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Analysis of polarized proton-^{6}He elastic scattering based on an improved di-neutron model

Y. Sakuragi [1,2], T. Yamamoto,[1] T. Furumoto,[1]

[1] *Graduate School of Science, Osaka City University*

[2] *RIKEN Nishina Center, RIKEN*

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   - Something wrong!
   - What's wrong?

2. "Improved di-neturon model for ^{6}He
   - A constraint upon "2n"- α wave function

3. Adiabatic-Recoil approximation (ARA)
   - "2n" size-effects on the elastic scattering

     → via break-up effect / folding potential

4. Effect of "2n"-p interaction ignored in ARA

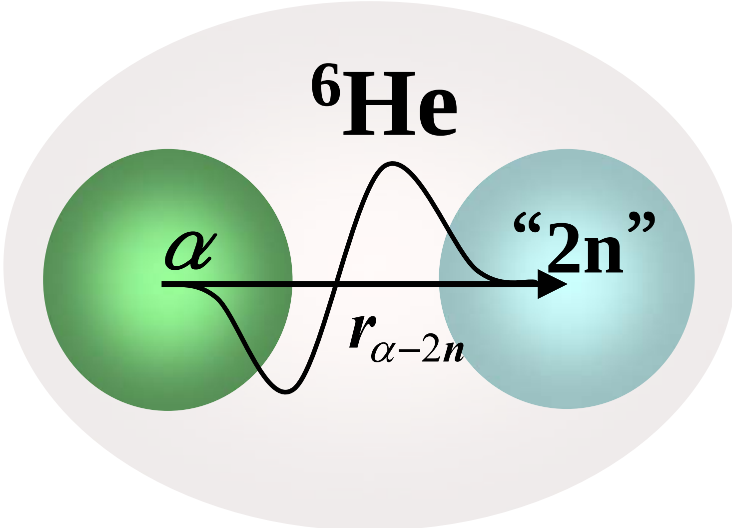
Problems of previous analyses

- **Folding model** : ***no break-up effect*** is included:
  - how important the breakup effect is?

  → estimate it within the framework of ***di-neutron*** model
  - BUT!

- ***"standard" di-neutron model*** on the market, which many authors have been using, ***may not be realistic***
  - Size of the whole nucleus (^{6}He) inevitably exceed the measured size.

  → Need modification/improvement to the "di-neutron" model



α-2n mean distance given by the **S.E.M.** so as to reproduce observed **B.E.(^{6}He)=0.976 MeV**

$$\overline{R}_{^6\mathrm{He}}^{\,2} = \frac{2}{3}\overline{R}_{\alpha}^{\,2} + \frac{1}{3}\overline{R}_{2n}^{\,2} + \frac{2}{9}\overline{r}_{\alpha-2n}^{\,2}$$

known from exp.data

size of di-neutron("2n")

$$\overline{R}_{^6\mathrm{He}} \cong 2.44\ \mathrm{fm},$$

$$\overline{R}_{\alpha} \cong 1.36\ \mathrm{fm}$$

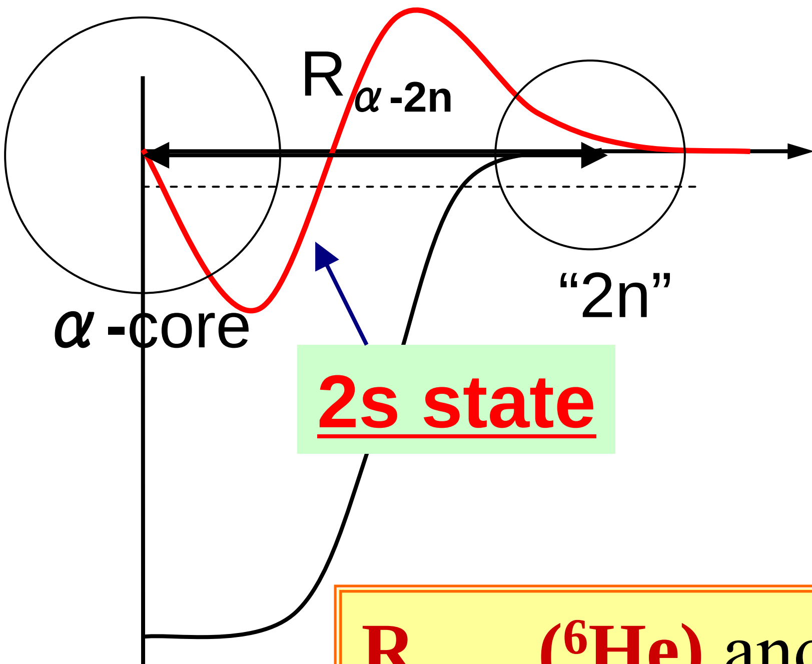
- should be!

$$\overline{r}_{\alpha-2n} \le 4.6\ \mathrm{fm}$$

even when $\overline{R}_{2n} = 0$

Conventional "di-neutron" model for ^{6}He

α+(2n) relative wave function is assumed to be 2s state and is given by the **separation energy method (SEM)** with the use of a single **attractive** Woods-Saxon potentail with a standard geometry (e.g. $R=1.2\times A^{1/3}$ **fm**, a=**0.5 fm**)



very small B.E. (0.976 MeV)

