The 20th International Conference on Hadron Spectroscopy and Structure (HADRON 2023),
Genova, Italy, June 5th – 9th 2023.

Kaonic atom optical potential by the high precision data of Kaonic He atoms

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KYOTO SANGYO UNIVERSITY

Time/Place: 17:20 – 17:40, 6 June (Tue.) 2023, DAD-Room 1A

【0】Introduction: Meson in nuclear medium

schematic view of the mass of π, K, η & η'

(1) Aspects of the Strong Int. Symmetry

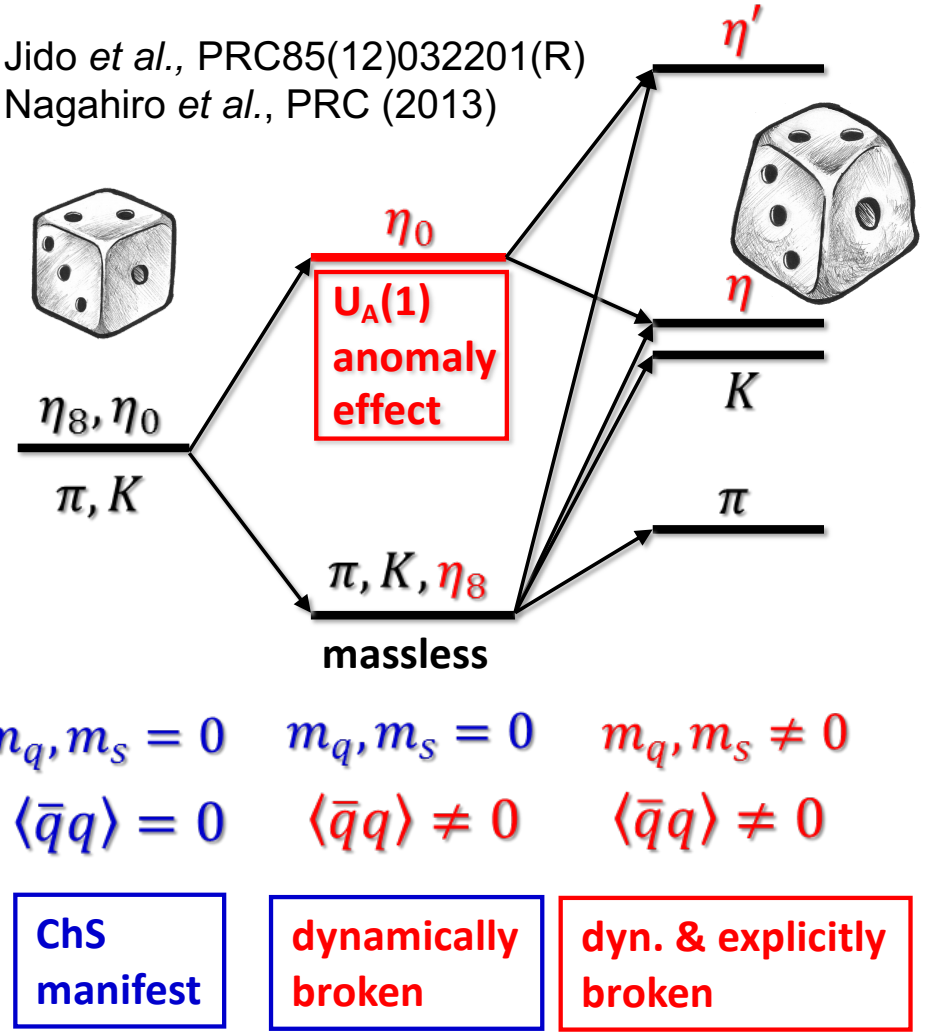
(2) Baryon resonance at finite density

$\Lambda(1405)$

$N^*(1535)$

(3) Exotic systems

Jido *et al.*, PRC85(12)032201(R)
Nagahiro *et al.*, PRC (2013)



Kaonic atom in ^{3,4}He

Hirenzaki, Okumura, Toki, Oset, Ramos
PRC61(2000)055205

anomalous Shift ??

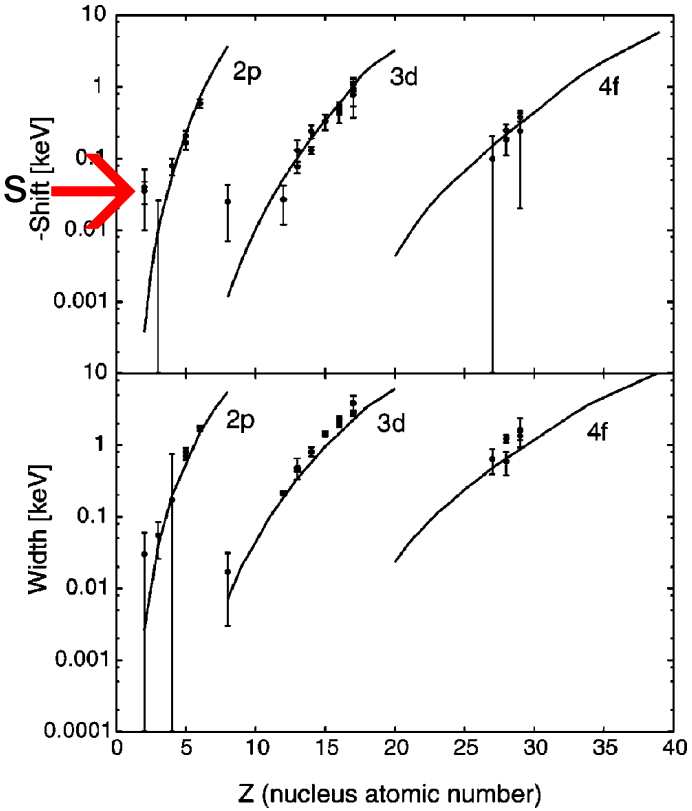


FIG. 3. The calculated energy shifts and widths are shown as functions of the nucleus atomic number for $2p$, $3d$, and $4f$ kaonic atom states. Experimental data are also shown [20].

Mystery in last century

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Hirenzaki, Okumura, Toki, Oset, Ramos
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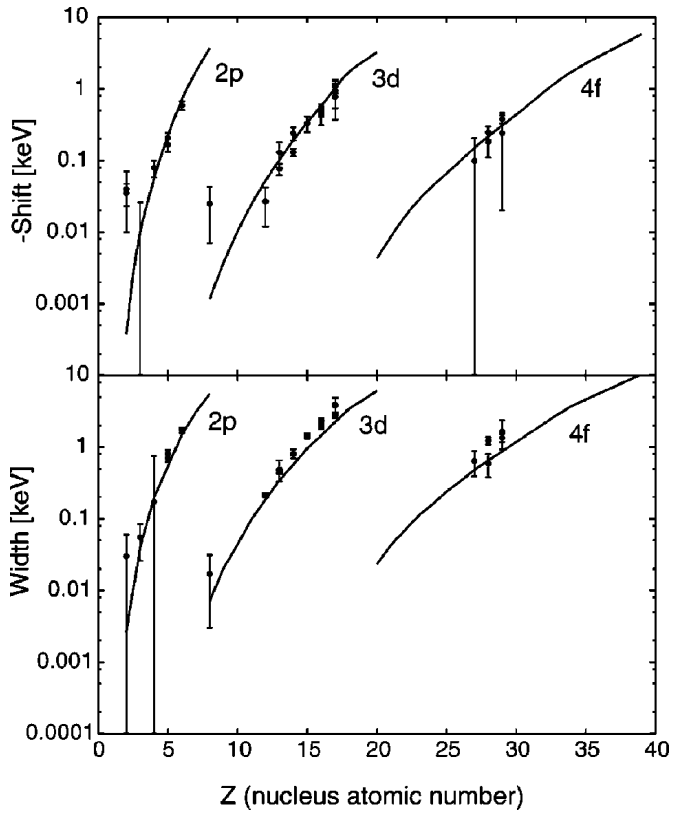


FIG. 3. The calculated energy shifts and widths are shown as functions of the nucleus atomic number for $2p$, $3d$, and $4f$ kaonic atom states. Experimental data are also shown [20].

