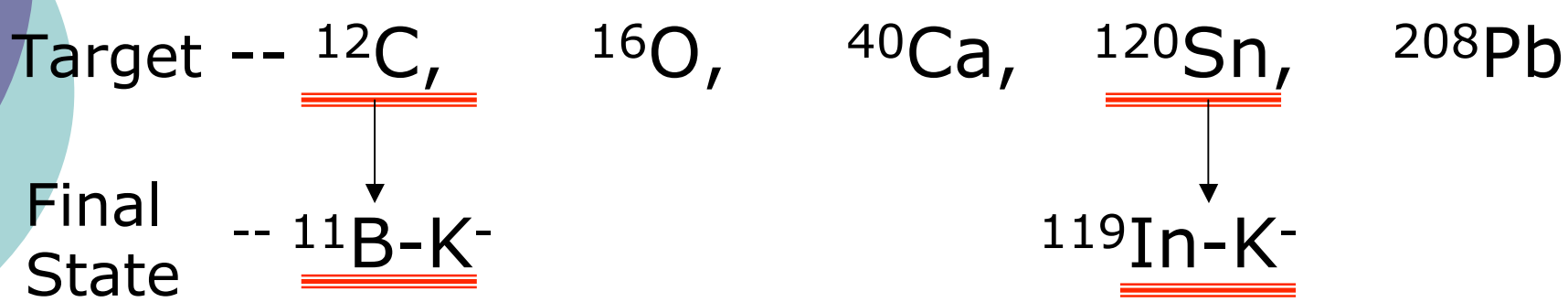
  - Kaonic Atoms and Kaonic Nuclei

- Structure of Kaon-Nucleus bound systems (Atom + Nucleus)
  - Energy-Dependent optical potentials
    Chiral Unitary Model, Phenomenological Model

- Theoretical formation spectra in (In-Flight K^-,p) reaction
(**RESONANCE DIP** was reported in PRC 74(06)014604
by J. Yamagata, H. Nagahiro, S. Hirenzaki)

Introduction

- Kaonic Atoms -- In-flight(K^-,p) reaction



- Spectrum
  - Kaon-Nucleus optical potential

    "Shallow"?

    "Deep"?

  - Contributions of Kaonic Nuclear state

    (Smooth background for atomic states)

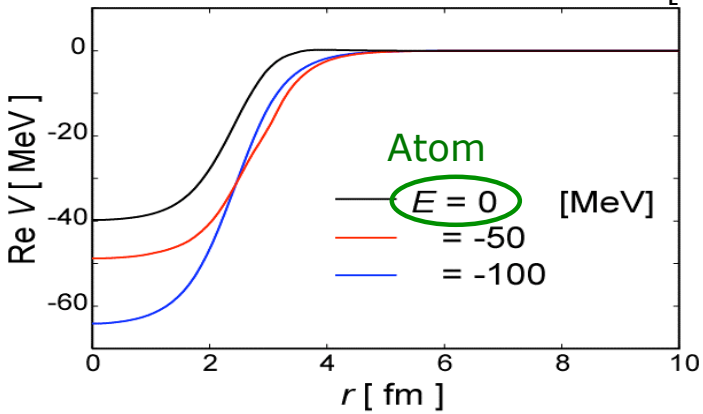
Formulation -- Structure

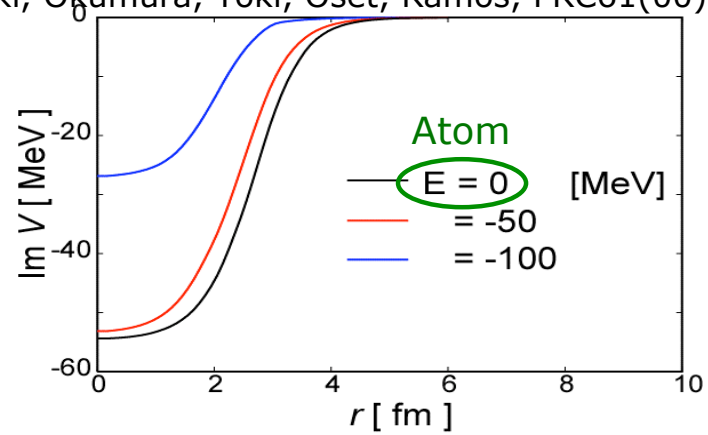
- Klein-Gordon equation

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

Chiral Unitary Model

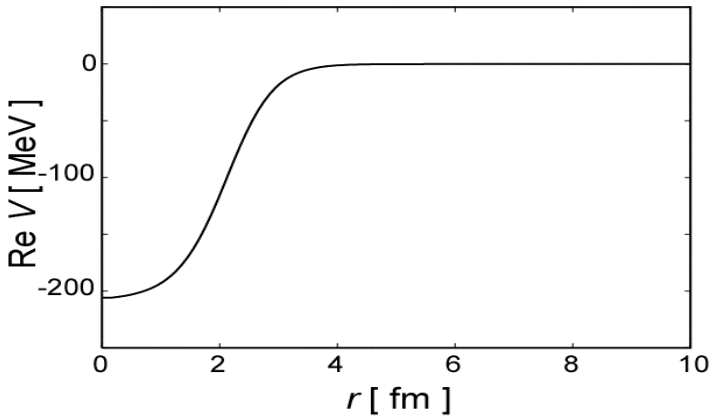
[A. Ramos, E. Oset, NPA671(00)481]
[Hirenzaki, Okumura, Toki, Oset, Ramos, PRC61(00)055205]

