Kaon bound states formation by Kaon beam

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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 be observed.

☆ Deeply Bound Pionic Atoms observed by (d, ^{3}He) reactions.
☆ New facility J-PARC --- Coming Soon!!

⇩

We can expect kaonic bound states formation
by using the (K^-,p) reaction.

Theoretical (K^-,p) spectra
→ Important!! Before experiment.

Introduction

(Kaonic Atoms + Kaonic Nuclei, Both!!)

- Our Studies
  - Theoretical Comprehensive spectra

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

    Kishimoto Group, Iwasaki, Suzuki Group, FINUDA Group
    Akaishi, Yamazaki, Dote
    Oset, Toki

  - Predict new Kaon-Nucleus bound systems (Deeply bound Kaonic Atoms and Kaonic Nuclei) formation by Kaon beam.

    - 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

Formulation -- Structure

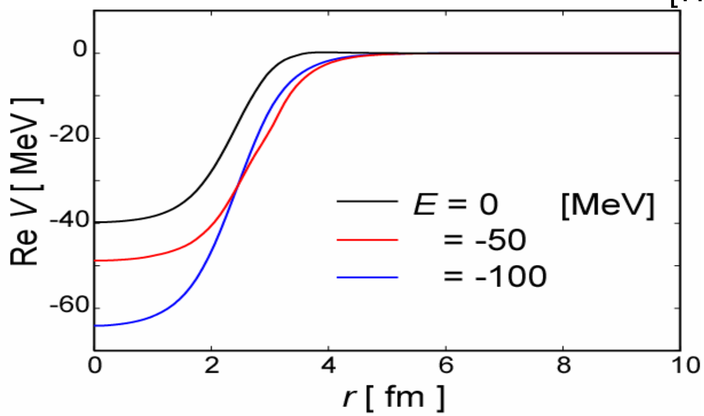
- Klein-Gordon equation

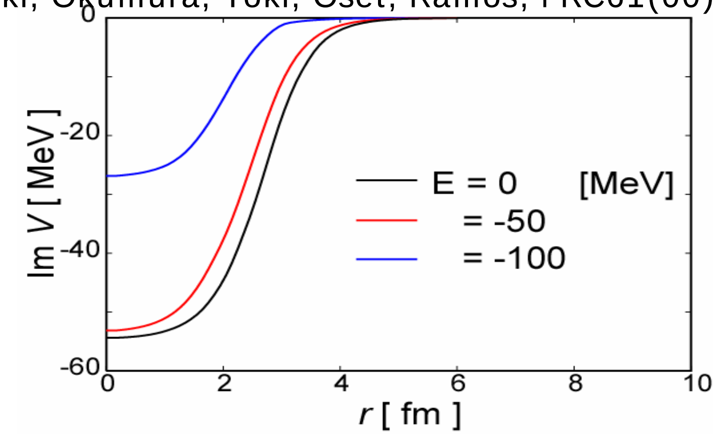
$$[-\vec{\nabla}^2 + \mu^2 + 2\mu V_{\rm opt}(r,E)]\phi(\vec{r}) = [\omega - V_{\rm coul}(r)]^2\phi(\vec{r})$$

Chiral Unitary Model

[A. Ramos, E. Oset, NPA671(00)481]

[Hirenzaki, Okumura, Toki, Oset, Ramos, PRC61(00)055205]

