Accurate calculation of kaonic atom structure for study of the kaon-nucleus interaction

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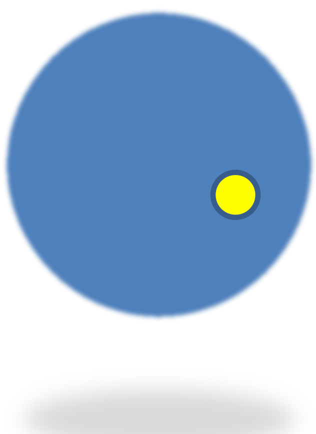
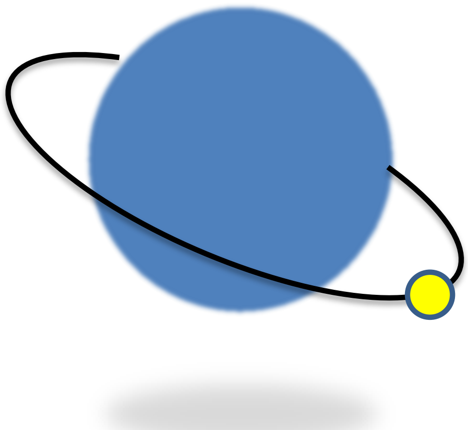
Introduction

- **Meson-Nucleus systems** are very important and useful objects to extract the meson properties at finite density.

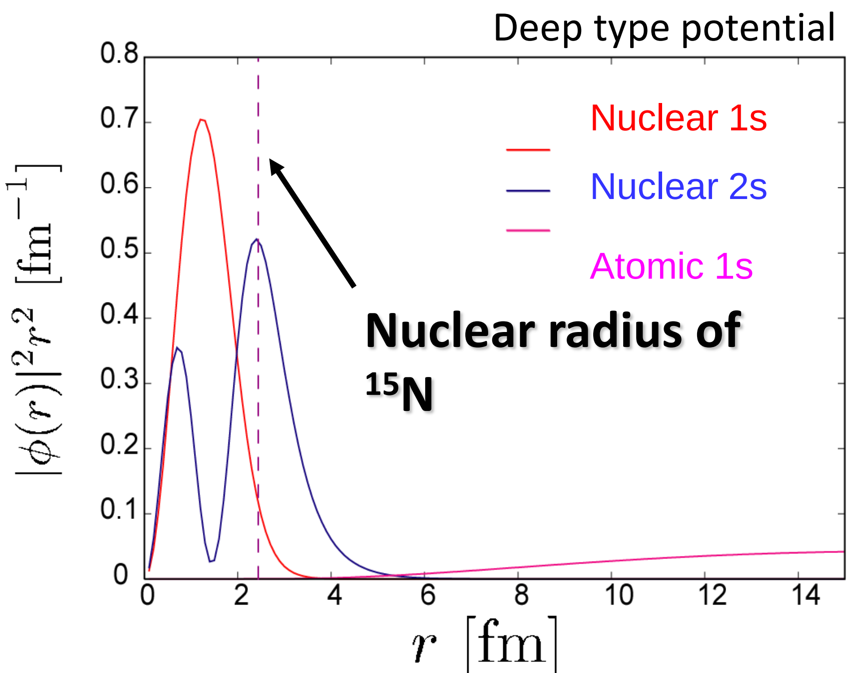
pion, kaon, omega, eta, eta’, phi …

From the meson properties at finite density, we may investigate the chiral symmetry breaking and its partial restoration in the nucleus.

Mesic Nuclei		Mesic Atoms
		
$K^-,\ \omega,\ \eta,\ \eta',\ \phi$	**Meson**	$\pi^-,\ K^-$
Strong interaction		Coulomb
[MeV]	**B.E.**	[10 keV - MeV]

Kaon-Nucleus systems

Kaonic Nuclei		Kaonic Atoms
Strong Int.	Bound system	Coulomb Int.
10 – 100 MeV ?	B.E.	keV-MeV
Wide (but, if B.E. > 100 MeV, Γ is narrow)	Width	Narrow
A few	EXP.	Many



Kaon-Nucleus systems

Kaonic Nuclei		Kaonic Atoms
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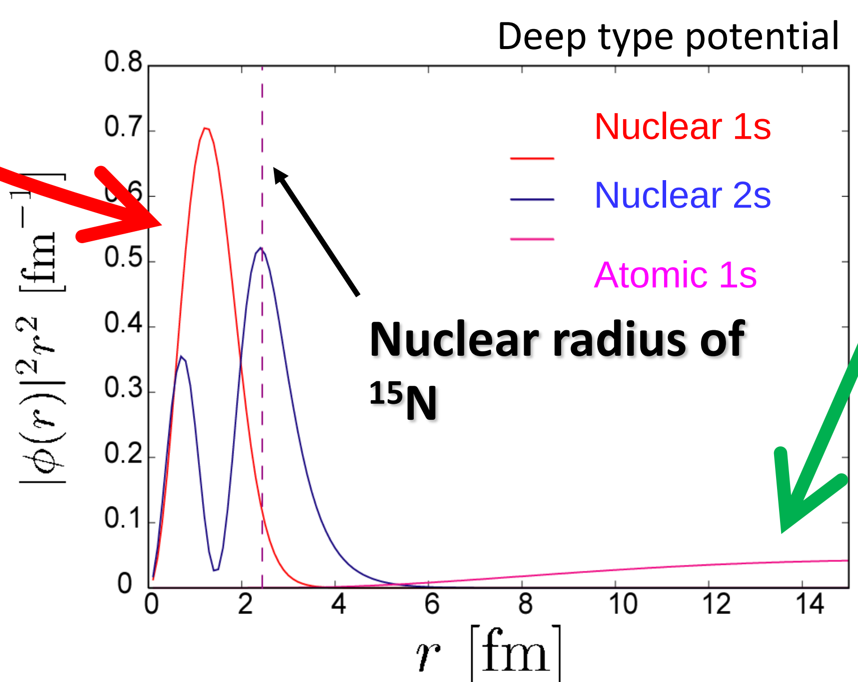


Kaon-Nucleus interaction

- The candidates of the kaon-nucleus interaction

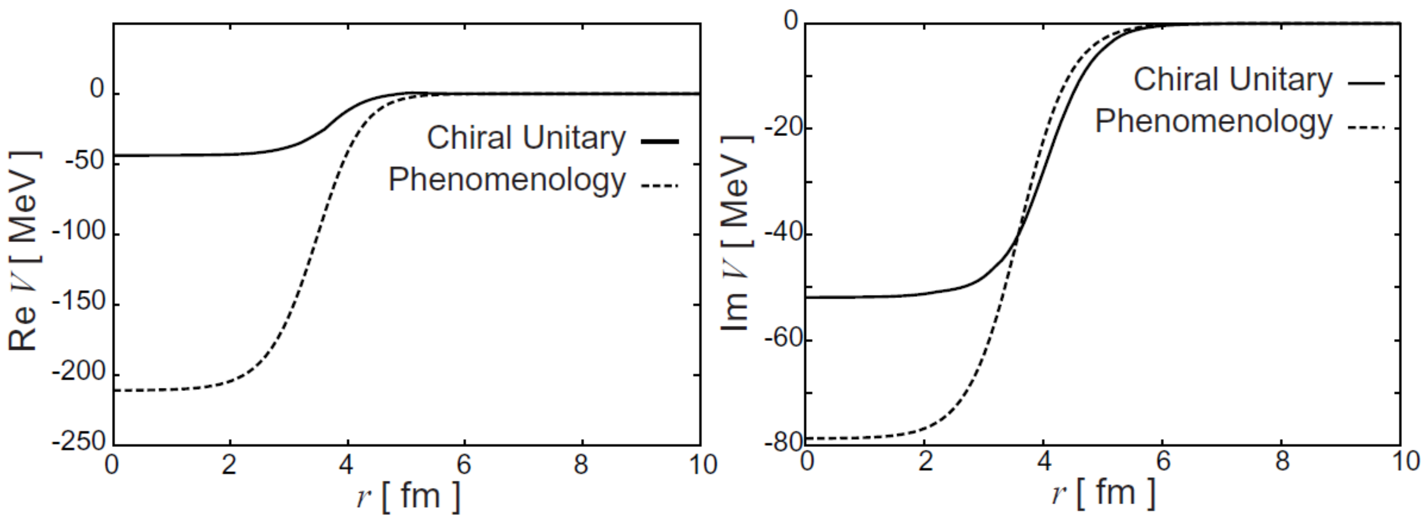
SHALLOW -- Chiral Unitary Model (Ramos, Oset, NPA671(00)481)

DEEP -- Phenomenological Model

(Batty, Friedman, Gal, PR287(97)385, Mares, Friedman, Gal, NPA770(06)84)