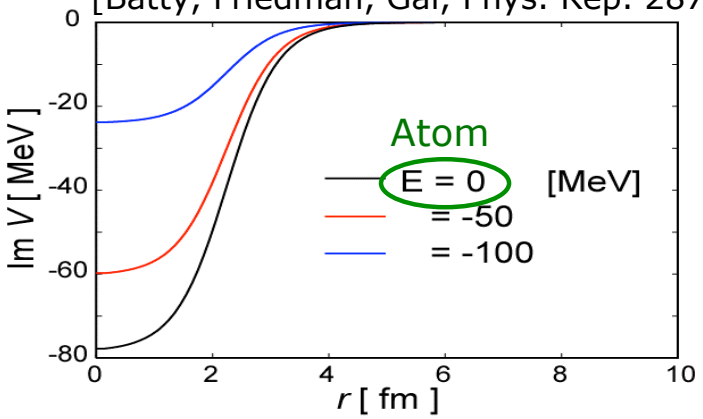




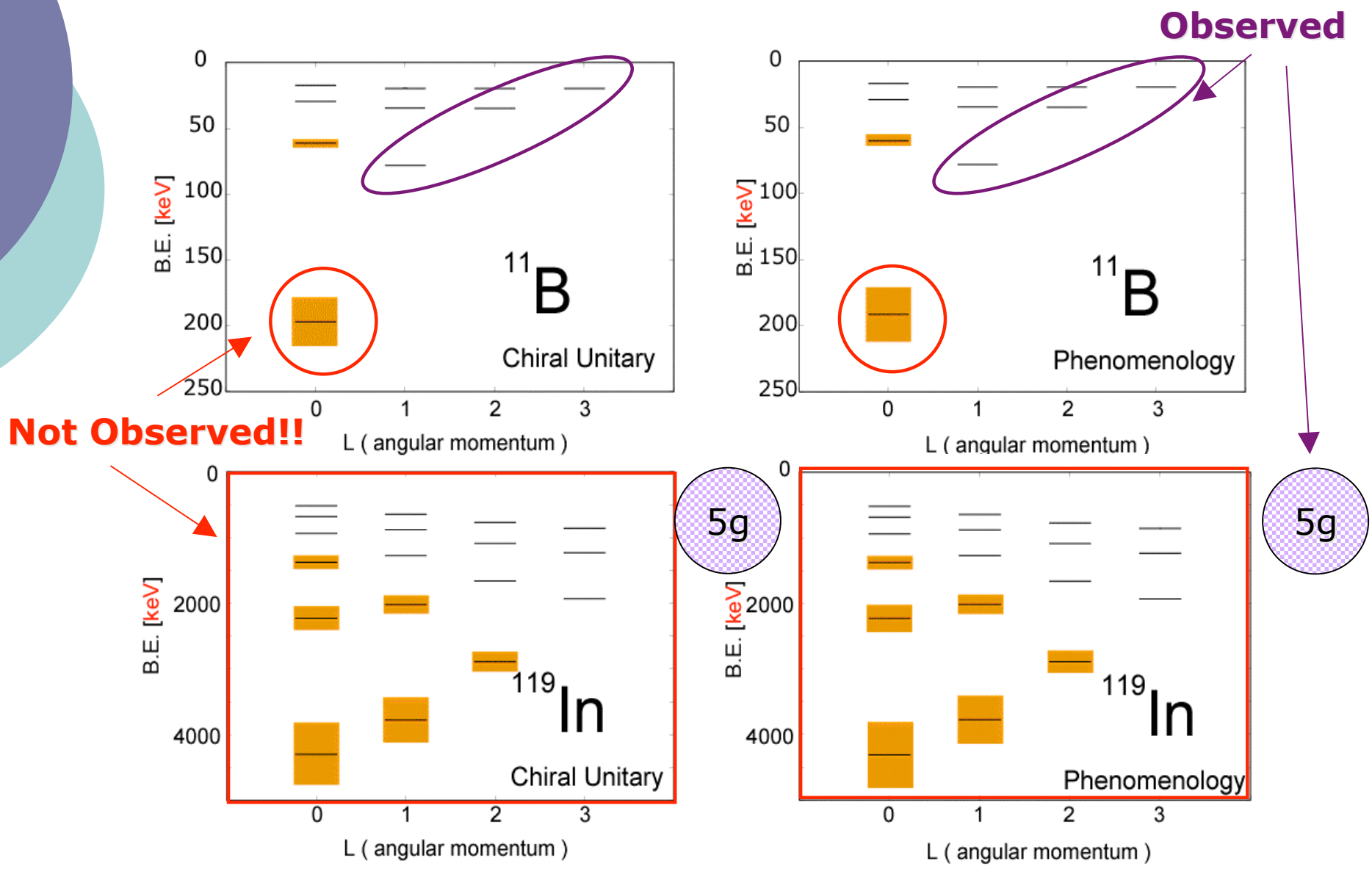
Phenomenological Model

[J. Mareš, E. Friedman, A. Gal, Phys. Lett. B606(2005)295]
[Batty, Friedman, Gal, Phys. Rep. 287(97)385]





Energy Level – Kaonic Atom –



Formulation -- Reaction In-Flight(K^-,p)

- Green Function Method

J. Yamagata et al., Phys. Rev. C 74 (06) 014604

O. Morimatsu, K. Yazaki NPA435(85)727, NPA483(88)493

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

- $\left(\frac{d\sigma}{d\Omega}\right)_{K^-p\to pK^-}$: Elementary cross section (Exp. data)
- $G(E;\vec{r}',\vec{r})$: Green function for K interacting with the nucleus