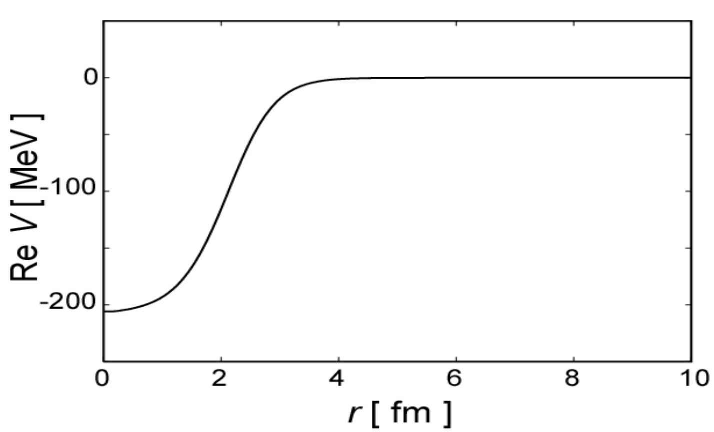


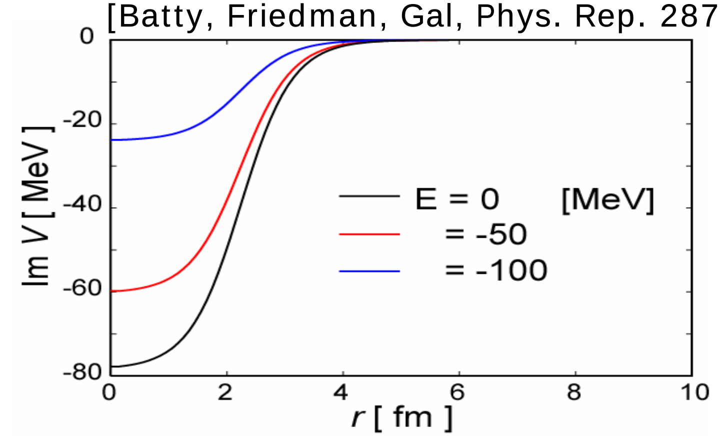


Phenomenological Model

[J. Mareš, E. Friedman, A. Gal, Phys. Lett. B606(2005)295]

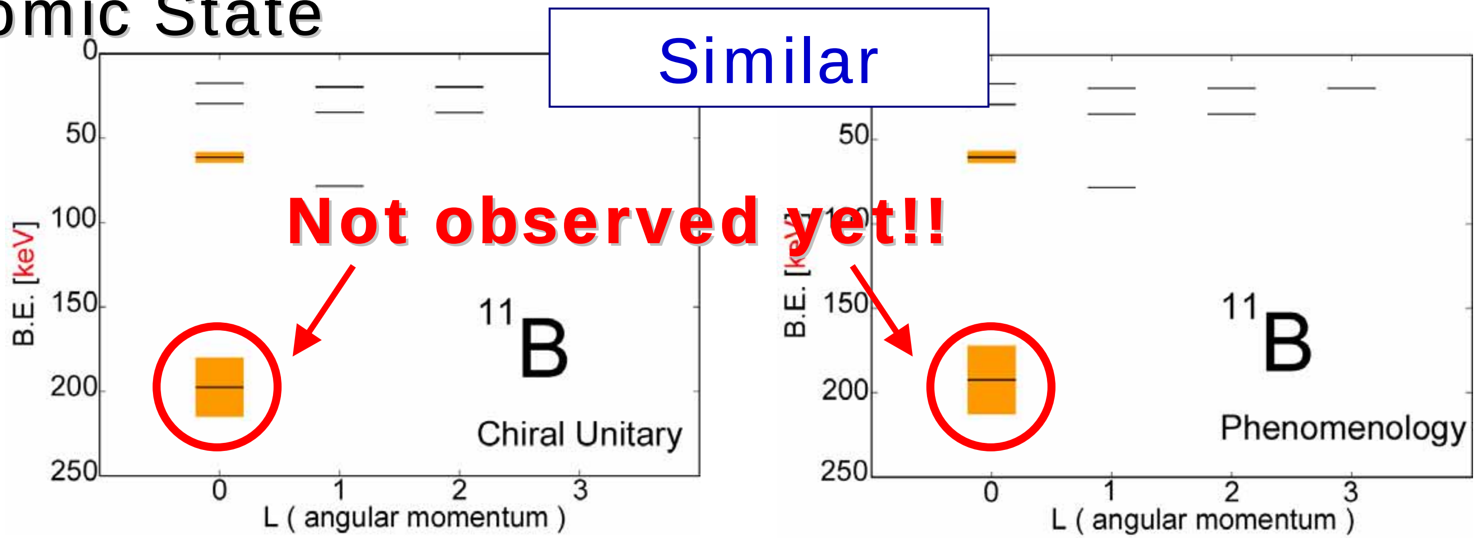
[Batty, Friedman, Gal, Phys. Rep. 287(97)385]



