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Investigation of kaonic atom optical potential by the high-precision data of kaonic ^{3}He and ^{4}He

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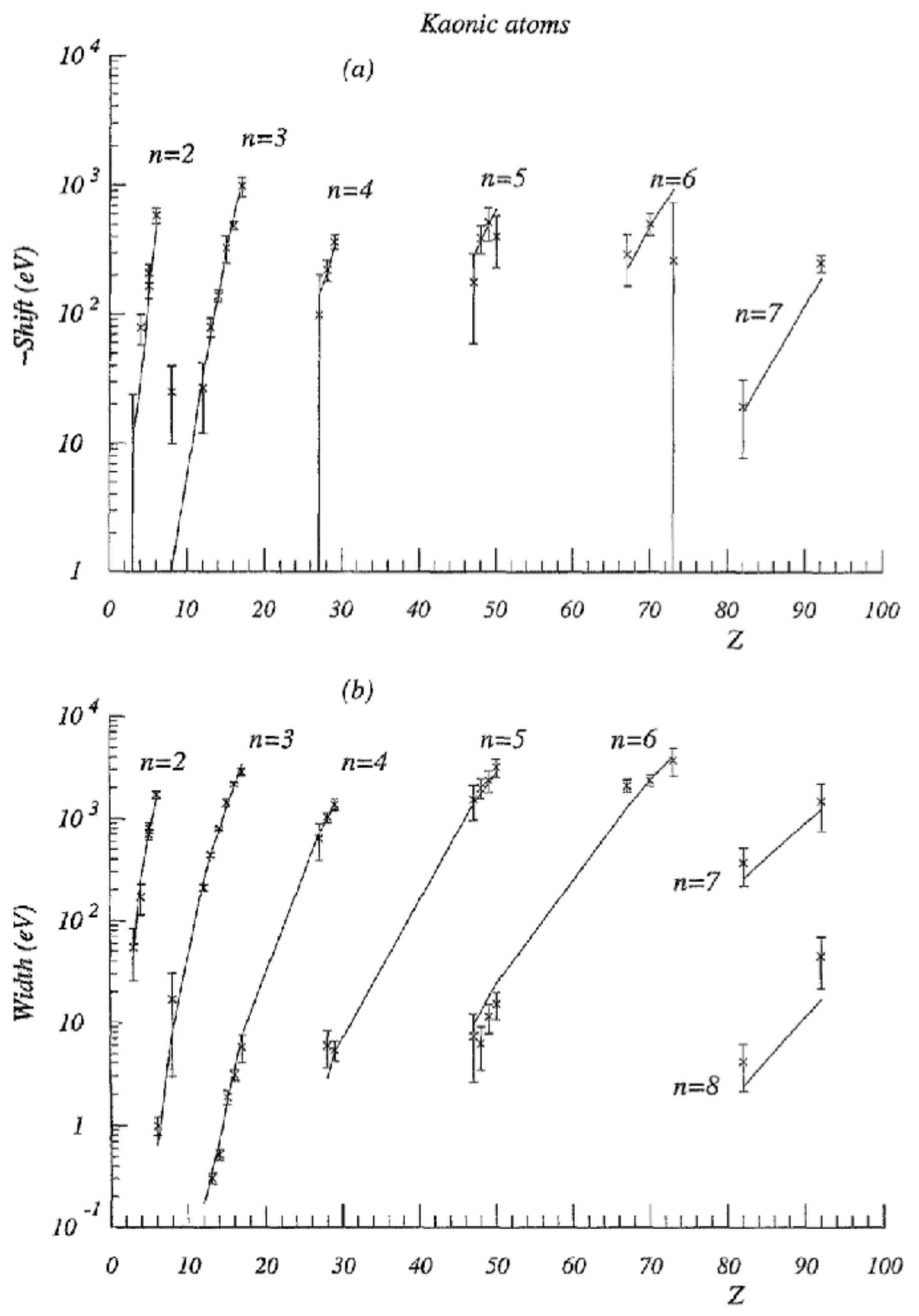
(Paper in preparation by J. Yamagata-Sekihara, Y. Iizawa, D. Jido, N. Ikeno, T. Hashimoto, S. Okada and S. Hirenzaki)

Kaonic atom data and kaon-nuclus potential

- Kaonic atoms carry important information concerning the K^- -nucleon interaction in the nuclear medium.
- This information is very important in understanding kaon properties at finite density.
- There are kaon-nucleus potentials that can well reproduce experimental data.

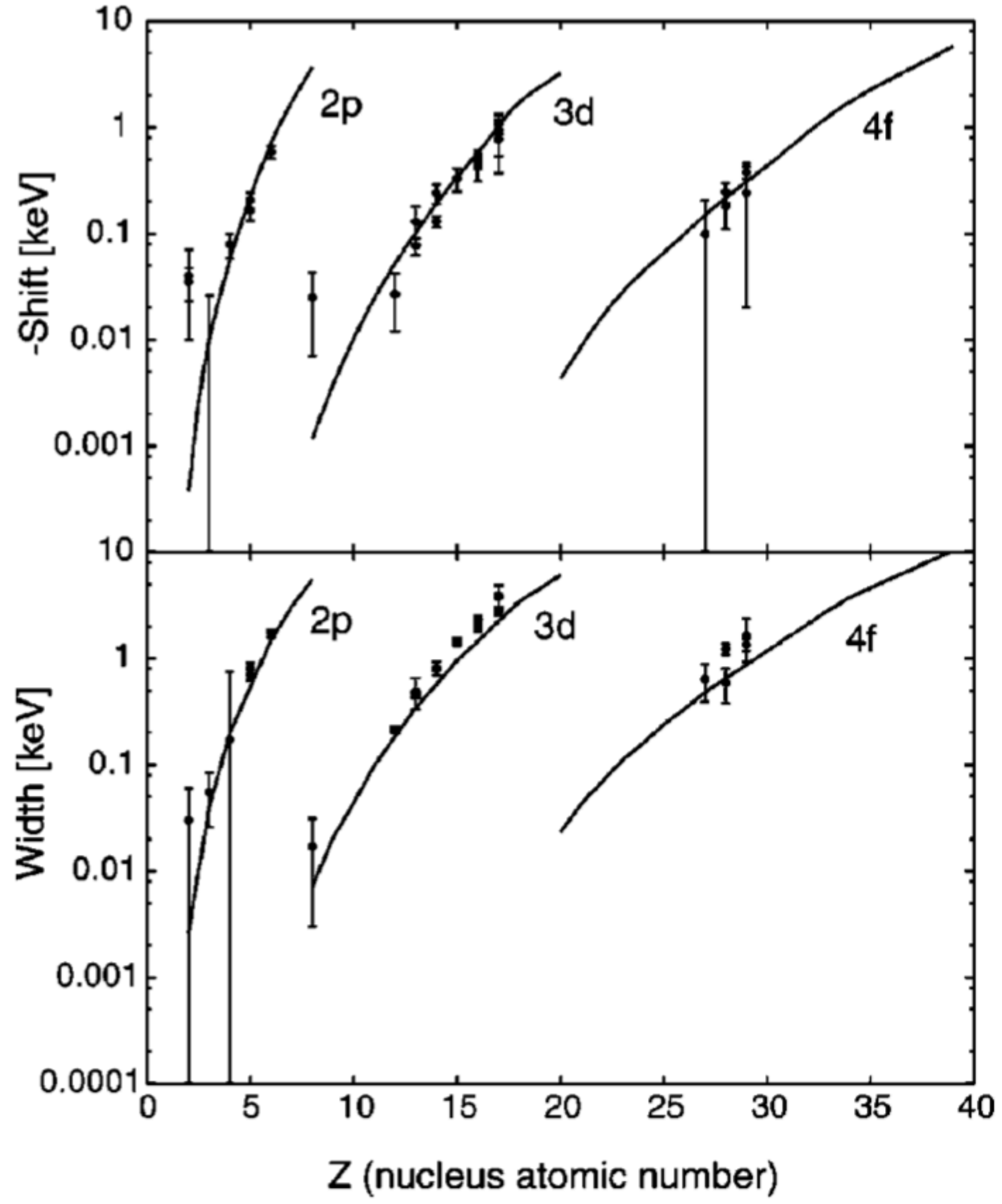
Well reproduced!!

χ^2 fitting potential



C. J. Batty, E. Friedman, A. Gal, Phys. Rept. 287(97)385

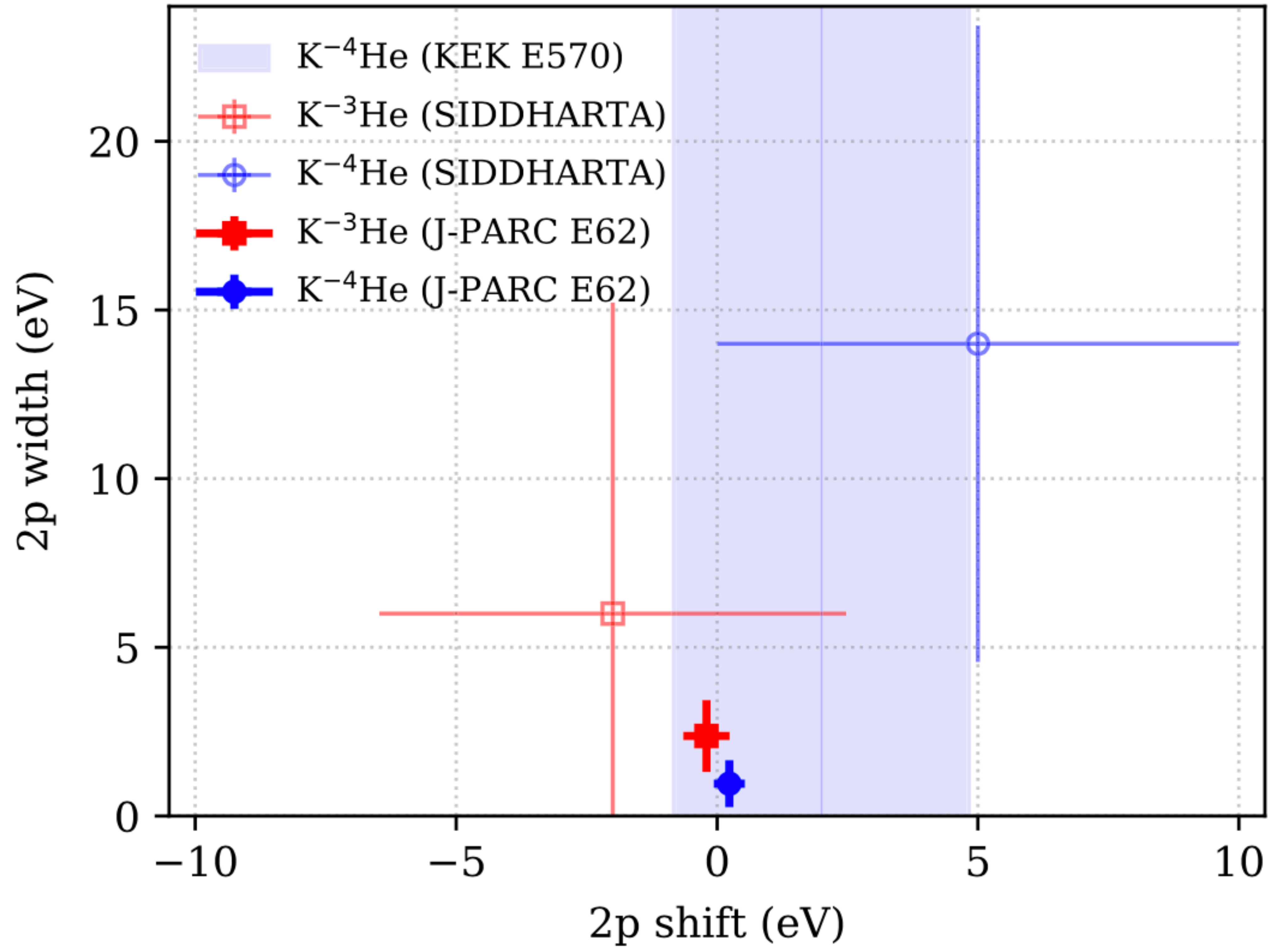
Chiral Unitary potential



S. Hirenzaki, Y. Okumura, H. Toki, E. Oset, and A. Ramos, Phys. Rev. C61(00)055205

J-PARC E62 experiment

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



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

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

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

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

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

- High-precision measurement of kaonic ^{3}He and ^{4}He.
- Measured X-rays from 3d to 2p atomic state.