- The kaon-nucleus potential at threshold energy

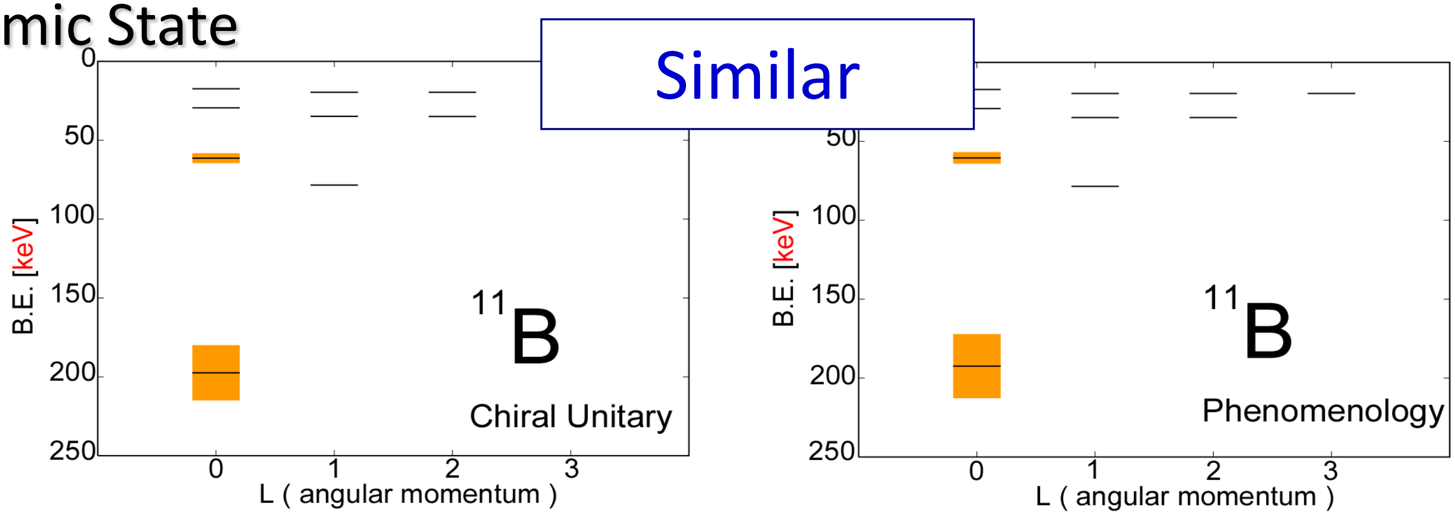
J. Yamagata et al, PTP114(05)301.



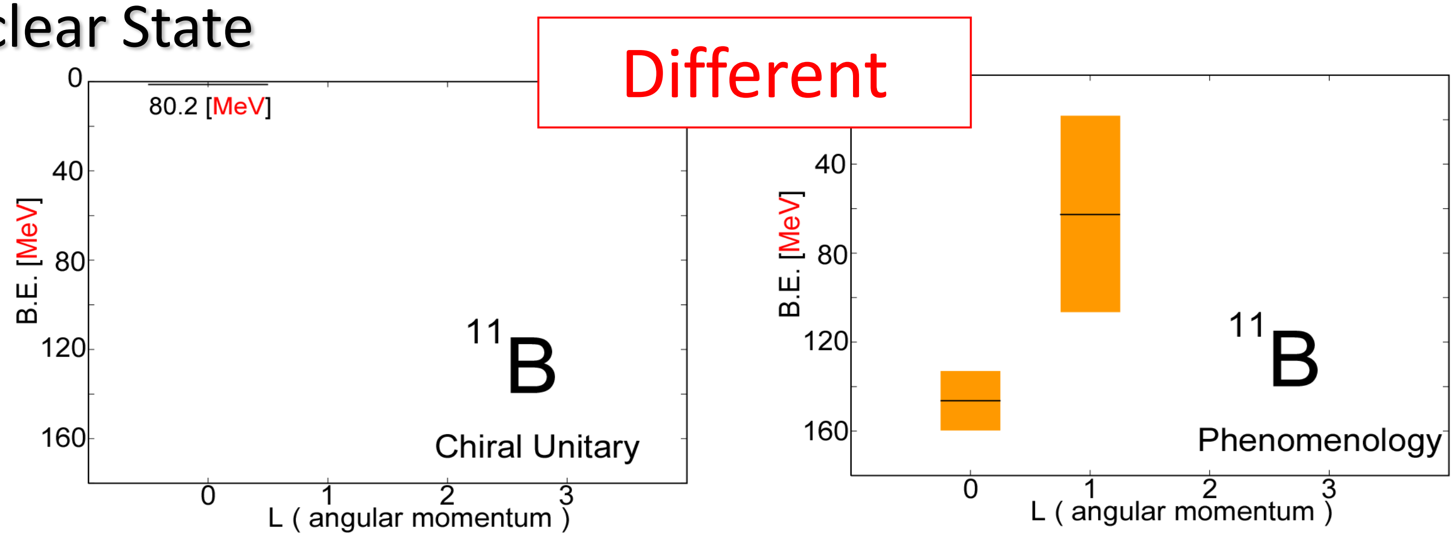
How can we distinguish these potentials?

Calculated binding energy and width

Atomic State



Nuclear State



The difference of two potentials could be shown in the kaonic nuclear state.

Kaon-Nucleus system at J-PARC

Experiment at J-PARC

E-15 : A search for deeply-bound kaonic nuclear states by in-flight 3He(K-,n) reaction

$$^{3}\mathrm{He}\ (K^-, n)K^-pp,\ \ K^-pp \to \Lambda + p/\Sigma^0 + p$$

E-17 : Precision spectroscopy of Kaonic 3He 3d -> 2p X-rays

E-27 : Search for a nuclear Kbar bound state K-pp in the d(pi+,K+) reaction

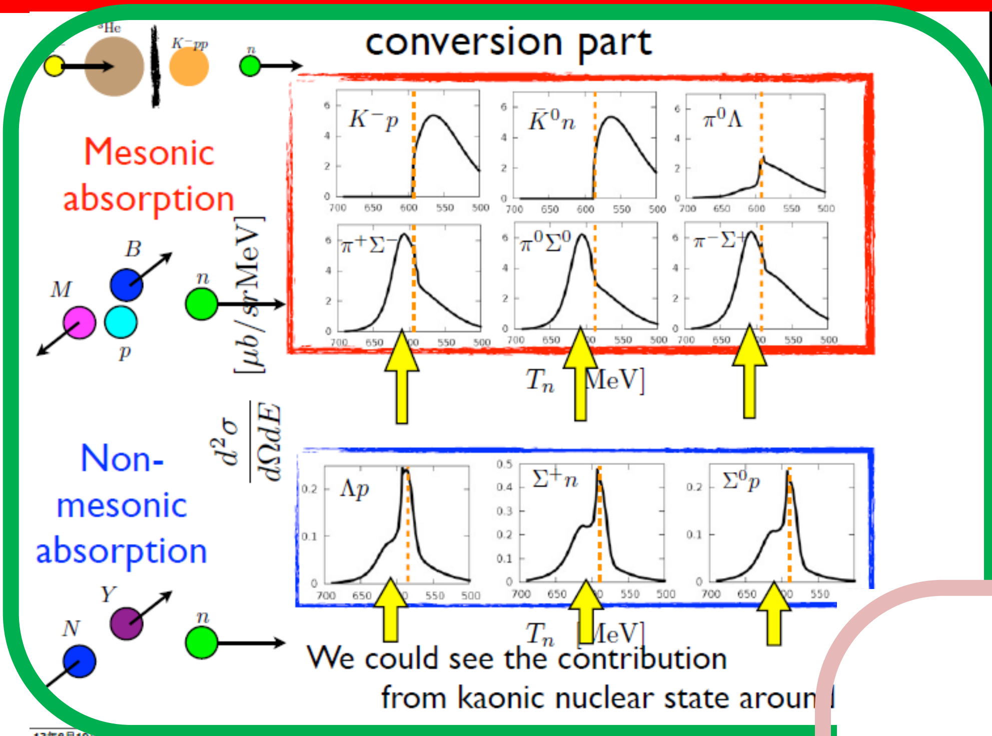
$$d(\pi^+, K^+)K^-pp,\ \ K^-pp \to \Lambda + p/\Sigma^0 + p$$