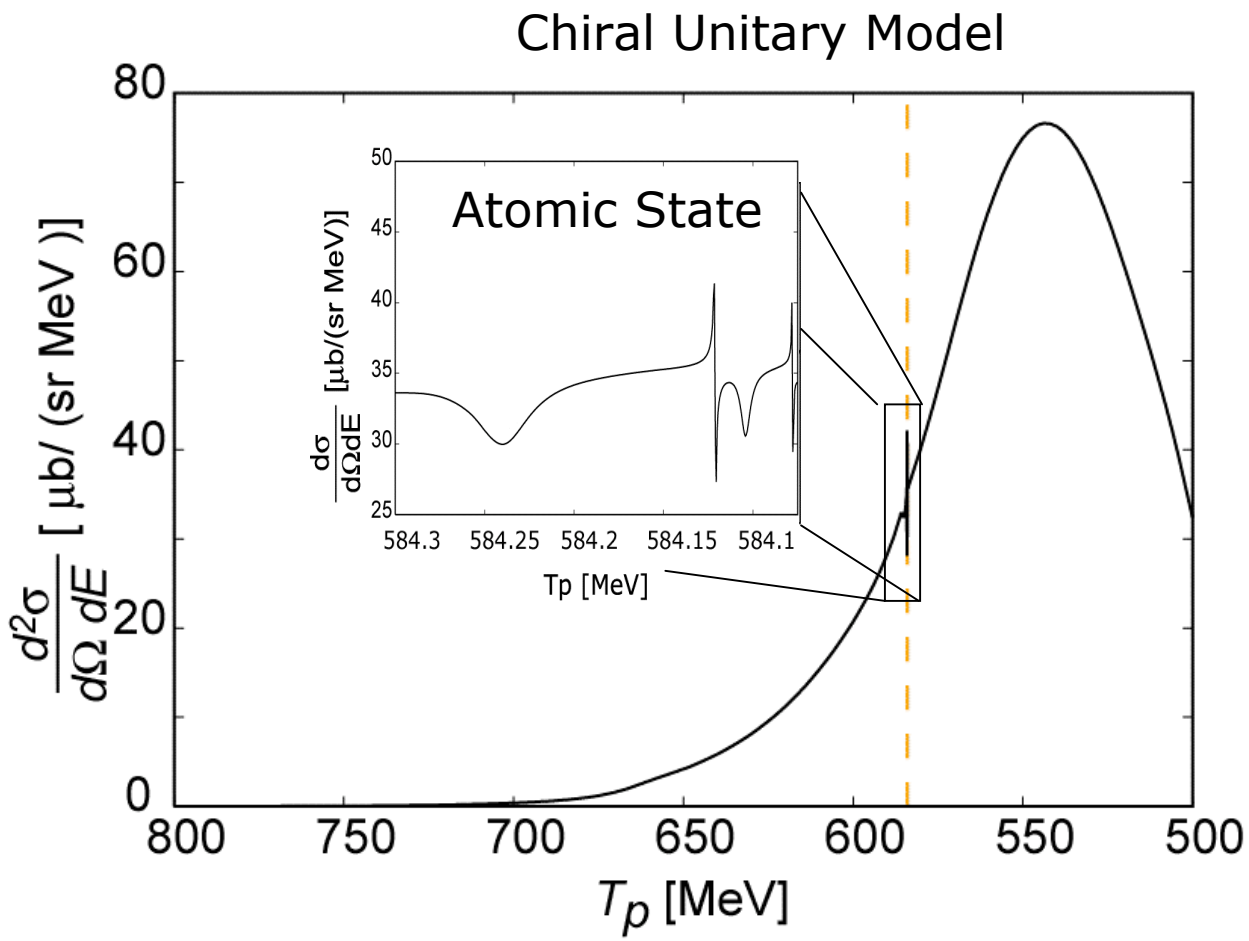
  $(H_{K^-} - E)G(E;\vec{r}',\vec{r}) = \delta^3(\vec{r}-\vec{r}')$
- $f_\alpha(\vec{r}) = \chi_p^*(\vec{r})\chi_K(\vec{r})\langle\alpha|\psi_p(\vec{r})|i\rangle$

- Excited states of daughter nuclei (→ deep proton hole states) ⇒ γ decay width (Not negligible!)

⇒ We only consider ground state of nuclei in final states.

Energy Spectrum

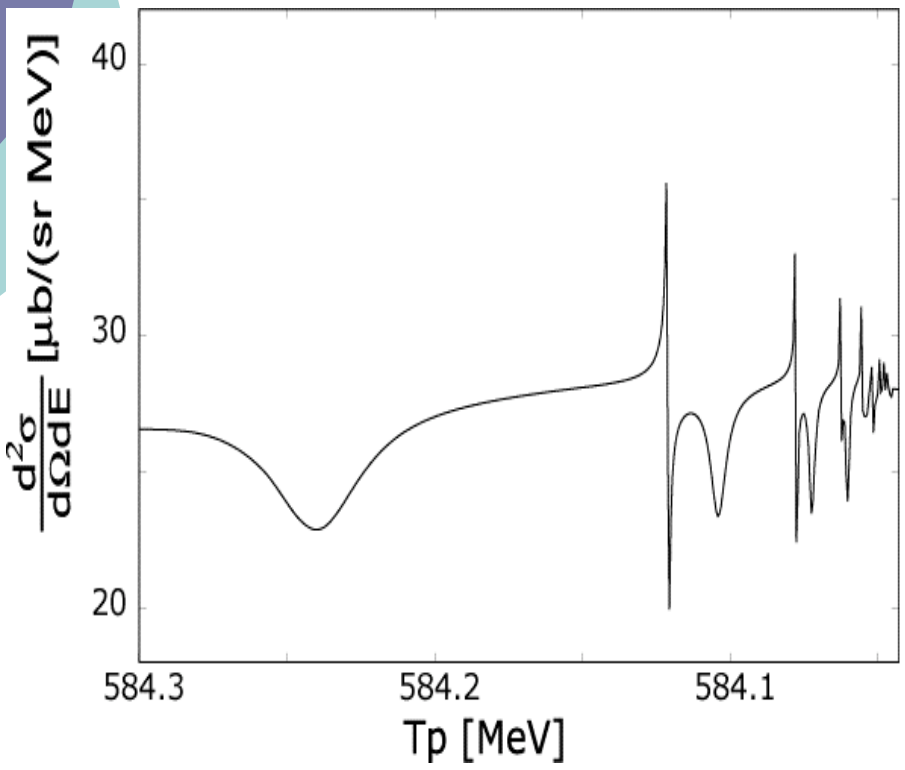
$^{12}\mathrm{C}(\text{In–flight } K^-, p) \quad P_{K^-} = 976 \text{ MeV/c} \;\; (T_{K^-} = 600 \text{ MeV})$