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

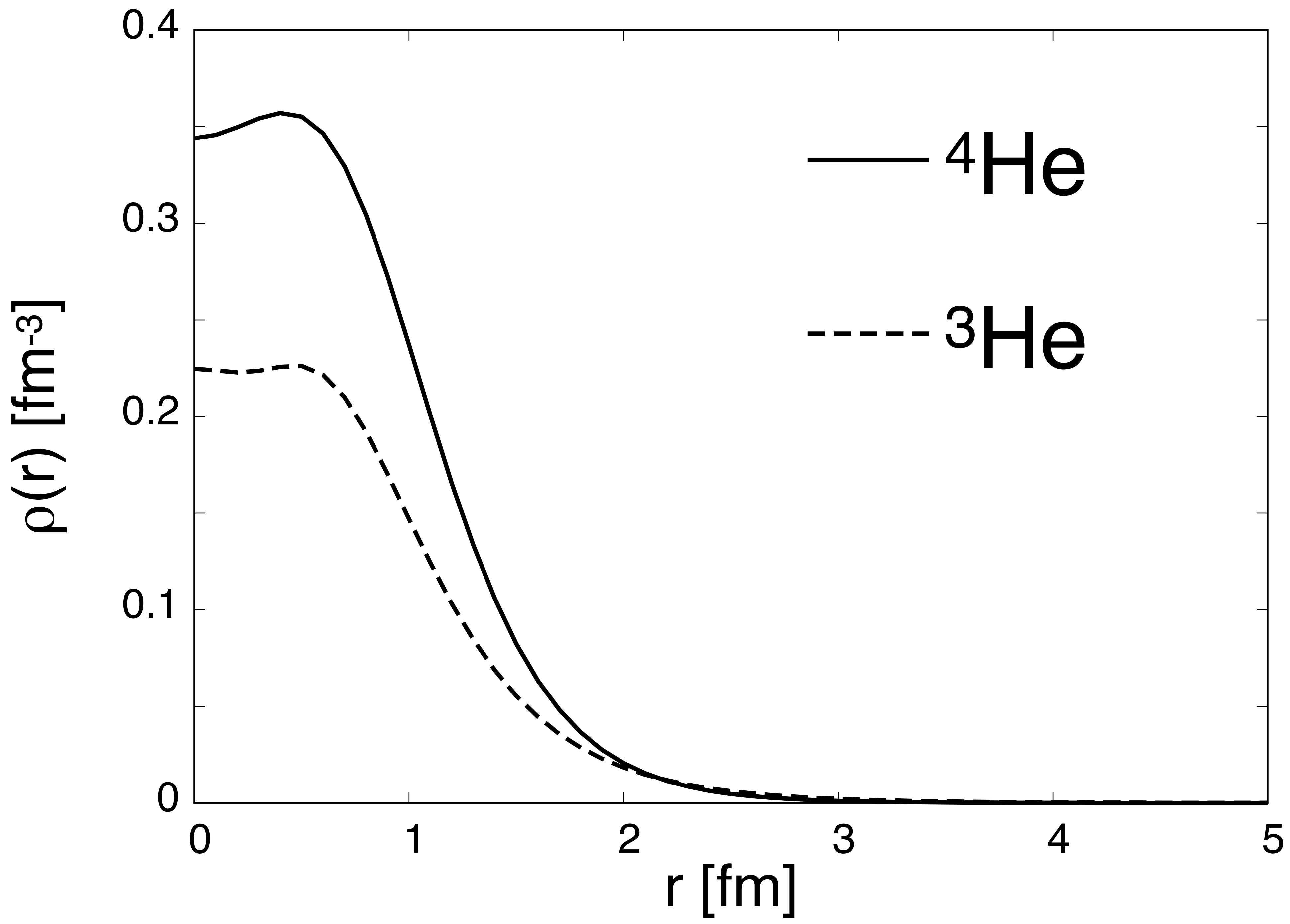
Motivation

- We want to theoretically investigate the constraints on the kaonic atom optical potential deduced from the latest data. Our aim is to understand the meaning of the data and its impact on the physics of kaon-nucleus systems.
- We consider the phenomenological optical potential as the kaon-nucleus potential. We obtain the potential parameters necessary to reproduce the experimental data.
- Kaonic $^{3}\mathrm{He}$ and $^{4}\mathrm{He}$ (J-PARC E62)
- Using the potential, we investigate the structure of the kaonic atoms for various nuclei up to Sn.
- Since the atomic 1s states are more sensitive to the strong interaction than the 2p states, we can expect to obtain further information by the study of the 1s states.

Nuclear density

✦ ^{4}He and ^{3}He nuclear density

[E. Hiyama, Y. Kino and M. Kamimura, Prog. Part. Nucl. Phys. 51, 223-307 (2003)]
[E. Hiyama, B. F. Gibson and M. Kamimura, Phys. Rev. C 70, 031001 (2004).]

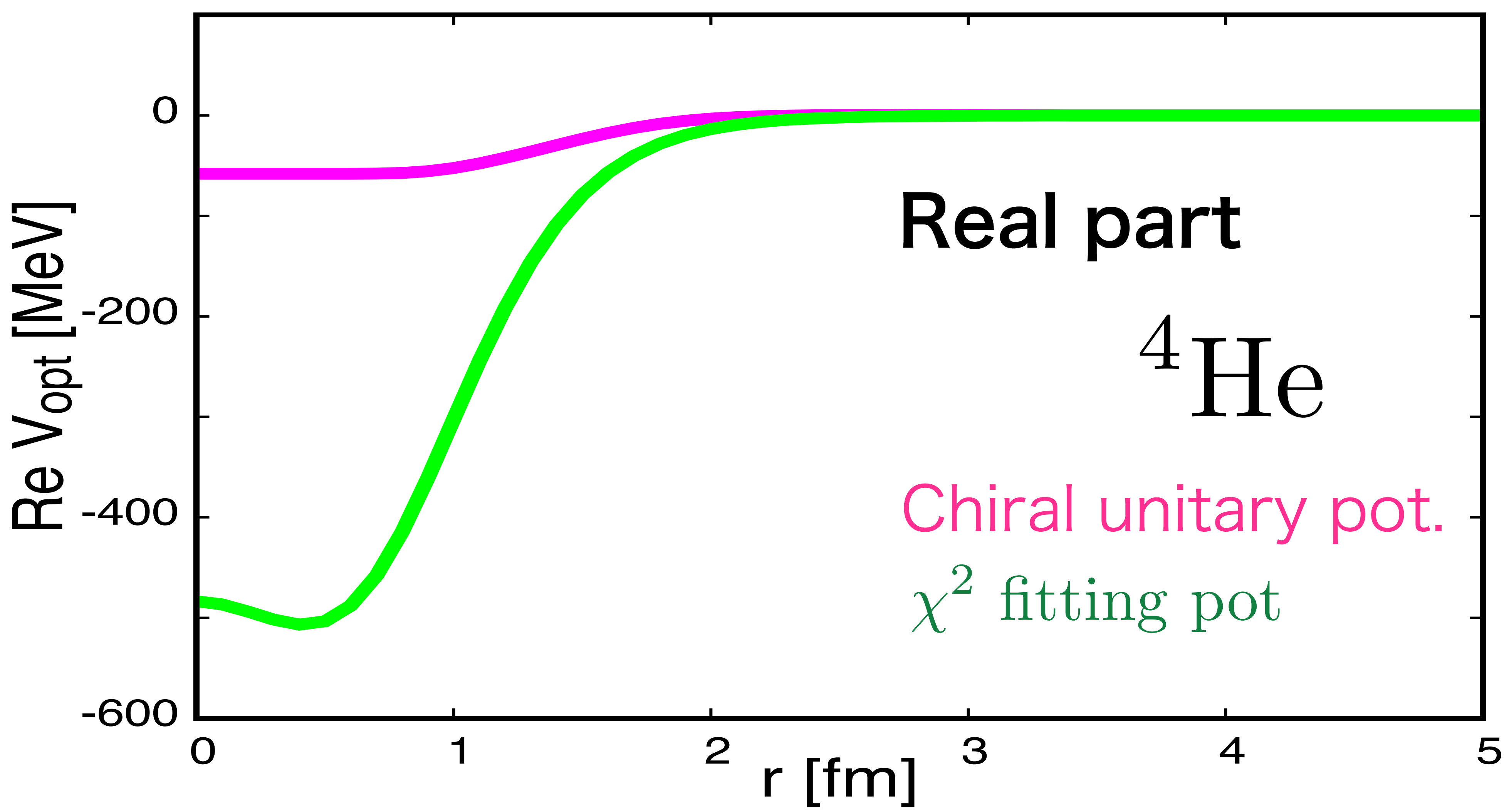


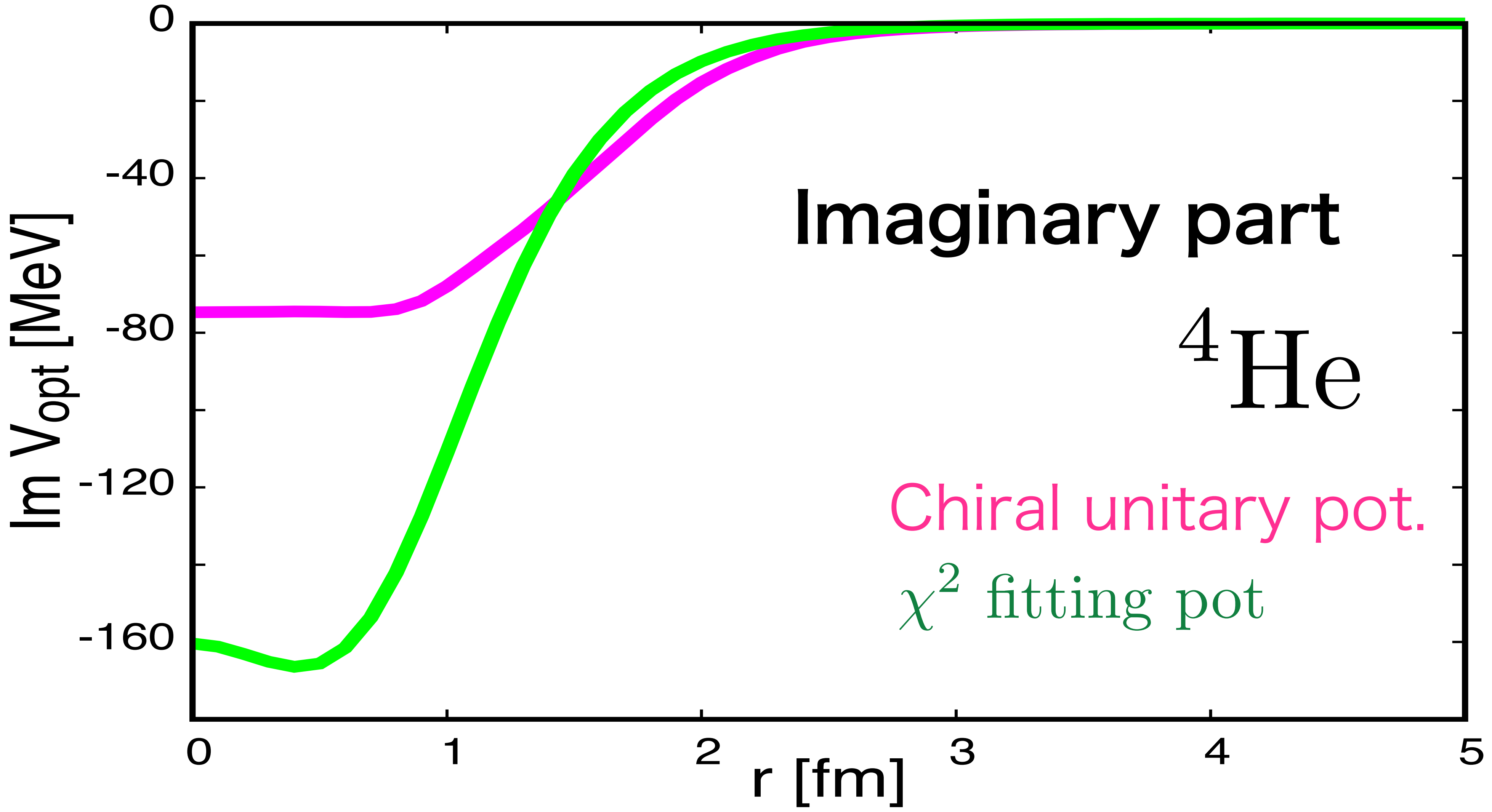
Chiral unitary pot.

[Ramos, Oset, Nucl. Phys. A671(00)481]
[Hirenzaki, Okumura, Toki, Oset, Ramos, Phys. Rev. C61(00)055025]

χ^2 fitting pot

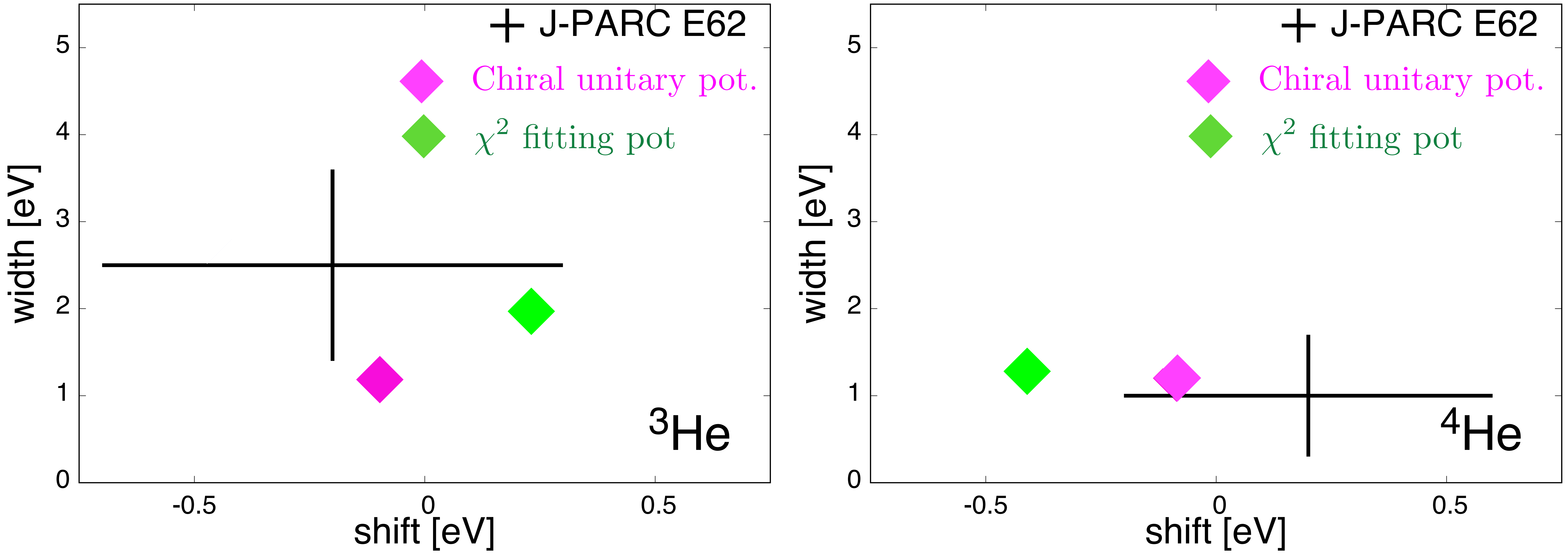
[Batty, Friedman, Gal, Phys. Rept. 287(97)385]
[Mares, Friedman, Gal, Nucl. Phys. A770(06)84]