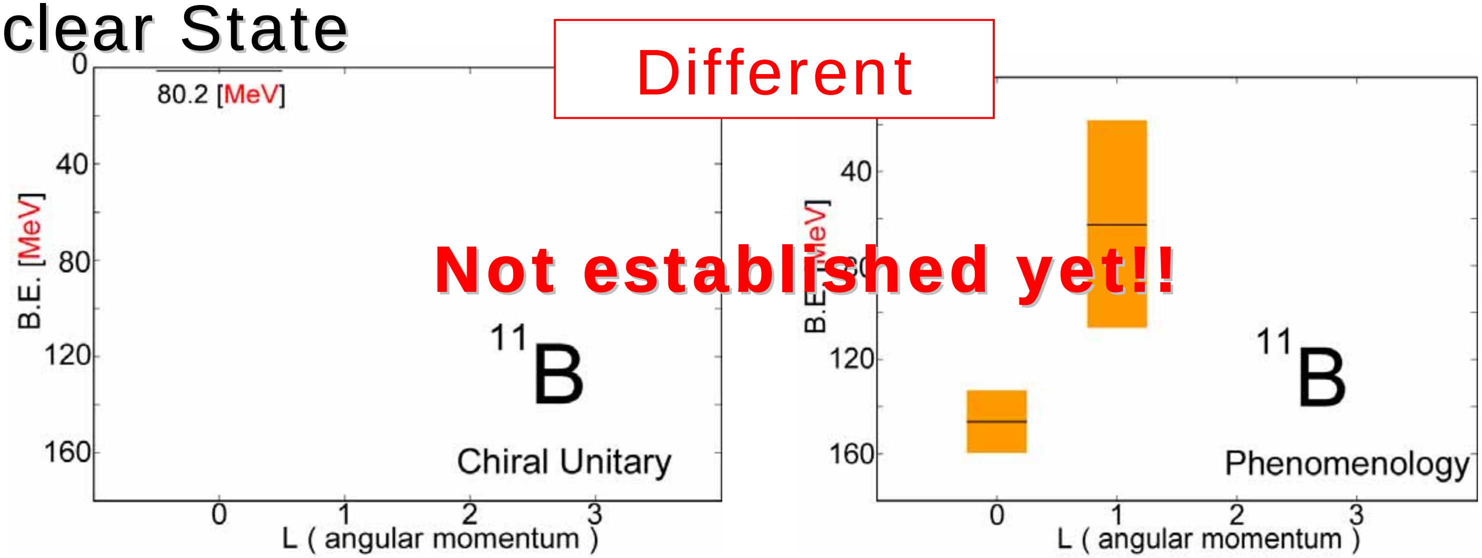


Energy level (Energy dep. Vopt)