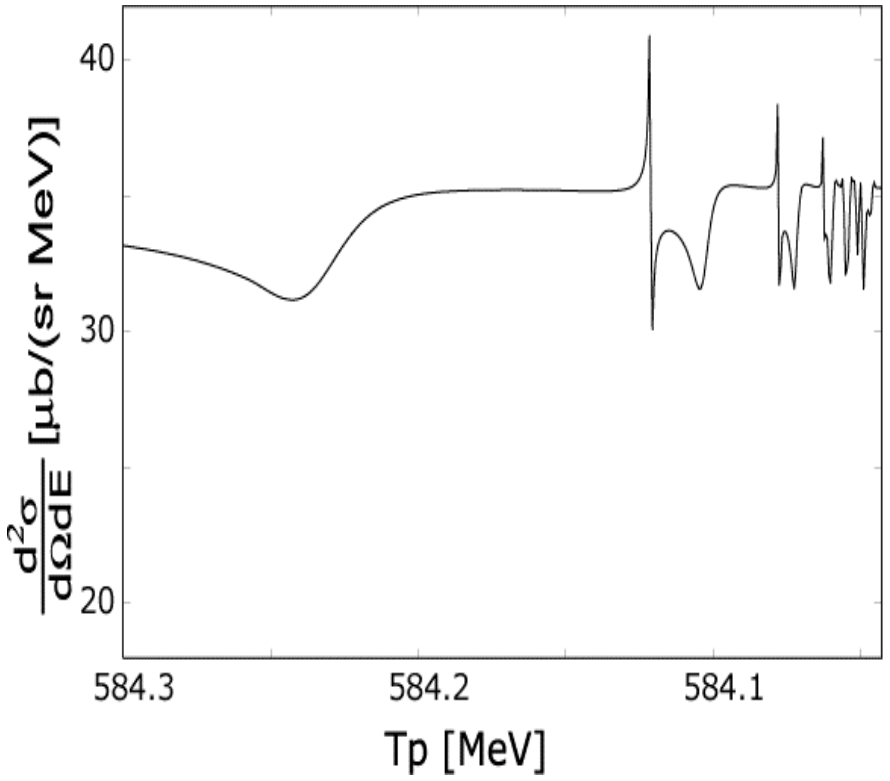
Energy Spectrum $^{12}C(K^-,p)$ T_K=600 MeV

- Proton hole state – $1p_{3/2}$

Chiral Unitary



Phenomenology



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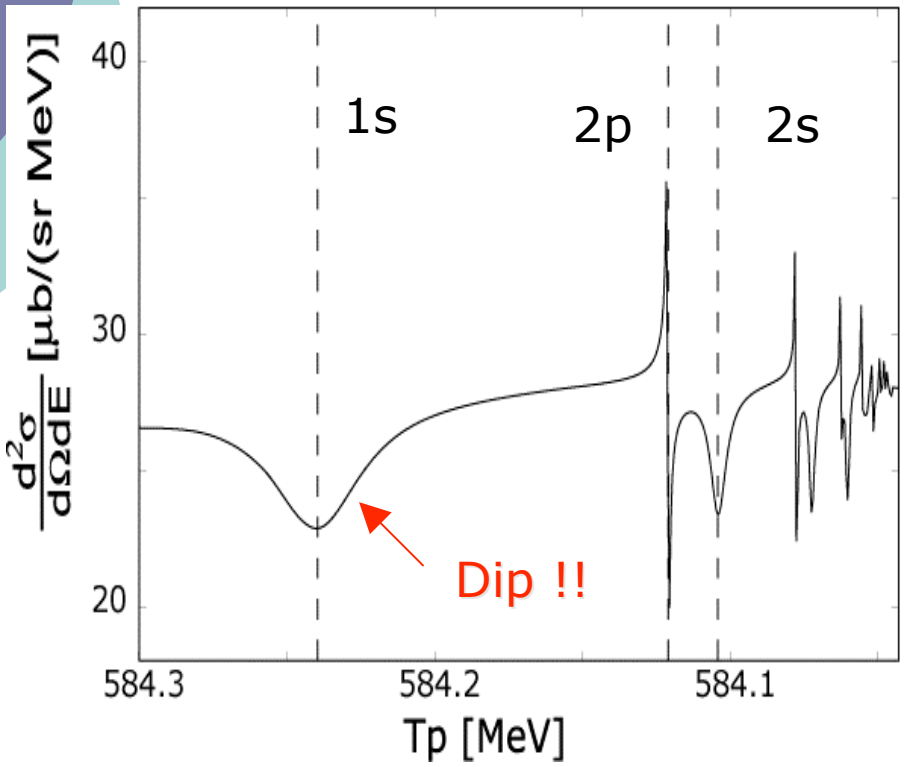
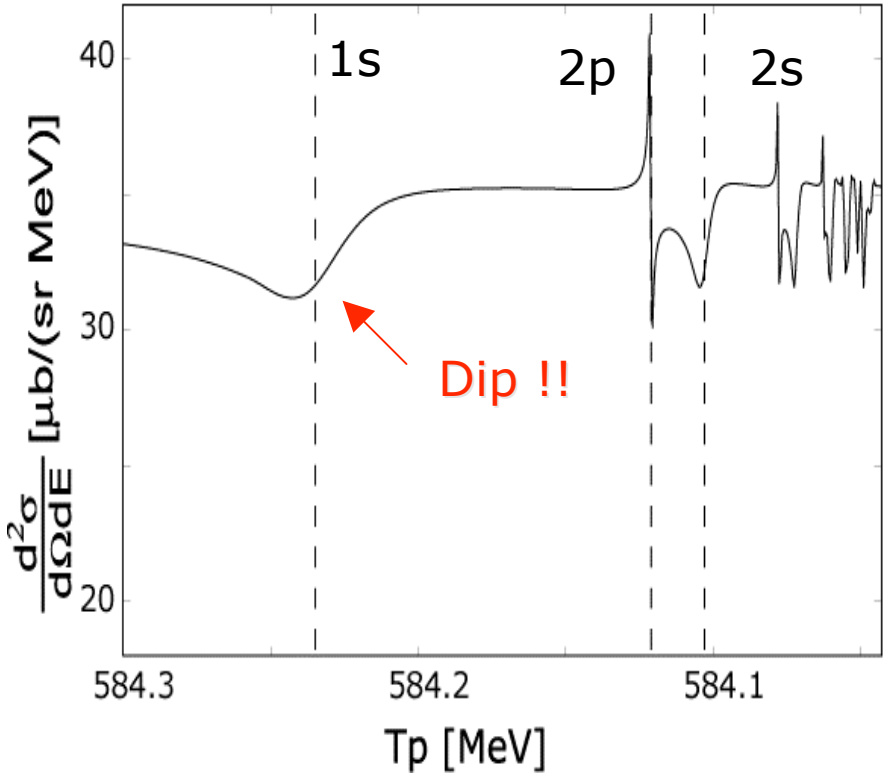