Mystery in last century and this century

Y. Akaishi, Proc. of EXA2005 (2006) 45-53

anomalous Shift ??

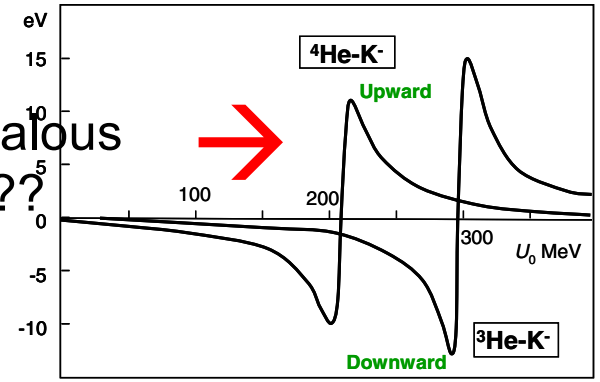


Figure 4: $2p$ level shifts of the K^--^{4}He and K^--^{3}He atoms calculated by the use of the coupled-channel model with $U_{\rm coupl} = 120$ MeV.

Large shift and width
<=> Generation of new nuclear state

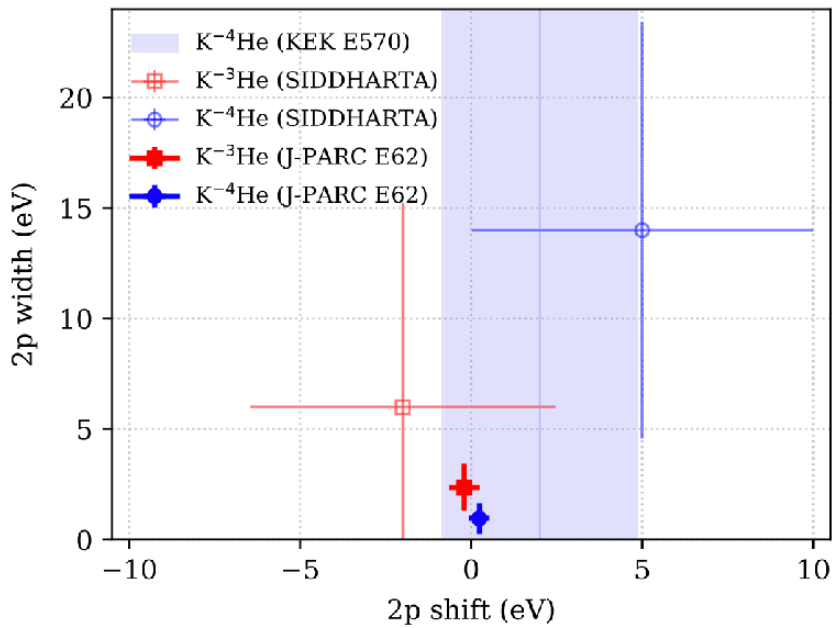
Kaonic atom in ^{3,4}He

Measurements of Strong-Interaction Effects in Kaonic-Helium Isotopes at Sub-eV Precision with X-Ray Microcalorimeters

X-ray, 3d→2p process, ^{3}He and ^{4}He
shift + width error ~ 1eV

J-PARC E62

T. Hashimoto et al., Phys. Rev. Lett. 128, 112503 (2022)



$$\Delta E_{2p} \equiv E^{\rm exp}_{3d\to 2p} - E^{\rm e.m.}_{3d\to 2p}$$

$$\Delta E_{2p}^{K^-{}^3\mathrm{He}} = -0.2 \pm 0.4(\mathrm{stat}) \pm 0.3(\mathrm{syst})\ \mathrm{eV},$$

$$\Delta E_{2p}^{K^-{}^4\mathrm{He}} = 0.2 \pm 0.3(\mathrm{stat}) \pm 0.2(\mathrm{syst})\ \mathrm{eV}.$$

$$\Gamma_{2p}^{K^-{}^3\mathrm{He}} = 2.5 \pm 1.0(\mathrm{stat}) \pm 0.4(\mathrm{syst})\ \mathrm{eV},$$

$$\Gamma_{2p}^{K^-{}^4\mathrm{He}} = 1.0 \pm 0.6(\mathrm{stat}) \pm 0.3(\mathrm{syst})\ \mathrm{eV}.$$

- High-precision measurement of kaonic ^{3}He and ^{4}He.

We theoretically investigate the information regarding the kaon-nucleus potential deduced from J-PARC E62.

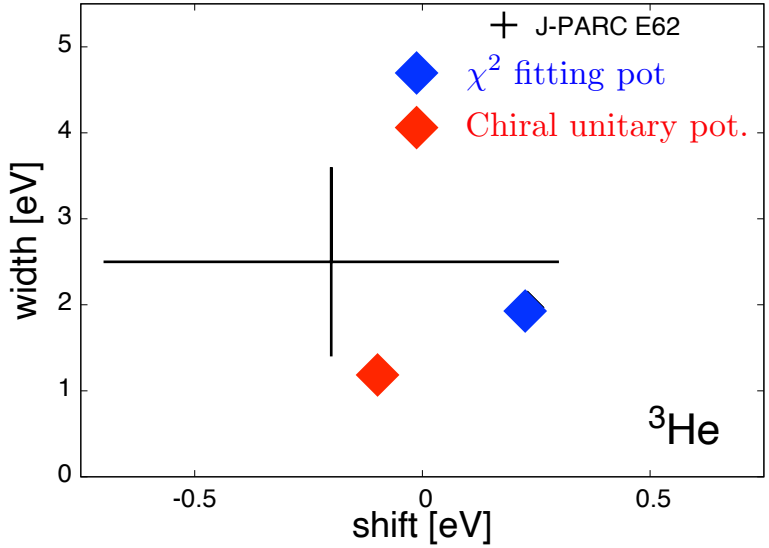
Kaonic atom in ^{3,4}He

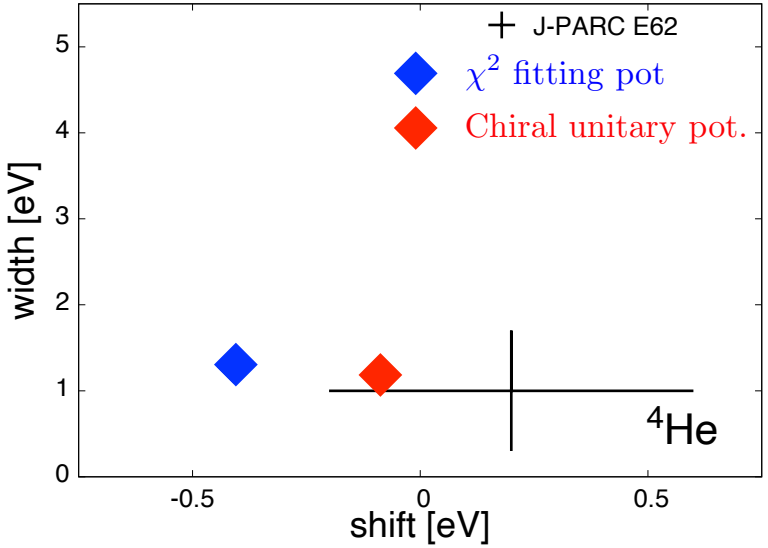
Results of Theoretical potentials $U_{\rm TH}(r) = -\frac{4\pi}{2\mu}\left(1+\frac{m_K}{M_N}\right)a(\rho)\rho(r)$

Chiral unitary pot. A. Ramos and E. Oset, Nucl. Phys. A **671**, 481-502 (2000).