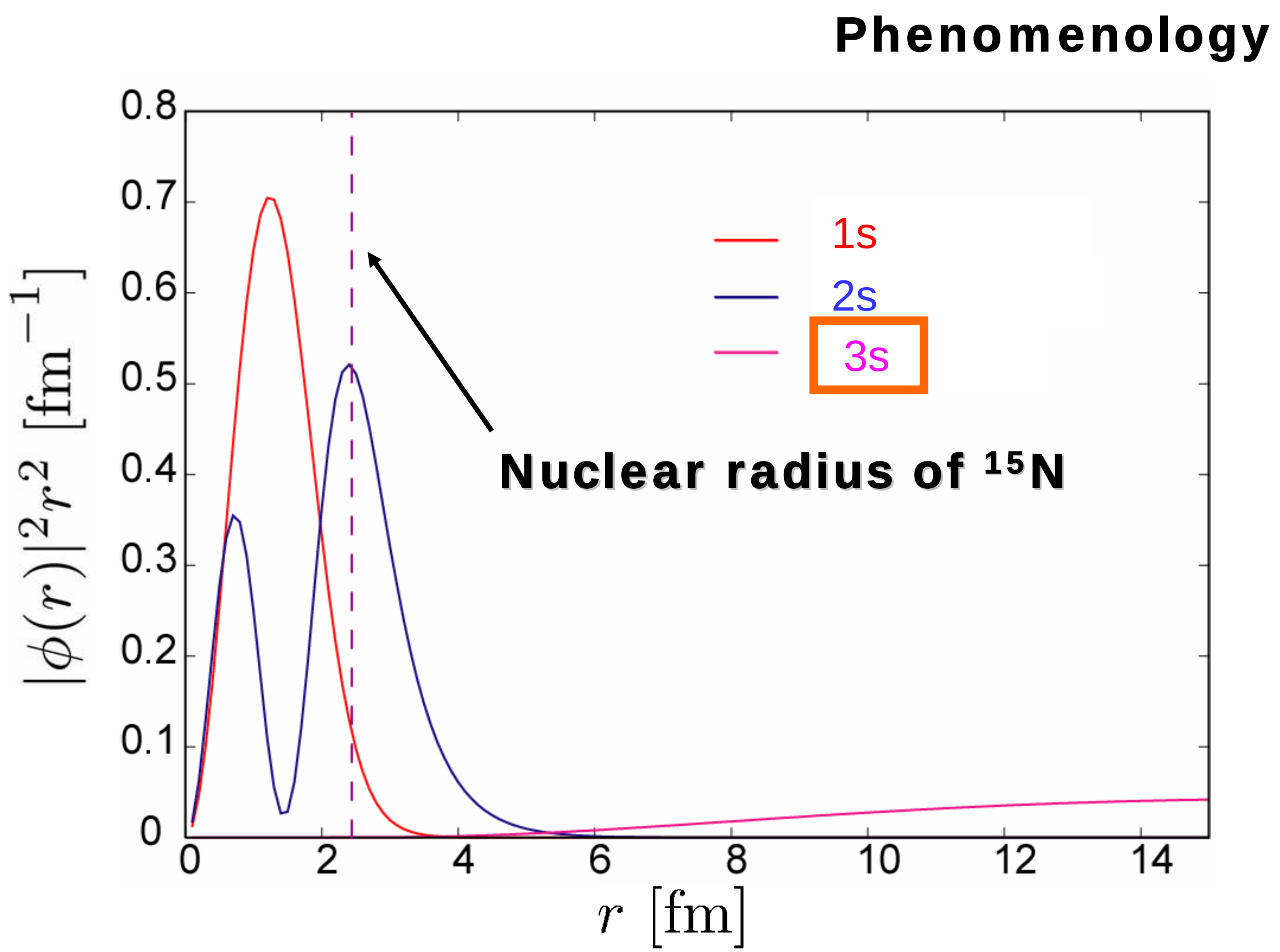
Atomic State



Nuclear State



Wave Function



Formulation -- Reaction $(\text{In–flight } K^-, p)$

- Green Function Method

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

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

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

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

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

  - Previous work: Effective Number Approach

(J. Yamagata et. al., PTP114(05)301)

$$\frac{d^2\sigma}{d\Omega dE} = \sum \frac{\Gamma_K}{2\pi}\frac{1}{\Delta E^2 + \Gamma_K^2/4} N_{\mathrm{eff}}\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{K^-p\to pK^-}}$$

$$\Delta E = T_p - (T_K - S_p(j_p^{-1}) + B.E.(nl))$$

$$N_{\mathrm{eff}} = \sum_{JMm_s} \left|\int \chi^*_p(\vec{r})\xi^*_{\frac{1}{2}m_s}(\sigma)[\phi_{L_K}(\vec{r})\otimes\psi_{j_p}(\vec{r},\sigma)]_{JM}\chi_K(\vec{r})d^3r d\sigma\right|^2$$

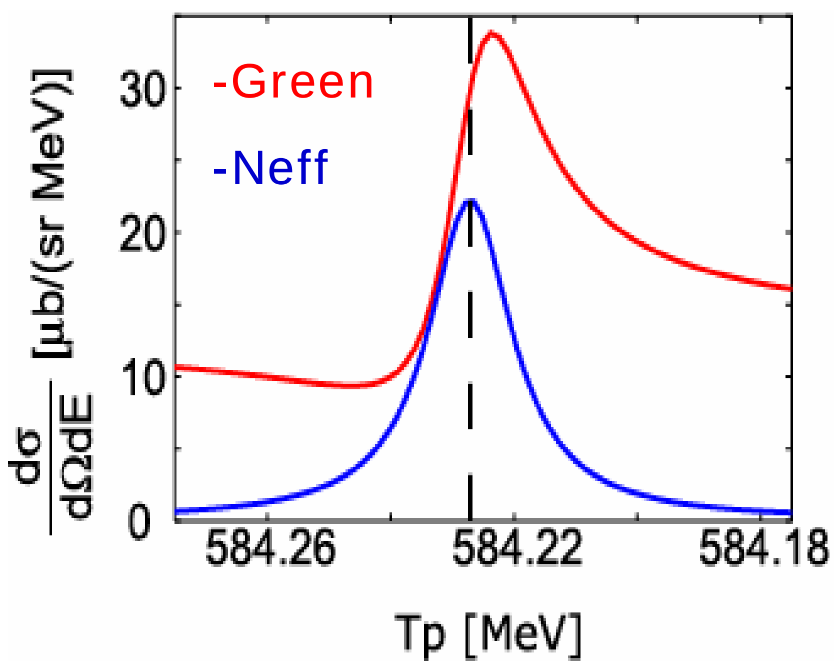
→ ^{12}C is interesting !

Energy Spectrum (Green vs. Neff)