E-31 : Spectroscopic study of hyperon resonances below KbarN threshold via the (K-,n) reaction on Deuteron

$$d(K^-, n)\Lambda(1405),\ \ \Lambda(1405) \to \pi\Sigma$$

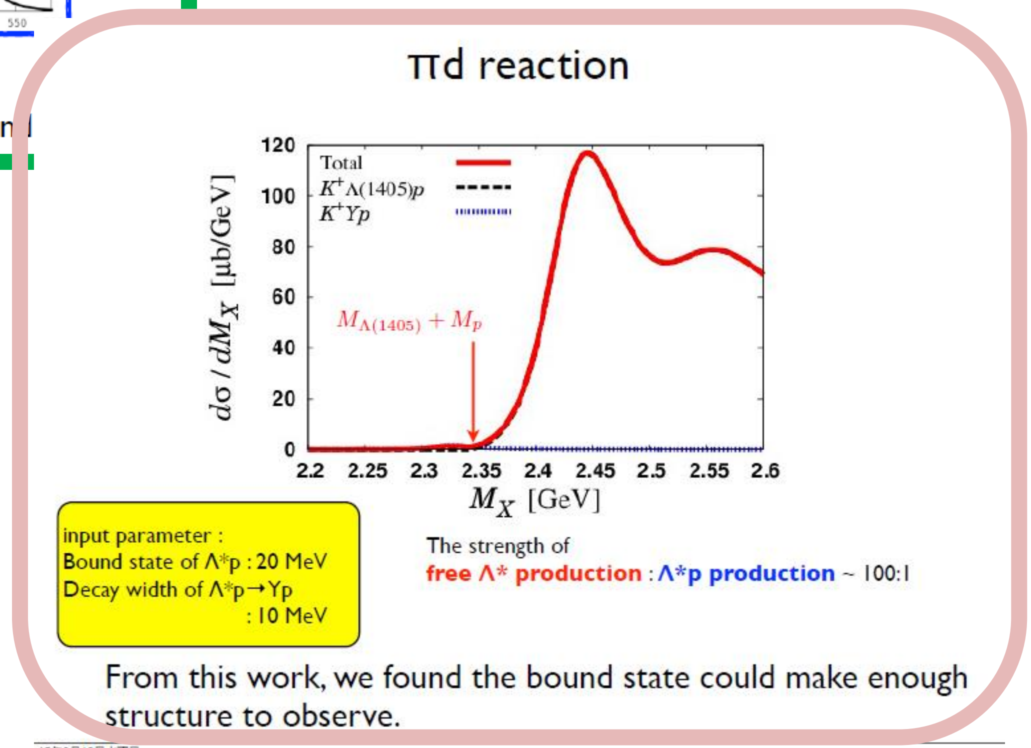
Kaon-Nucleus system at J-PARC

J-PARC **E-15**

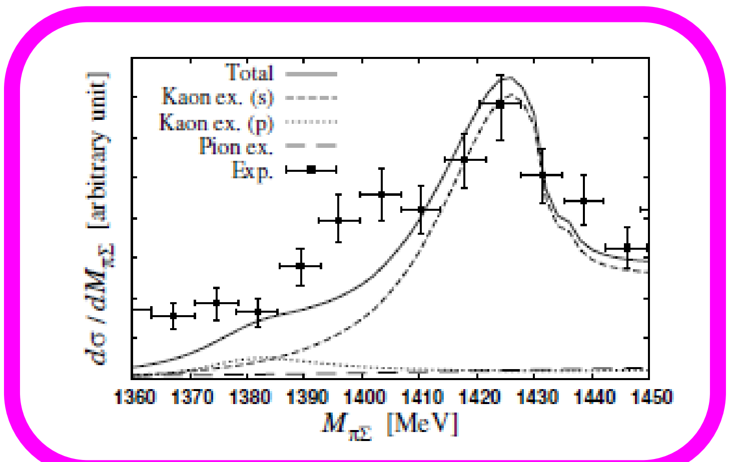


Our calculated results related to J-PARC experiments

J-PARC **E-27**



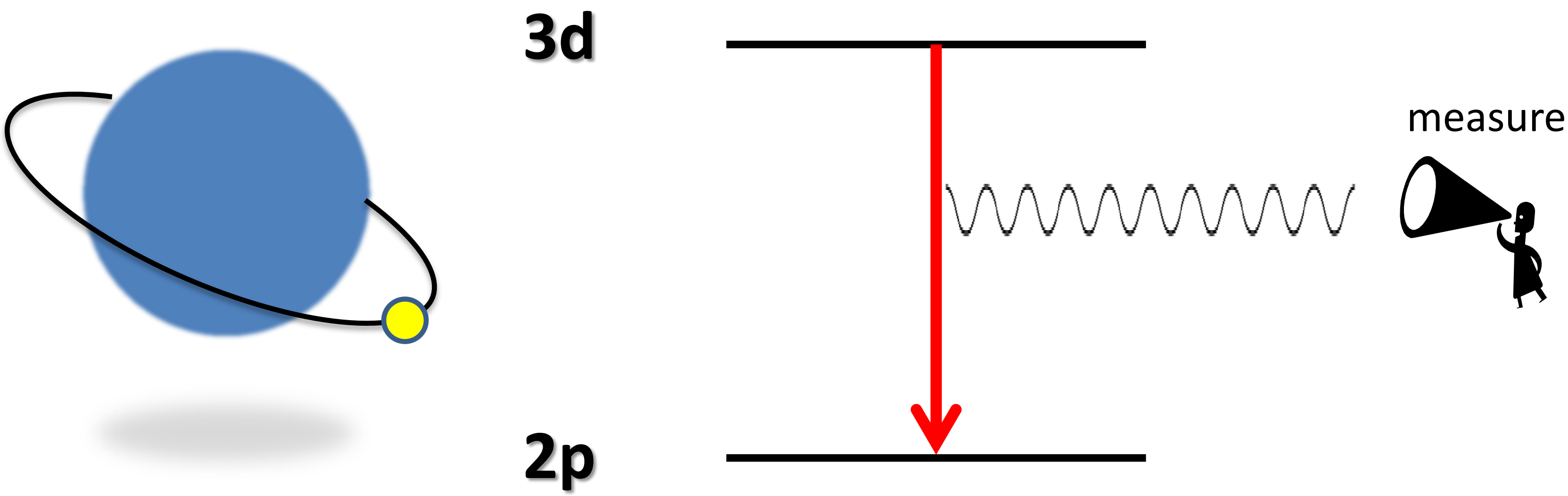
J-PARC **E-31**



Kaonic Atoms

- We try to obtain the information on the kaon-nucleus interaction from the **kaonic atoms**.

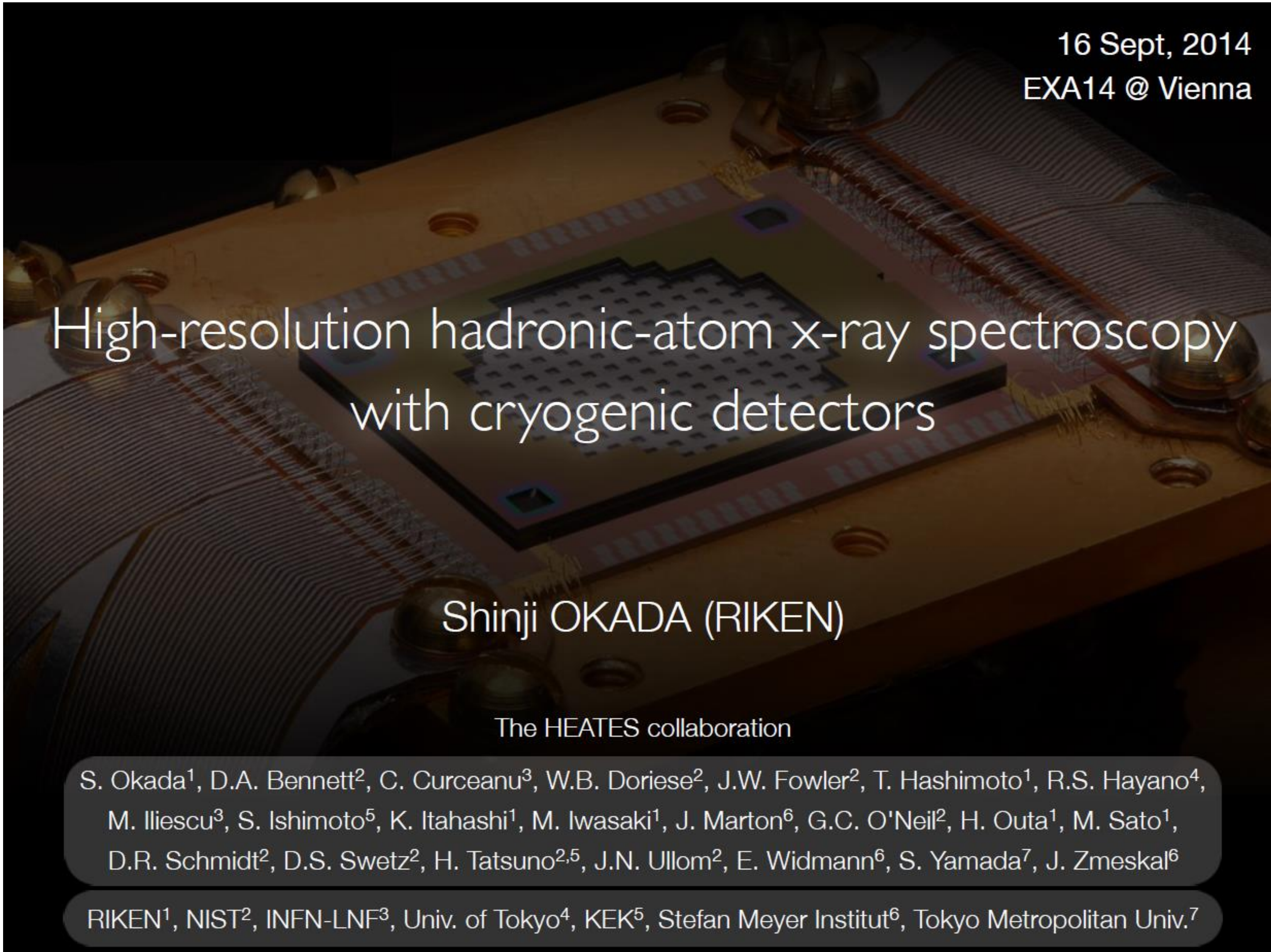
X-ray spectroscopy of kaonic atoms



$$\Delta E(2p) = E_X^{\rm exp} - E_X^{\rm EM}$$

- By measuring the shift ΔE and width,
  we could obtain the information on the strong interaction.

