Spectrum of kaonic atom and kaon-nucleus interaction revisited

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Motivation

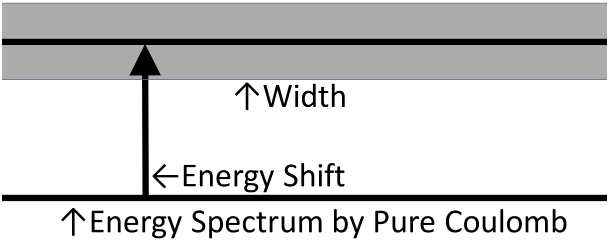
K^--nucleus interaction is

- the fundamental information of hadron physics (K is one of NG bosons)

Kaonic atom spectrum $\rightarrow$ K^--nucleus interaction

Kaonic atom

- Kaonic atom is a bound system of K^- and nucleus mainly by Coulomb interaction
  i.e. The orbital electron is replaced by K^-
- K^- interacts strongly with nucleus $\rightarrow$ EM + strong
- The strong interaction provides energy shift from pure Coulomb spectrum
- Nuclear absorption provides decay width



Phenomenological potential by Friedman, Gal and Batty[1]

- global fit with all data
- 4 model ($t_{\rm eff}\rho$, Infl., Comp, Nominal)
- $t_{\rm eff}\rho$ **model** is linear in nuclear density :

  $V_{\rm opt}(r) = -\frac{4\pi}{2\mu}(1+\frac{\mu}{m_N})(0.69+0.94i)\rho(r)$

  ${\rm Re}\,V_{\rm opt}(0) \sim -80$ MeV, ${\rm Im}\,V_{\rm opt}(0) \sim -110$ MeV

- **Nominal model** is famous "**deep**" potential including **non-linear term** :

  $V_{\rm opt}(r) = -\frac{4\pi}{2\mu}\left(1+\frac{\mu}{m_N}\right)\left[(-0.15+0.62i)+(1.63-0.01i)\left(\frac{\rho(r)}{\rho(0)}\right)^{0.21}\right]\rho(r)$

  ${\rm Re}\,V_{\rm opt}(0) \sim -180$ MeV, ${\rm Im}\,V_{\rm opt}(0) \sim -70$ MeV

[1] E. Friedman, A. Gal, C.J. Batty, Nucl. Phys. A579(1994)518-538

Aim of this study

- Puzzle :
  - The energy shift is found to be **repulsive** in all kaonic atoms
  - But the K^-N interaction is known to be **attractive**
  - How do we understand the inconsistency between K^-A and K^-N ?
- Possible solutions of this puzzle :
  1. **Attractive** strong interaction provides **Bound state (nuclear state)**. It repels the atomic states upwards (**level repulsion**)
  2. **Large imaginary part of optical potential** works as **repulsively**.
- Purpose : Which solution is realized in actual kaonic atom ?

Klein-Gordon equation

$$\left[-\left\{\mu - B.E. - \frac{i}{2}\Gamma - V_c(r)\right\}^2 - \frac{\mathrm{d}^2}{\mathrm{d}r^2} + \frac{l(l+1)}{r^2} + \mu^2 + 2\mu V_{\mathrm{opt}}(r)\right] rR(r) = 0$$

$V_c(r)$: finite Coulomb potential $\rightarrow$ EM interaction
$2\mu V_{\mathrm{opt}}(r)$: self energy $\rightarrow$ Strong interaction

$K^{-}A$ strong interaction linear potential

$$V_{\mathrm{opt}}(r) = (V_0 + iW_0)\frac{\rho_N(r)}{\rho_0} = (V_0 + iW_0)\frac{1}{1+\exp\left(\frac{r-R_B}{a}\right)}$$

V_0, W_0 : parameters fitted by datum for each kaonic atom
$W_0 < 0$ because of nuclear absorption
assume : potential is proportional to ρ_N
and $V_0 < 0$ because $K^{-}N$ interaction is attractive

Our approach

We study strong potential in the following 2 steps :

1. determine potential parameters so as to reproduce one experimental datum for each kaonic atom
   Datum (ΔE, Γ) $\xrightarrow[\text{each nucleus}]{\text{input}}$ KG eq $\xrightarrow{\text{output}}$ Parameter($V_0,\ W_0$)
2. confirm whether these potentials describe the data of other kaonic atoms
   check universality : potential fitted by Cu $\rightarrow$ Co, Ni

1 : determine potential parameters

Potential is not determined uniquely.