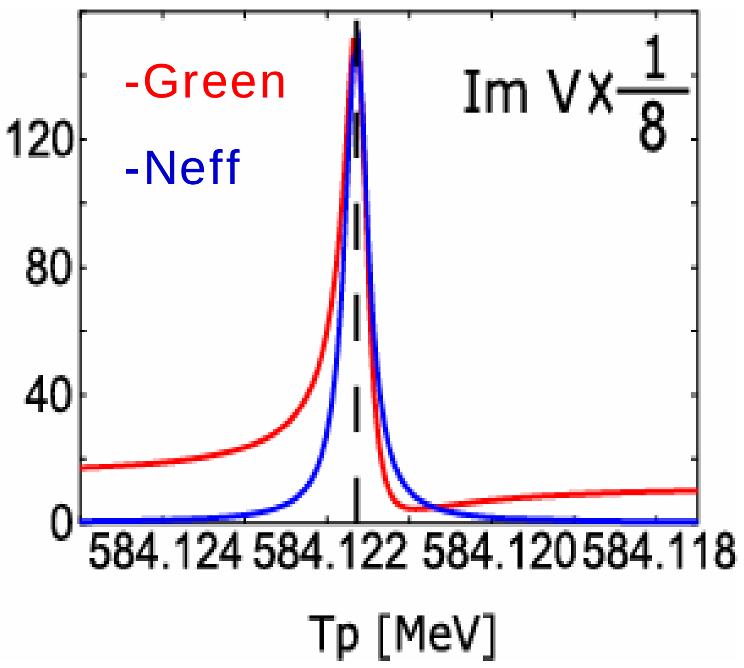
Atomic State

- $^{12}\mathrm{C}(\text{In–flight } K^-, p) \quad P_{K^-} = 976\ \mathrm{MeV/c}\ \ (T_{K^-} = 600\ \mathrm{MeV})$
- V_{opt} : Chiral Unitary Model ($E = 0$)
- state: $(s,p)_{K^-} \otimes p_{3/2}^{-1}$

Atomic 1s state



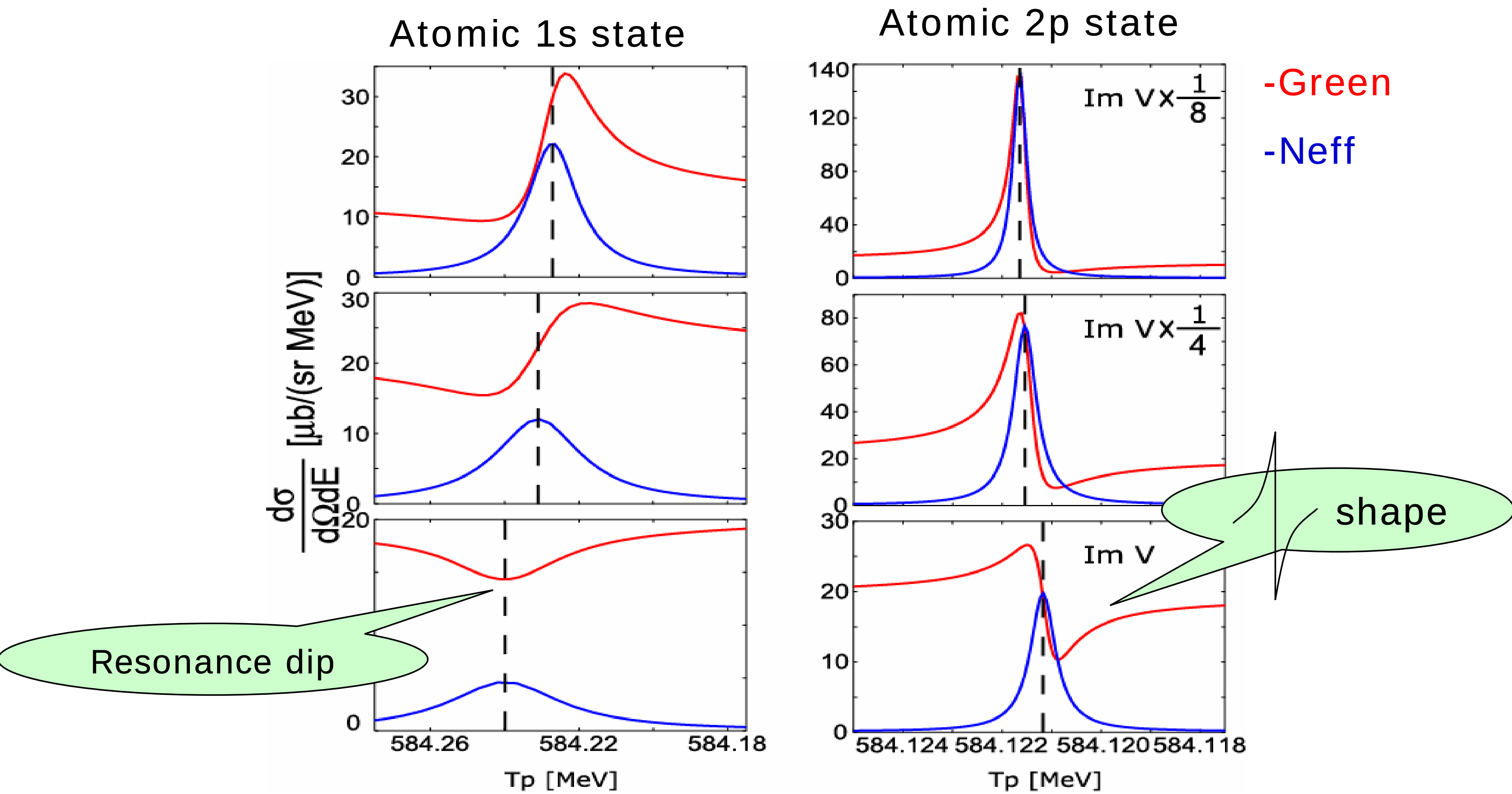
Atomic 2p state



Energy Spectrum (Green vs. Neff)