Phenomenology



These are very interesting structures !!

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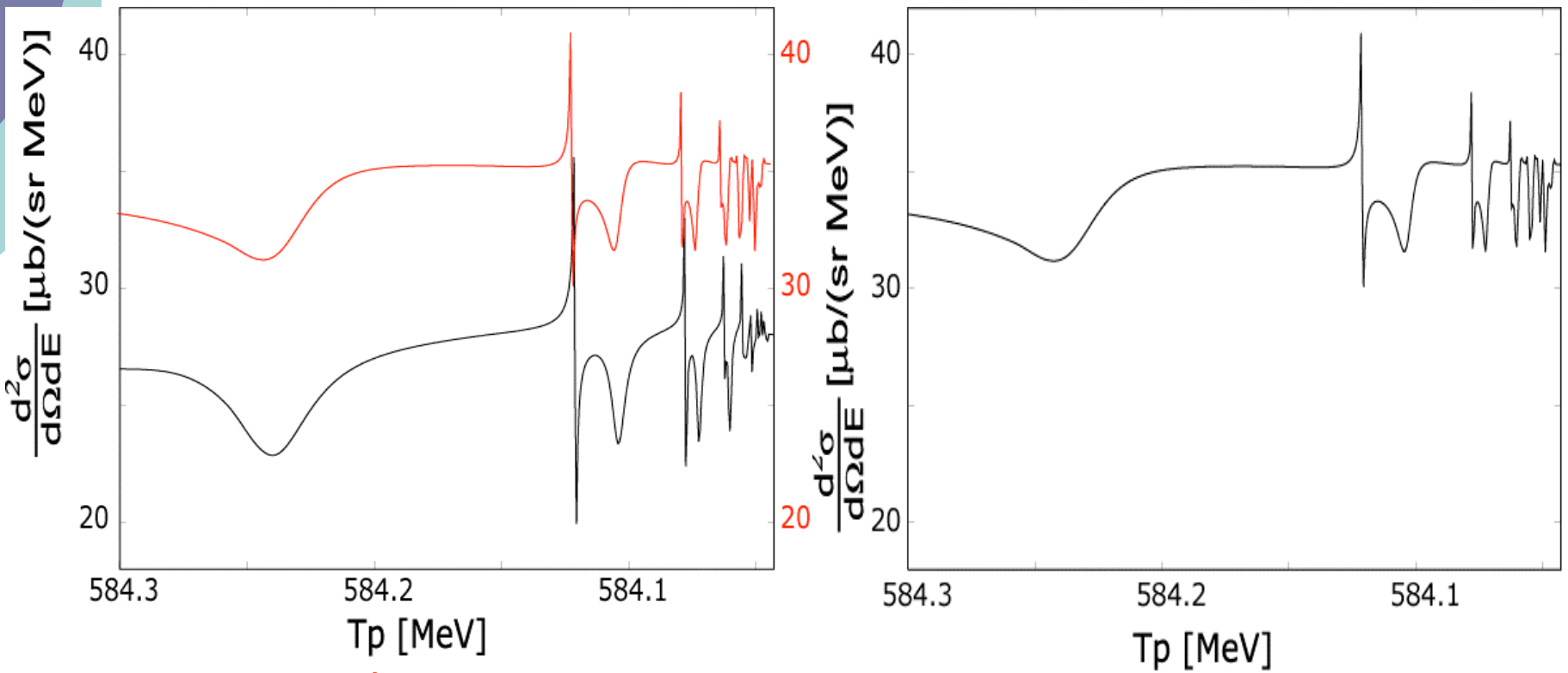
Phenomenology