Exp. data vs. theor. results

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



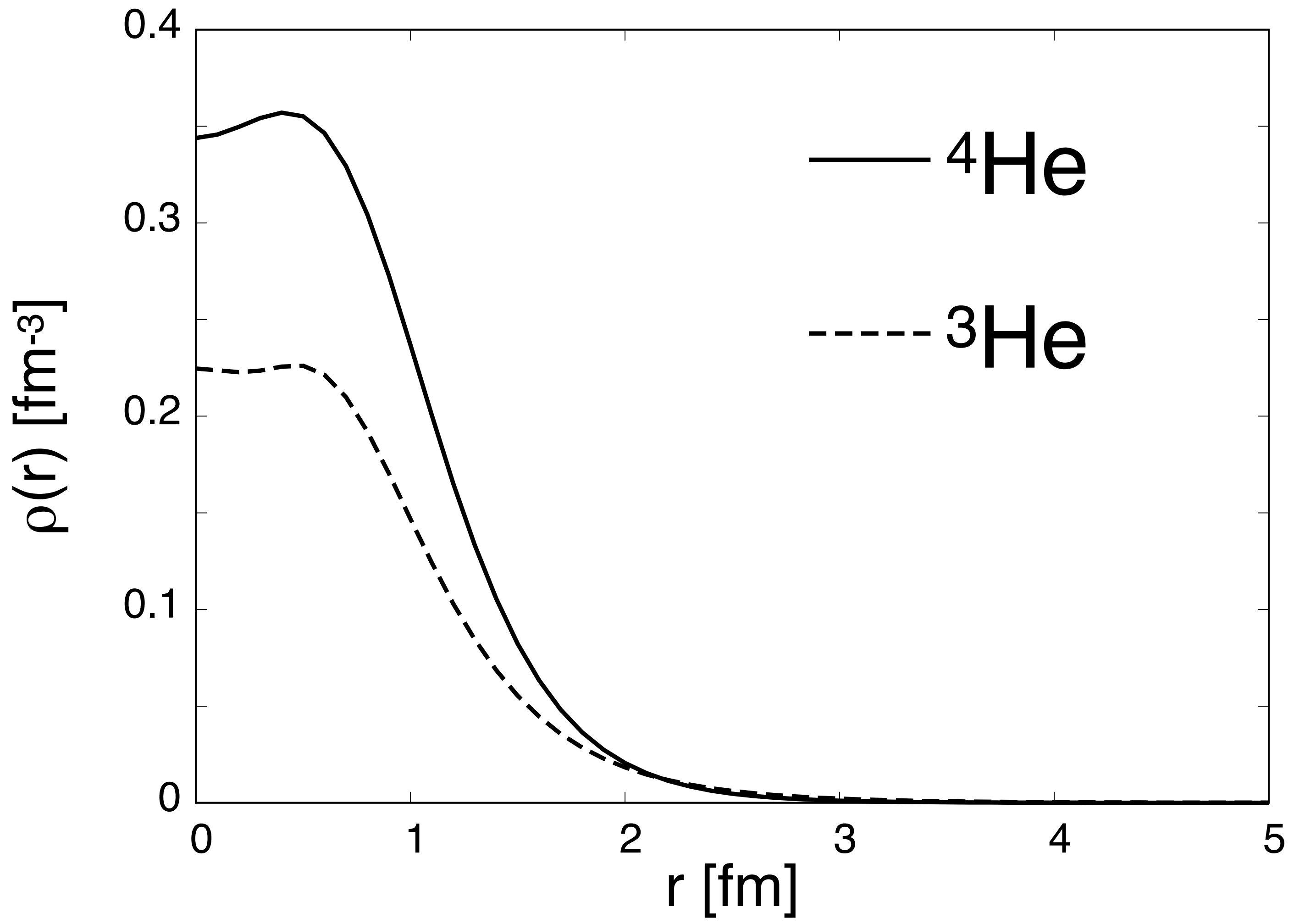
“Shift” positive means “attraction”.

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

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

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

Kaon-Nucleus interaction



- ^{4}He and ^{3}He nuclear density

[E. Hiyama, Y. Kino and M. Kamimura, Prog. Part. Nucl. Phys. 51, 223-307 (2003)]
[E. Hiyama, B. F. Gibson and M. Kamimura, Phys. Rev. C 70, 031001 (2004).]

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

● : parameter

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

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

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

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

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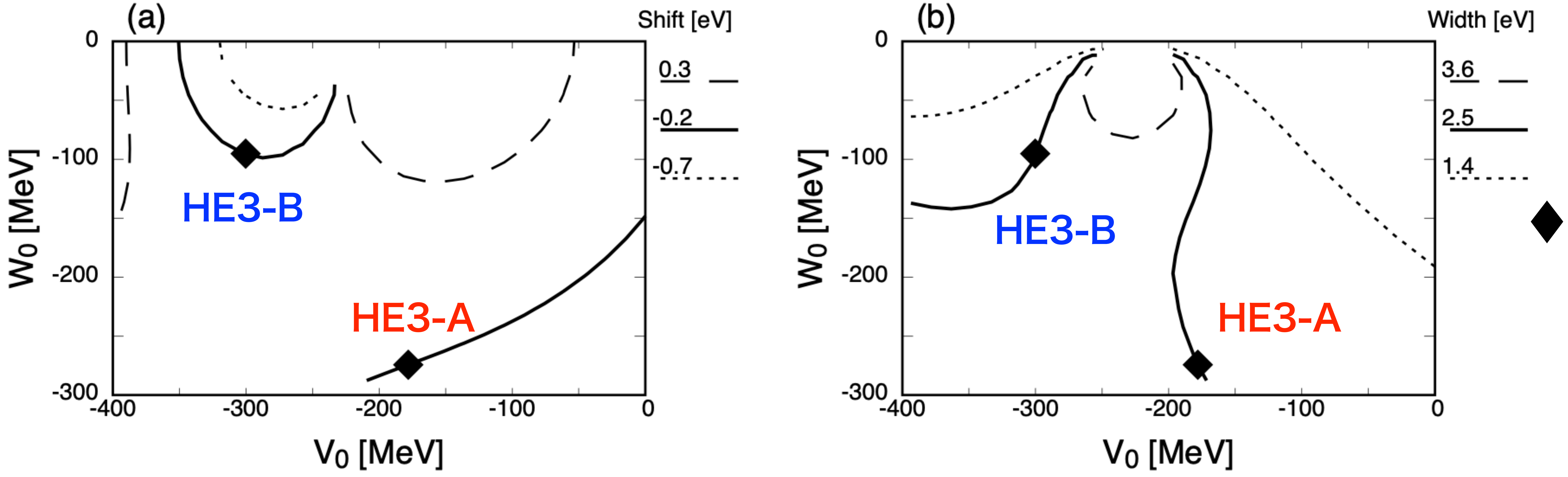
$$\text{shift} = (E_{3d}^{\text{opt+em}} - E_{2p}^{\text{opt+em}}) - (E_{3d}^{\text{em}} - E_{2p}^{\text{em}})$$

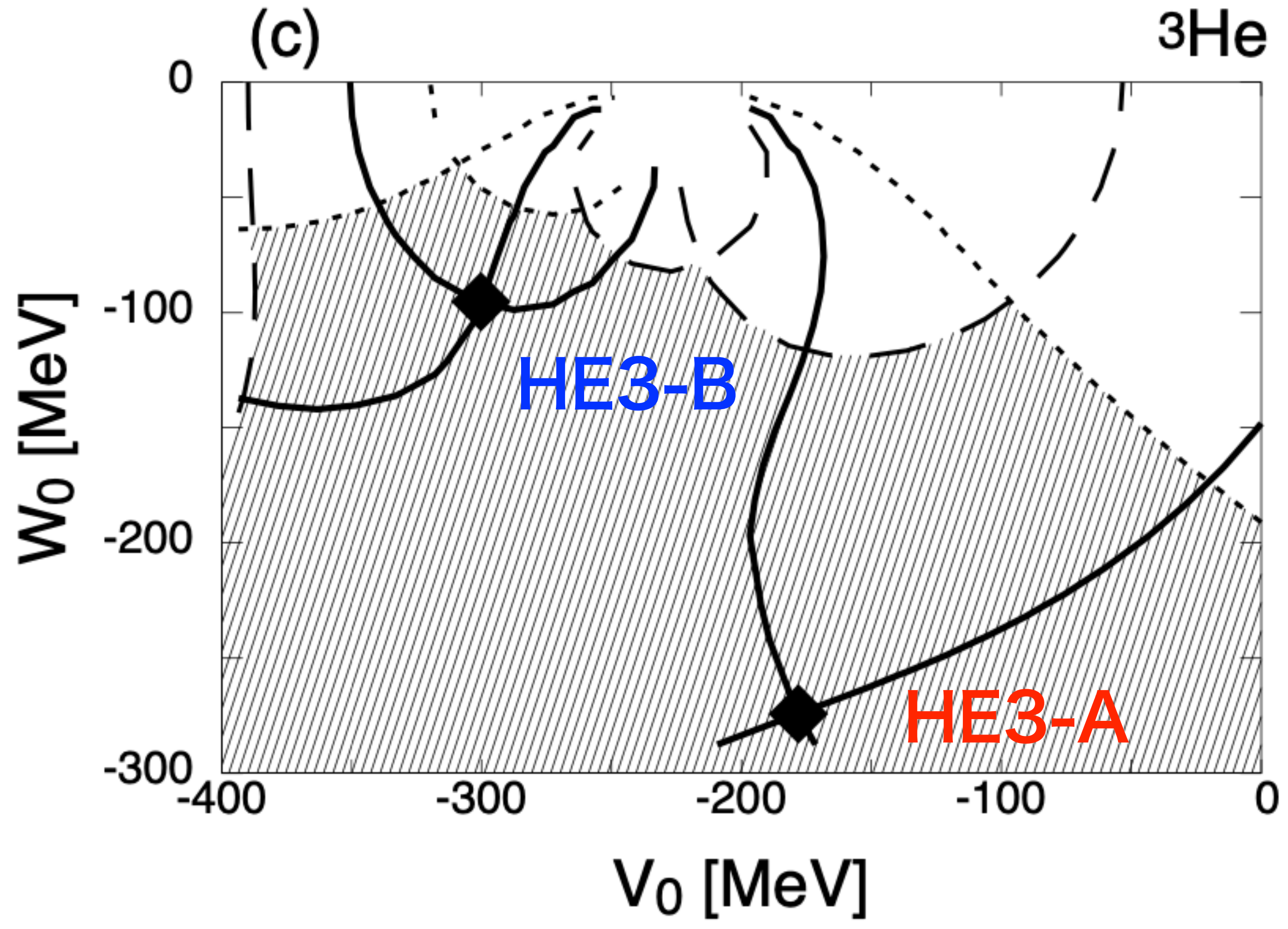
Calculated results : $^3\mathrm{He}$

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

Shift

Width





◆ : (V0, W0)

HE3-A : (-178,-274) [MeV]

HE3-B : (-300,-95) [MeV]

(This parameter can reproduce the experimental data.)

$$\boxed{\begin{aligned}\Delta E_{2p}^{K^-{}^3\mathrm{He}} &= -0.2 \pm 0.4(\mathrm{stat}) \pm 0.3(\mathrm{syst})\ \mathrm{eV},\\ \Gamma_{2p}^{K^-{}^3\mathrm{He}} &= 2.5 \pm 1.0(\mathrm{stat}) \pm 0.4(\mathrm{syst})\ \mathrm{eV},\end{aligned}}$$