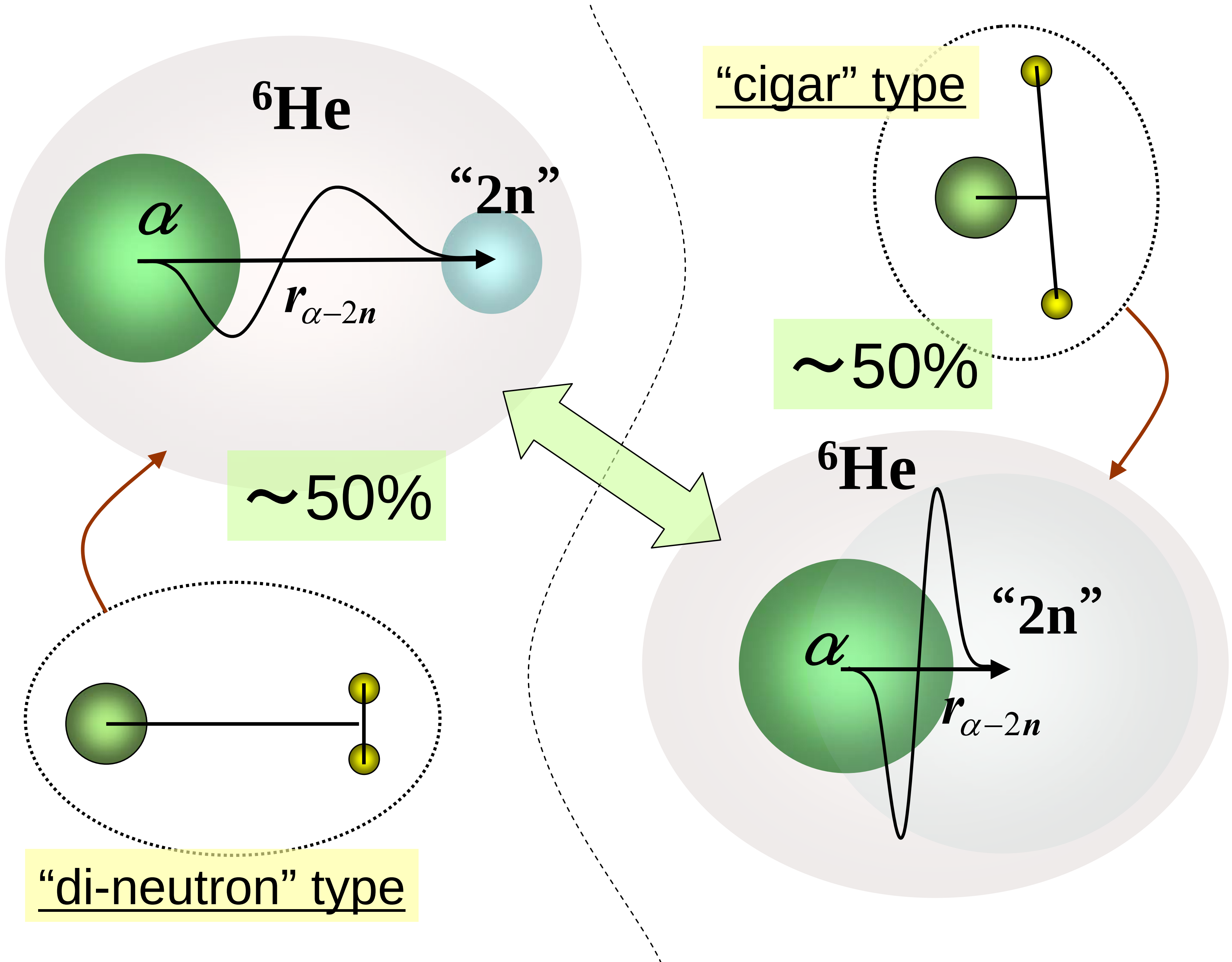
→ w.f. has a very long-range tail

→ $R_{\alpha\text{-2n}} \geq$ 4.7 fm ∼5.1 fm

→ leads to an unrealistic size of the whole nucleus ^{6}He

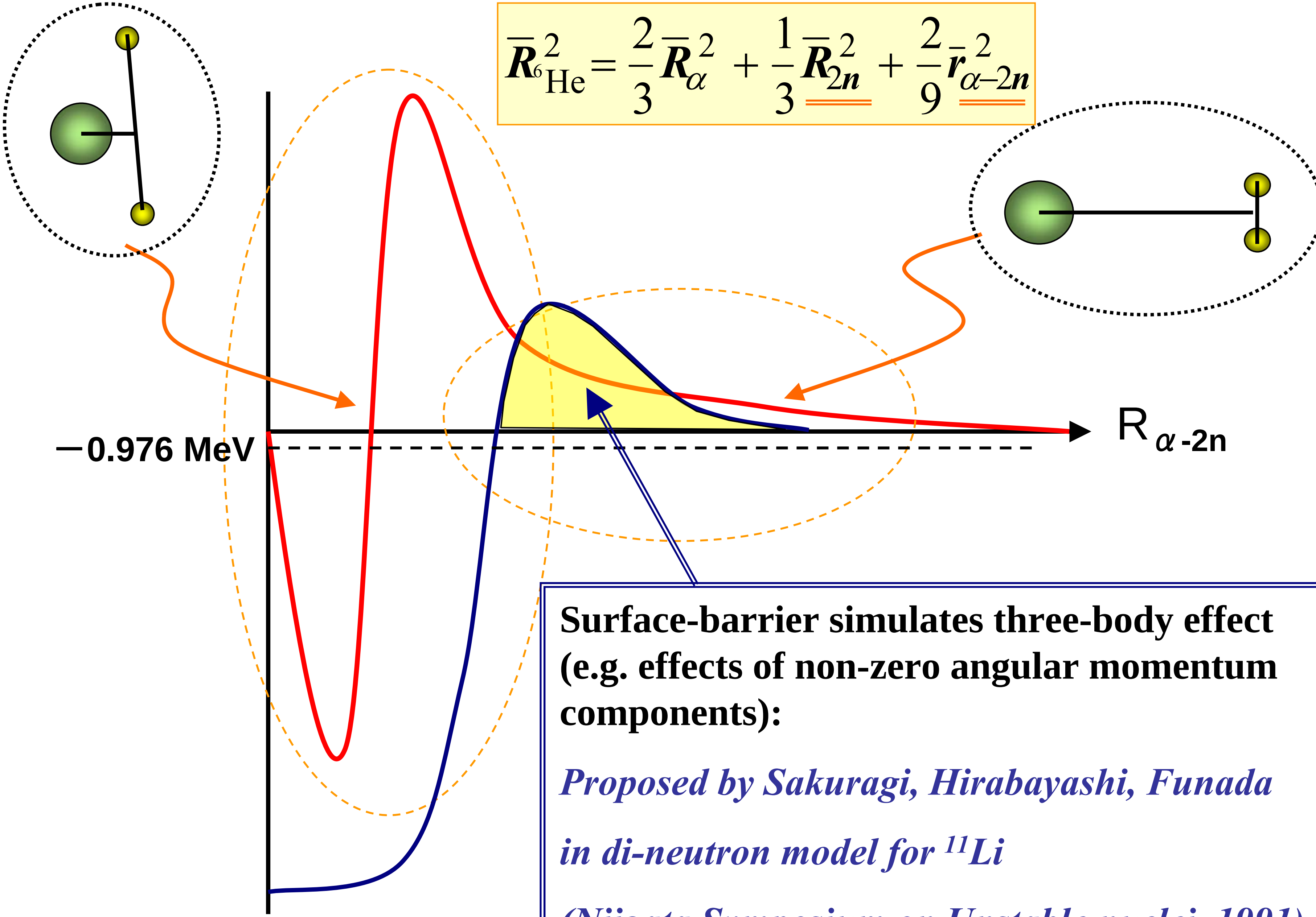
$R_{r.m.s.}$(^{6}He) and **B.E.$_{\alpha\text{-2n}}$** cannot be reproduced simultaneously by the standard di-neutron model, as long as one uses a single attractive potentail.

→ **need α+n+n three-body treatment?**



^{6}He
α
“2n”
$r_{\alpha-2n}$
“cigar” type
~50%
~50%
^{6}He
α
“2n”
$r_{\alpha-2n}$
“di-neutron” type

$$\overline{\boldsymbol{R}}^2_{{}^6\mathrm{He}} = \frac{2}{3}\overline{\boldsymbol{R}}^2_{\alpha} + \frac{1}{3}\overline{\boldsymbol{R}}^2_{2\boldsymbol{n}} + \frac{2}{9}\bar{\boldsymbol{r}}^2_{\alpha-2\boldsymbol{n}}$$



Surface-barrier simulates three-body effect (e.g. effects of non-zero angular momentum components):

Proposed by Sakuragi, Hirabayashi, Funada

in di-neutron model for ^{11}Li

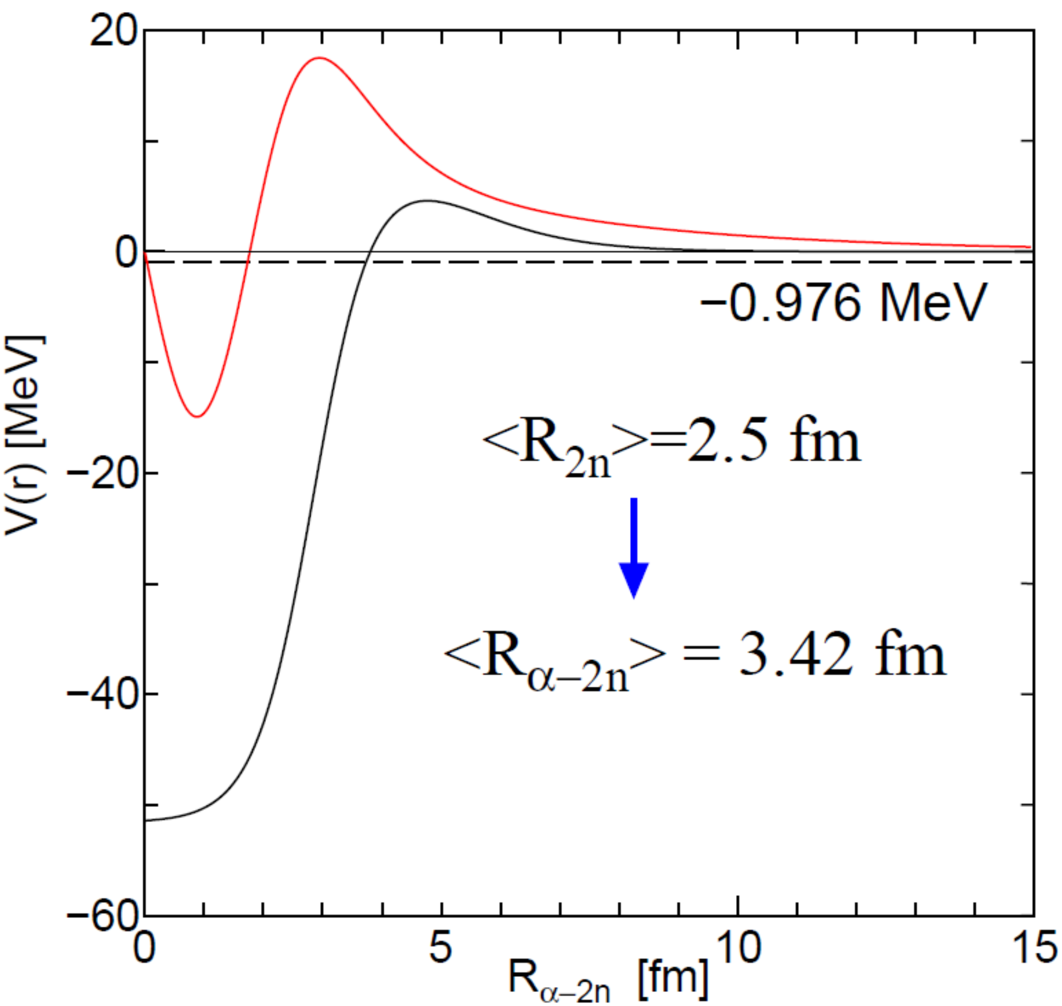
(Niigata Symposium on Unstable nuclei, 1991)