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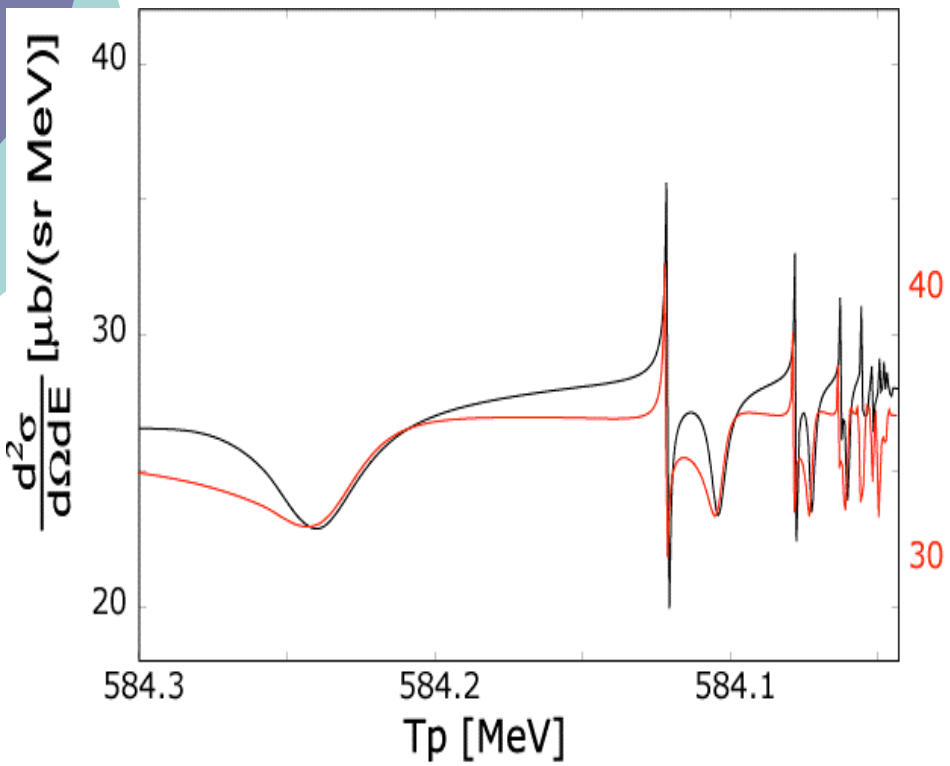


Chiral Unitary

Phenomenology

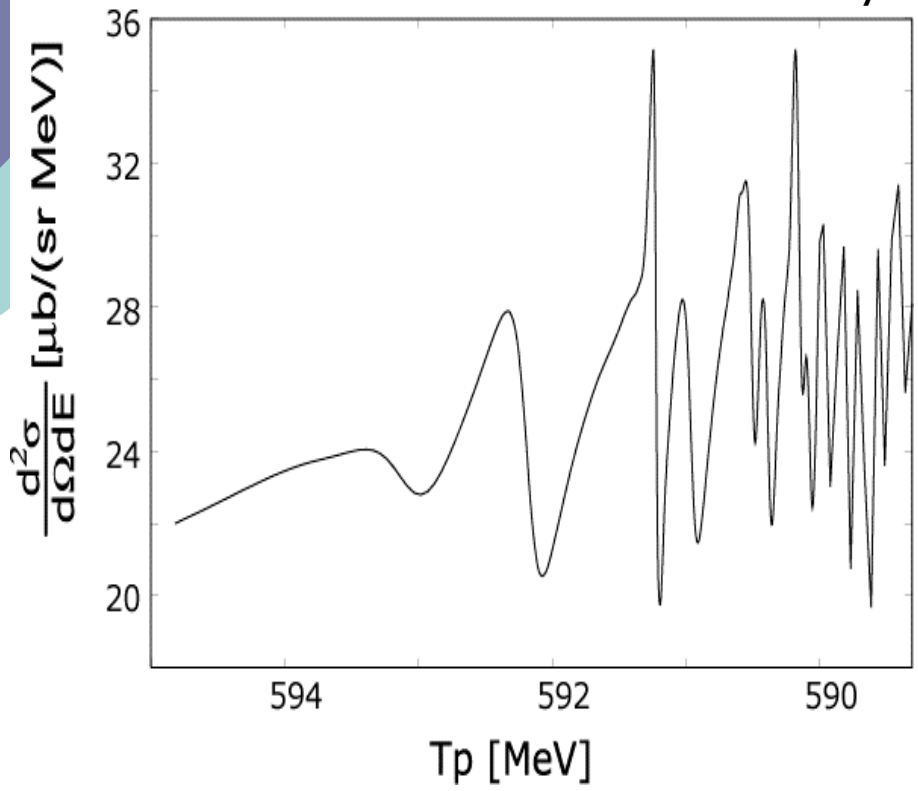
These are very interesting structures !!

We need high energy resolution in this case.

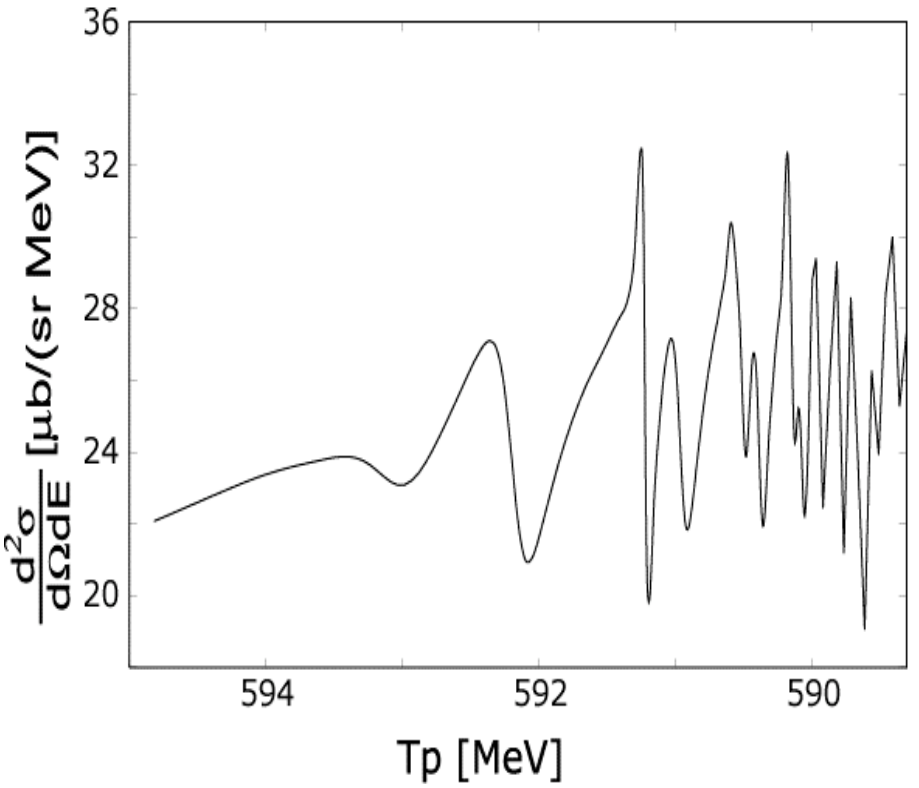
Energy Spectrum $^{120}Sn(K^-,p)$ T_K=600 MeV