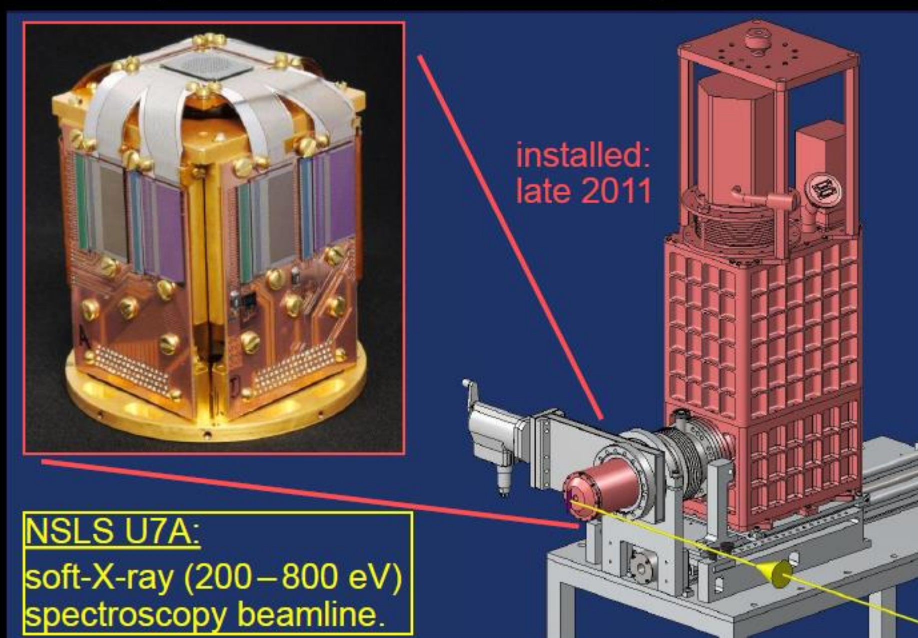
Slide from S. Okada-san’s talk in EXA14



Slide from S. Okada-san's talk in EXA14

NIST's TES array system for x-rays

e.g., soft-X-ray spectroscopy @ BNL



W.B. Doriese, TES Workshop @ ASC (Portland), Oct 8, 2012

NIST's standard TES

- 1 pixel : 300 x 320 μm^2
- 240 array : total ~ **23 mm^2**
- **2~3 eV (FWHM)** @ 6 keV

well established system!

two-order improved resolution

~ 200 eV (FWHM) @ 6 keV
... a typical Silicon detector
used in the previous K-atom exp.

Slide from S. Okada-san’s talk in EXA14

Is 240 pixel (~23 mm^2) enough?

estimated K-^{4}He Kα yield w/ realistic setup
~ 20 events / day

	K-4He Kα events	Energy resolution in FWHM	Stat. accuracy of ene. determining (6 keV)
KEK-E570 with SDD	1500 events	190 eV	2 eV = 190 / 2.35 / sqrt(1500)
	ONE order lower	TWO orders higher	ONE order better
TES	150 events (~ a-week beam)	2 ~ 3 eV	~ 0.1 eV = 2 ~ 3 / 2.35 / sqrt(150)

Kaonic Atoms

- We improve our calculation with high precision EM term.

- Nucleus : 4He, 7Li
- Density distribution :

  4He -- 3 parameter Fermi distribution

  Jager, Vries, Vries, Atom. Data Nucl. Data Tabl. 14(74)479

$$\rho(r) = \rho_0 \left(1 + \omega \left(\frac{r}{c}\right)^2\right) \frac{1}{1 + \exp((r-c)/z)}$$

Set (A): c=1.008, z=0.327, ω=0.445 [fm]
Set (B): c=0.964, z=0.322, ω=0.517 [fm]

  7Li -- Modified Harmonic Oscillator

  Friedman, Gal, Batty, Nucl. Phys. A579(94)518

$$\rho(r) = \rho_0 \left(1 + \alpha \left(\frac{r}{a}\right)^2\right) \exp\left(-\left(\frac{r}{a}\right)^2\right)$$

a=1.623, α=0.429 [fm]

Klein-Gordon equation

- **The meson energy is obtained by solving the Klein-Gordon equation.**

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

μ : reduced mass of kaon-nucleus system
Vopt(r) : the optical potential of kaon-nucleus system

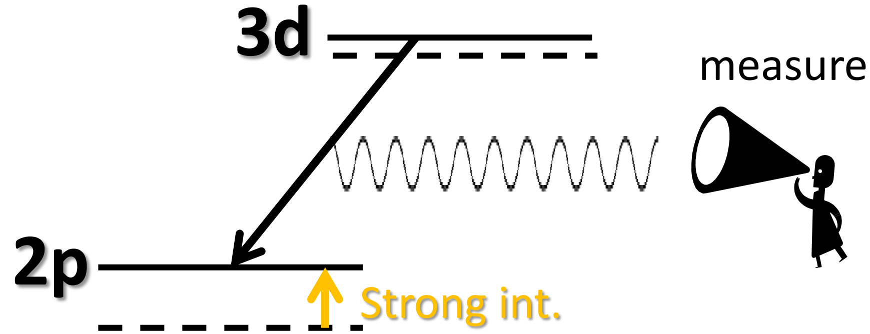
- Chiral Unitary Model
  (Ramos, Oset, NPA671(00)481)

- Phenomenological Model
  (Batty, Friedman, Gal, PR287(97)385,
  Mares, Friedman, Gal, NPA770(06)84)

Vcoul(r) : finite-size coulomb potential

$$V_{\rm coul}(r) = -e^2 \int \frac{\rho_p(r')}{|\vec{r} - \vec{r'}|}$$

Calculated results of 4He

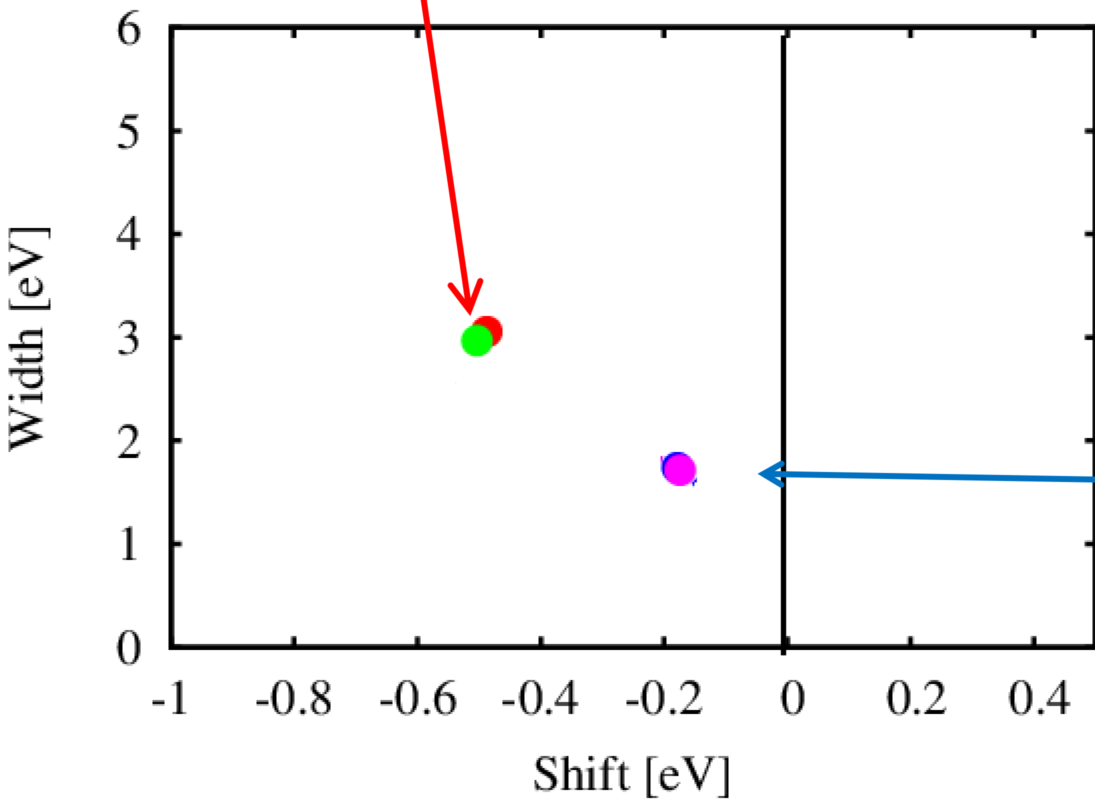


$$\text{SHIFT} = (E_K(3d) - E_K(2p)) - (E^{\text{EM}}(3d) - E^{\text{EM}}(2p))$$

Phenomenological Model
(Mares, Friedman, Gal, NPA770(06)84)