Atomic State

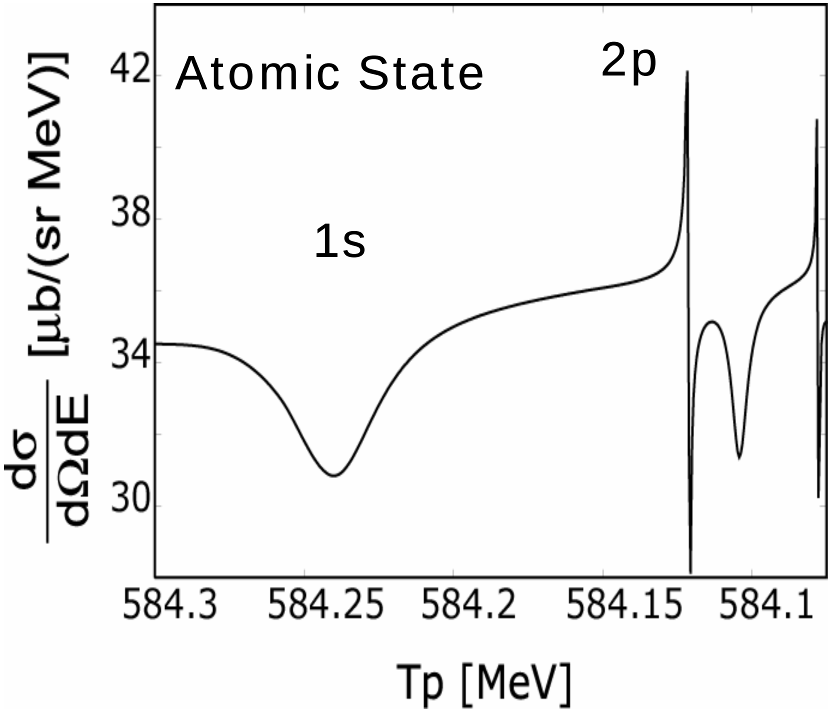
- $^{12}\mathrm{C}(\text{In–flight } K^-, p) \quad P_{K^-} = 976\ \mathrm{MeV/c} \quad (T_{K^-} = 600\ \mathrm{MeV})$
- state: $(s,p)_{K^-} \otimes p_{3/2}^{-1}$



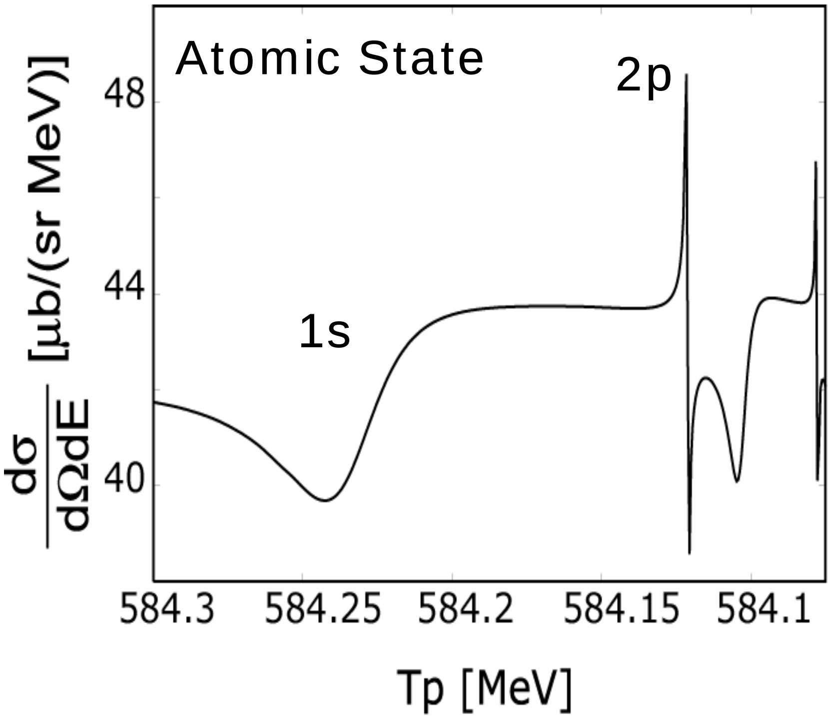
Energy Spectrum

- $^{12}\mathrm{C}(\text{In–flight } K^-, p)$ $P_{K^-} = 976$ MeV/c $(T_{K^-} = 600$ MeV$)$
- V_{opt} : Energy Dependence