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

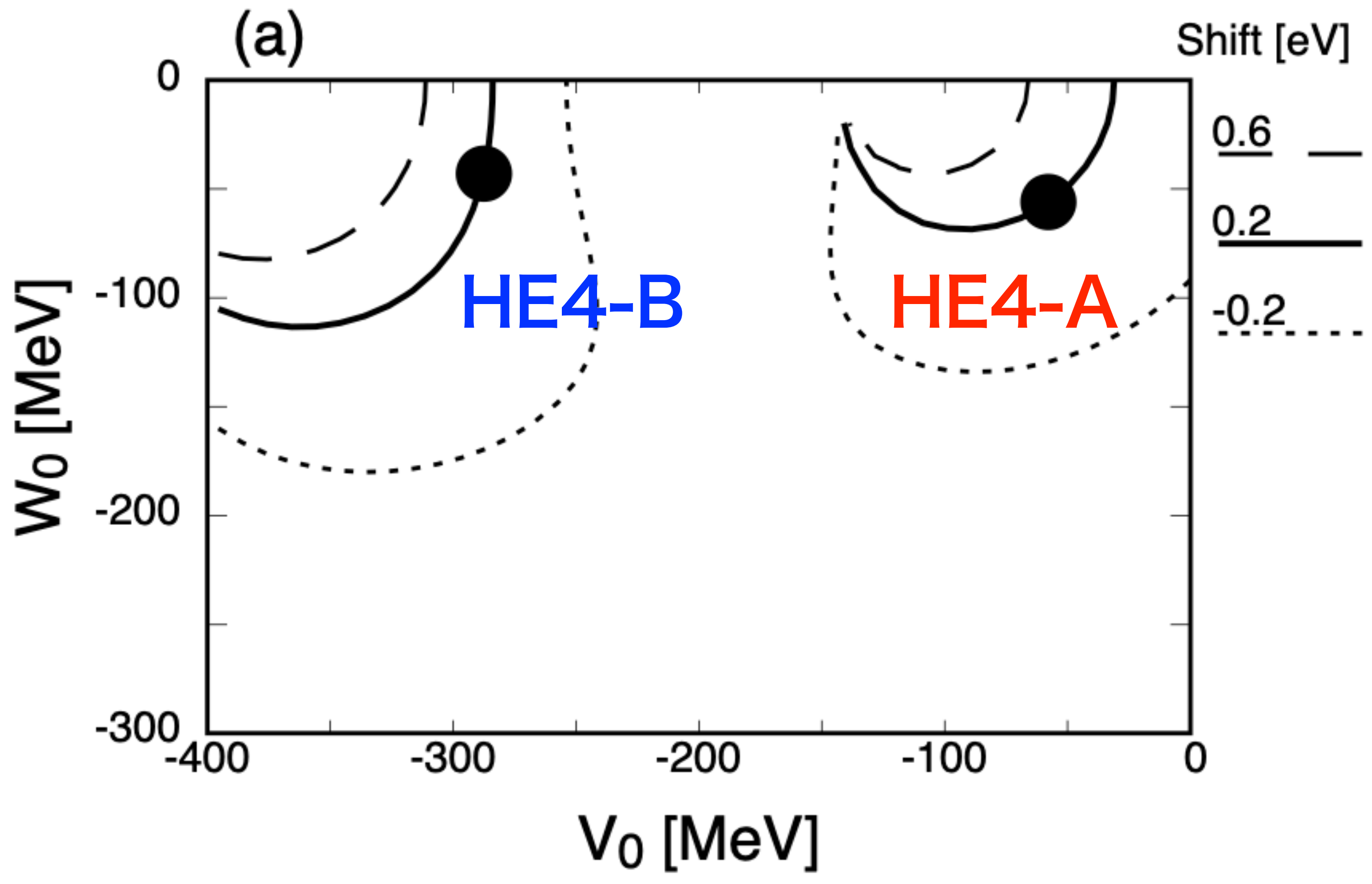
J. Yamagata-Sekihara et al, in preparation

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

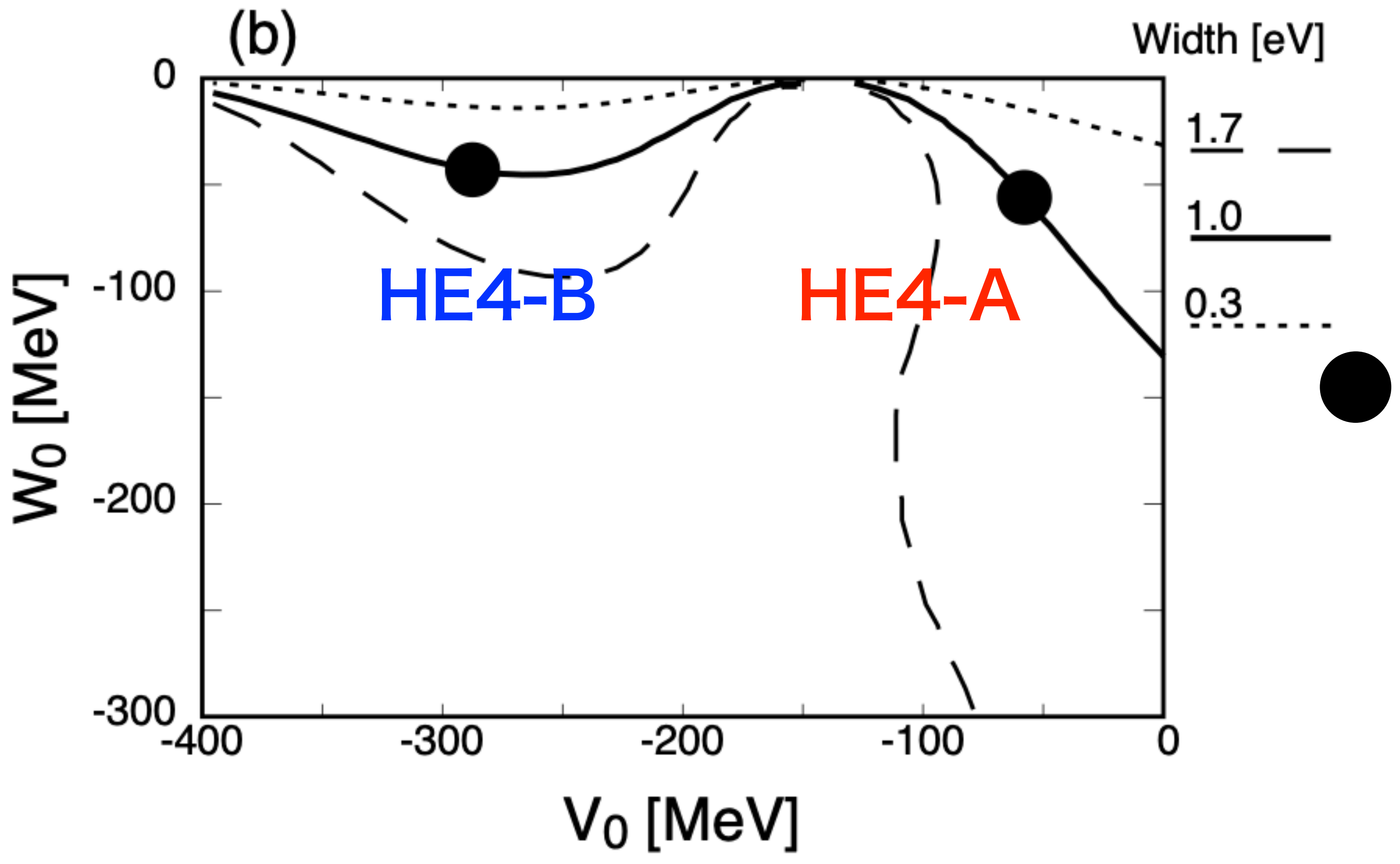
Calculated results : $^4\mathrm{He}$

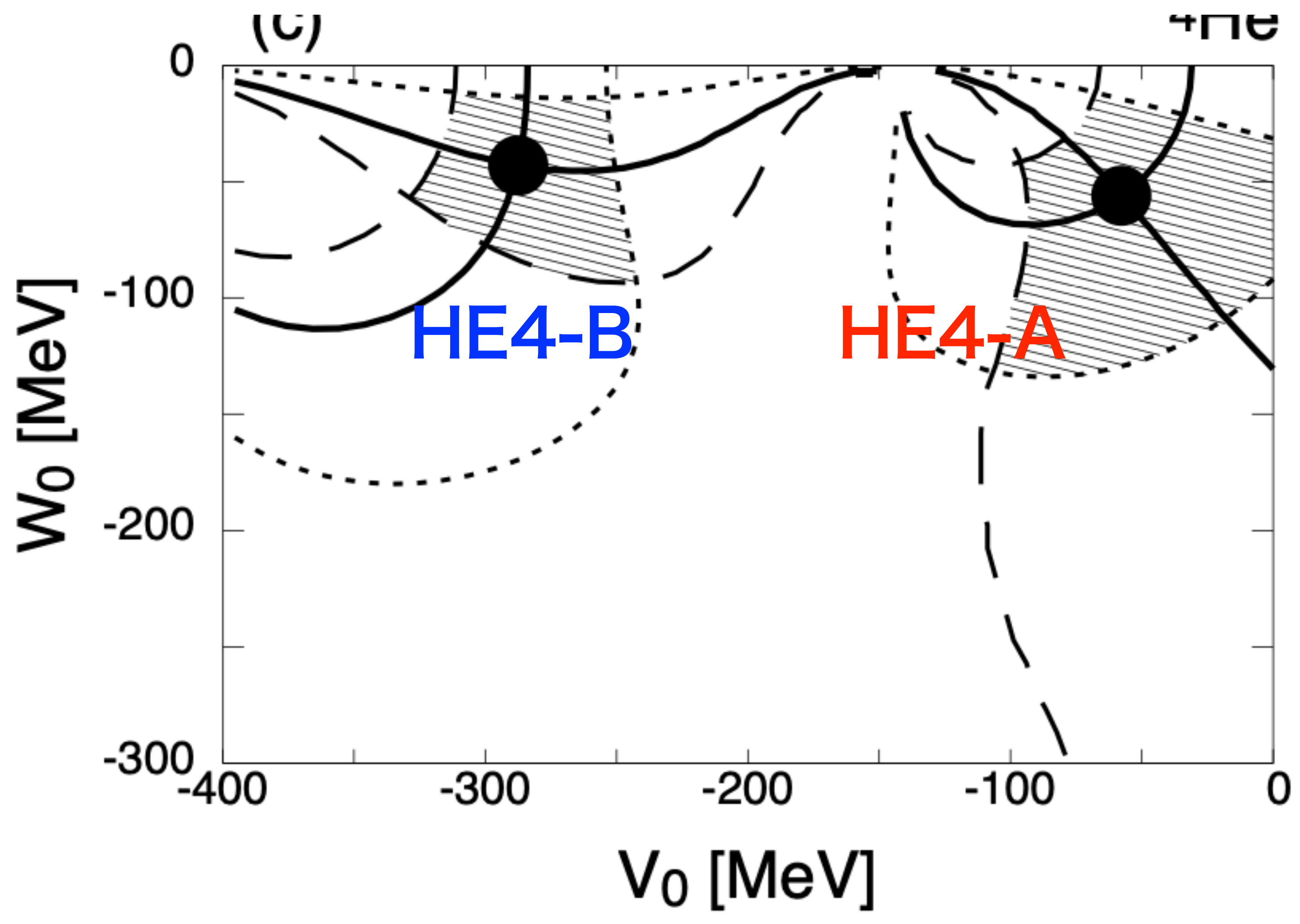
$$U_{\mathrm{PH}}(r) = (V_0 + iW_0)\frac{\rho(r)}{\rho_0}$$

Shift



Width





● : (V0, W0)

HE4-A : (-58,-56) [MeV]

HE4-B : (-287,-43) [MeV]

(This parameter can reproduce the experimental data.)

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

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

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

Isospin dependence of potentials

$$\tilde{U}(r) = [\tilde{V}_0 + i\tilde{W}_0]\frac{\rho(r)}{\rho_0} + [\tilde{V}_I + i\tilde{W}_I]\frac{\rho_n(r) - \rho_p(r)}{\rho_0}$$

^{3}He $$\tilde{U}(r) = [\tilde{V}_0 + i\tilde{W}_0]\frac{\rho(r)}{\rho_0} - [\tilde{V}_I + i\tilde{W}_I]\frac{1}{3}\frac{\rho(r)}{\rho_0}$$

^{4}He $$\tilde{U}(r) = [\tilde{V}_0 + i\tilde{W}_0]\frac{\rho(r)}{\rho_0}$$

$\tilde{V}_I$ and $\tilde{W}_I$ are large and they could indicate the existence of the relatively large isospin dependence in the kaon-nucleus optical potential.

—— HE3-A ····· HE4-A

—— HE3-B ····· HE4-B

(V_0, W_0)

^{3}He	^{4}He = $(\tilde{V}_0, \tilde{W}_0)$	$(\tilde{V}_I, \tilde{W}_I)$
(-178, -274)	(-58, -56)	(360, 654)
(-178, -274)	(-287, -43)	(-327, 693)
(-300, -95)	(-58, -56)	(726, 117)
(-300, -95)	(-287, -43)	(39, 156)