X^2 fitting pot. J. Mares, E. Friedman and A. Gal, Nucl. Phys. A **770**, 84-105 (2006)

$$[-\nabla^2 + \mu^2 + 2\mu U(r)]\phi(\boldsymbol{r}) = [E - V_{\rm em}(r)]^2\phi(\boldsymbol{r})$$





"Shift" positive means "attraction".

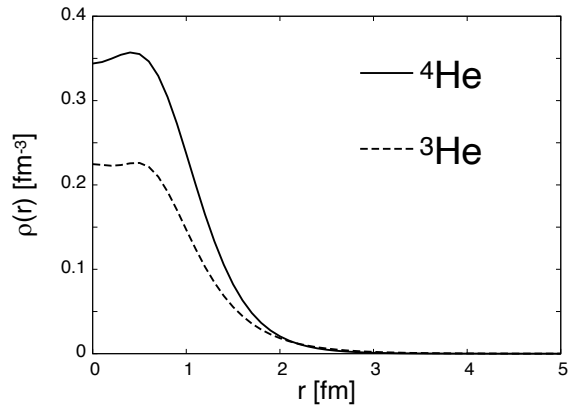
$V_{\rm em}(r)$: Finite size Coulomb + Uehling

$$\text{shift} = (E_{3d}^{\rm opt+em} - E_{2p}^{\rm opt+em}) - (E_{3d}^{\rm em} - E_{2p}^{\rm em})$$

$$\text{width} = \Gamma_{2p}$$

T. Hashimoto et al., [J-PARC E62], Phys. Rev. Lett. 128 , 112503(2022)

Kaon-Nucleus interaction



- ^{4}He and ^{3}He nuclear density
  (calculated by Prof. Hiyama)

  [Hiyama, Pro. Theor. Exp. Phys. 12(12)01A204]
  [Hiyama and Kamimura, Front. Phys. (Beijing) 13(18) 132106]

- Kaon-nucleus potential : Phenomenological Type $U_{\rm PH}(r)$

$$U_{\rm PH}(r) = (V_0 + iW_0)\frac{\rho(r)}{\rho_0}$$

$\rho_0 = 0.17\ {\rm fm}^{-3}$

: parameter

We postulate that the kaon-nucleus interaction is dominated by the isoscalar potential.

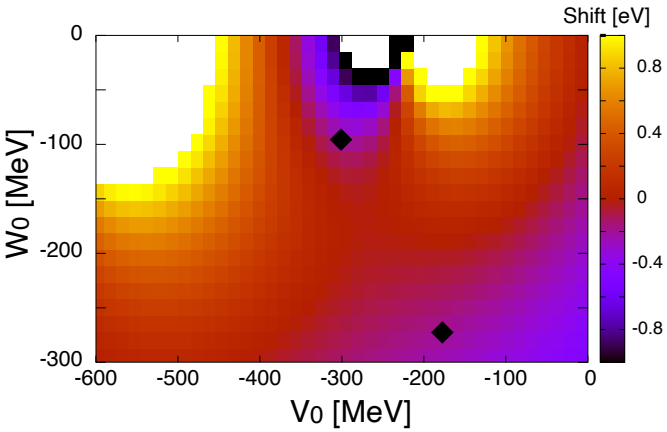
- Using this simple $T\rho$ potential, we try to reproduce the J-PARC E62 data.

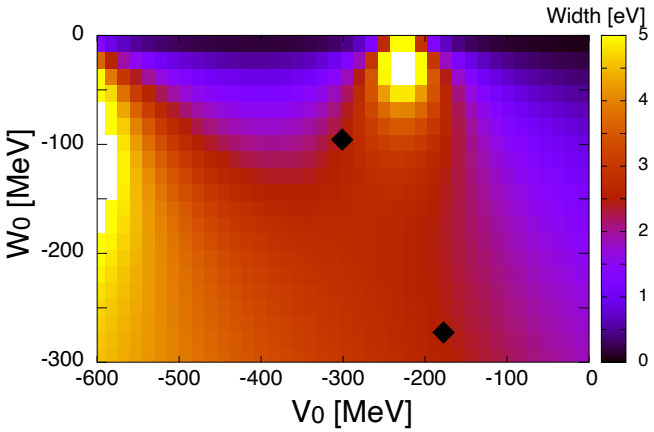
$$[-\nabla^2 + \mu^2 + 2\mu U_{\rm PH}(r)]\phi(\boldsymbol{r}) = [E - V_{\rm em}(r)]^2\phi(\boldsymbol{r})$$

Kaonic atom in ^{3,4}He : Results for ^{3}He

- Calculated Results
- Potential depth at normal nuclear density
- Realistic density (by Prof. Hiyama)

$$U_{\mathrm{PH}}(r) = (V_0 + iW_0)\frac{\rho(r)}{\rho_0}$$





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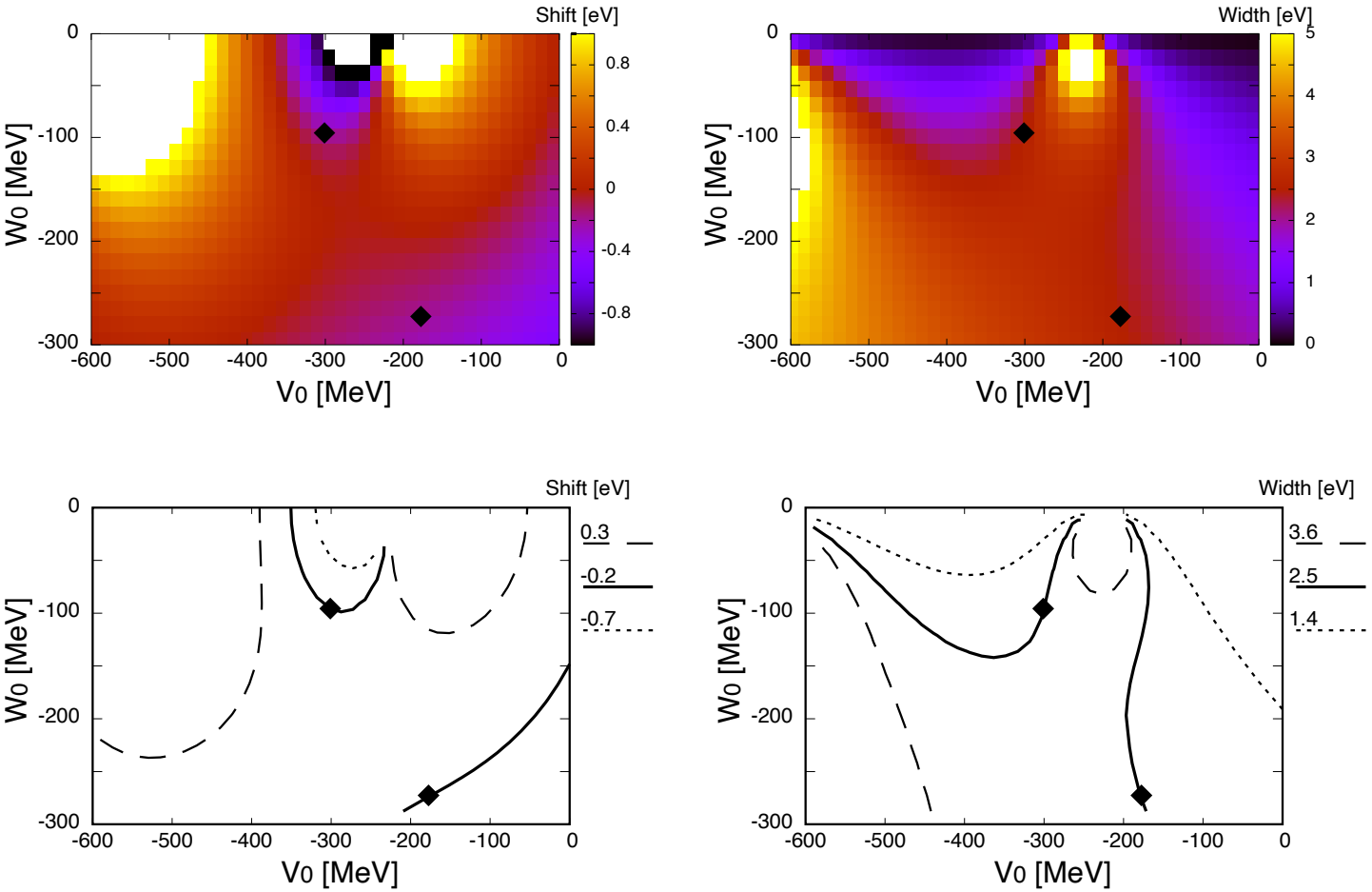