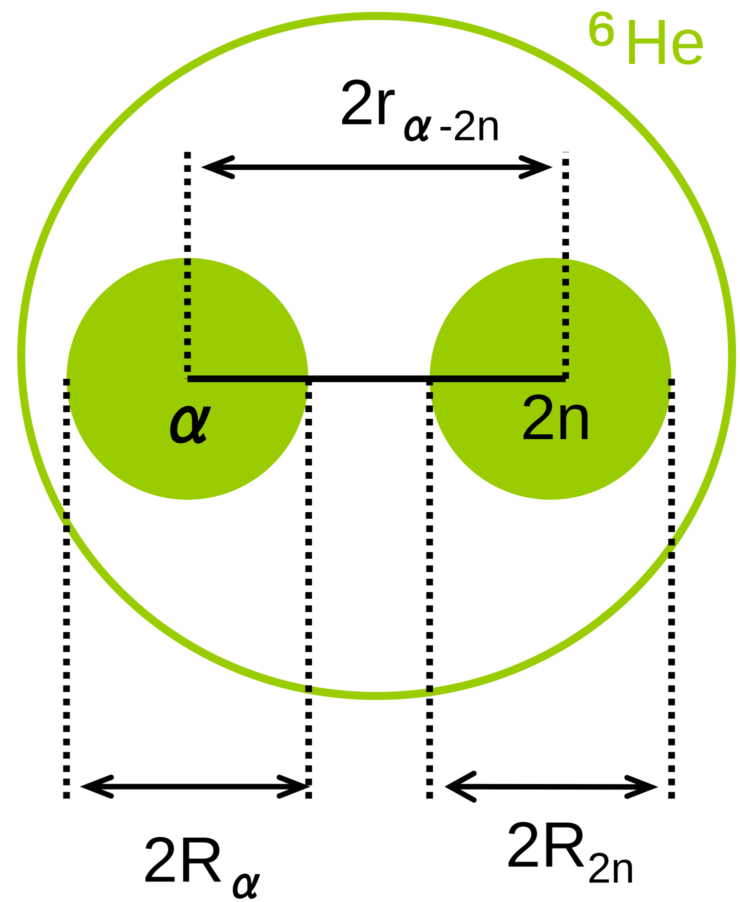
$$\overline{R}_{^6\mathrm{He}}^{\,2} = \frac{2}{3}\overline{R}_{\alpha}^{\,2} + \frac{1}{3}\overline{R}_{2n}^{\,2} + \frac{2}{9}\overline{r}_{\alpha-2n}^{\,2}$$

Total size of ^{6}He should be fixed to exp. value!