→We find 3 potentials which provide same datum (0<$-V_0$, $-W_0$<500 MeV)

These potentials have different features from each other.

Potentials for kaonic Cu atom (last orbit : 4f)

using datum (ΔE, Γ) = (0.240 keV, 1.65 keV)

nucleus	ℓ	potential	$-V_0$[MeV]	$-W_0$[MeV]	feature
Cu	3	pot 1	79.5	114.5	large $\mathrm{Im}\, V_{\mathrm{opt}}$
		pot 2	78.5	20.0	small $\mathrm{Im}\, V_{\mathrm{opt}}$
		pot 3	199.5	28.5	deep $\mathrm{Re}\, V_{\mathrm{opt}}$, small $\mathrm{Im}\, V_{\mathrm{opt}}$

How about wave functions of kaonic atom using these potentials ?

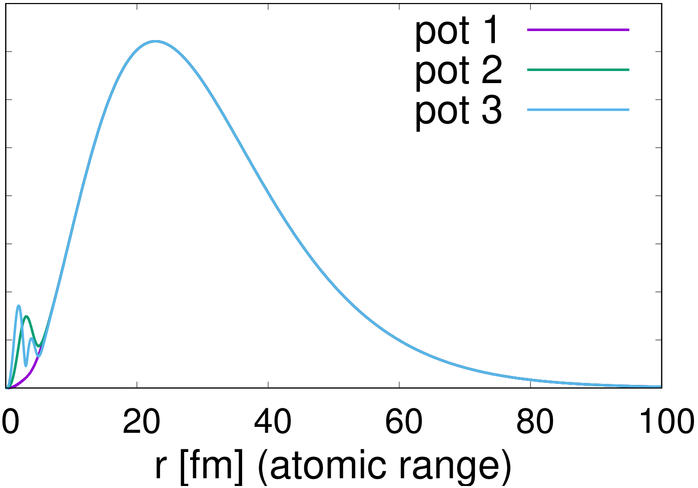


Figure 1: wave functions of Cu kaonic atom

Wave functions are similar to one another in atomic range ($r = 10 \sim 100$ fm)

Wave function of kaonic atom

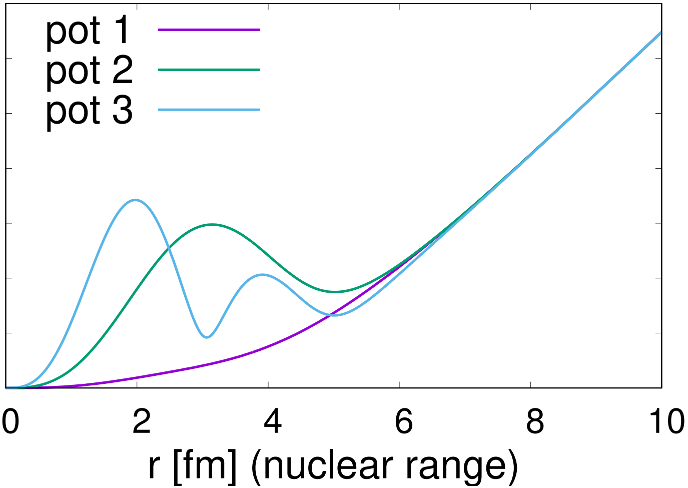


Figure 2: wave functions of Cu kaonic atom

Wave functions are different in nuclear range ($r = 0 \sim 10\ \mathrm{fm}$)

The number of nodes(nuclear states) is different

Nuclear state which has same angular momentum (Cu, $l = 3$)

- **Potential 1** provides no nuclear states ($l = 3$)
- **Potential 2** provides a nuclear state ($l = 3$):
  $-B.E. - i\Gamma/2 = (-5.8 - i22.4/2)$ MeV $\rightarrow$ level repulsion
- **Potential 3** provides 2 nuclear states ($l = 3$):
  $-B.E. - i\Gamma/2 = (-102.5 - i57.0/2)$ MeV(ground state)
  $-B.E. - i\Gamma/2 = (-17.65 - i32.0/2)$ MeV $\rightarrow$ level repulsion

Large Im part (Potential 1)