$V_{\text{opt}}(r=0) \sim -(180+73i)$ MeV

set(A)
set(B)



Chiral Unitary Model
(Ramos, Oset, NPA671(00)481)

$V_{\text{opt}}(r=0) \sim -(40+55i)$ MeV

set(A)
set(B)

Calculated results of 4He

Phenomenological Model
(Mares, Friedman, Gal, NPA770(06)84)

$V_{\rm opt}(r=0) \sim -(180+73i)$ MeV

set(A)
set(B)

PHENO: estimated with fit errors

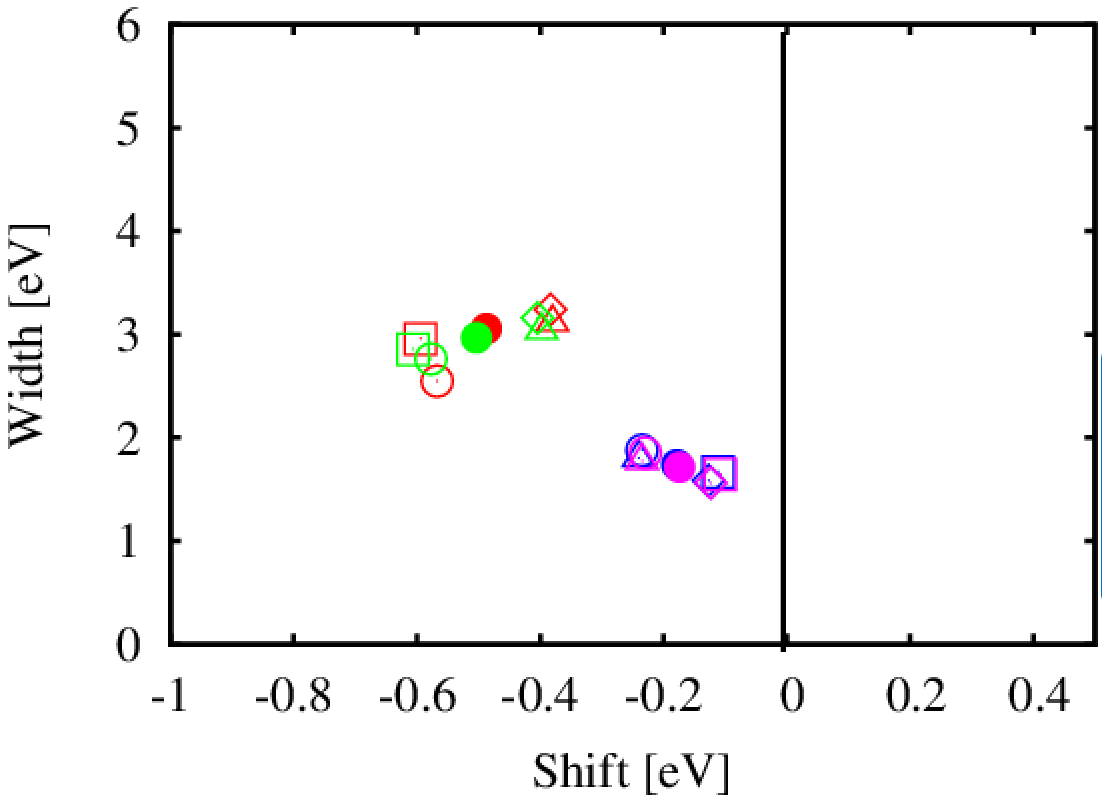
$V_{\rm opt}(r=0) \sim -(170-187)-(70-75)i$ MeV

S D S D

$V_{\rm opt}(r=0) \sim -(36-44)-(50-60)i$ MeV

CHIRAL: assuming 10% errors

○ D D
□ D S
△ S D
◇ S S



Chiral Unitary Model
(Ramos, Oset, NPA671(00)481)

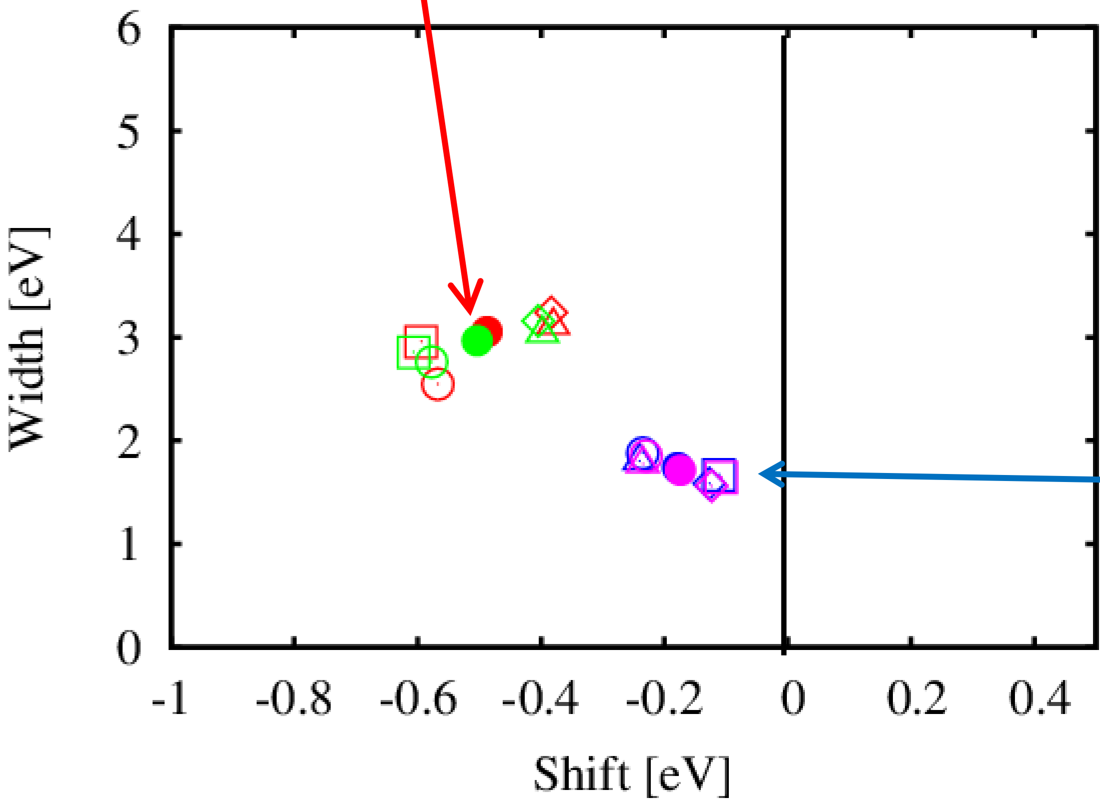
$V_{\rm opt}(r=0) \sim -(40+55i)$ MeV

set(A)
set(B)

Calculated results of 4He

Phenomenological Model
(Mares, Friedman, Gal, NPA770(06)84)
$V_{\rm opt}(r=0) \sim -(180+73i)$ MeV
set(A)
set(B)

High-resolution experiment is planed at J-PARC. (RIKEN, Okada-san)
Is it possible to distinguish these two potentials from the data of kaonic atoms??