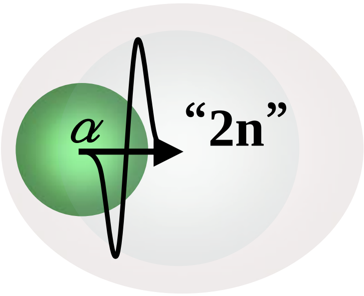
Exp.data

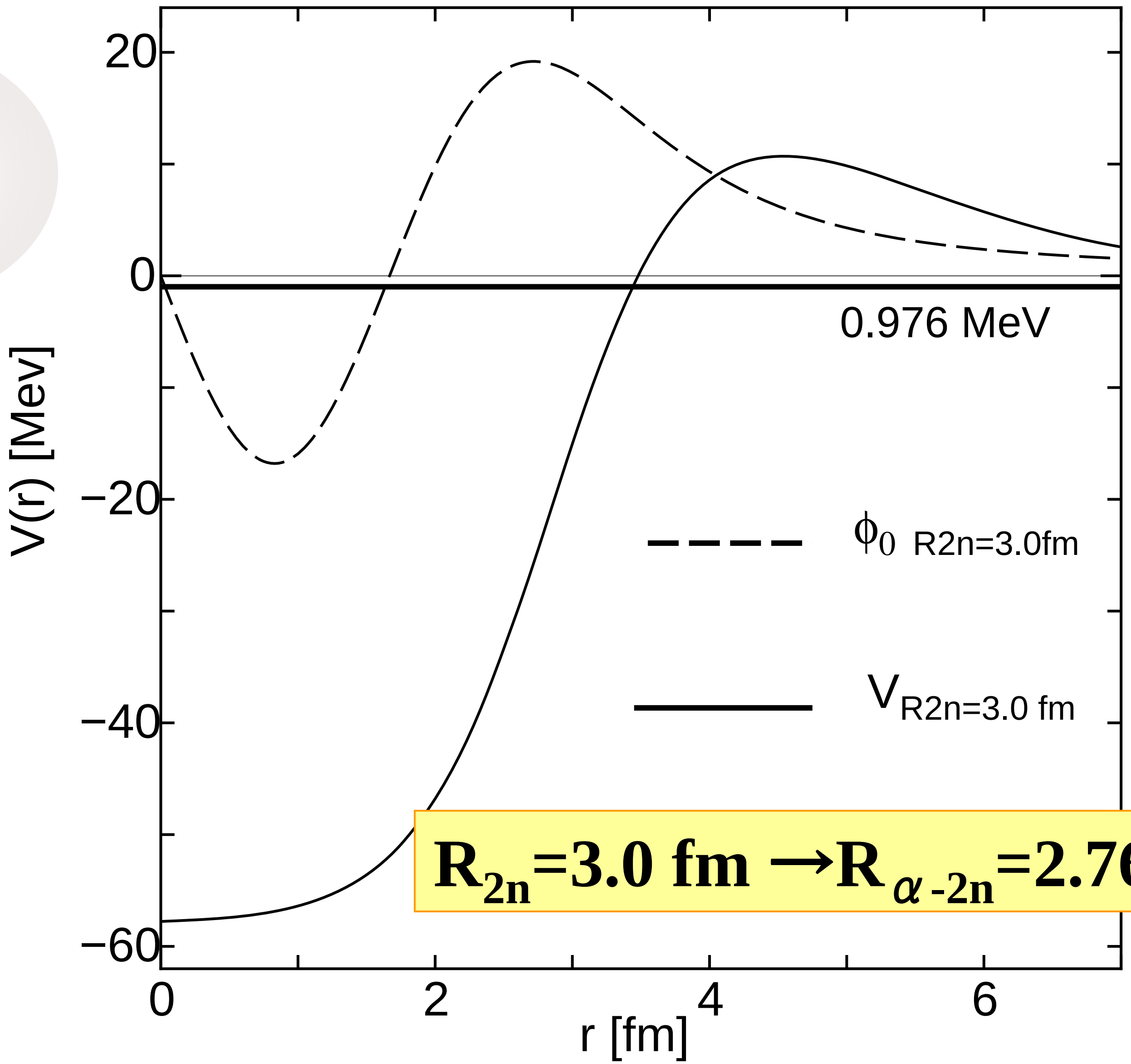
free-parameter ← “2n” size





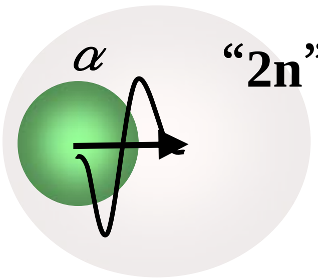
“2n”- α relative wave function

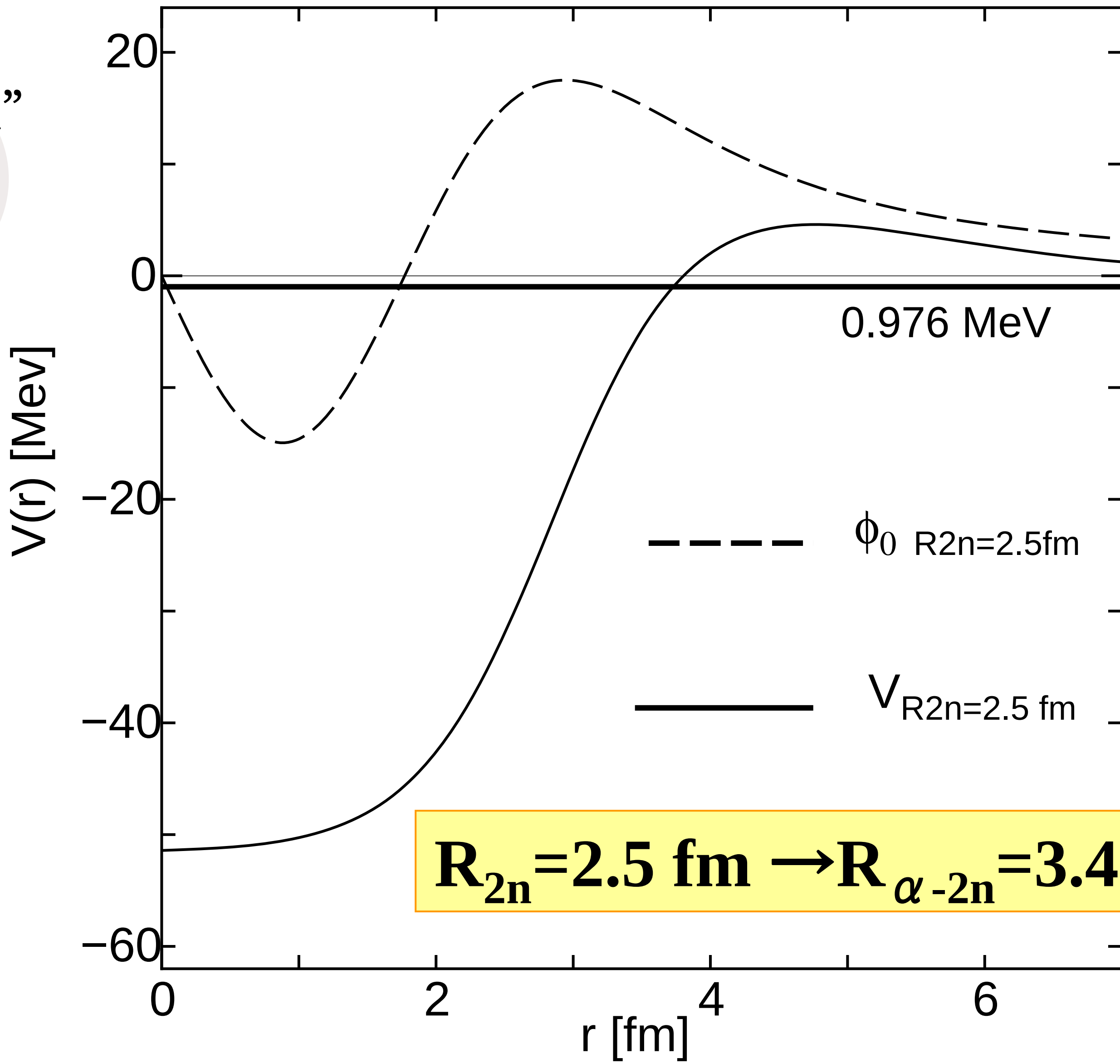




R_{2n}=3.0 fm →$R_{\alpha\text{-}2n}$=2.76 fm

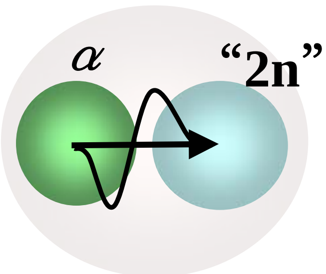