Chiral Unitary Model

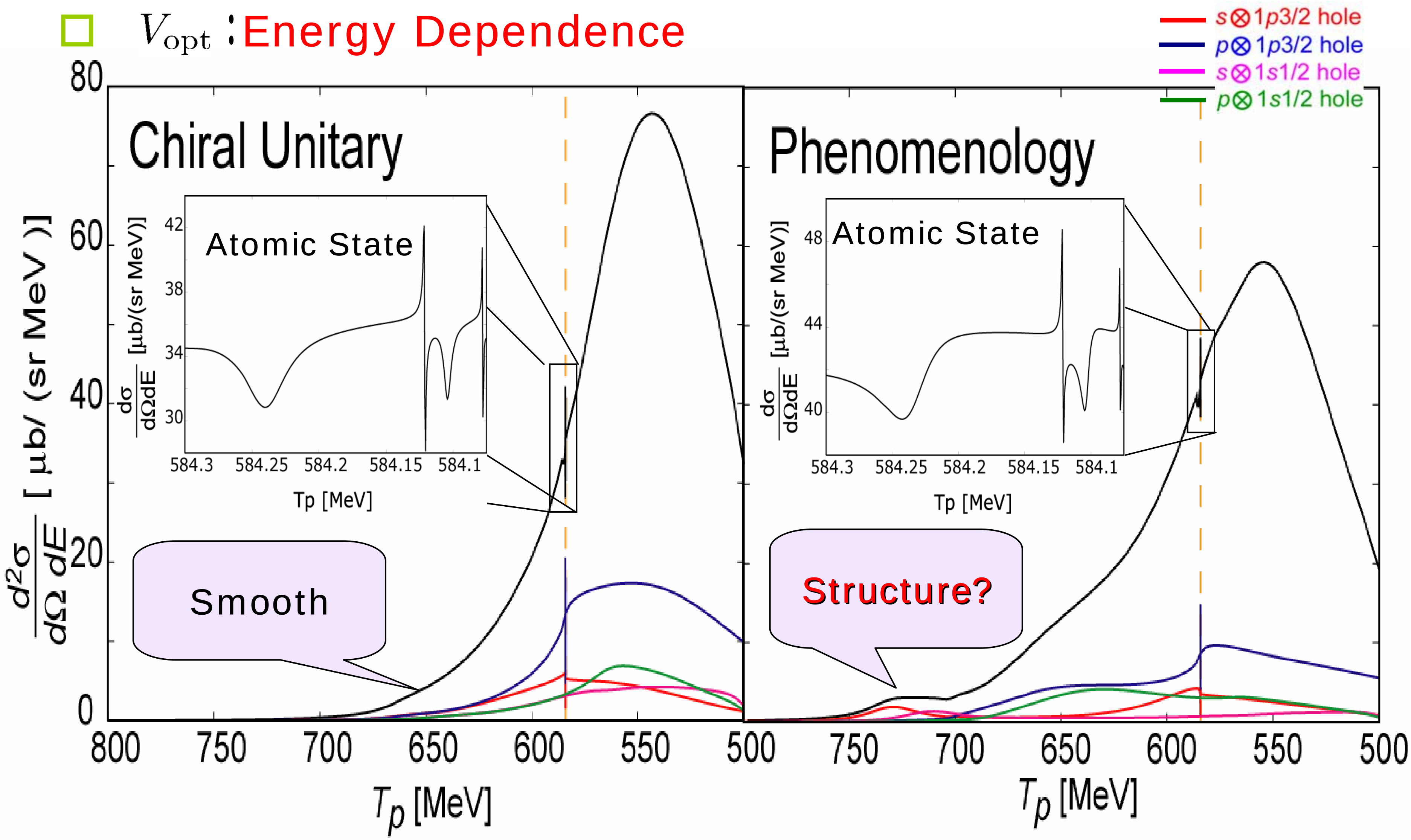


Phenomenology



Energy Spectrum

- $^{12}\mathrm{C}(\text{In–flight } K^-, p)$ $P_{K^-} = 976$ MeV/c $(T_{K^-} = 600$ MeV$)$
- V_{opt} : Energy Dependence