We find that potentials of other kaonic atoms have similar feature

last orbit : 3d	pot 1	
nucleus(Z,A)	$-V_0$[MeV]	$-W_0$[MeV]
Mg	24.5	79.0
Al	46.0	126.0
Si	61.5	120.5
P	67.0	142.0
S	79.0	142.0
Cl	79.0	142.0

last orbit : 4f	pot 1	
nucleus(Z,A)	$-V_0$[MeV]	$-W_0$[MeV]
Co	28.5	91.0
Ni	79.0	164.0
Cu	79.5	114.5
Cu2[2]	23.5	134.0

Potentials 1 have large imaginary part.

[2] another experimental datum of Cu

Small Im part (Potential 2)

We find that potentials of other kaonic atoms have similar feature

last orbit : 3d	pot 2	
nucleus(Z,A)	$-V_0$[MeV]	$-W_0$[MeV]
Mg	128.5	24.0
Al	126.0	28.0
Si	116.5	31.0
P	100.5	26.5
S	93.0	27.0
Cl	84.0	26.5

last orbit : 4f	pot 2	
nucleus(Z,A)	$-V_0$[MeV]	$-W_0$[MeV]
Co	93.5	17.5
Ni	82.5	16.0
Cu	78.5	20.0
Cu2	82.5	14.5

Potentials 2 have small imaginary part.

Deep Re part, small Im part(Potential 3)

We find that potentials of other kaonic atoms have similar feature

last orbit : 3d	pot 3	
nucleus(Z,A)	$-V_0$[MeV]	$-W_0$[MeV]
Mg	305.0	24.5
Al	316.0	32.5
Si	301.0	35.5
P	270.0	36.5
S	258.0	38.5
Cl	231.0	38.5

last orbit : 4f	pot 3	
nucleus(Z,A)	$-V_0$[MeV]	$-W_0$[MeV]
Co	215.5	19.5
Ni	203.5	27.0
Cu	199.5	28.5
Cu2	197.0	20.0

Potentials 3 have deep real part and small imaginary part.

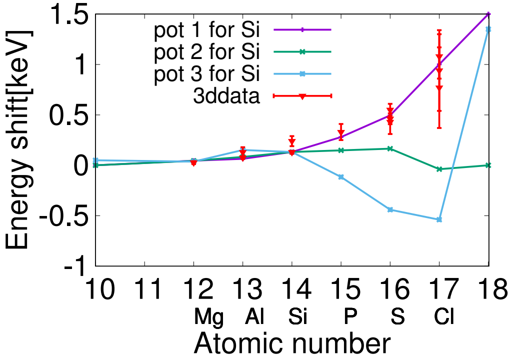
2 : confirm universality of potentials

Potentials fitted by Si

datum (E shift, Γ) = (0.130 keV, 0.800 keV)

($-V_0$ [MeV],$-W_0$ [MeV]) = (61.5, 120.5), (116.5, 31.0), (301.0, 35.5)

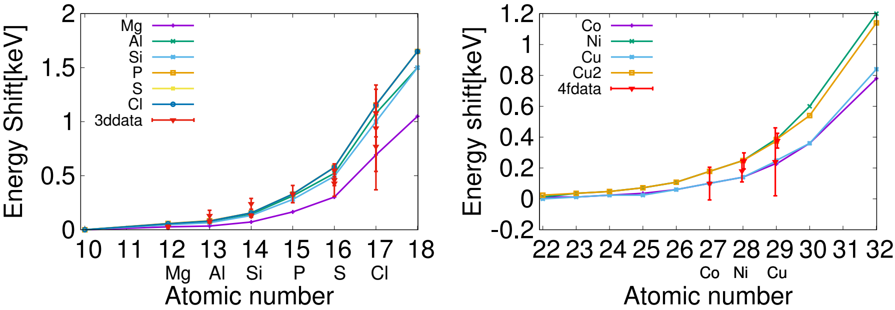
Pot 1 Pot 2 Pot 3



It seems that potential 1 is best of 3 potentials.