"2n"- α relative wave function

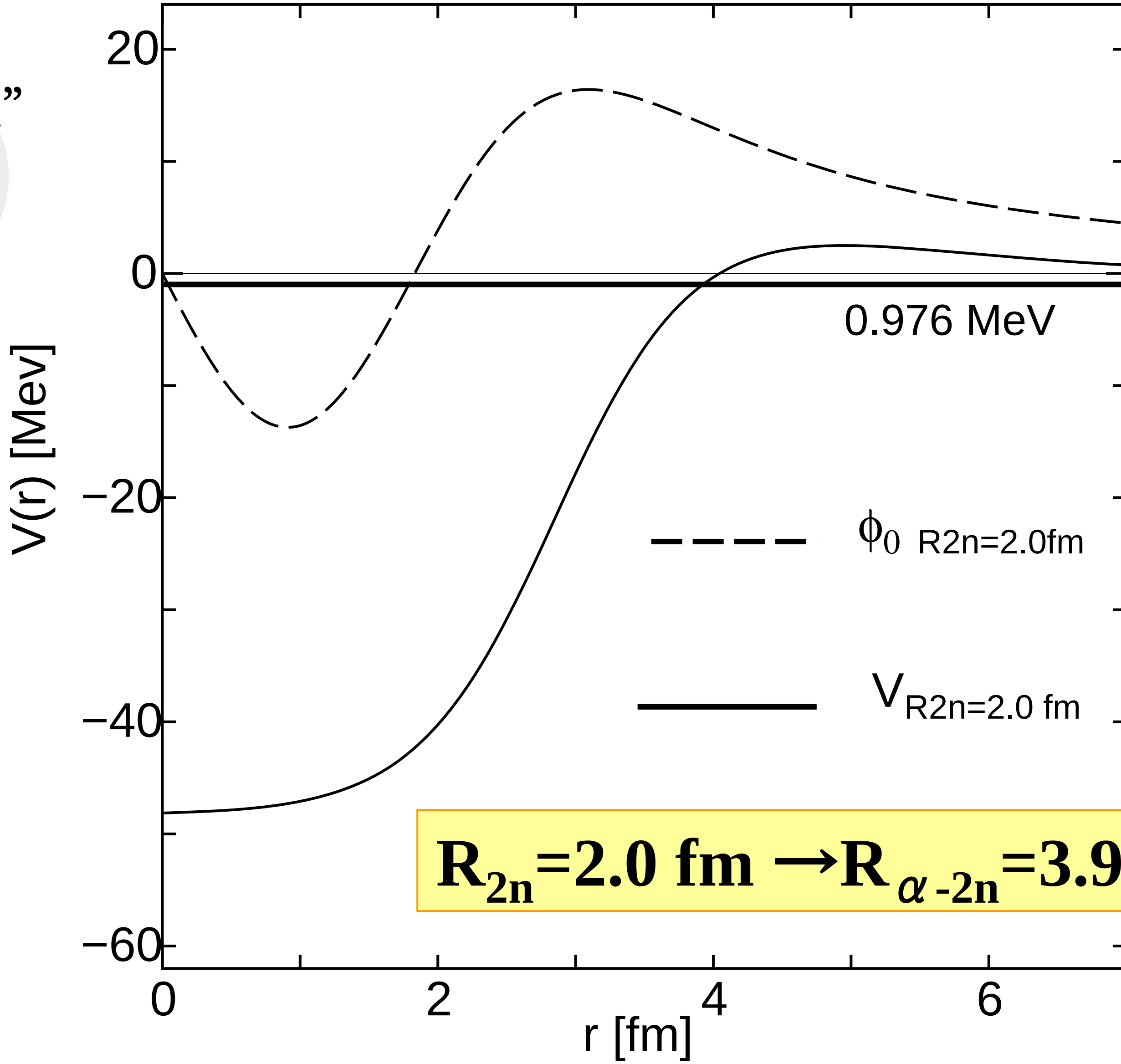




R_{2n}=2.5 fm →$R_{\alpha\text{-}2n}$=3.42 fm

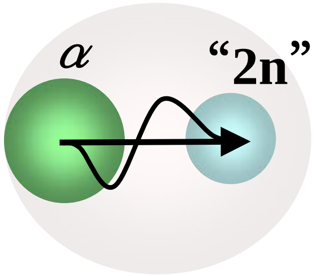
"2n"- α relative wave function

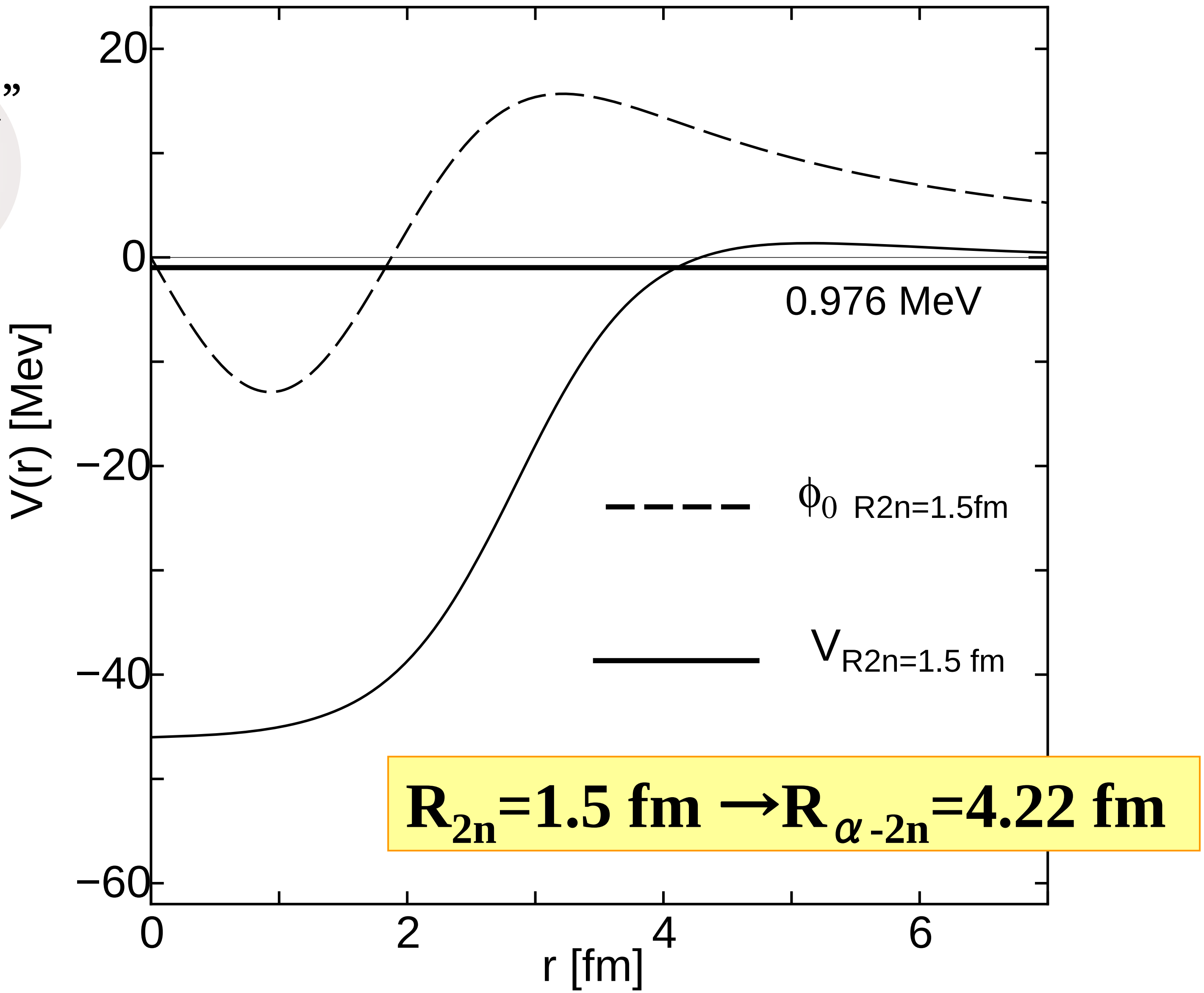




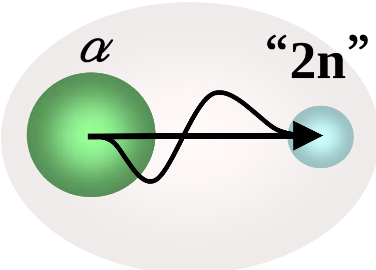
R_{2n}=2.0 fm →$R_{\alpha\text{-}2n}$=3.91 fm