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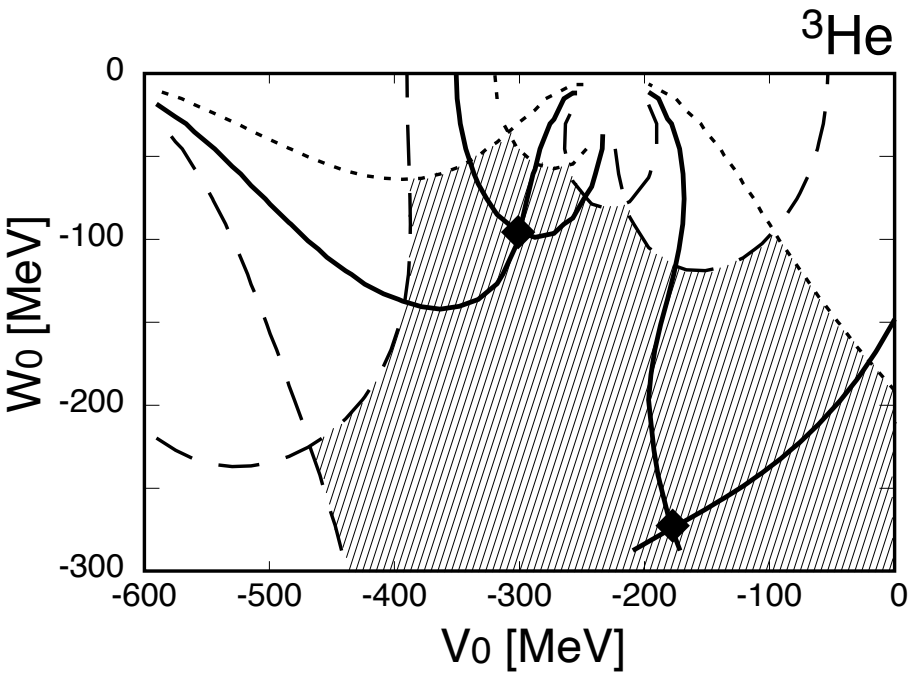


Solid points

$$(V_0, W_0) = (-301, -98)$$

$$(-180, -268)\ \mathrm{MeV}$$

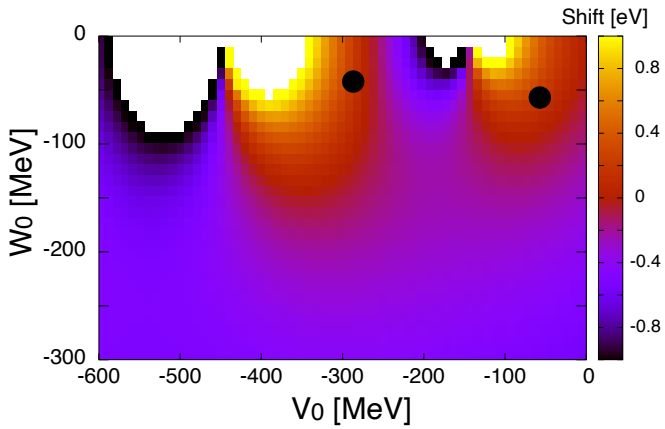
Hatched area

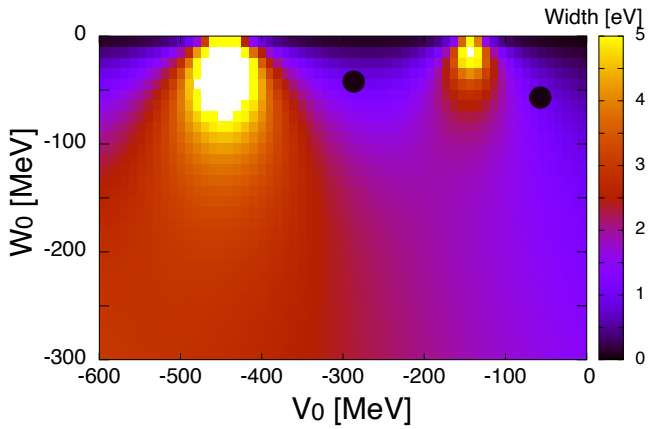
Overlap Regions of errors for Shift and Width

Kaonic atom in ^{3,4}He : Results for ^{4}He

- Calculated Results
- Potential depth at normal nuclear density
- Realistic density (by Prof. Hiyama)