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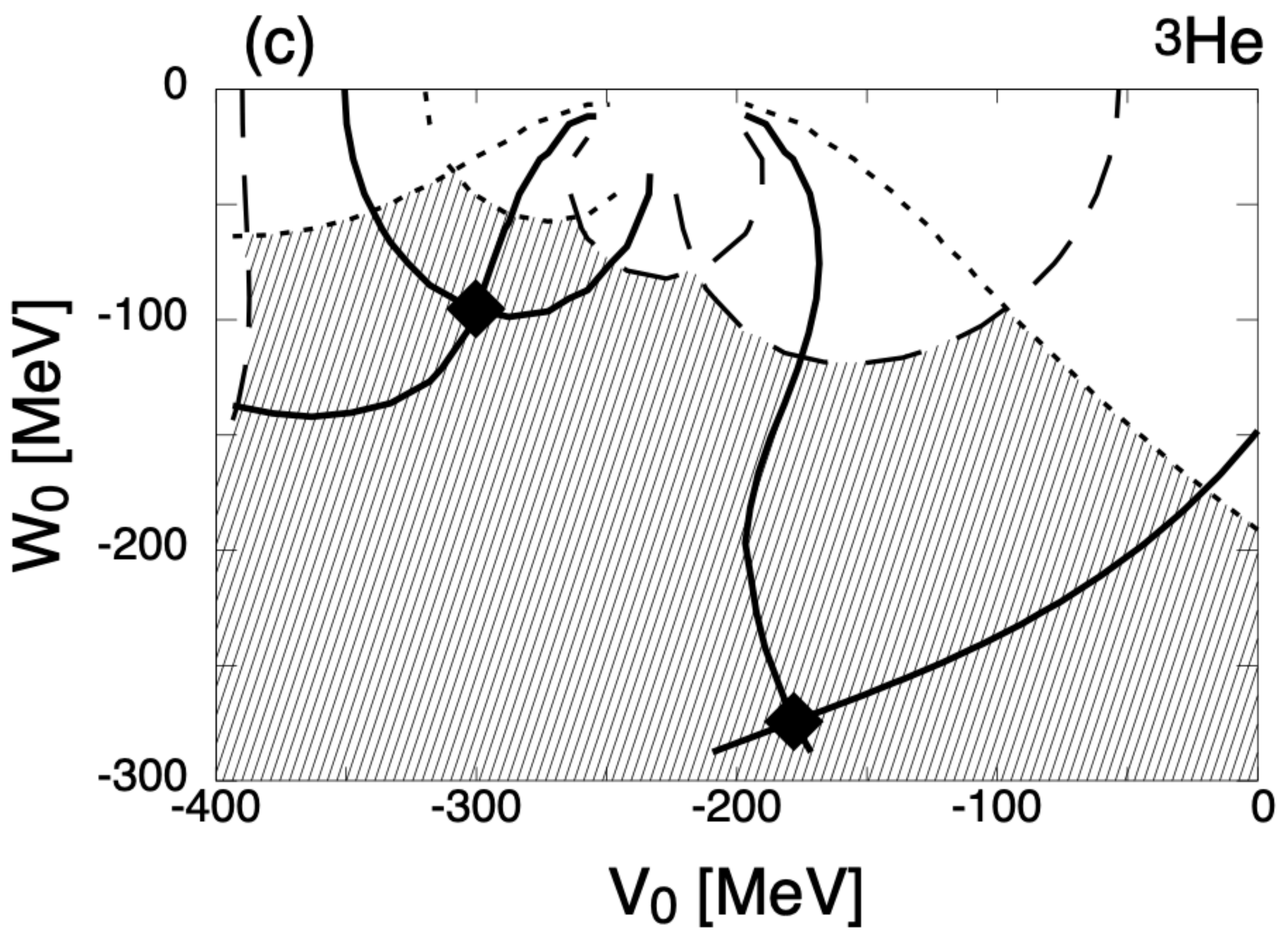
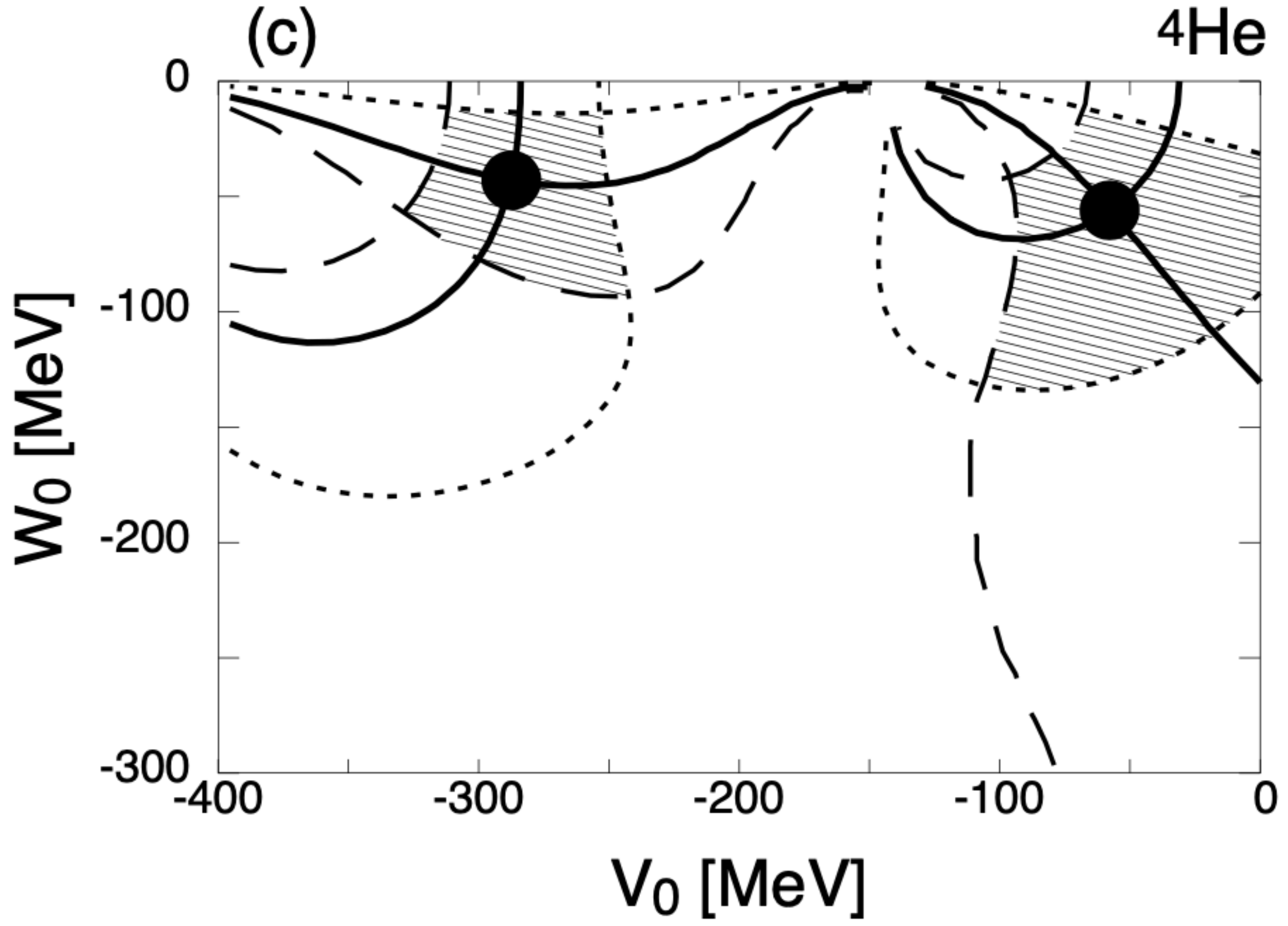
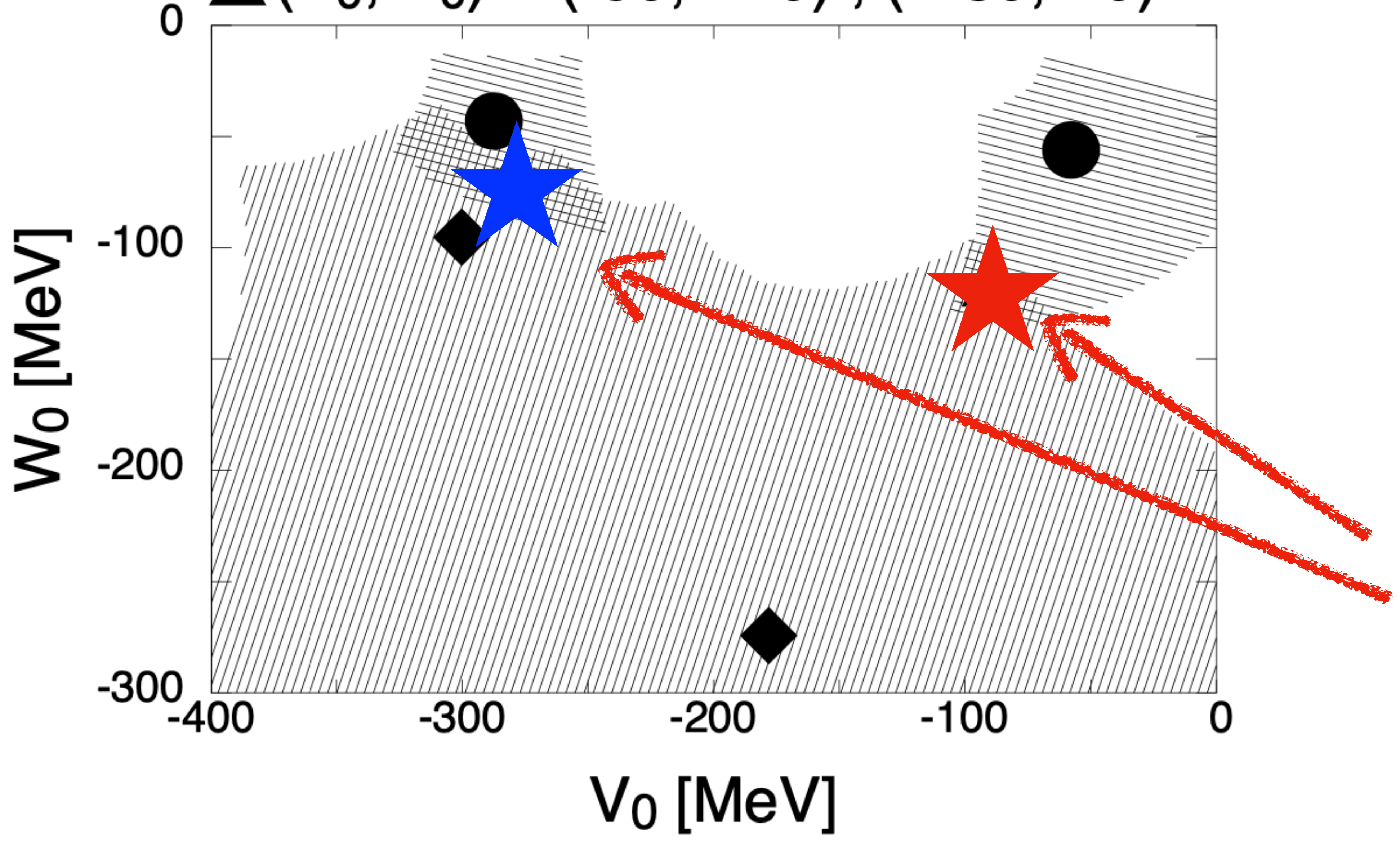
Combined study of ^{3}He and ^{4}He

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





▲(V_0,W_0) = (-90,-120) , (-280,-70)



Reproduce

$K^- -{}^3$He and $K^- -{}^4$He within the errors!!

IS-A

★		V_0	W_0
ρ_0		**-90**	**-120**
^{3}He	$\rho(0)$	-119	-159
^{4}He	$\rho(0)$	-182	-243

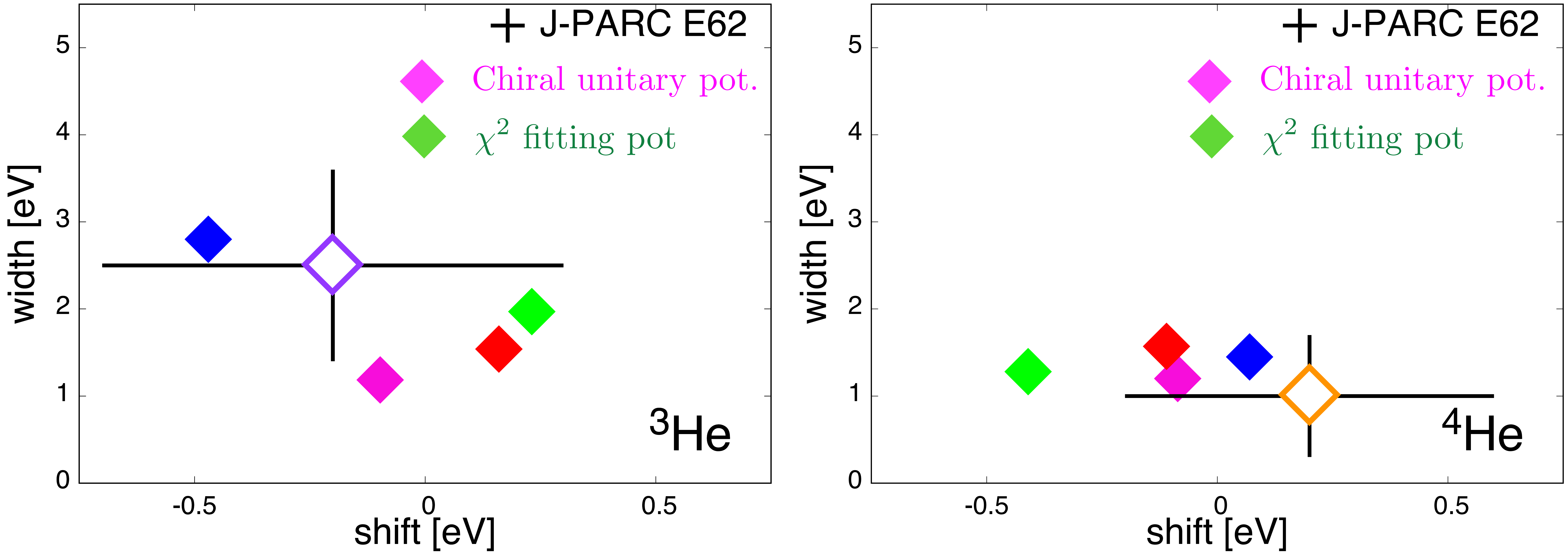
IS-B

★		V_0	W_0
ρ_0		**-280**	**-70**
^{3}He	$\rho(0)$	-357	-93
^{4}He	$\rho(0)$	-566	-142

Combined study of ^{3}He and ^{4}He

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

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



◇ HE3-A : (-178, -274), HE3-B : (-300, -95) ◆ IS-A : (-90, -120)