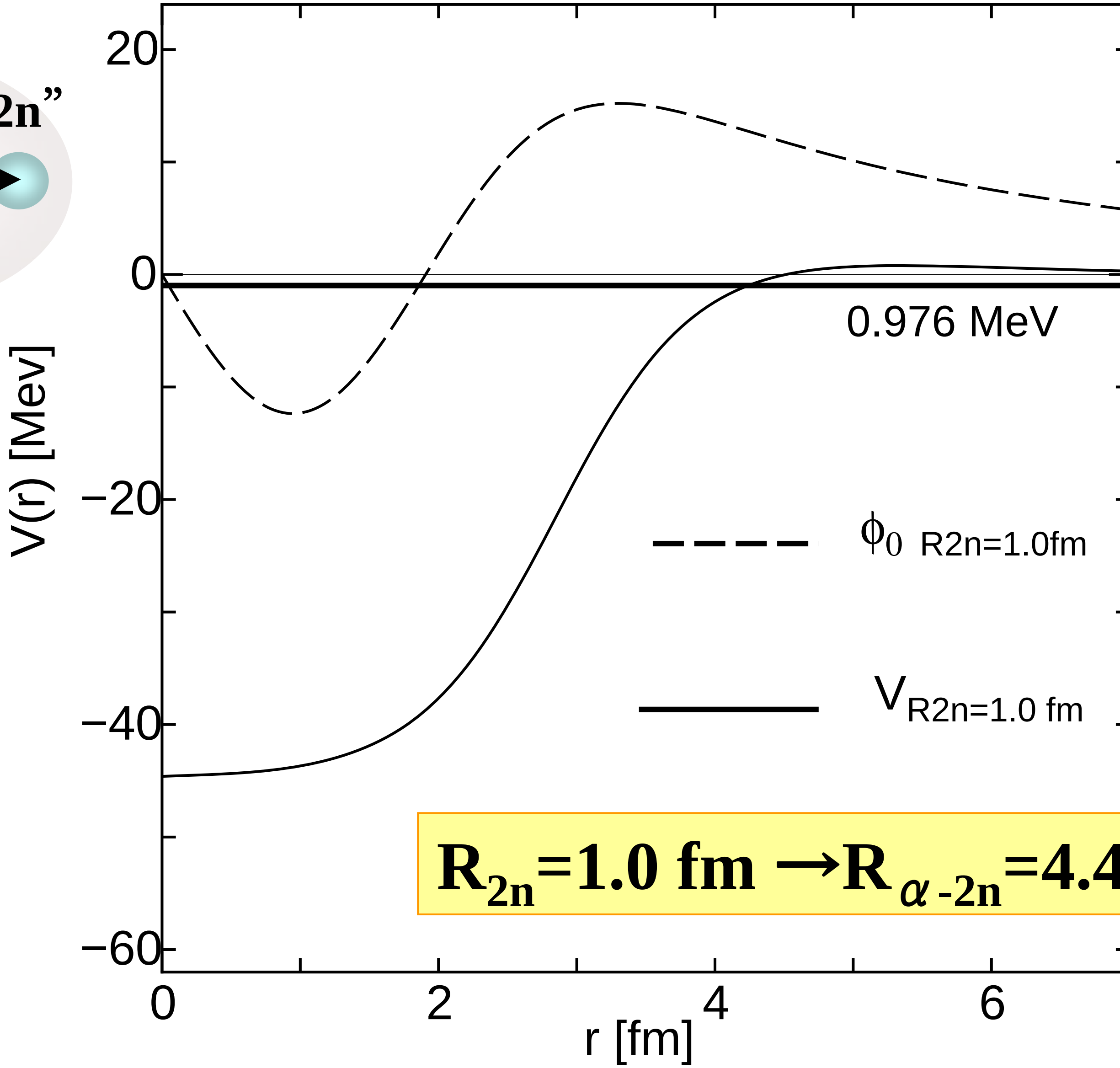
"2n"- α relative wave function





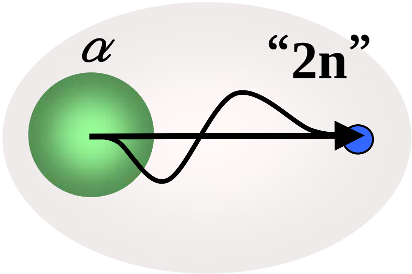
“2n”- α relative wave function

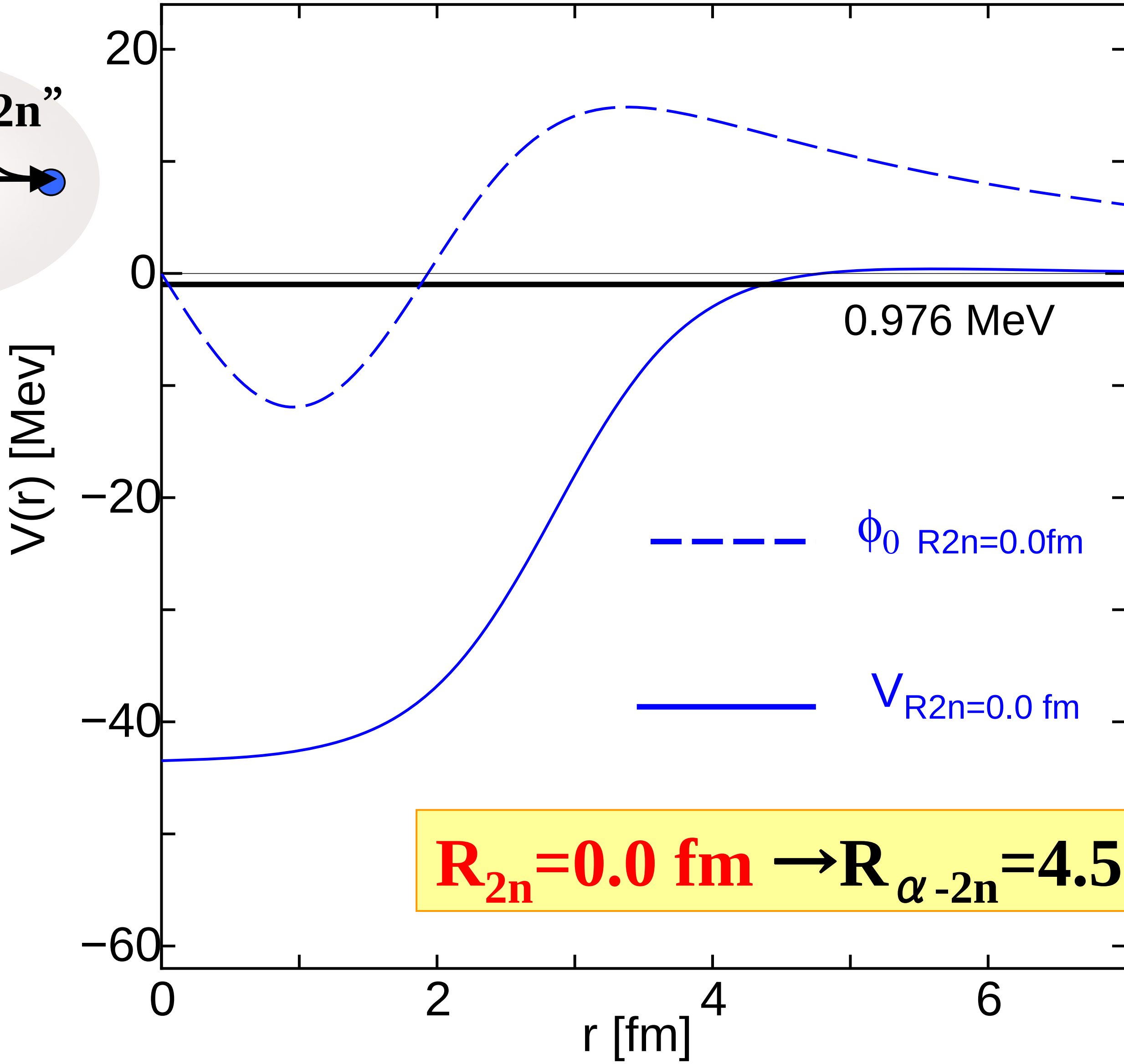




R_{2n}=1.0 fm →$R_{\alpha\text{-}2n}$=4.43 fm

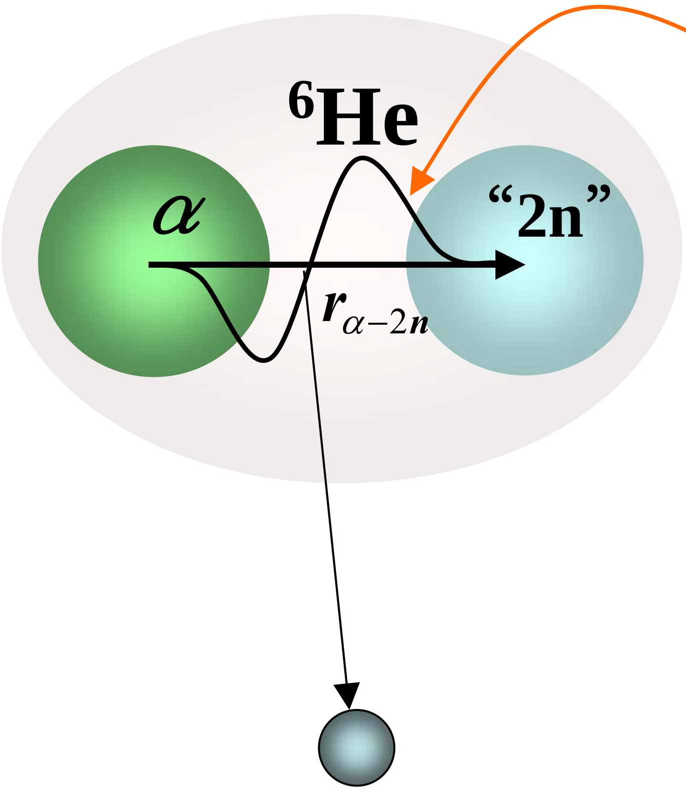
"2n"- α relative wave function





R_{2n}=0.0 fm →$R_{\alpha\text{-}2n}$=4.59 fm

How “2n” size in ^{6}He can be probed by scattering with proton?



Size of “2n” correlates with α-2n relative wave function

$$\overline{R}^2_{^6\mathrm{He}} = \frac{2}{3}\overline{R}^2_{\alpha} + \frac{1}{3}\overline{R}^2_{2n} + \frac{2}{9}\overline{r}^2_{\alpha-2n}$$

Exp. data

free-parameter
“2n” size

Adiabatic-Recoil approx. (R.C.Johnson et al., PRL79, 2771(1997))

$$\left[T_R + T_r + V_{\mathrm{Ab}}(r) + V_{\mathrm{Cb}}(R_{\mathrm{Cb}}) + V_{\mathrm{CA}}(R_{\mathrm{CA}}) - E\right]\Psi(r,R) = 0$$

$T_r + V_{\mathrm{Ab}}(r) \rightarrow \varepsilon_0$ $V_{\mathrm{Cb}}(R_{\mathrm{Cb}}) \rightarrow 0$

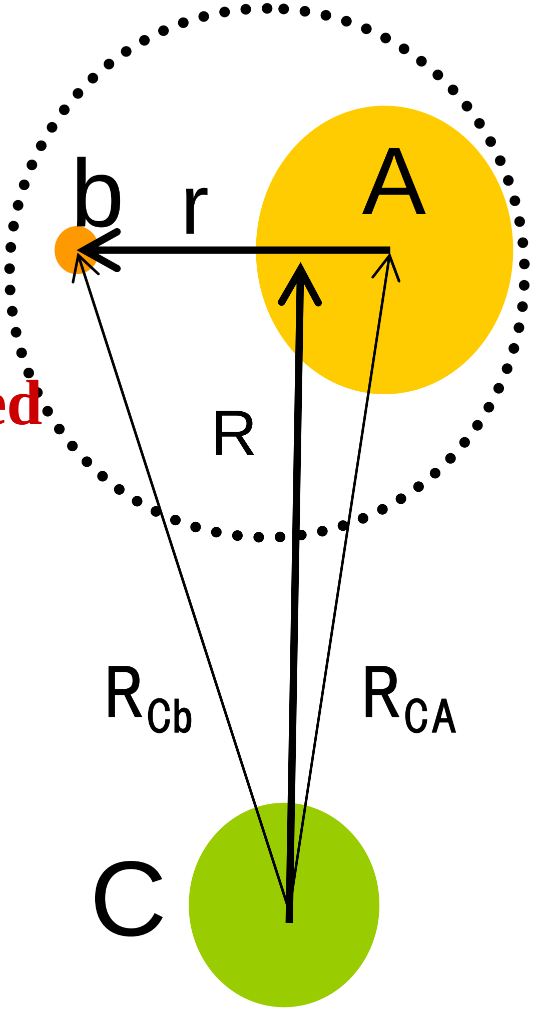
$$\left[T_R + V_{\mathrm{CA}}(R_{\mathrm{CA}}) - E_0\right]\Psi^{(\mathrm{AD})}(r,R) = 0,$$
$$\left(E_0 = E - \varepsilon_0\right)$$

① b-A relative motion is slow enough compared with C-(b+A) one (Adiabatic approx,)

⇨ $$\left[T_r + V_{Ab}(r)\right]\Psi(r,R) \cong \varepsilon_0 \Psi(r,R)$$

② ignore b-C interaction if it is weak enough compared with A-C interaction:

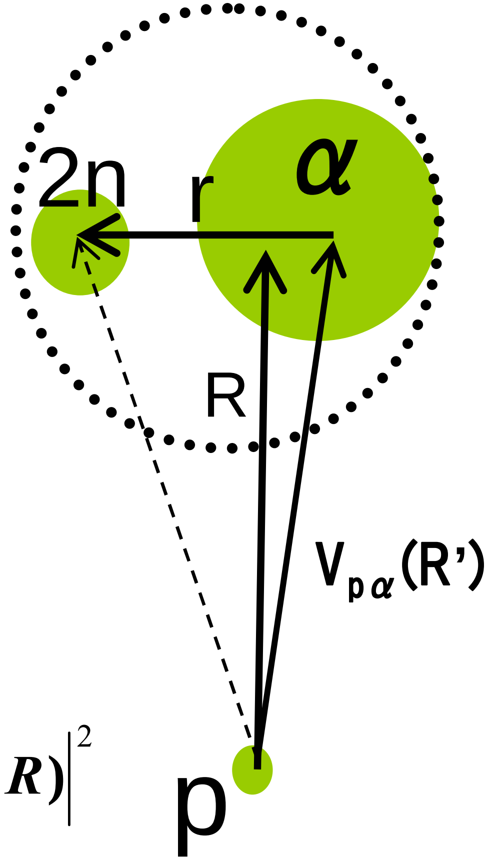
⇨ $$V_{CA}(R_{CA}) >> V_{Cb}(R_{Cb}) \approx 0$$