Energy Spectrum

^{16}O(In-flight K,n) P_K = 930 MeV/c

Please ask
Kishimoto-san Group

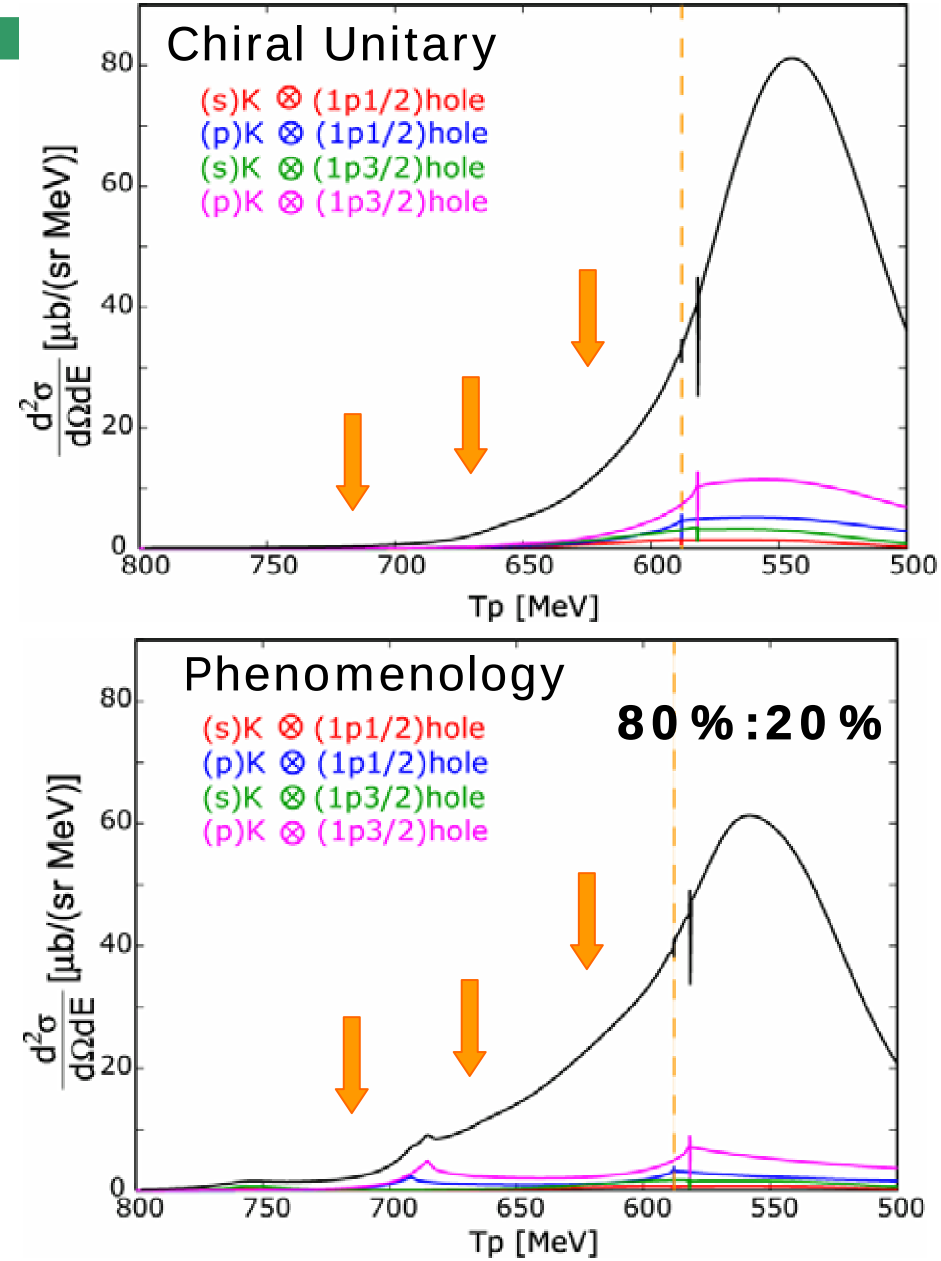
Comparison with
Kishimoto group's data

[T.Kishimoto *et al*., Prog. Theor. Phys. Suppl. 149 (2003)264]

[Fig. taken from the seminar slide @NWU by Dr. Hayakawa]

Energy dependent V_{opt}

$^{16}\mathrm{O}(\text{In–flight } K^-, p) \quad P_{K^-} = 976\ \mathrm{MeV/c}$



Summary

* J. Yamagata, H. Nagahiro, Y. Okumura, S. Hirenzaki
Prog. Theor. Phys. 114 (2005) 301.
* J. Yamagata, H. Nagahiro, S. Hirenzaki Phys. Rev. C 74, 014604 (2006)

Study of Kaonic Atoms

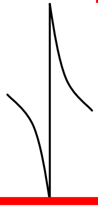
- To know the kaon properties at finite density.
- Deeply bound atomic states have not been observed yet.

Our Study

"Resonance Dip"

Kaonic Atoms

Structure -- New deeply bound Atomic States are expected.

Reaction -- Not simple peak structure, But dips,  shapes etc.

We can expect to obtain new information !!

Kaonic Nuclei

Structure -- Always exist in our calculation.

Reaction -- It seems very hard to observe signals.

Experimental info. of 2-body absorption $\bar{K}NN \to YN$ preferable.
(Old atomic data -> low ρ , FINUDA data -> higher ρ (?))

Future Plan

- Deeply Atomic States formation – Systematic Study to find most interesting cases

- Effects of possible nuclear structure change due to K

- Evaluation of 2 body absorption, $\bar{K}NN \to YN$