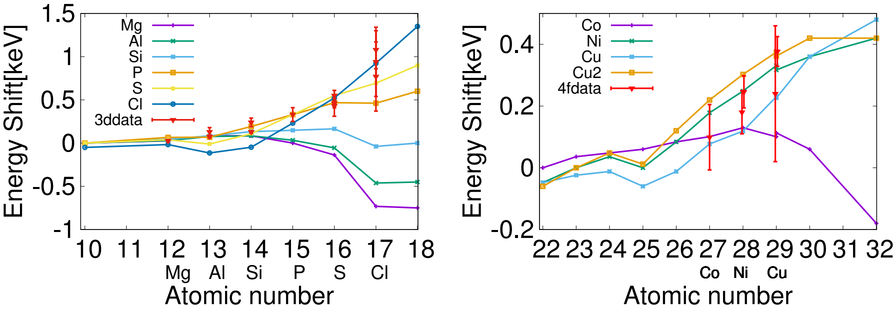
$\rightarrow$ How about potentials fitted by other kaonic atoms ?

Large Im part (Potential 1)



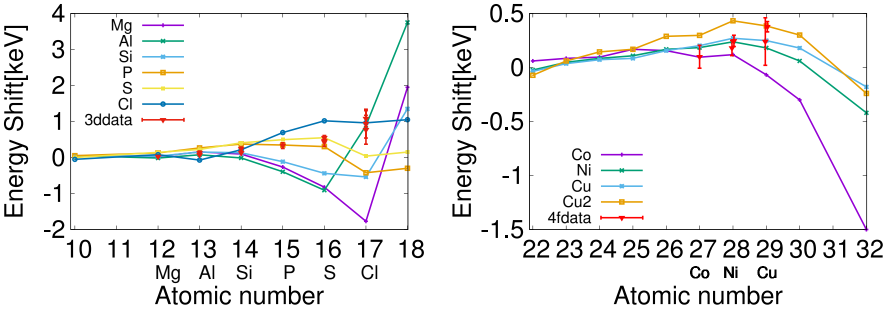
Potential 1 (large $\mathrm{Im}\,V_{\mathrm{opt}}$) globally explains the data
and provides repulsive shifts in all kaonic atoms.

Small Im part (Potential 2)



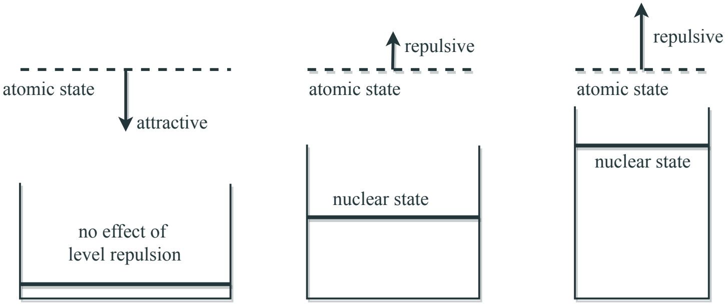
It is hard to explain repulsive shifts universally using **Potential 2** (small $\mathrm{Im}\,V_{\mathrm{opt}}$).

Deep Re part, small Im part(Potential 3)



It is hard to explain repulsive shifts universally using **Potential 3** (small $\mathrm{Im}\, V_{\mathrm{opt}}$).

Why do not potentials 2 and 3 work well ?



Potentials 2 and 3 provide nuclear state (NS) and repulsive shift in atomic state (AS) is provided by level repulsion of NS.
AS is sensitive to energy spectrum of NS.
Energy spectrum of NS depends on potential size, which is proportional to mass number A.
$\rightarrow$Potential fitted by one kaonic atom does not necessarily provide repulsive shifts in other kaonic atoms

summary - 1

- Potential 1 (large $\mathrm{Im}\, V_{\mathrm{opt}}$) globally explains the data and provides repulsive shifts in all kaonic atoms.
    - large imaginary potential $\mathrm{Im}\, V_{\mathrm{opt}}$ works well !

  It is hard to explain repulsive shifts universally using Potentials 2 and 3 (small $\mathrm{Im}\, V_{\mathrm{opt}}$).

summary - 2

Puzzle

- The energy shift is found to be **repulsive** in all kaonic atoms
- But the $K^- N$ interaction is known to be **attractive**
- How do we understand the inconsistency between $K^- A$ and $K^- N$?