Apply this approximation to (α+“2n”)+p system

$$\left[T_R + V_{p\alpha}(R') - E_0\right]\Psi_K^{(AD)}(r,R) = 0$$

$$\Psi_K^{(AD)}(r,R) = \varphi_0(r)\cdot e^{i\mu k\cdot r}\cdot X_K(R')$$



$$\left[T_{R'} + V_{p\alpha}(R') - E_0\right]X_K(R') = 0$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{el} = \left|\int dr \int dR\, \varphi_0(r) e^{iK'R}\left\{V_{p\alpha}(R') + V_{p2n}(R_{p2n})\right\}\Psi_K(r,R)\right|^2$$

$$\cong \left|\int dr |\varphi_0(r)|^2 e^{i\mu qr}\right|^2 \times \left|\int dR'\, e^{-iK'R'} V_{p\alpha}(R') X_K(R')\right|^2$$

$$= |F(q)|^2 \times \left(\frac{d\sigma}{d\Omega}\right)_{pt}$$

R.C.Johnson et al., PRL79, 2771(1997)

Adiabatic-Recoil approximation

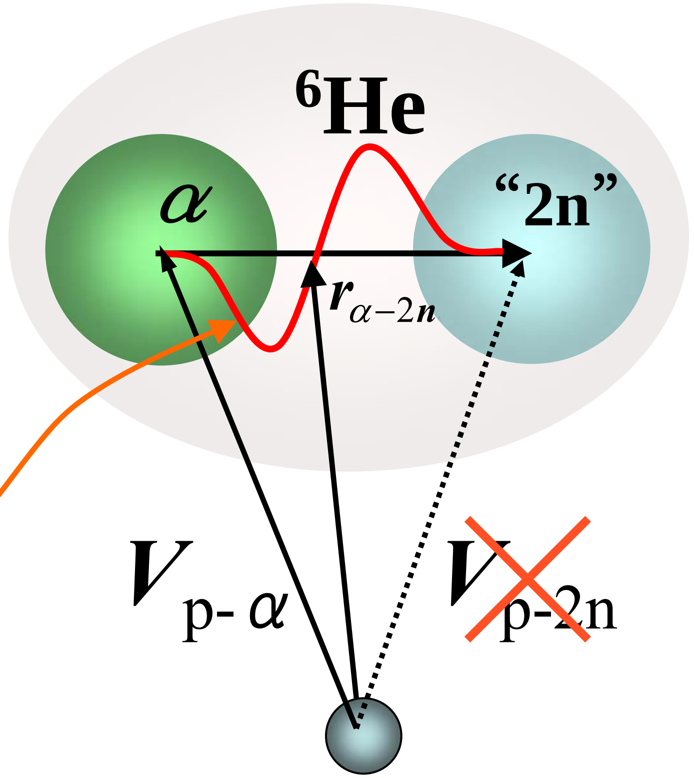
(R.C.Johnson et al., PRL79, 2771(1997))

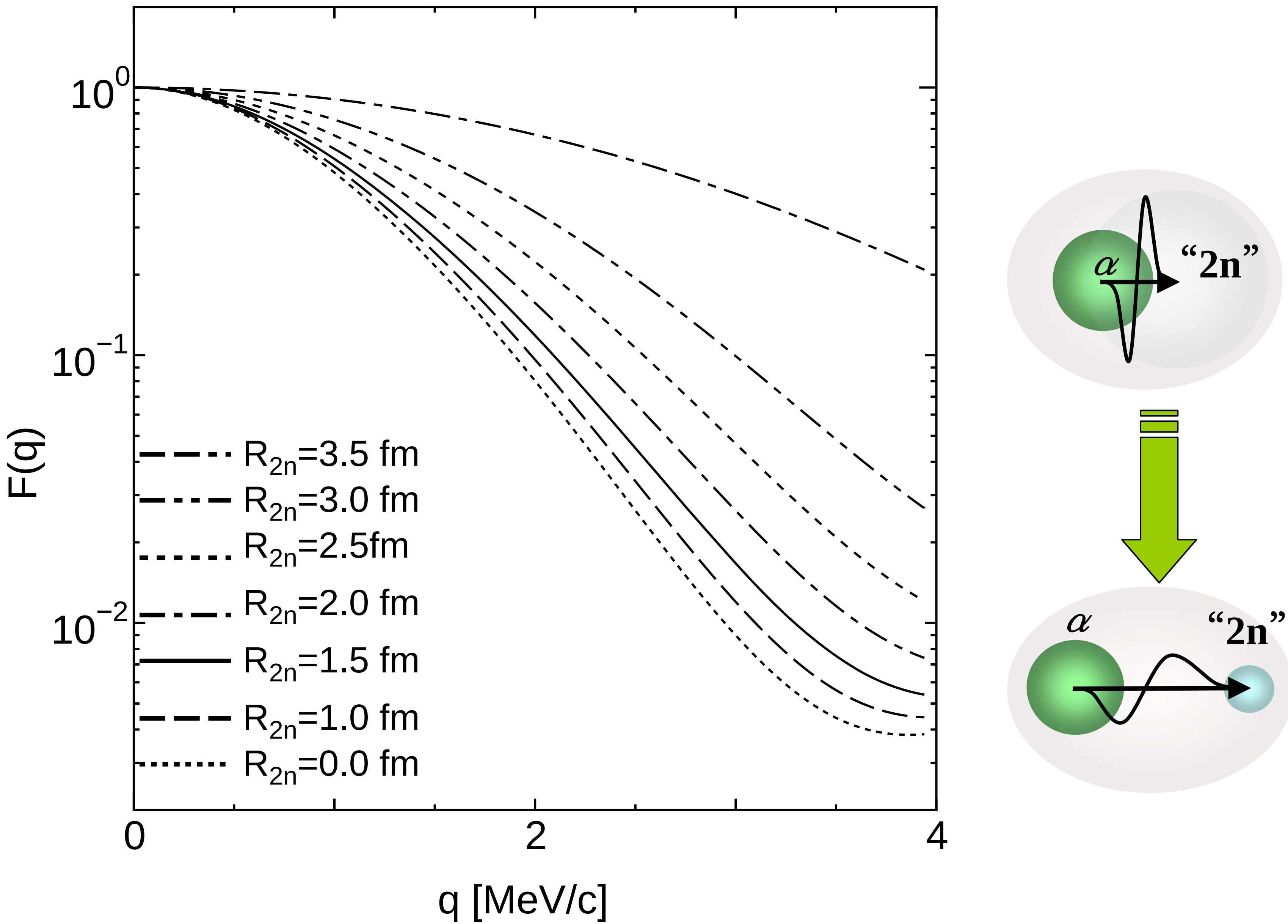
$$\left(\frac{d\sigma}{d\Omega}\right)_{p-{}^{6}\mathrm{He}} = \left|F(q)\right|^{2} \times \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{point}}$$

Form factor

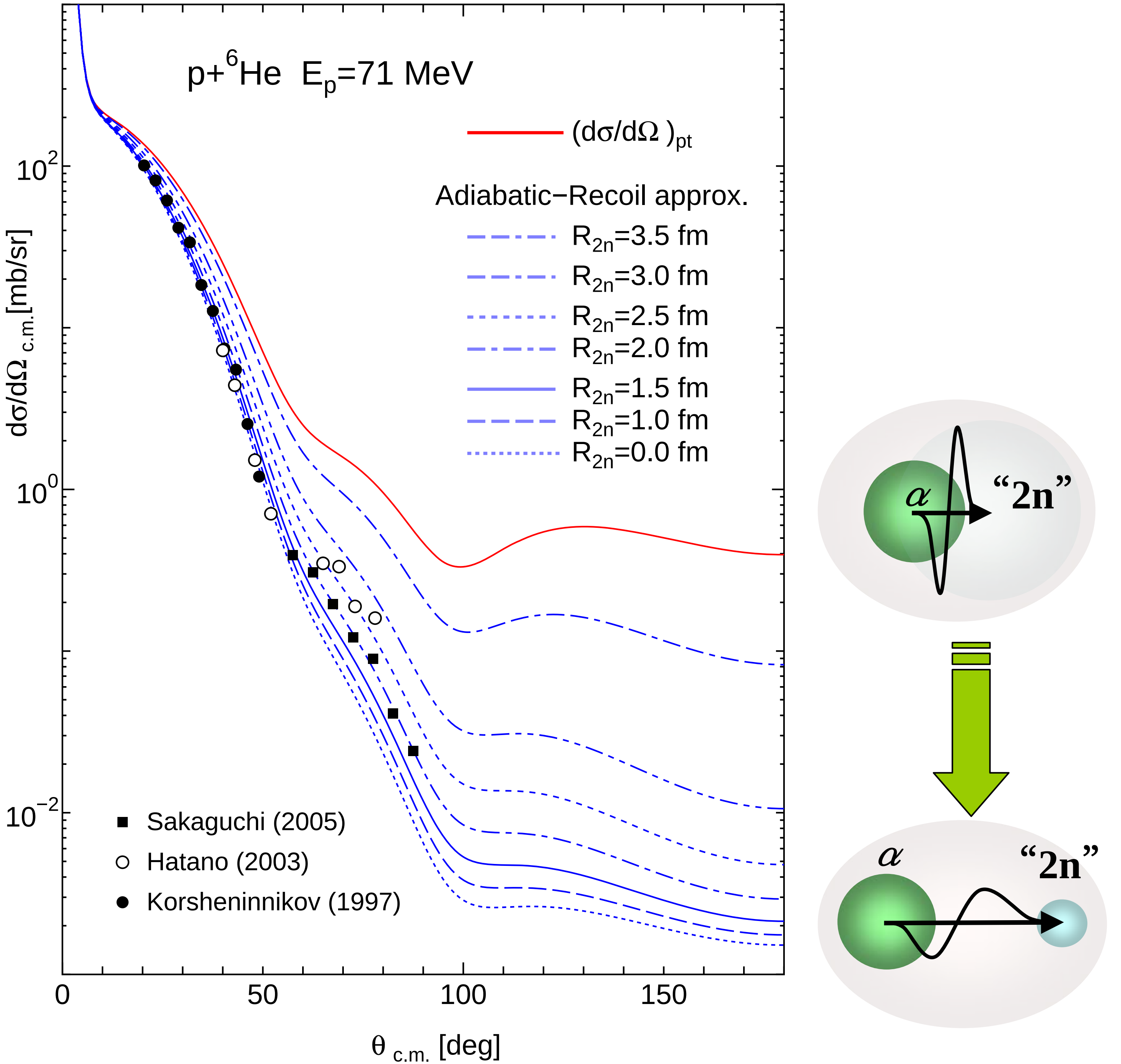
$$F(q) = \int e^{i\mu q r} \left|\varphi_{2n-\alpha}(r)\right|^{2} dr^{3} ,$$