$$U_{\mathrm{PH}}(r) = (V_0 + iW_0)\frac{\rho(r)}{\rho_0}$$

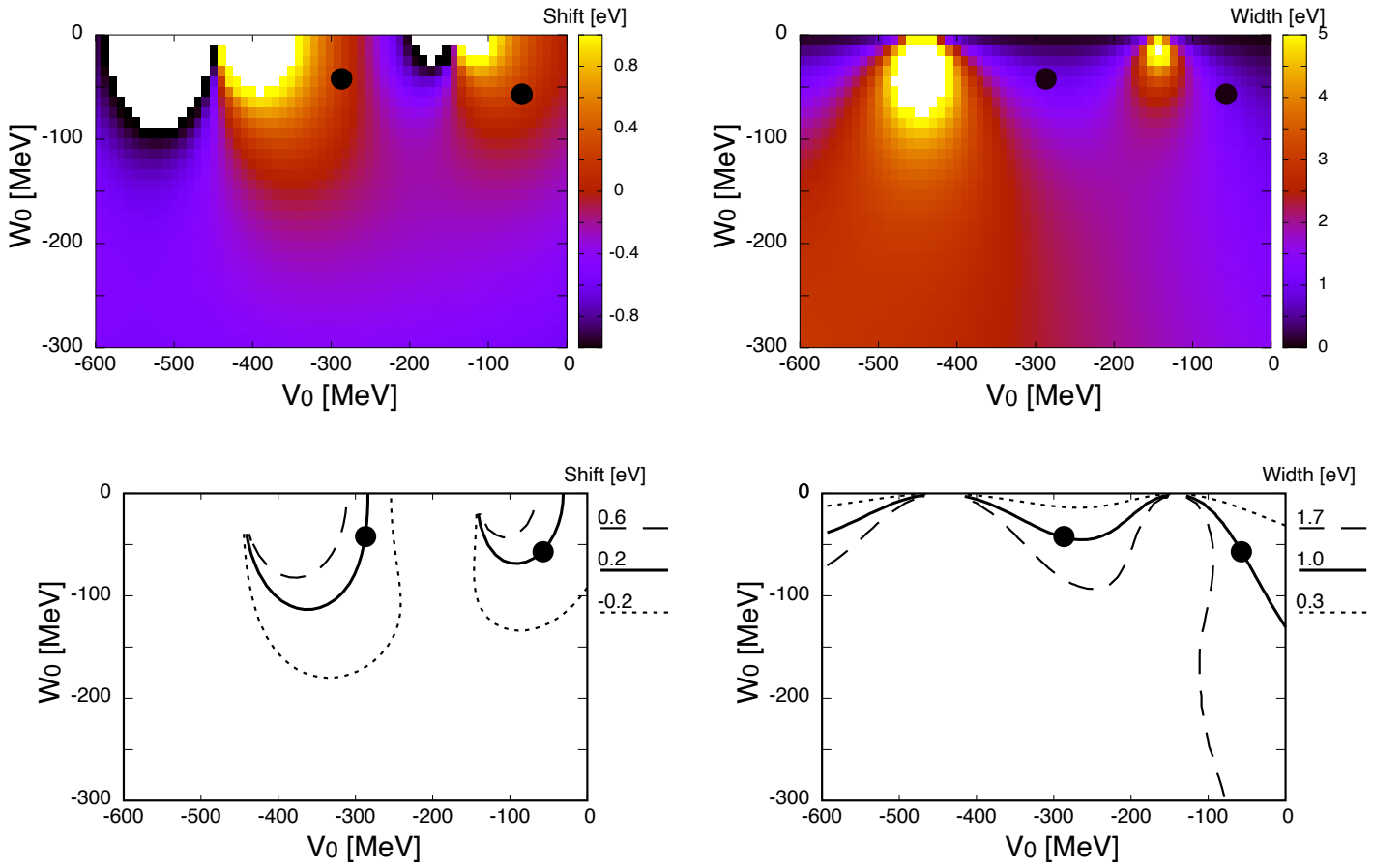




Kaonic atom in ^{3,4}He : Results for ^{4}He

- Calculated Results
- Potential depth at normal nuclear density
- Realistic density (by Prof. Hiyama)

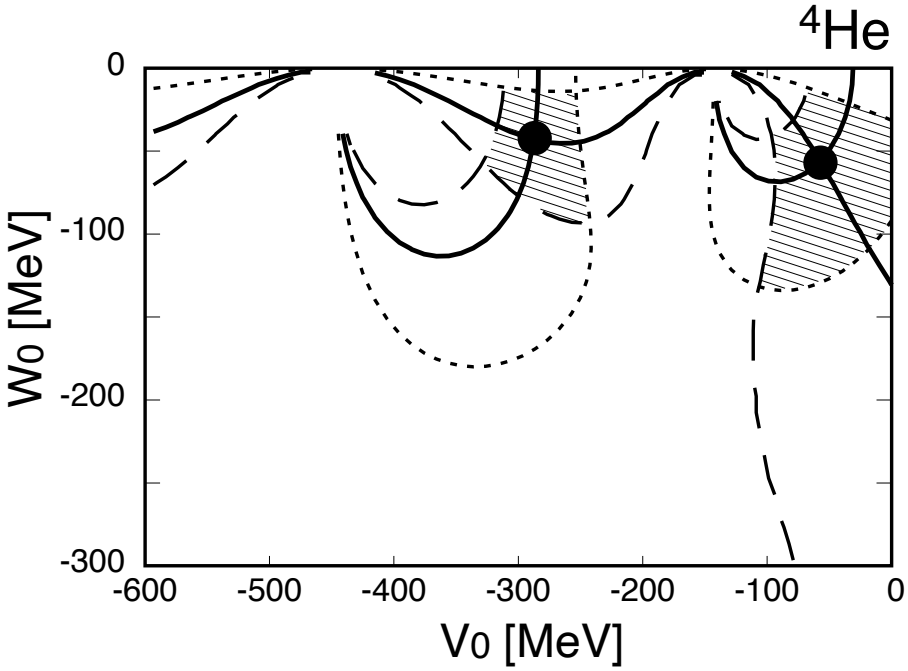
$$U_{\mathrm{PH}}(r) = (V_0 + iW_0)\frac{\rho(r)}{\rho_0}$$



Kaonic atom in ^{3,4}He : Results for ^{4}He

- Calculated Results
- Potential depth at normal nuclear density
- Realistic density (by Prof. Hiyama)

$$U_{\mathrm{PH}}(r) = (V_0 + iW_0)\frac{\rho(r)}{\rho_0}$$



Solid points

$$(V_0, W_0) = (-56, -58)$$

$$(-286, -43)\ \mathrm{MeV}$$

Hatched area

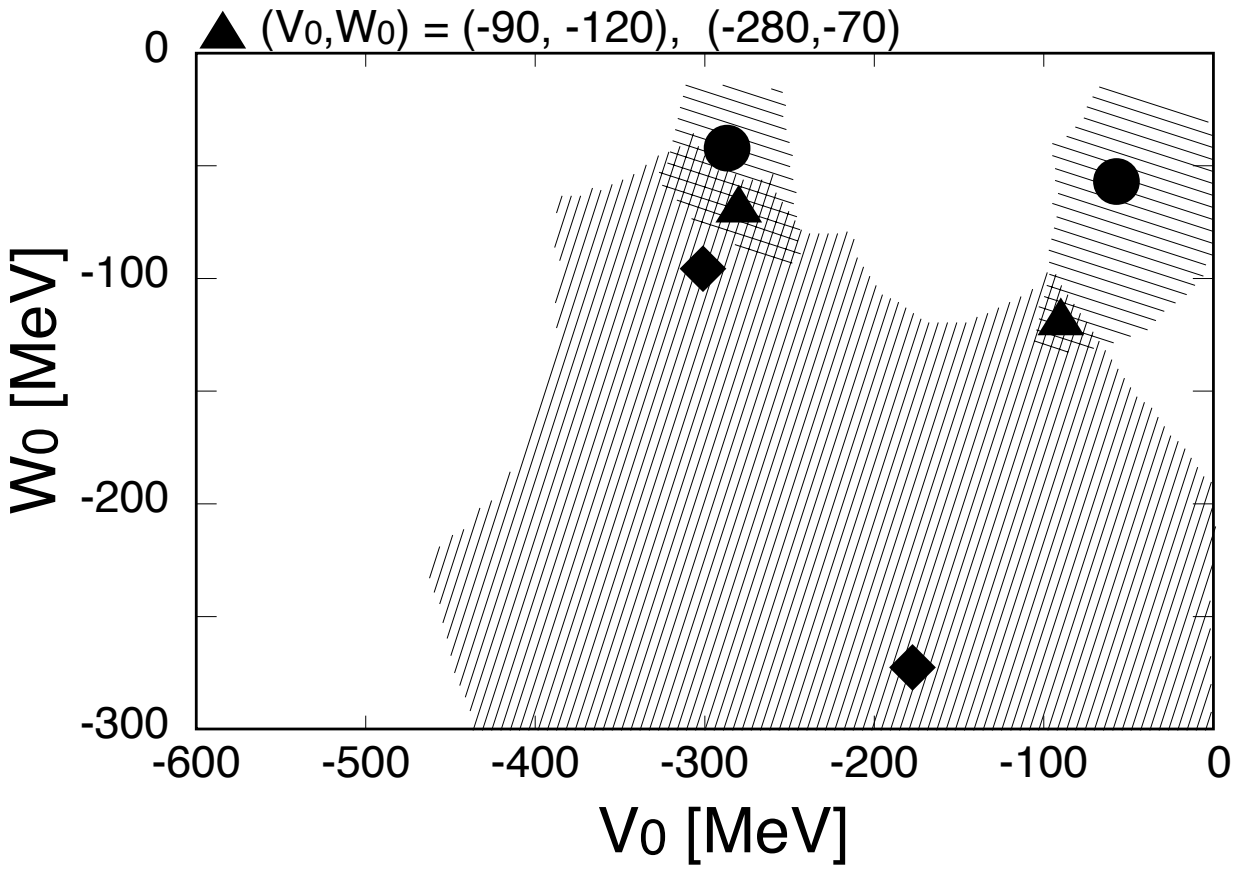
Overlap Regions of errors
for Shift and Width