◇ HE4-A: (-58, -56), HE4-B : (-287,-43) ◆ IS-B : (-280, -70) MeV

Discussion on kaonic atom optical potential

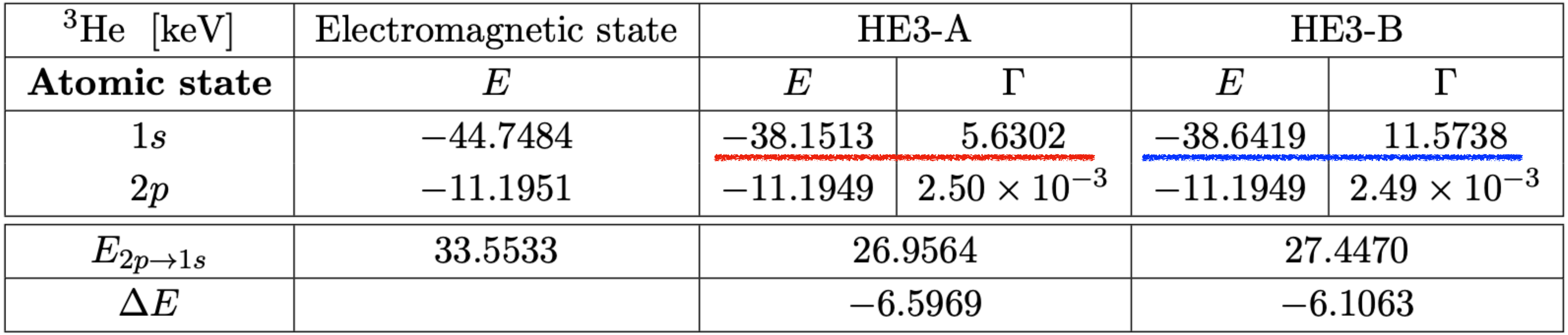
- Kaonic 1s atoms in ^{3}He and ^{4}He
  - ◇ HE3-A : (-178, -274), HE3-B : (-300, -95)
  - ◇ HE4-A: (-58, -56), HE4-B : (-287,-43)
- Kaonic atoms in heavier nuclei
  - ◆ IS-A : (-90, -120) MeV
  - ◆ IS-B : (-280, -70) MeV

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

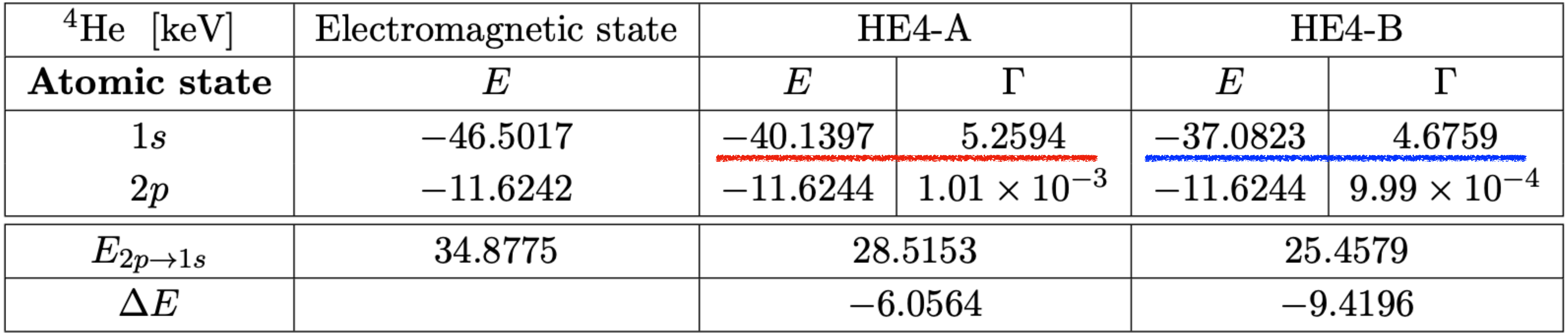
- Kaonic nuclei

Kaonic 1s atoms

HE3-A : (-178, -274), HE3-B : (-300, -95)
HE4-A: (-58, -56), HE4-B : (-287,-43)



^{3}He [keV]	Electromagnetic state	HE3-A		HE3-B	
Atomic state	E	E	Γ	E	Γ
$1s$	-44.7484	-38.1513	5.6302	-38.6419	11.5738
$2p$	-11.1951	-11.1949	2.50×10^{-3}	-11.1949	2.49×10^{-3}
$E_{2p \to 1s}$	33.5533	26.9564		27.4470	
ΔE		-6.5969		-6.1063	



^{4}He [keV]	Electromagnetic state	HE4-A		HE4-B	
Atomic state	E	E	Γ	E	Γ
$1s$	-46.5017	-40.1397	5.2594	-37.0823	4.6759
$2p$	-11.6242	-11.6244	1.01×10^{-3}	-11.6244	9.99×10^{-4}
$E_{2p \to 1s}$	34.8775	28.5153		25.4579	
ΔE		-6.0564		-9.4196	

The 1s states are found to exist as **the discrete states**

as in the case of the deeply bound pionic atoms !!

Kaonic 1s atoms

HE3-A : (-178, -274), HE3-B : (-300, -95)
HE4-A: (-58, -56), HE4-B : (-287,-43)

^{3}He [keV]	Electromagnetic state	HE3-A		HE3-B	
Atomic state	E	E	Γ	E	Γ
$1s$	-44.7484	-38.1513	5.6302	-38.6419	11.5738
$2p$	-11.1951	-11.1949	2.50×10^{-3}	-11.1949	2.49×10^{-3}
$E_{2p \to 1s}$	33.5533	26.9564		27.4470	
ΔE		-6.5969		-6.1063	

^{4}He [keV]	Electromagnetic state	HE4-A		HE4-B	
Atomic state	E	E	Γ	E	Γ
$1s$	-46.5017	-40.1397	5.2594	-37.0823	4.6759
$2p$	-11.6242	-11.6244	1.01×10^{-3}	-11.6244	9.99×10^{-4}
$E_{2p \to 1s}$	34.8775	28.5153		25.4579	
ΔE		-6.0564		-9.4196	

We found that the energies of the 1s atomic states show **some differences for the two potentials both for 3He and 4He cases!**

Kaonic Atoms in heaven nuclei

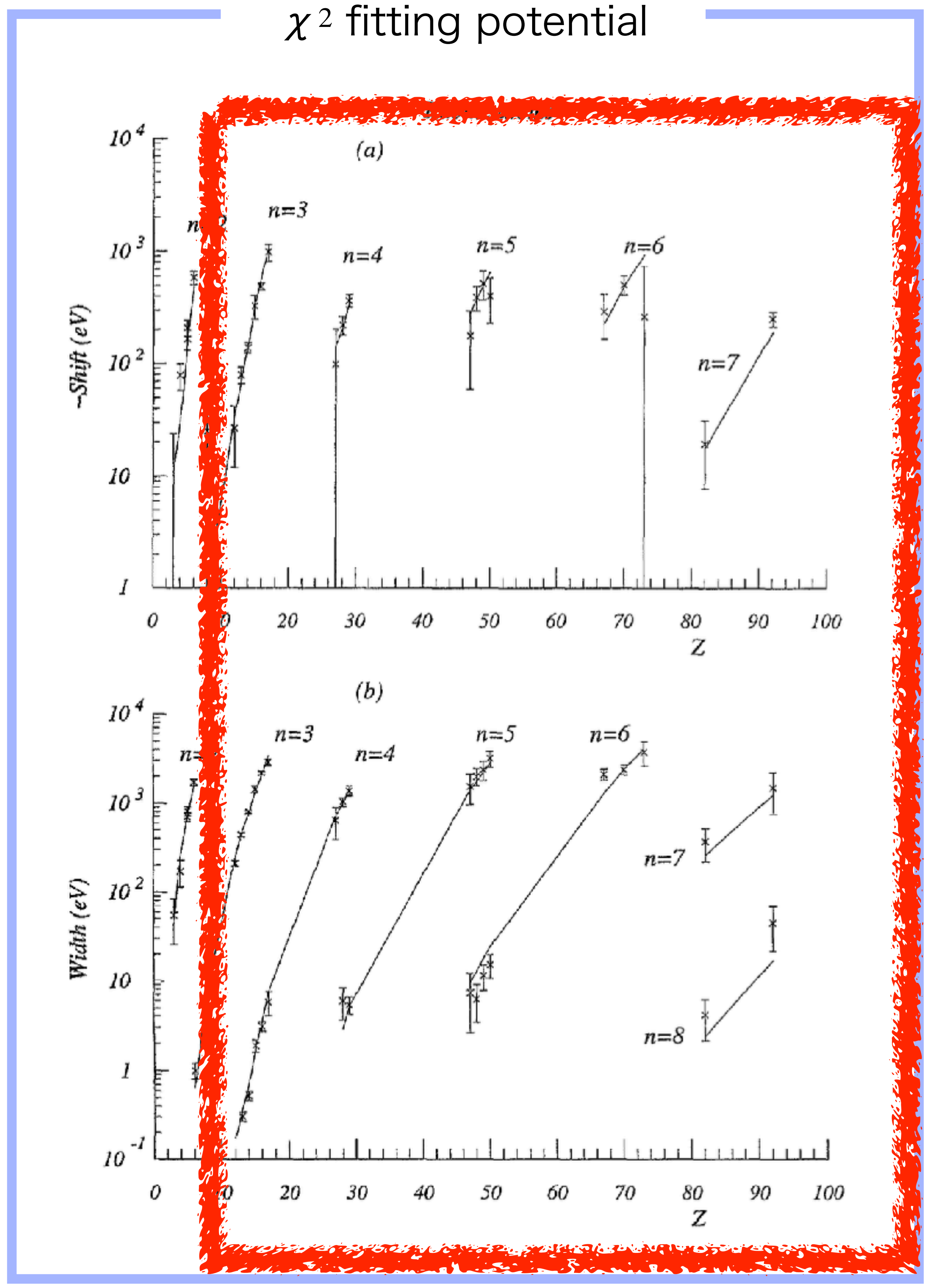
- Using the parameters

$$(V_0, W_0) = (-280, -70)$$
$$(V_0, W_0) = (-90, -120)$$

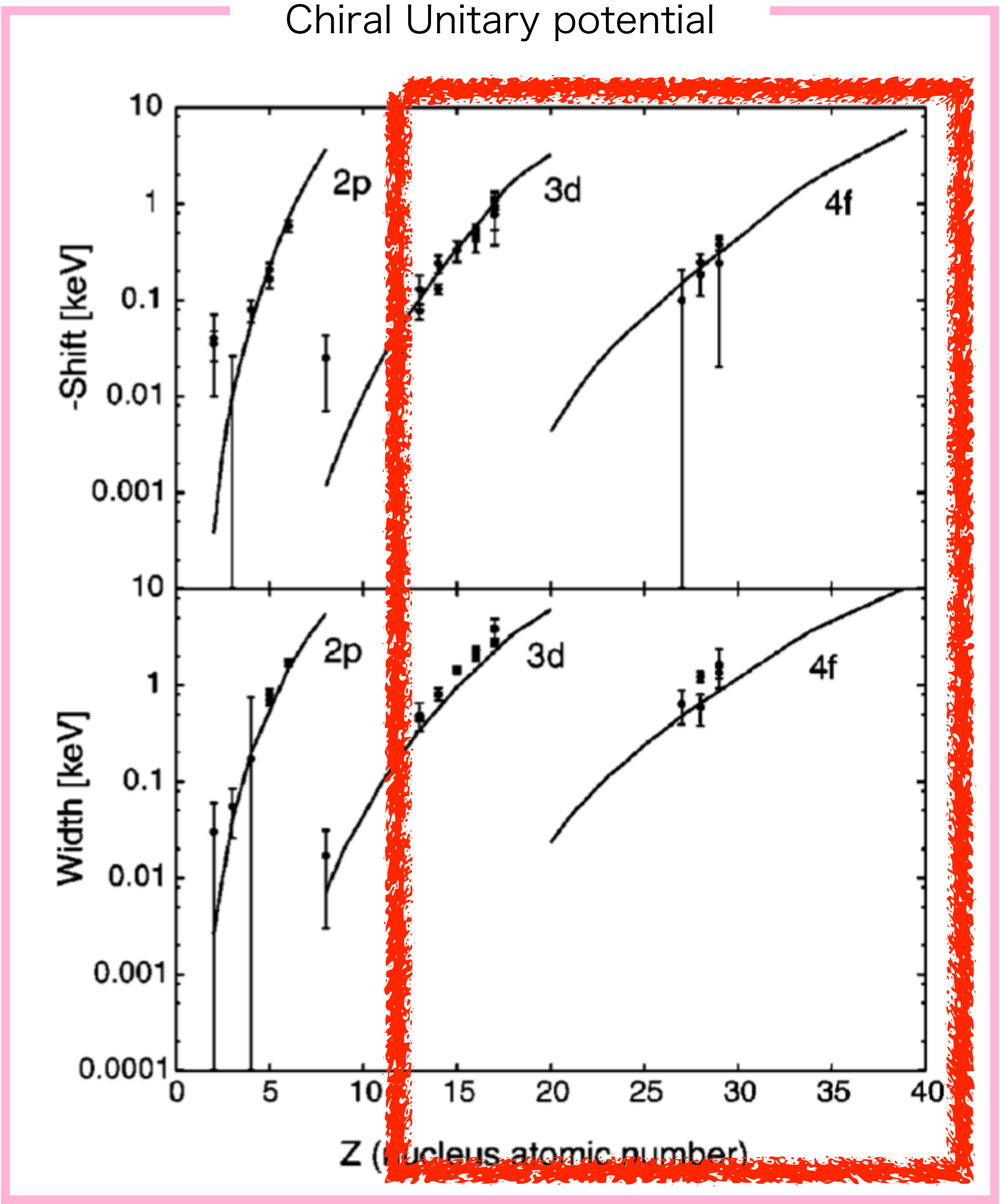
we calculate the shift and width.