- Proton hole state – $1g_{9/2}$

Chiral Unitary



Phenomenology



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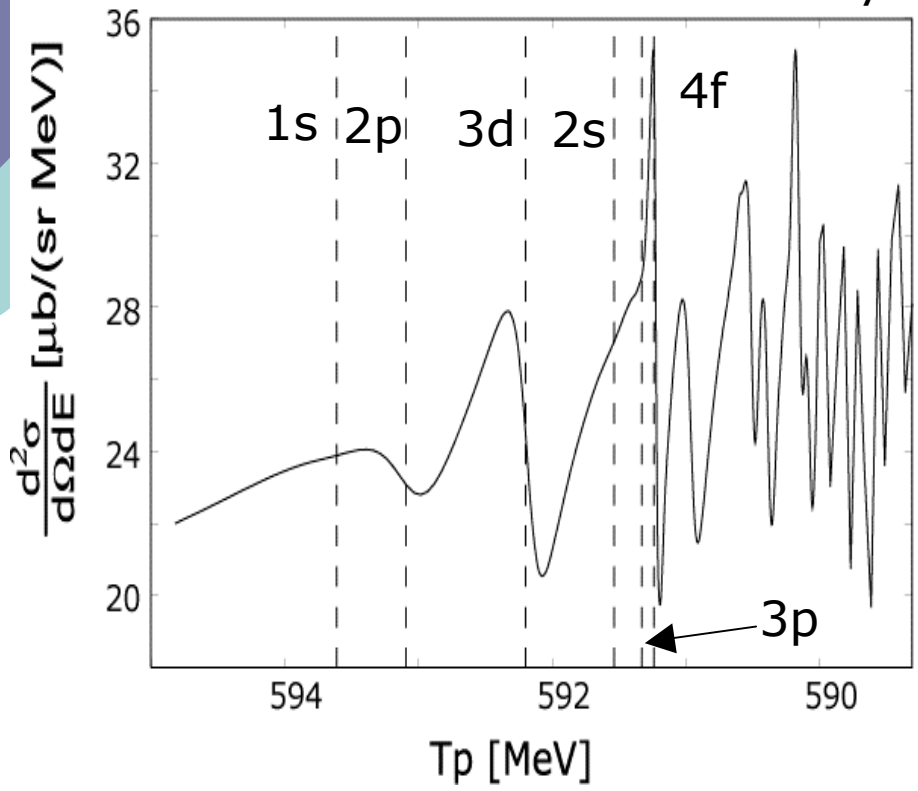
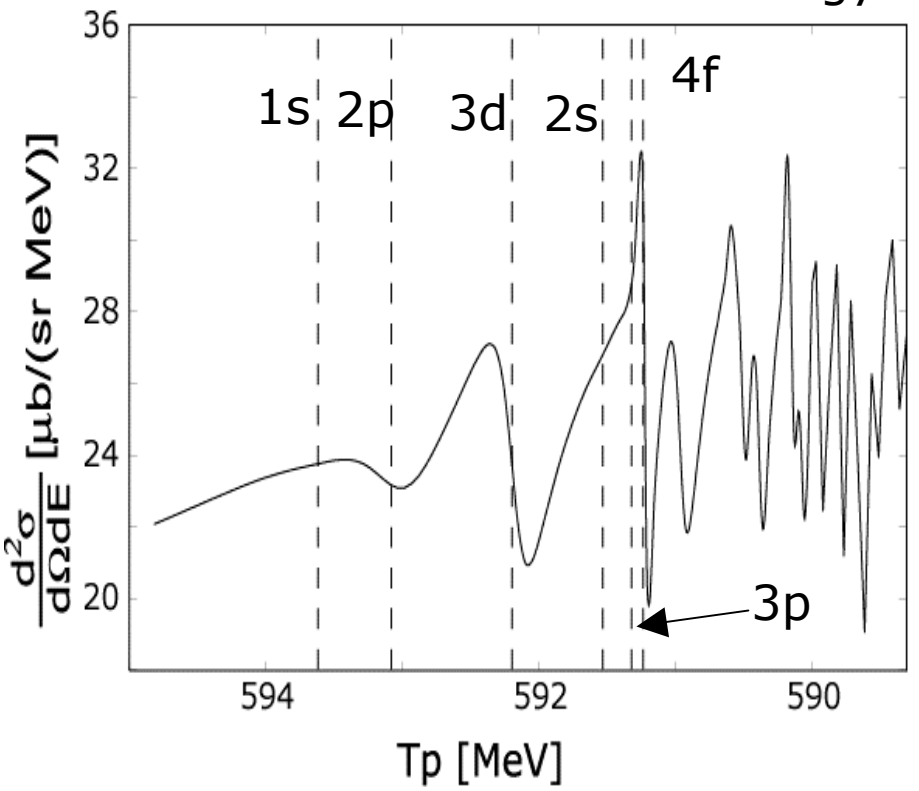
Chiral Unitary



Phenomenology



These spectra are also interesting.