Kaonic atom in ^{3,4}He : ^{3}He and ^{4}He

- Calculated Results
- Potential depth at normal nuclear density
- Realistic density (by Prof. Hiyama)

$$U_{\mathrm{PH}}(r) = (V_0 + iW_0)\frac{\rho(r)}{\rho_0}$$

Two sets of parameters consistent with ^{3}He and ^{4}He data within errors



Hatched area

Overlap Regions of errors for Shift and Width of ^{3}He and ^{4}He

Kaonic atoms in heavier Nuclei

Z	Atom	Transition	ΔE [keV]	Γ [keV]	Ref.
3	Li	$3d \to 2p$	0.002 ± 0.026	0.055 ± 0.029	[26]
4	Be	$3d \to 2p$	-0.079 ± 0.021	0.172 ± 0.58	[26]
5	B	$3d \to 2p$	-0.167 ± 0.035	0.700 ± 0.080	[27]
6	C	$3d \to 2p$	-0.590 ± 0.080	1.730 ± 0.150	[27]
8	O	$4f \to 3d$	-0.025 ± 0.018	0.017 ± 0.014	[28]
12	Mg	$4f \to 3d$	-0.027 ± 0.015	0.214 ± 0.015	[28]
13	Al	$4f \to 3d$	-0.130 ± 0.050	0.490 ± 0.160	[29]
			-0.076 ± 0.014	0.442 ± 0.022	[28]
14	Si	$4f \to 3d$	-0.240 ± 0.015	0.810 ± 0.120	[29]
			-0.130 ± 0.015	0.800 ± 0.033	[28]
15	P	$4f \to 3d$	-0.330 ± 0.08	1.440 ± 0.120	[27]
16	S	$4f \to 3d$	-0.550 ± 0.06	2.330 ± 0.200	[27]
			-0.43 ± 0.12	2.310 ± 0.170	[30]
			-0.462 ± 0.054	1.96 ± 0.17	[28]
17	Cl	$4f \to 3d$	-0.770 ± 0.40	3.80 ± 1.0	[27]
			0.94 ± 0.40	3.92 ± 0.99	[31]
			-1.08 ± 0.22	2.79 ± 0.25	[30]
27	Co	$5g \to 4f$	-0.099 ± 0.106	0.64 ± 0.25	[28]
28	Ni	$5g \to 4f$	-0.180 ± 0.070	0.59 ± 0.21	[29]
			-0.246 ± 0.052	1.23 ± 0.14	[28]
29	Cu	$5g \to 4f$	-0.240 ± 0.220	1.650 ± 0.72	[29]
			-0.377 ± 0.048	1.35 ± 0.17	[28]
47	Ag	$6h \to 5g$	-0.18 ± 0.12	1.54 ± 0.58	[28]
48	Cd	$6h \to 5g$	-0.40 ± 0.10	2.01 ± 0.44	[28]
49	In	$6h \to 5g$	-0.53 ± 0.15	2.38 ± 0.57	[28]
50	Sn	$6h \to 5g$	-0.41 ± 0.18	3.18 ± 0.64	[28]

[26] C. J. Batty, S. F. Biagi, M. Blecher, R. A. J. Riddle, B. L. Roberts, J. D. Davies, G. J. Pyle, G. T. A. Squier and D. M. Asbury, Nucl. Phys. A **282**, 487-492 (1977).

[27] G. Backenstoss, A. Bamberger, I. Berström, P. Bounin, T. Bunaciu, J. Egger, S. Hultberg, H. Koch, M. Krell and U. Lynen, *et al.* Phys. Lett. B **38**, 181-187 (1972),
G. Backenstoss, J. Egger, H. Koch, H. P. Povel, A. Schwitter and L. Tauscher, Nucl. Phys. B **73**, 189-201 (1974).

[28] C. J. Batty, S. F. Biagi, M. Blecher, S. D. Hoath, R. A. J. Riddle, B. L. Roberts, J. D. Davies, G. J. Pyle, G. T. A. Squier and D. M. Asbury, *et al.* Nucl. Phys. A **329**, 407-428 (1979).

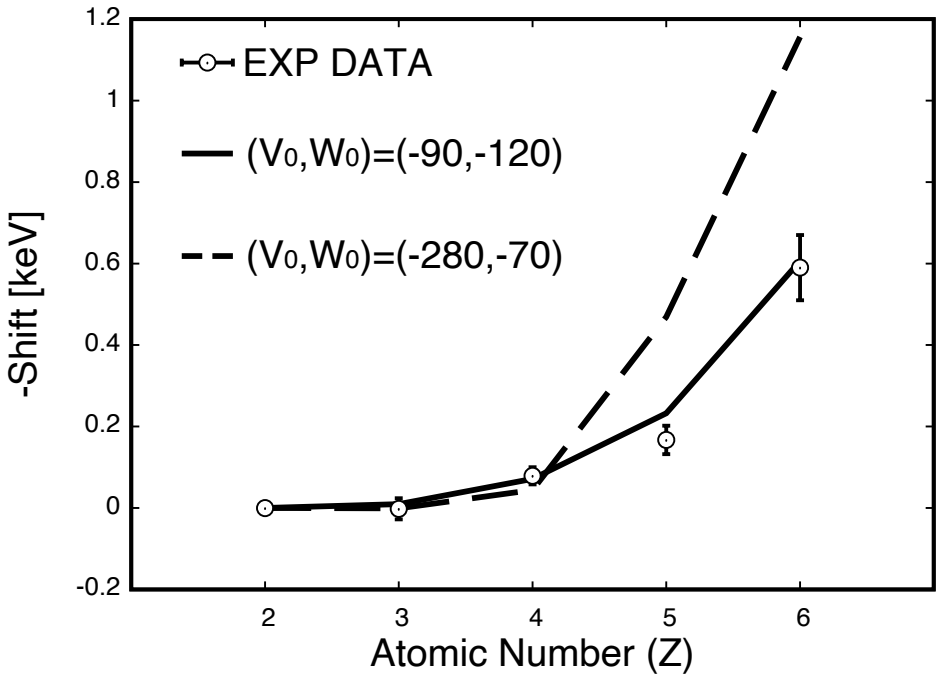
[29] P. D. Barnes, R. A. Eisenstein, W. C. Lam, J. Miller, R. B. Sutton, M. Eckhause, J. R. Kane, R. E. Welsh, D. A. Jenkins and R. J. Powers, *et al.* Nucl. Phys. A **231**, 477-492 (1974).