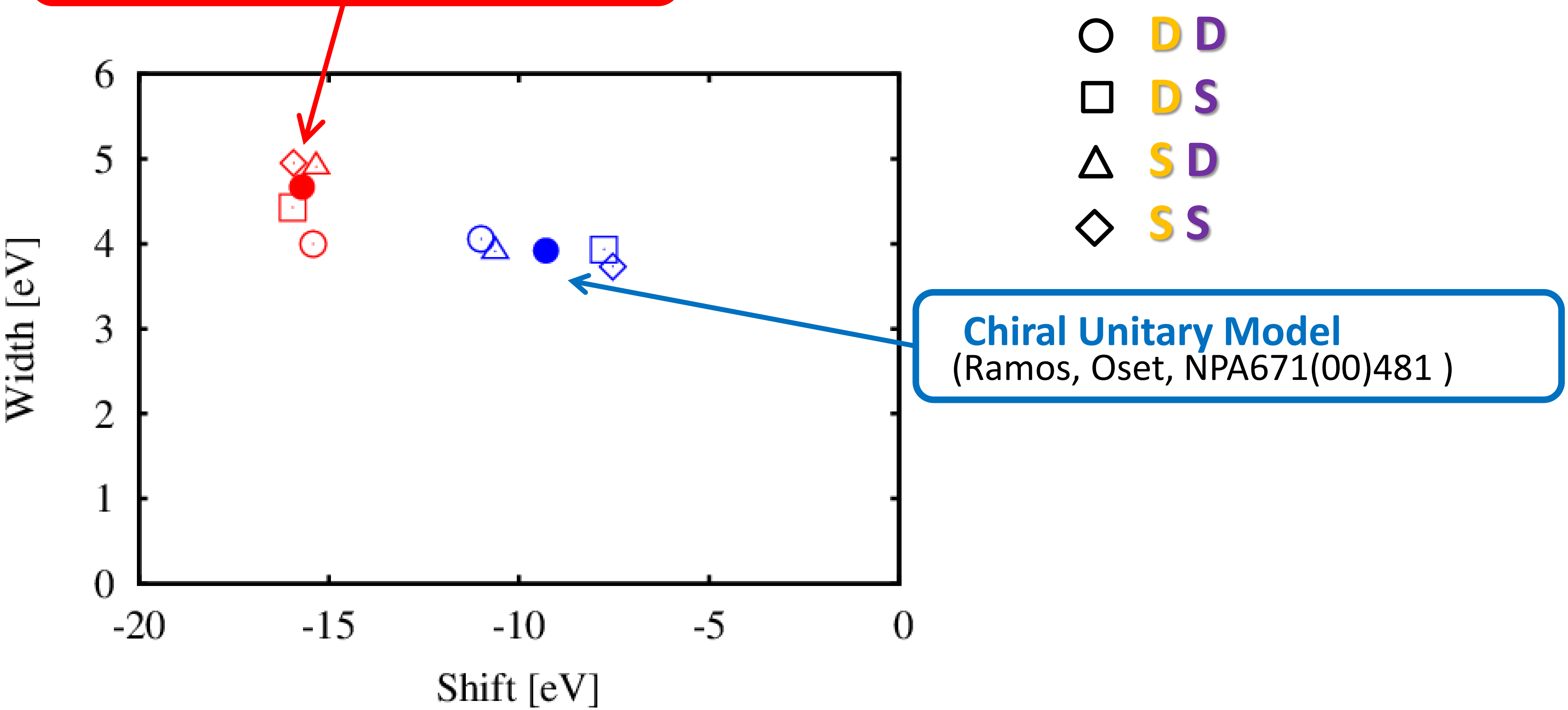


Chiral Unitary Model
(Ramos, Oset, NPA671(00)481)
$V_{\rm opt}(r=0) \sim -(40+55i)$ MeV
set(A)
set(B)

Calculated results of 7Li

Difference of energy shift is larger for 7Li than for 4He.
Can we distinguish these two potentials?

Phenomenological Model
(Mares, Friedman, Gal, NPA770(06)84)



SUMMARY

- We try to obtain the information on the kaon-nucleus interaction from the kaonic atoms.
- We calculated the energy shift for 4He/7Li corresponding to the X-ray spectroscopy experiment.
- From the calculated results, we found that high-resolution experiment is needed to distinguish two potentials.
  We expect high resolution for new experiment at J-PARC!
- We should not use the optical potential to a light nuclear case for more accurate calculation ?
- We search the kaon-nucleus systems (kaonic atom, kaonic nucleus) which gives us an answer for the potential strength.

Possibility of nuclear deformation by anti-kaon in Thomas-Fermi model

Junko Yamagata-Sekihara (RCNP, Osaka Univ.)
Satoru Hirenzaki (Nara Women's Univ.)

In this work

- We study **the possibility of nuclear deformation** by the existence of meson, especially **anti-kaon** as a typical example.

For a kaonic nuclear state, anti-kaon is mainly bound with the strong interaction to the nucleus. The strength of the interaction is still controversial.

- **The Thomas-Fermi model** is used in this work.

We could obtain the nuclear density all over the nuclear chart in a systematic manner.

- The nuclear shape is determined to minimize the total energy of the meson-nucleus system determined by following equation.

$$E_{\text{total}}[\rho] = E_{\text{nucleus}}[\rho] + E_{\text{meson}}[\rho]$$

Meson(Kaon) Energy : Klein-Gordon equation

In this work

STEP 1

We obtain **the nuclear density distribution** **(ρ_N)** by the Thomas-Fermi model by minimizing **the energy of nucleus** $E_{\mathrm{nucleus}}[\rho_N]$.

E_{nucleus} : The energy of nucleus is mainly determined with a equation of state (EOS) of uniform nuclear matter.

STEP 2

We obtain **the nuclear density** **(ρ)** of **meson-nucleus system** by minimizing **the total energy** $E_{\mathrm{total}}[\rho]$. The total energy is determined as

$$E_{\mathrm{total}}[\rho] = E_{\mathrm{nucleus}}[\rho] + E_{\mathrm{meson}}[\rho]$$

E_{nucleus} : The energy of nucleus is mainly determined with a equation of state (EOS) of uniform nuclear matter.

E_{meson} : The meson energy is obtained by solving the Klein-Gordon equation.

STEP 1 : The nuclear density

Thomas-Fermi model

Oyamatsu, NPA561(1993)181

- This model could describe well nuclear property (mass, radius, …) and is applied systematically to unstable nucleus, supernova matter, neutron star matter, not only stable nucleus.

$$E_{\text{nucleus}}[\rho] = \int d^3r \epsilon(\rho_n(\vec{r}), \rho_p(\vec{r})) + F_0 \int d^3r |\nabla \rho(\vec{r})|^2$$

$$+ \frac{e^2}{2} \int d^3r \int d^3r' \frac{\rho_p(\vec{r})\rho_p(\vec{r}')}{|\vec{r} - \vec{r}'|}$$

* **Main term** (determined by a equation of state (EOS) of uniform nuclear matter)
* **Density inhomogeneity term** (the most important term in determining the shape of the nuclear surface)
* **Coulomb term**

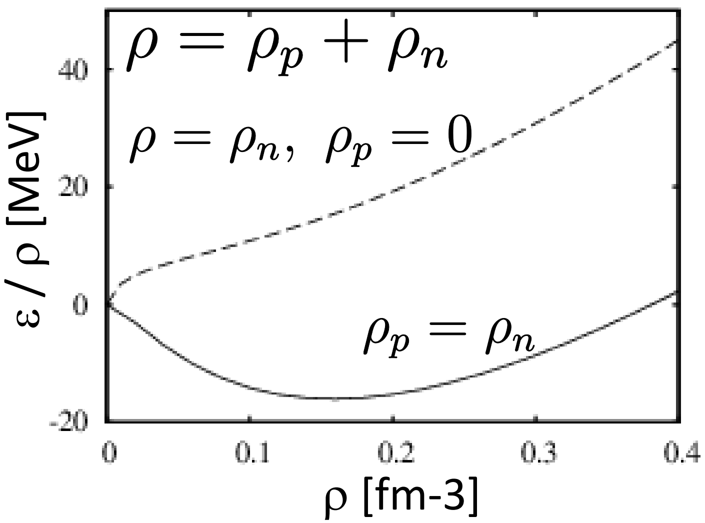
We use the Woods-Saxon form as the density distribution. Two parameters (c, a) are obtained by minimizing the energy of nucleus.

$$\rho(r) = \frac{\rho_0}{1 + \exp((r-c)/a)}$$

STEP 1 : The nuclear density

- EOS (equation of state)

  Oyamatsu, NPA561(1993)181



- Density distribution

Woods-Saxon form

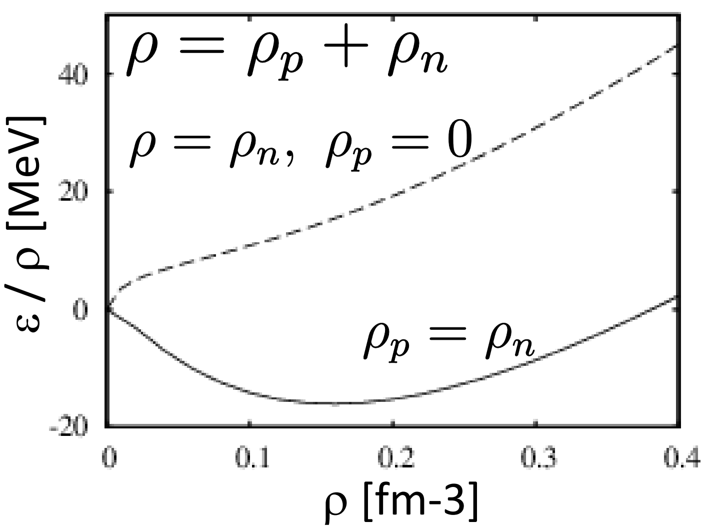
$$\rho(r) = \frac{\rho_0}{1 + \exp((r - c)/a)}$$

c, a : parameter

STEP 1 : The nuclear density

- EOS (equation of state)