- Nuclear density distribution (Woods-Saxon type)

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



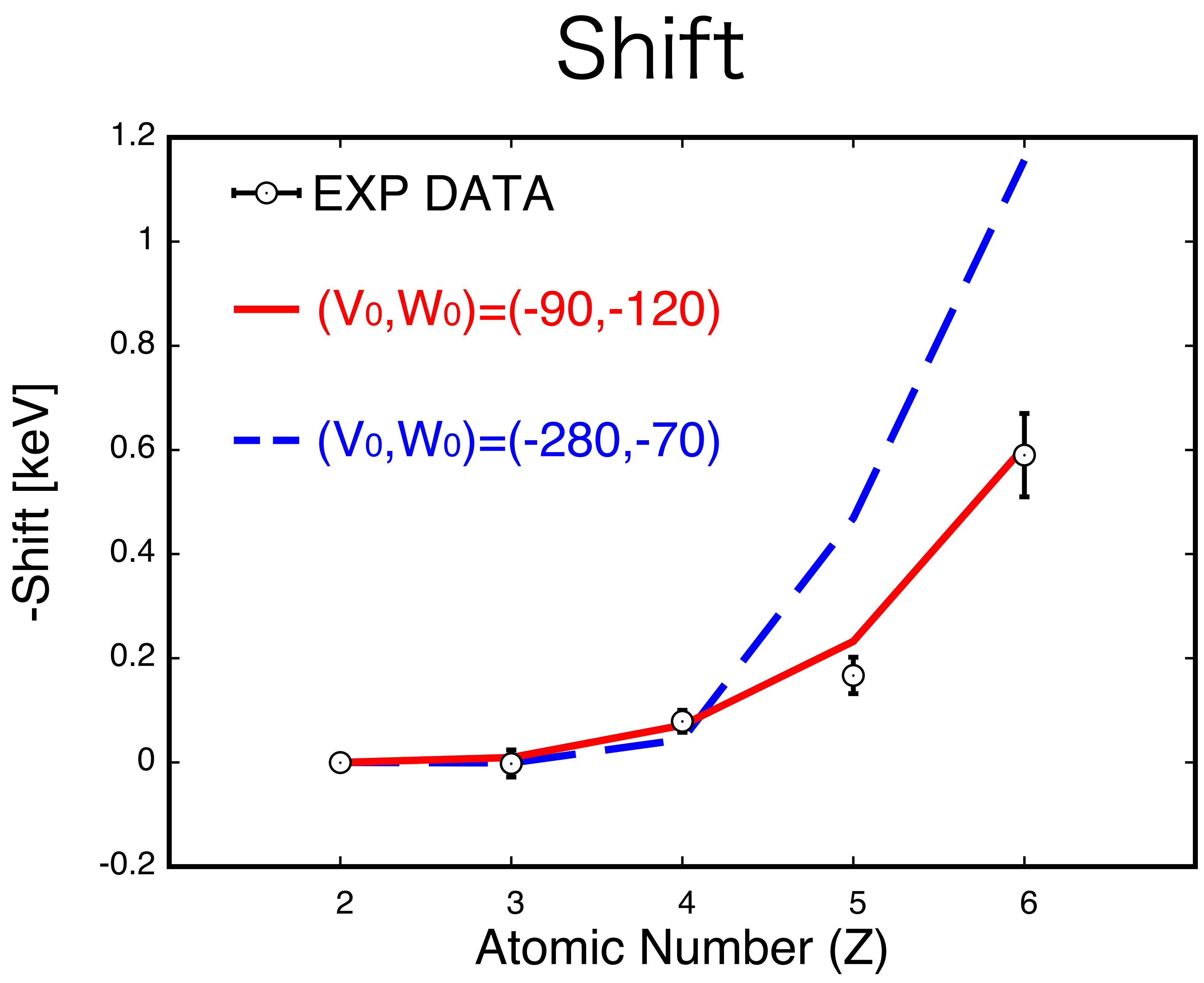
C. J. Batty, E. Friedman, A. Gal, Phys. Rept. 287(97)385



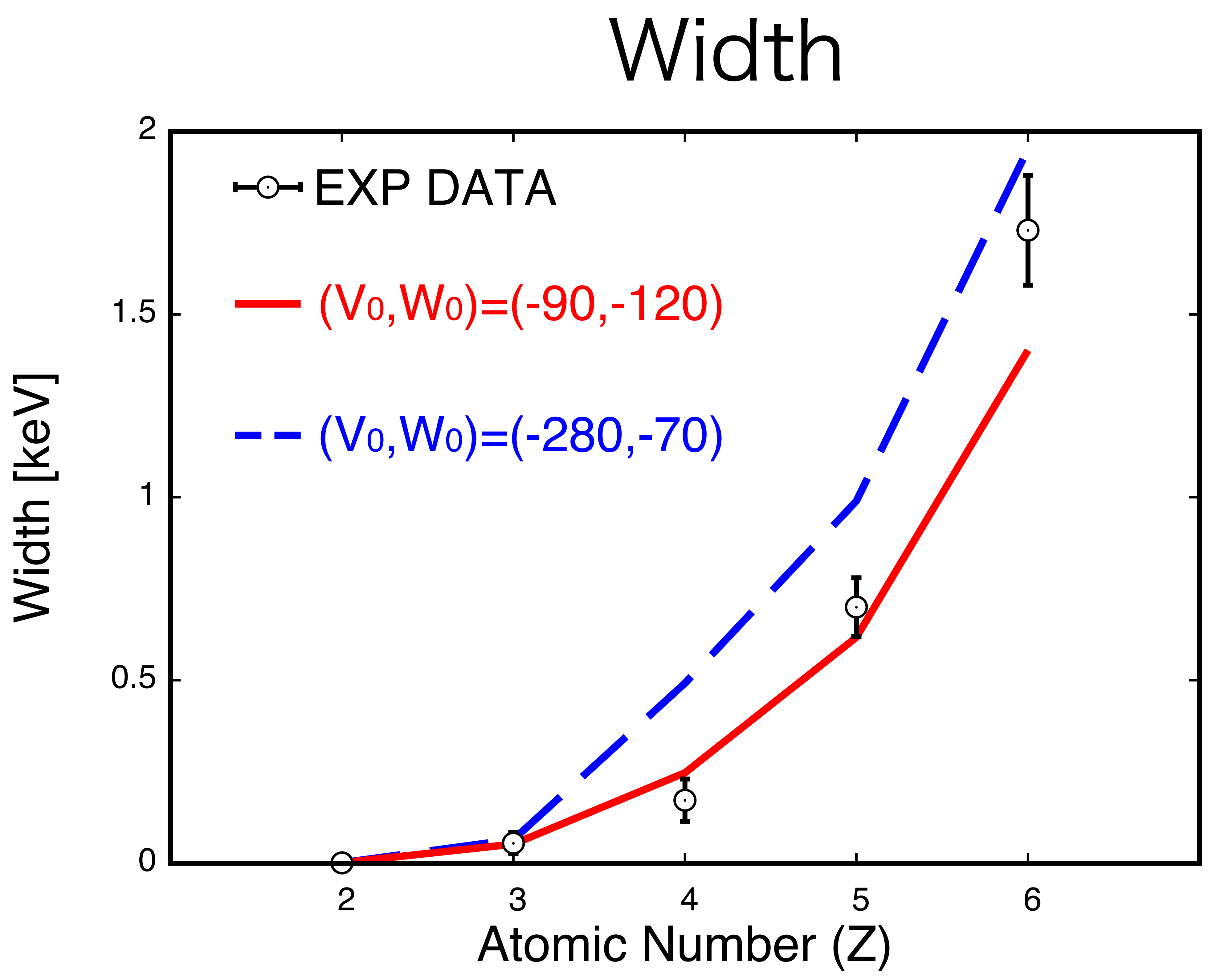
S. Hirenzaki, Y. Okumura, H. Toki, E. Oset, and A. Ramos, Phys. Rev. C61(00)055205

Results ($2 \leq Z \leq 6$)

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



Shift



Width

$3d \rightarrow 2p$

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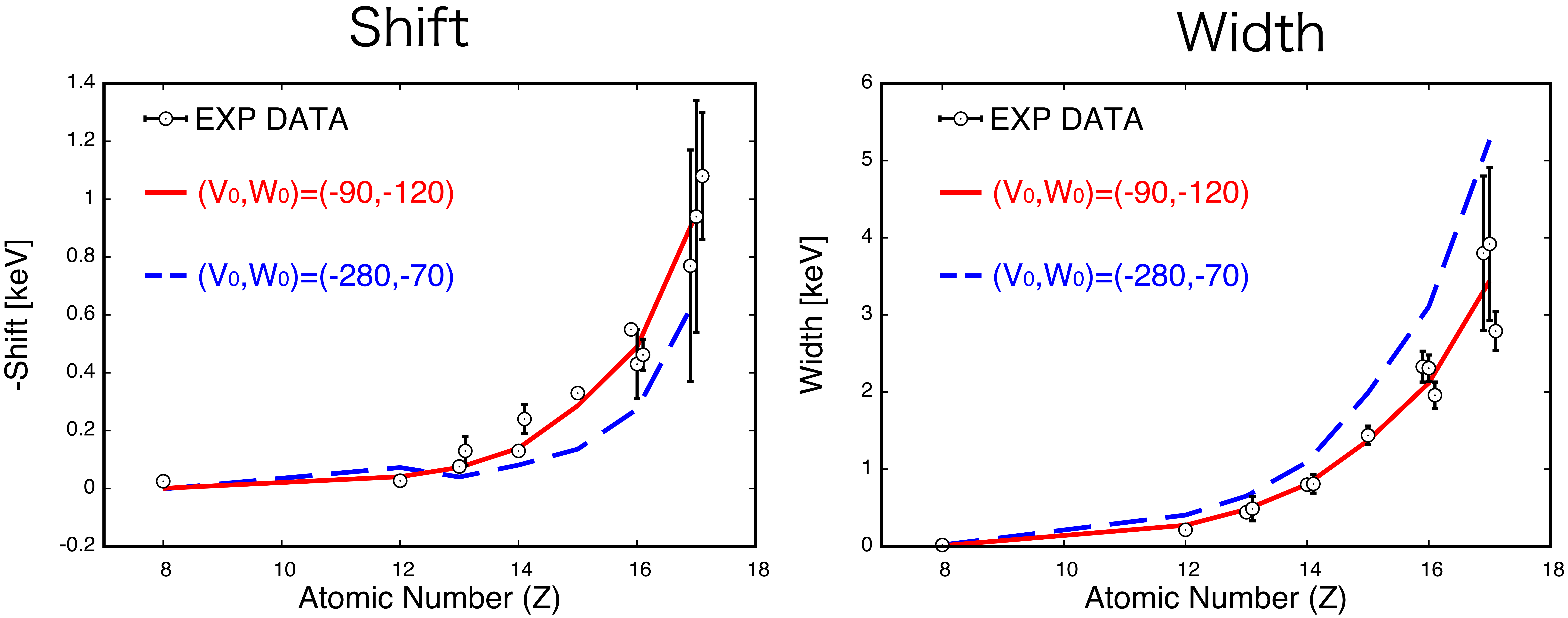
Results ($8 \leq Z \leq 17$)