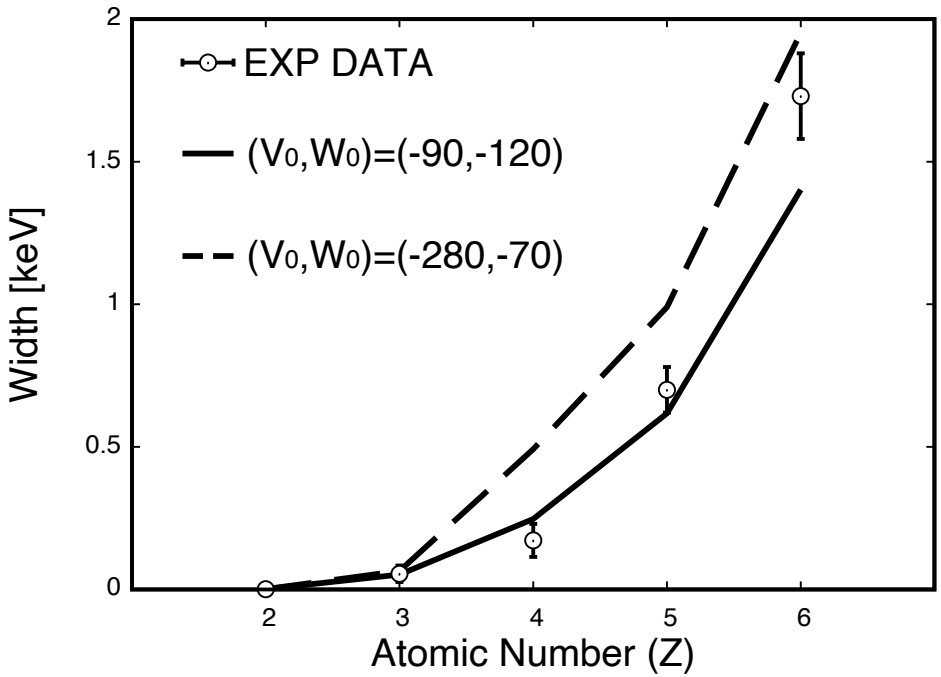
[30] C. E. Wiegand and G. L. Godfrey, Phys. Rev. A **9**, 2282 (1974).

[31] R. Kunselman, Phys. Lett. B **34**, 485-487 (1971),
Phys. Rev. C **9**, 2469-2470 (1974).

Kaonic atoms in heavier Nuclei

$$3d \rightarrow 2p$$

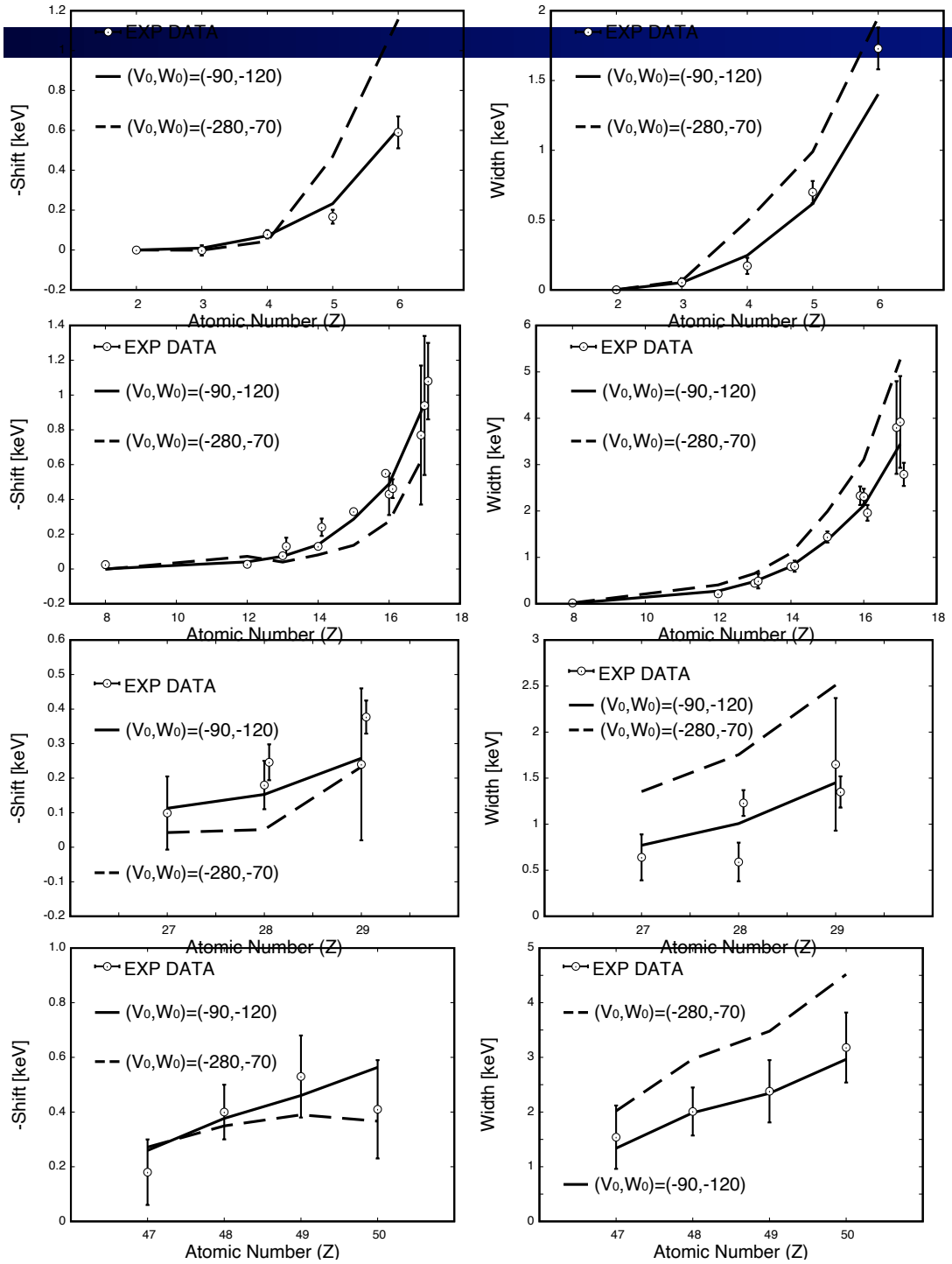




Two sets of potential, consistent with the latest He data,

are applied to heavier kaonic atoms.

Kaonic atoms in heavier Nuclei



$3d \rightarrow 2p$

$4f \rightarrow 3d$

$5g \rightarrow 4f$

$6h \rightarrow 5g$

$$(V_0, W_0) = (-90, -120)\ \text{MeV}$$

is better suited for the global description of the kaonic atoms.

Summary

- J-PARC E62, high precision data: ^{3,4}He kaonic 2p atoms.
- Kaon-Nucleus interaction in a phenomenological form

$$U_{\mathrm{PH}}(r) = (V_0 + iW_0)\frac{\rho(r)}{\rho_0}$$

- 2 stets of parameters consistent with the data within experimental errors are found.