  Oyamatsu, NPA561(1993)181



- Density distribution

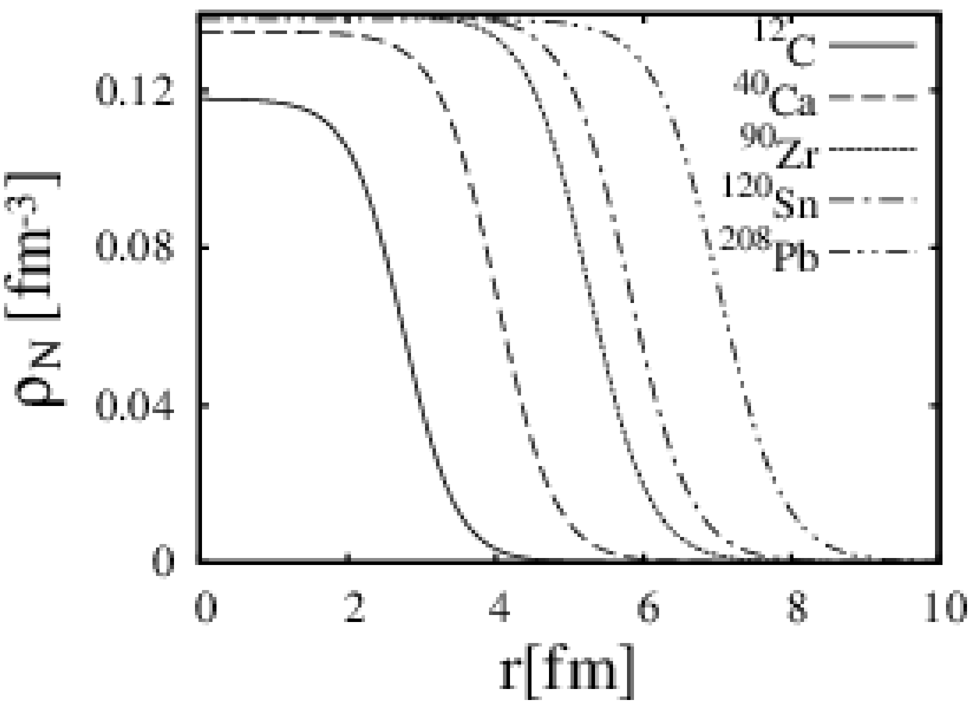
Woods-Saxon form

$$\rho(r) = \frac{\rho_0}{1 + \exp((r - c)/a)}$$

c, a : parameter

- **Results of nuclear density**

Nucleus : ^{12}C, ^{40}Ca, ^{90}Zr, ^{120}Sn, ^{208}Pb



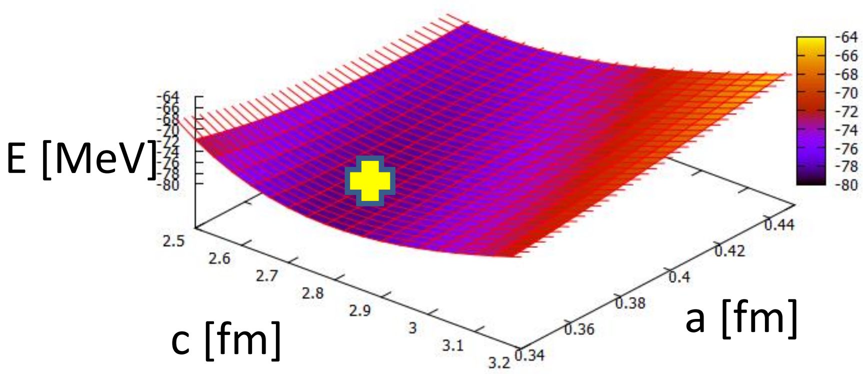
- Good systematics from light to heavy nuclei
- Central densities tend to be small.

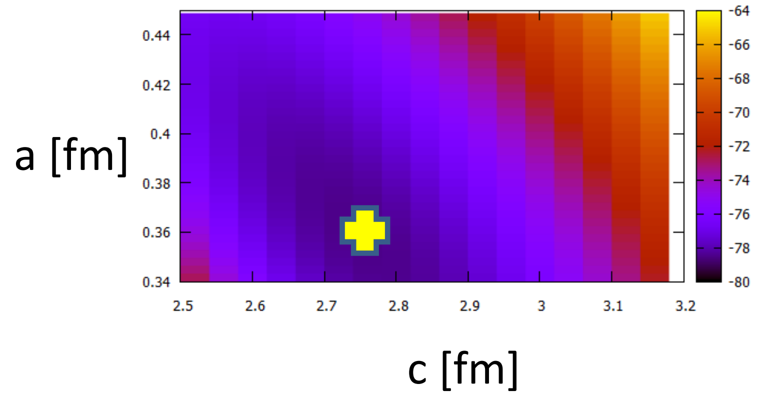
STEP 2 :The nuclear density of meson-nucleus system

- We search the parameters of nuclear density of meson-nucleus system which satisfy **the minimum total energy condition**.
- The nuclear density distribution with the minimum total energy is the solution we look for.

$$\rho(r) = \frac{\rho_0}{1 + \exp((r-c)/a)}$$

$$E_{\rm total}[\rho] = E_{\rm nucleus}[\rho] + E_{\rm meson}[\rho]$$





STEP 2 :The nuclear density of meson-nucleus system

- **We search parameters in the nuclear density.**

We use the Woods-Saxon form as the density distribution and look for two parameters (c, a) satisfying the total energy minimum condition.

$$\rho(r) = \frac{\rho_0}{1 + \exp((r - c)/a)}$$

- **The energy of nucleus is determined in the same manner as the Thomas-Fermi model.**

Oyamatsu, NPA561(1993)181

$$E_{\mathrm{nucleus}}[\rho] = \int d^3r \epsilon(\rho_n(\vec{r}), \rho_p(\vec{r})) + F_0 \int d^3r |\nabla \rho(\vec{r})|^2 + \frac{e^2}{2} \int d^3r \int d^3r' \frac{\rho_p(\vec{r})\rho_p(\vec{r}')}{|\vec{r} - \vec{r}'|}$$

* Main term (determined by a equation of state (EOS) of uniform nuclear matter)
* Density inhomogeneity term (the most important term in determining the shape of the nuclear surface)
* Coulomb term

STEP 2 :The nuclear density of meson-nucleus system

- **The meson energy is obtained by solving the Klein-Gordon equation.**

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

μ : reduced mass

Vopt(r) : the optical potential of kaon-nucleus system

$$\mathrm{Re}V_{\mathrm{opt}}(r) = V_0 \frac{\rho(r)}{\rho_N(0)}$$

V0 : **parameter** (-50 to -150 MeV)

ρ_N : nuclear density without kaon
(obtained by minimizing **only** Enucleus)

$$\mathrm{Im}V_{\mathrm{opt}}(r, E)$$

: Chiral Unitary Model
Ramos, Oset, NPA671(06)84

Vcoul(r) : finite-size coulomb potential

$$V_{\mathrm{coul}}(r) = -e^2 \int \frac{\rho_p(r')}{|\vec{r} - \vec{r'}|}$$

The strength of kaon-nucleus interaction is still controversial. Thus, we treat V0 as parameter with the range of V0 = -50 to -150 MeV which is roughly covering the strength of the candidates of kaon-nucleus potential.

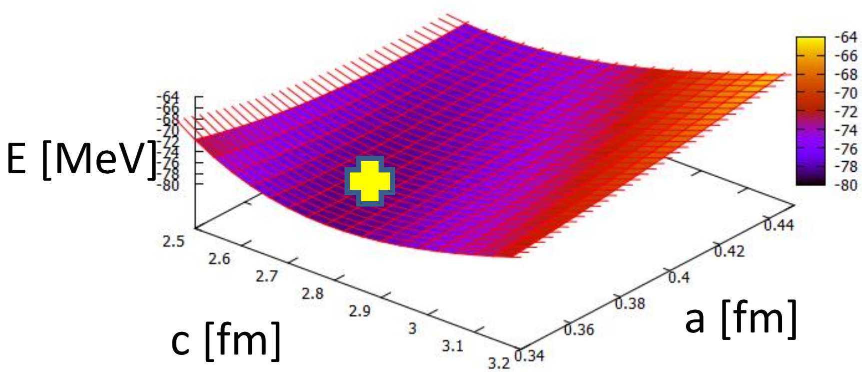
We solve the KG equation to obtain a kaon energy of the deepest state.

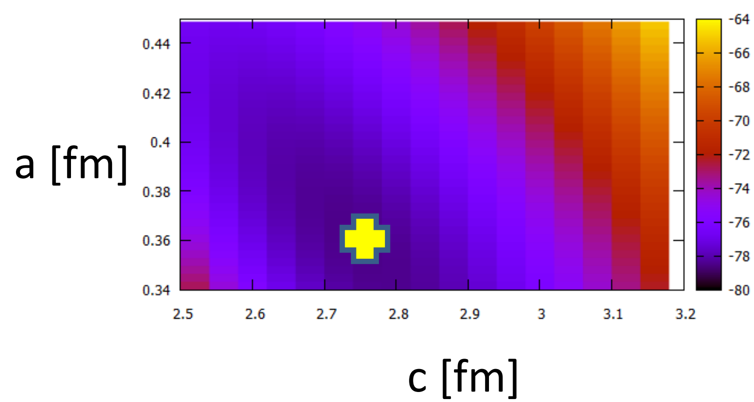
STEP 2 :The nuclear density of meson-nucleus system

- We search the parameters of nuclear density of meson-nucleus system which satisfy **the minimum total energy condition**.
- The nuclear density distribution with the minimum total energy is the solution we look for.