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



$$4f \to 3d$$

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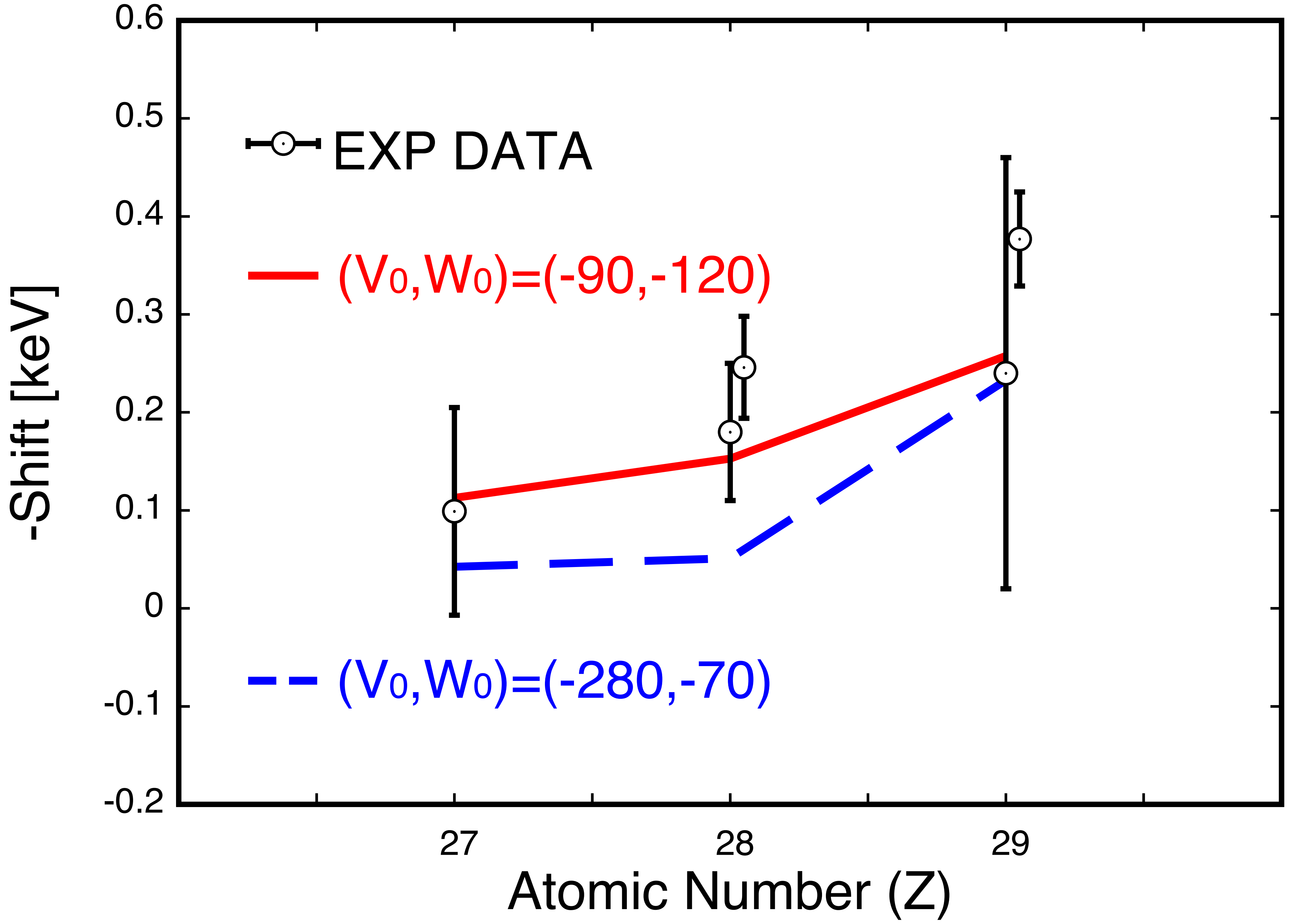
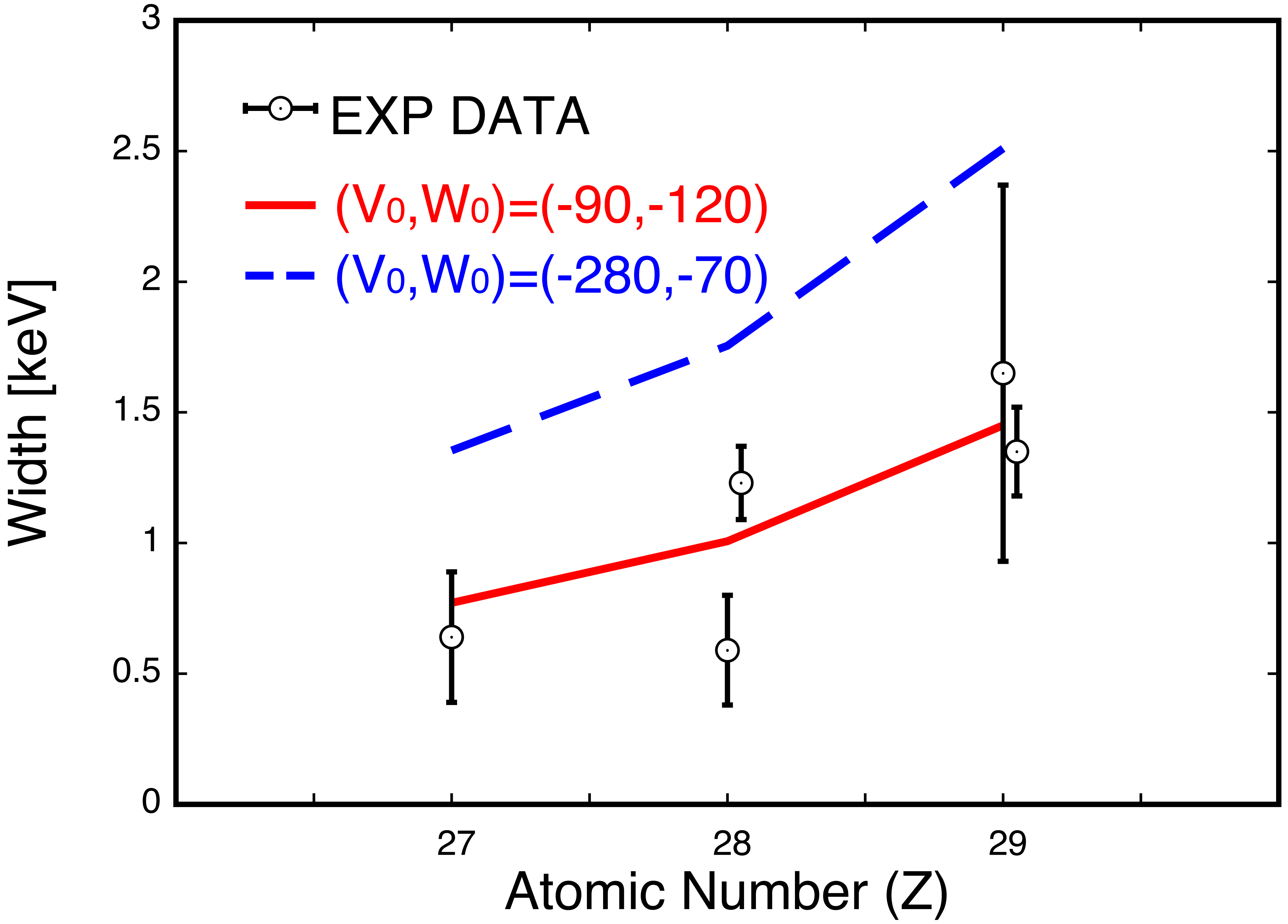
Results ($27 \leq Z \leq 29$)

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

Shift



Width



$$5g \rightarrow 4f$$

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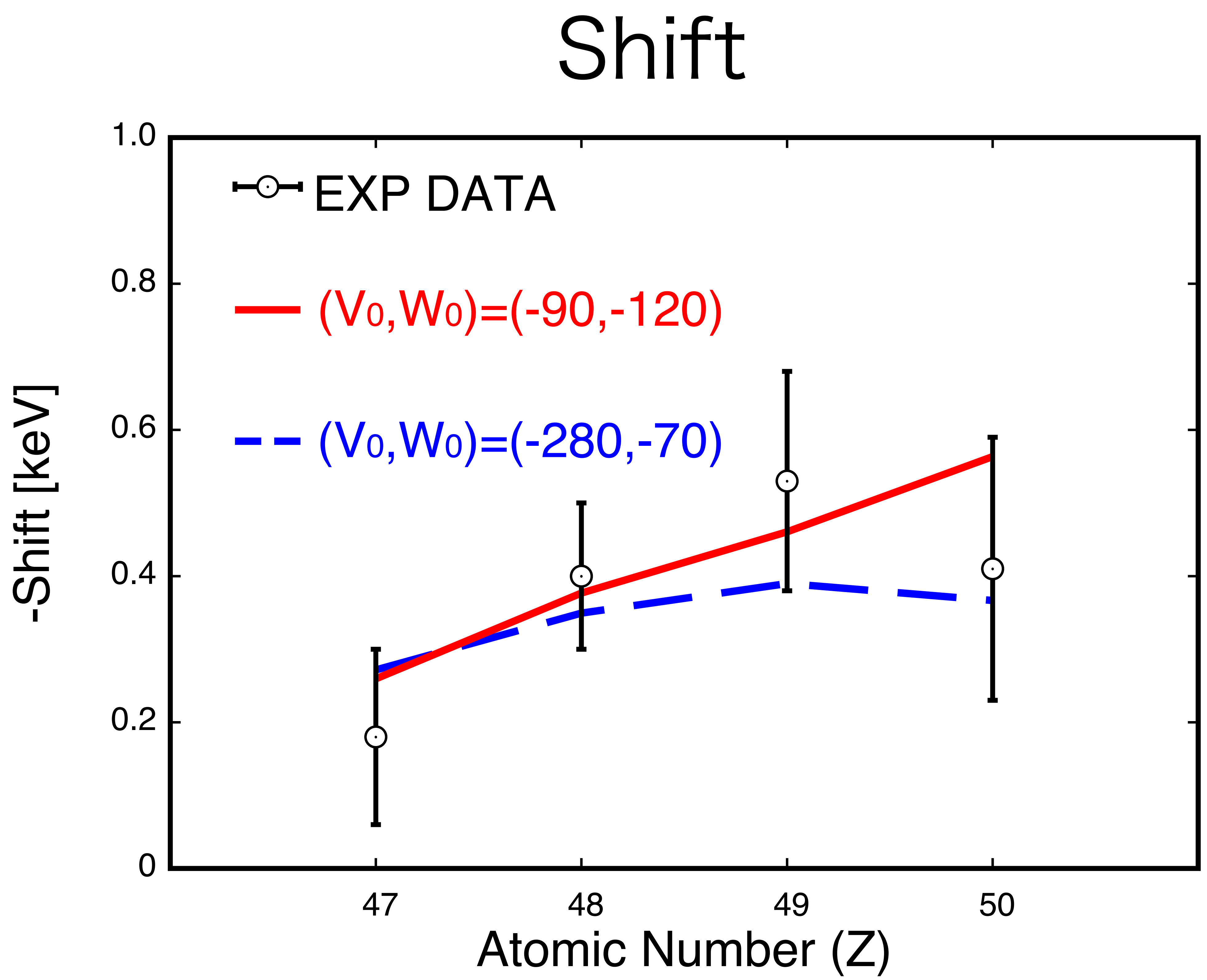
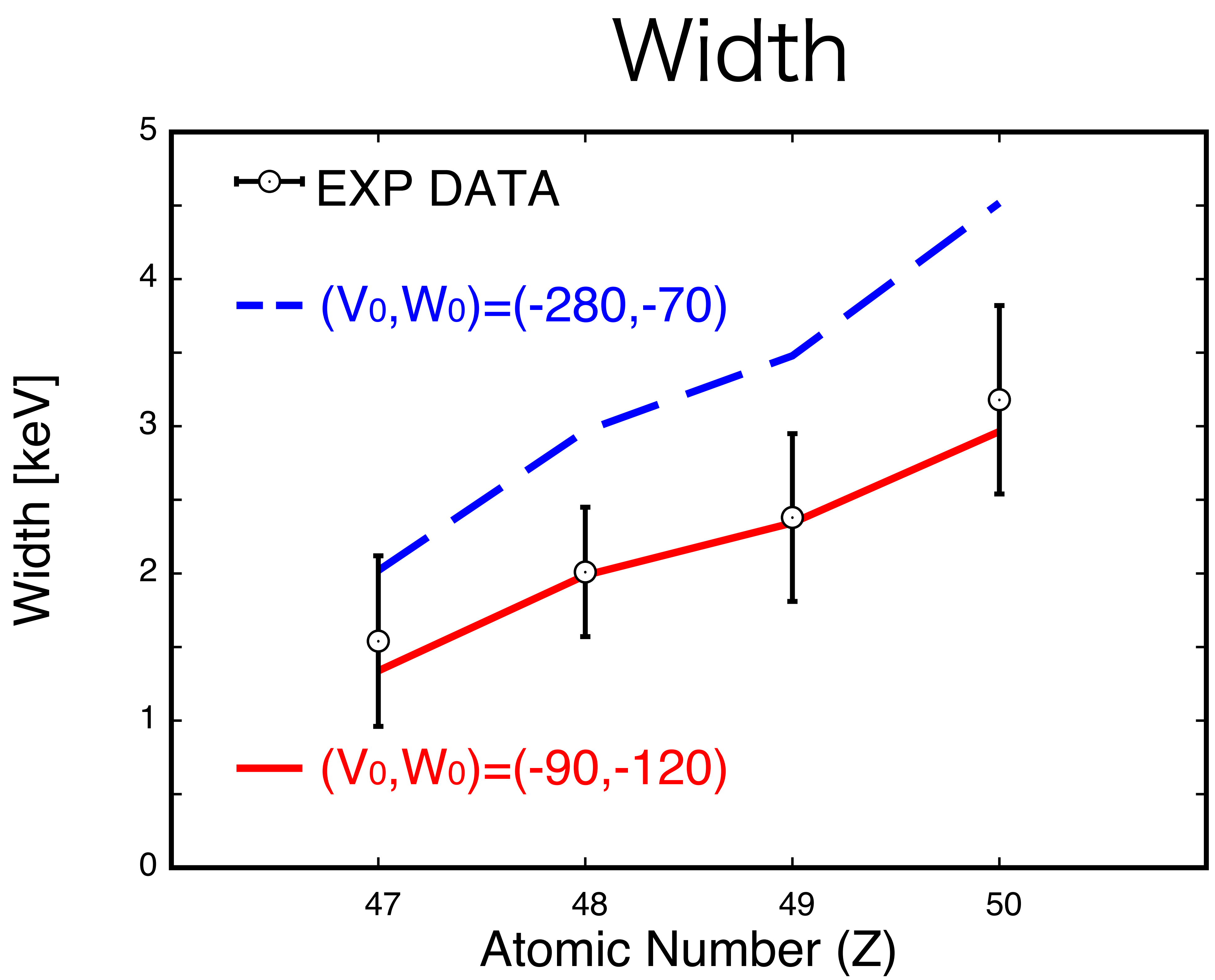
Results ($47 \leq Z \leq 50$)

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

$6h \to 5g$





With the potential parameter $(V_0,W_0)=(-90,-120)$,

we can well reproduce the experimental data !! J. Yamagata-Sekihara et al, in preparation

Summary

- We theoretically investigate the constraints on the optical potential of kaonic atoms deduced from the latest data, in order to understand the meanings of the data and its impacts on the physics of kaon-nucleus systems.

- We obtained the kaon-nucleus potential at $E = m_K$ that reproduces the precise experimental data of J-PARC E62.

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

- We calculated the atomic 1s states in ^{3}He and ^{4}He using the potential parameters HE3-A, -B and HE4-A, -B.
  We found that the 1s states exist as the discrete states and they will provide the further information on the optical potential.

Summary

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

- We also studied the kaonic atoms in heavier nuclei and found that the $(V_0, W_0) = (-90, -120)$ are better suited for the global description of the kaonic atoms in the wide range of the periodic table.

  The IS-A parameter set has the relatively weak real part and strong imaginary part.

- Based on the present study of the kaon-nucleus bound systems by the optical potential framework, we conclude that the further studies of the kaonic atoms especially **1s states in ^{3,4}He** are interesting and important to determine the kaon-nucleus interaction decisively and to develop the unified understandings of the kaonic atoms and kaonic nuclei.