- Set $(V_0, W_0) = (-90, -120)\ \mathrm{MeV}$ is suited for the global description of the kaonic atoms

- Discussions ------ ongoing

∗ Kaonic nuclear states, ∗ Kaonic 1s atoms in ^{3,4}He,

∗ Other parameter sets, ∗ Theoretical potentials,

T. Hashimoto *et al.* [J-PARC E62], Phys. Rev. Lett. **128**, no.11, 112503 (2022).

Table 1 Experimental shifts and widths [7] of the kaonic ^{3}He and ^{4}He atomic $2p$ states are compiled in this table in unit of eV. The errors shown in the parentheses are the square root of the quadratic sum of the statistical and systematical errors in Ref. [7]. Please note that the signs of the shifts are opposite for ^{3}He and ^{4}He as indicated in the table.

eV	Shift	Width
K^-–^{3}He	(Repulsive shift)	
	$-0.2 \pm 0.4\,(\text{stat}) \pm 0.3\,(\text{syst})$	$2.5 \pm 1.0\,(\text{stat}) \pm 0.4\,(\text{syst})$
	(± 0.5)	(± 1.1)
K^-–^{4}He	(Attractive shift)	
	$0.2 \pm 0.3\,(\text{stat}) \pm 0.2\,(\text{syst})$	$1.0 \pm 0.6\,(\text{stat}) \pm 0.3\,(\text{syst})$
	(± 0.4)	(± 0.7)

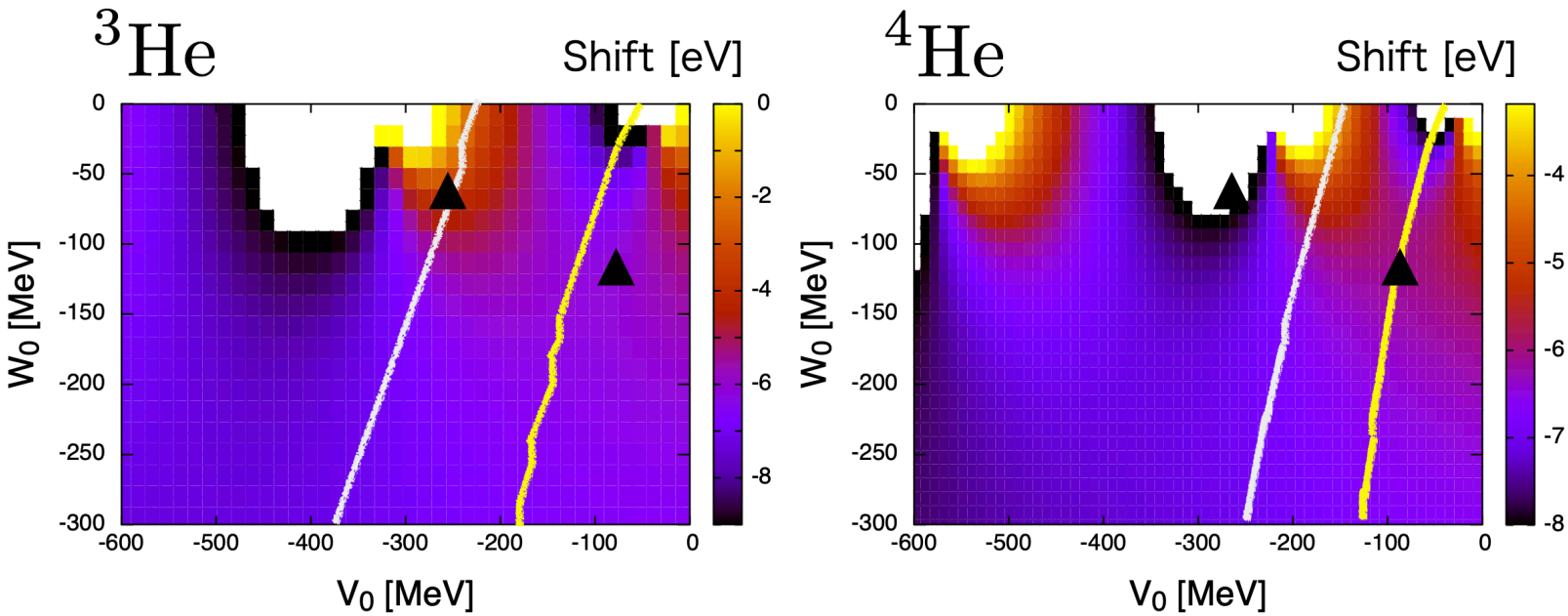
Table 2 The strengths of the kaon-nucleus optical potentials obtained by fitting the data in Ref. [7] are summarized for the phenomenological potential $U_{\rm PH}$ defined in Eq. (2). The potential depths at normal nuclear density, which are actually same as the values of the V_0 and W_0 parameters in Eq. (2), and those at the center of the nuclei ^{3}He and ^{4}He are shown for two potentials (Set 1 and Set 2). These potentials are corresponding to the solid triangles in Fig. 5.

MeV		Set 1		Set 2	
		Real	Imaginary	Real	Imaginary
$U_{\rm PH}$ at $\rho = \rho_0$		-90	-120	-280	-70
$U_{\rm PH}(r=0)$	^{3}He	-119	-159	-357	-93
	^{4}He	-182	-243	-566	-142

Shift of 2p →1s transition energy

Nuclear s state existence boundary: Yellow line
p : White line

Solid triangle: potential determined by 2p Atom



K-Nucleus potential from ^{12}C(K,p) spectrum

Y. Ichikawa, J. Yamagata-Sekihara, J. K. Ahn, Y. Akazawa, K. Aoki, E. Botta, H. Ekawa, P. Evtoukhovitch, A. Feliciello and M. Fujita, *et al.* PTEP **2020** (2020) no.12, 123D01 doi:10.1093/ptep/ptaa139

We mention here that a set of the potential parameter is determined in Ref. [34] by investigating the $^{12}\mathrm{C}(K^-, p)$ spectrum. The best potential strength to reproduce the spectrum in the wide energy range for the K^- binding energy $-300 \sim +40$ MeV was concluded to be $(-80, -40)$ MeV at the nuclear center of ^{11}B [34]. Since the nuclear density at the center of ^{11}B in Ref. [34] is slightly different from the normal nuclear density 0.17 fm^{-3}, the potential strength in Ref. [34] is corresponding to the value of $(V_0, W_0) = (-74, -37)$ MeV in this article. This value is different from the Set 1 and Set 2, however (almost) consistent to the latest ^{4}He data [7] as shown in Fig. 4 (Lower). One of the reasons of the discrepancy of the potential value is considered to be the possible energy dependence of the potential strength.

Theoretical pot.

Medium effects are implemented into ‘density dependent scattering length’

$$U_{\mathrm{TH}}(r) = -\frac{4\pi}{2\mu}\left(1+\frac{m_K}{M_N}\right)a(\rho)\rho(r)$$

Scaled pot.

Scale the theoretical medium effects by the data

$$\begin{aligned} U_{\mathrm{SC}}(r) &= -\frac{4\pi}{2\mu}\left(1+\frac{m_K}{M_N}\right)\{f_1\ \mathrm{Re}(a(\rho)-a(0))+f_2\ \mathrm{Im}(a(\rho)-a(0))\}\,\rho(r) \\ &\quad -\frac{4\pi}{2\mu}\left(1+\frac{m_K}{M_N}\right)a(0)\rho(r) \end{aligned}$$

Scaled pot.

Chiral Unitary model

Kaonic 4He atom 2p