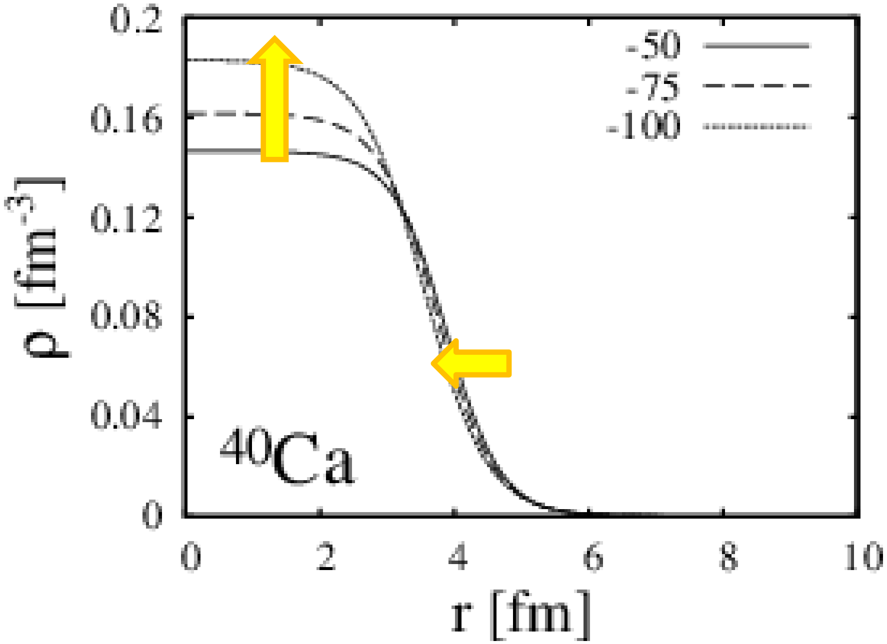
$$E_{\mathrm{total}}[\rho] = \underline{E_{\mathrm{nucleus}}[\rho]} + \underline{E_{\mathrm{meson}}[\rho]}$$

$$\rho(r) = \frac{\rho_0}{1 + \exp((r-c)/a)}$$





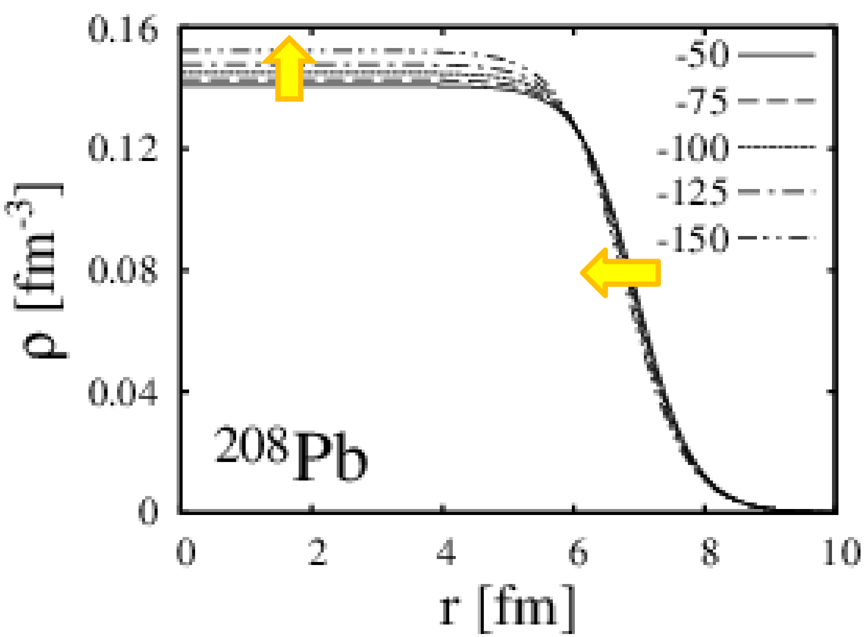
RESULTS



$$\mathrm{Re}V_{\mathrm{opt}}(r) = V_0 \frac{\rho(r)}{\rho_N(0)}$$

BE and Width of Deepest Kaon state

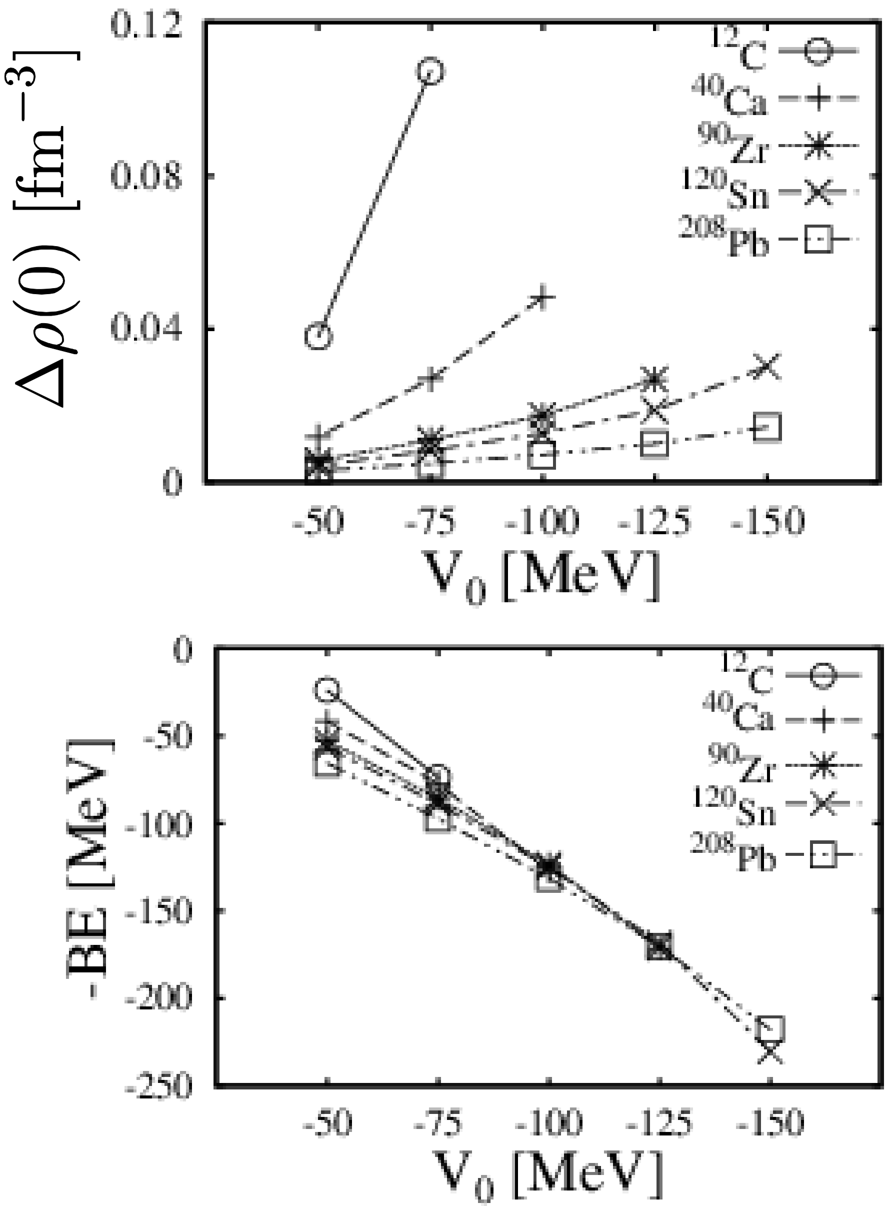
V0	BE [MeV]	Width [MeV]
-50	41.89	91.48
-75	77.24	82.81
-100	127.59	39.11



V0	BE [MeV]	Width [MeV]
-50	65.71	94.70
-75	97.45	49.05
-100	131.40	28.75
-125	170.18	12.45
-150	217.80	5.40

The central nuclear density becomes higher for the deeper kaon state in each nucleus.

RESULTS



$$\Delta\rho(0) \equiv \rho(0) - \rho_N(0)$$

In the case of 12C, the change of the central nuclear density is the largest .

We find the effect of meson existence is larger for lighter nucleus.

We also find the stronger potential causes deeper kaon states and higher nuclear density in each nucleus.

However, the density distribution is fixed to the Woods-Saxon functional form in this work.

Very ‘local’ meson effect could not be expressed by this form.

We should use more flexible density form to Thomas-Fermi model in the next step.

SUMMARY

- We report the possibility of nuclear deformation by the existence of meson, especially **anti-kaon** as a typical example.
- **The Thomas-Fermi model** is used in this work.

We could obtain the nuclear density all over the nuclear chart systematically.

- The density form we assumed is **the Woods-Saxon functional form**.

- From the calculated results, we find the strong potential causes deeper kaon states and higher nuclear density in each nucleus and the effect of meson existence is larger for lighter nucleus.

- We should use a flexible density form to Thomas-Fermi model to consider the 'local' deformation. We will use the mixing form of two types of functions which has four parameters.

$$\rho_{\mathrm{WSG}}(r) = \frac{(1-F)\rho_0}{1+\exp((r-c)/a_1)} + F\exp(-\frac{r^2}{2a_2})$$

SUMMARY

- This is a first step to investigate proper meson-nucleus systems to study the aspect of symmetry at various nuclear densities !!
- In case with mesons of quite strong interaction, the system could be also used to investigate the equation of state itself.

Thank you for your attention !