Answer

- **Imaginary part plays an important role in K^--nucleus potential**

× Bound state provided by attractive strong interaction (nuclear state), which repels the atomic states upwards (**level repulsion**) : potential 2, 3

○ **Imaginary potential $\mathrm{Im}\, V_{\mathrm{opt}}$, which works as repulsive interaction : potential 1**

outlook

Nominal type potential includes non-linear term.
$\rightarrow$ We are studying an effect of non-linear term.

Imaginary part of nominal type potential is large :
$\mathrm{Im}\, V_{\mathrm{opt}}(0) \sim -70$ MeV
$\rightarrow$ It seems that imaginary part plays essential role for repulsive shifts in kaonic atoms like $t_{\mathrm{eff}}\rho$ (potential 1).

Large Im part (Potential 1)

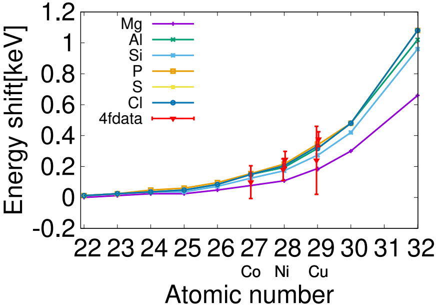


Figure 3: potentials fitted by l.o = 3d are applied to l.o = 4f

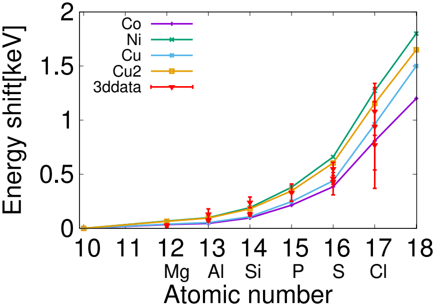


Figure 4: potentials fitted by l.o = 4f are applied to l.o = 3d

Potential 1 (large $\mathrm{Im}\, V_{\mathrm{opt}}$) globally explains the data and provides repulsive shifts in all kaonic atoms.

Small Im part (Potential 2)

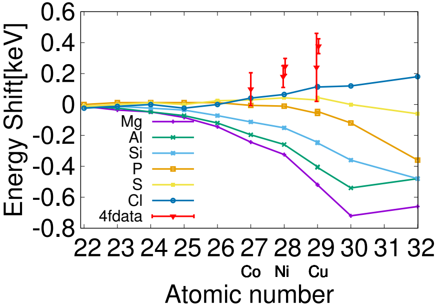


Figure 5: potentials fitted by l.o = 3d are applied to l.o = 4f

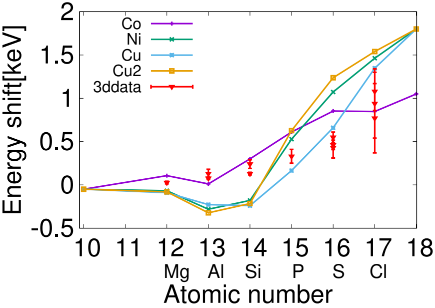


Figure 6: potentials fitted by l.o = 4f are applied to l.o = 3d

It is hard to explain repulsive shifts universally using **Potential 2** (small $\mathrm{Im}\, V_{\mathrm{opt}}$).

Deep Re part, small Im part(Potential 3)

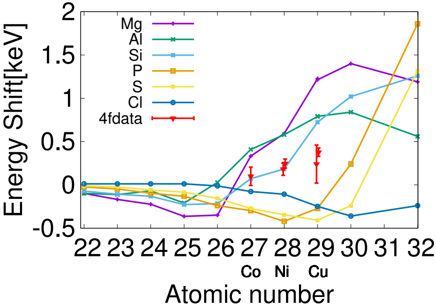


Figure 7: potentials fitted by l.o = 3d are applied to l.o = 4f

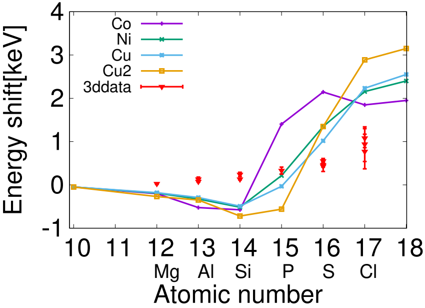


Figure 8: potentials fitted by l.o = 4f are applied to l.o = 3d

It is hard to explain repulsive shifts universally using **Potential 3** (small $\mathrm{Im}\, V_{\mathrm{opt}}$).