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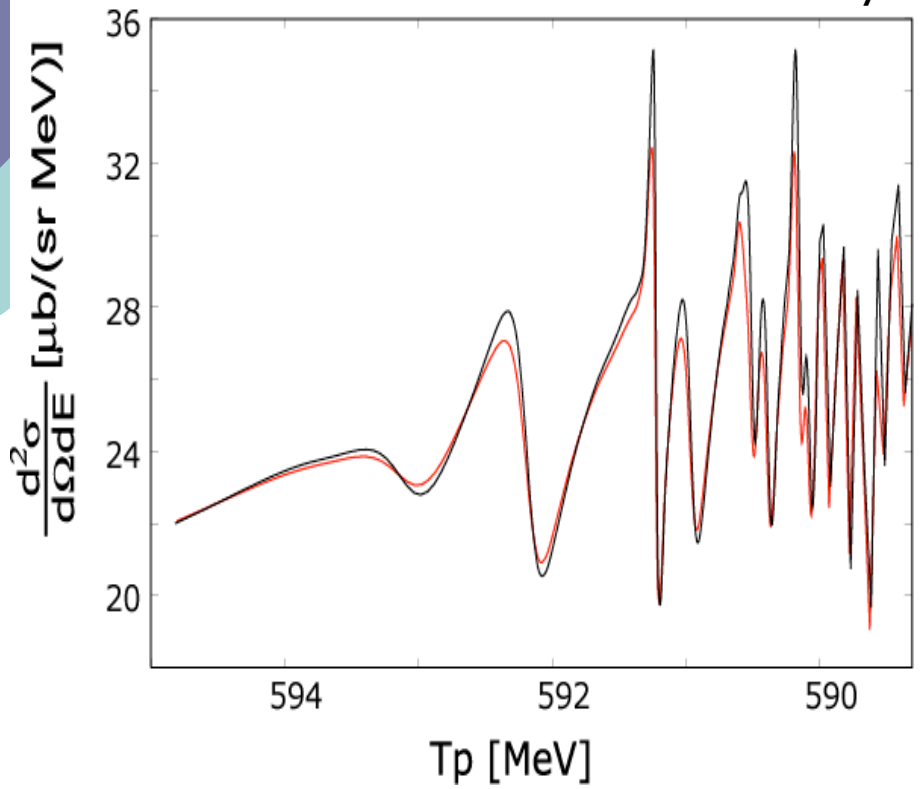
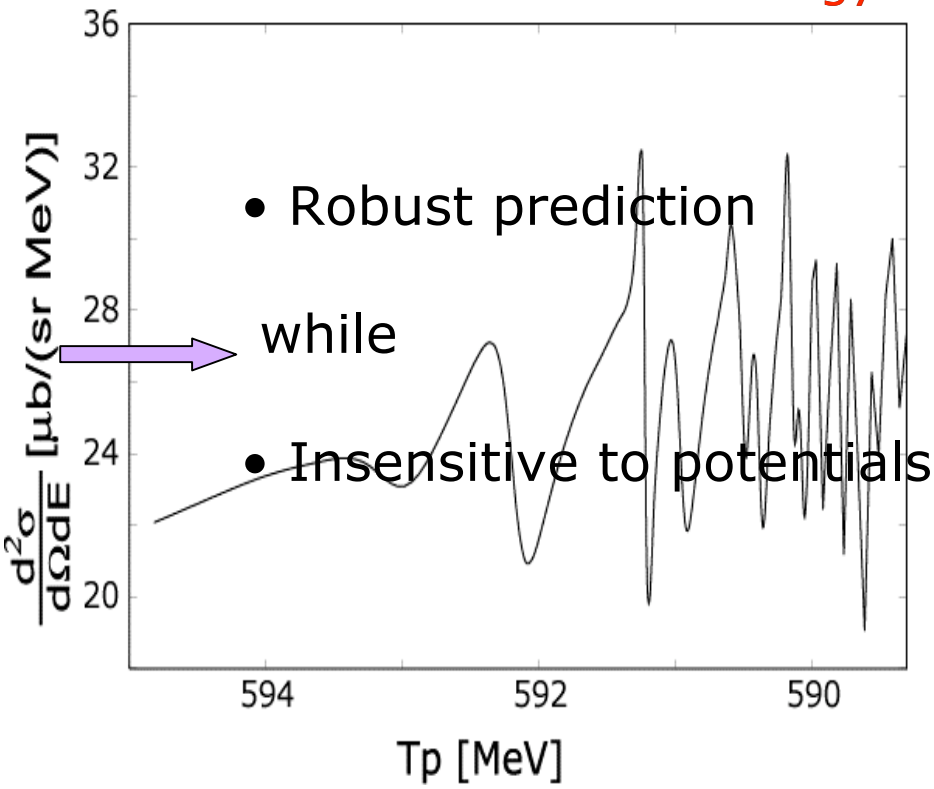


Phenomenology



- Robust prediction

while

- Insensitive to potentials

These spectra are also interesting and resemble each other.

Summary

- Study of Kaonic Atoms
  - To know the kaon properties at finite density.
  - Deeply bound atomic states have not been observed yet.
- Our study
  - Structure
    - New deeply bound atomic states are expected.
  - Reaction
    - Not simple peak structure. But dips,  shapes etc.
    - Peaks are expected!! (^{12}C, ^{120}Sn, other nuclei)
    - 'Robust prediction!' while 'Insensitive?'

Further investigations.

Future Work

- Kaonic atom
  - In-Flight(K^-,n) reaction
  - Stopped(K^-,N) reaction
    (kinematically different cases)

  Systematically

- Experimental feasibilities
  - J-PARC
  - DAΦNE

etc.