$$(\mu = \mathrm{m}_{2\mathrm{n}} / \mathrm{m}_{{}^{6}\mathrm{He}} = 1/3)$$





F(q)
10^0
10^{-1}
10^{-2}
0
2
4
q [MeV/c]
R_{2n}=3.5 fm
R_{2n}=3.0 fm
R_{2n}=2.5fm
R_{2n}=2.0 fm
R_{2n}=1.5 fm
R_{2n}=1.0 fm
R_{2n}=0.0 fm
α
"2n"
α
"2n"



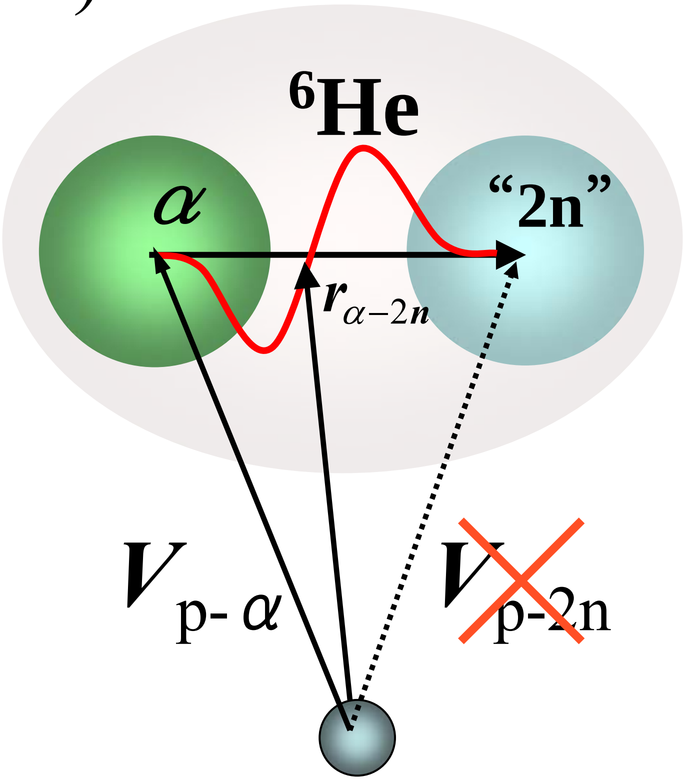
p+^{6}He E$_p$=71 MeV
(dσ/dΩ)$_{pt}$
Adiabatic−Recoil approx.
R$_{2n}$=3.5 fm
R$_{2n}$=3.0 fm
R$_{2n}$=2.5 fm
R$_{2n}$=2.0 fm
R$_{2n}$=1.5 fm
R$_{2n}$=1.0 fm
R$_{2n}$=0.0 fm
Sakaguchi (2005)
Hatano (2003)
Korsheninnikov (1997)
dσ/dΩ $_{c.m.}$[mb/sr]
θ $_{c.m.}$ [deg]
10^2
10^0
10^{-2}
0
50
100
150
α
"2n"
α
"2n"

^{6}He→ α + "2n" break-up effect

We compare ;

a) Adiabatic-Recoil approx.(ARA) cal.

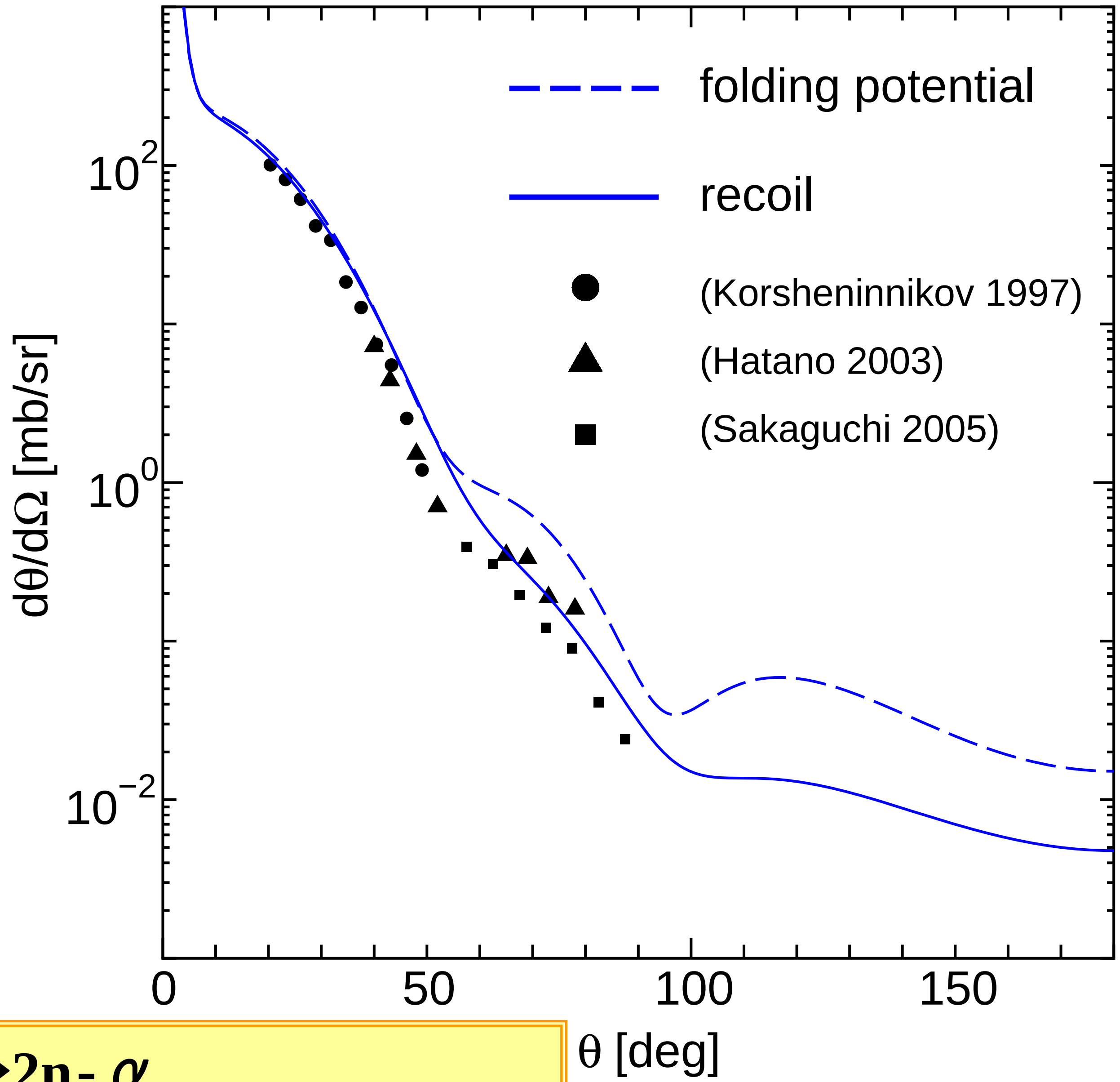
→ with break-up effect



b) Folding-model calculation

(without $V_{p\text{-}2n}$)

→ no break-up effect



^{6}**He→2n- *α***

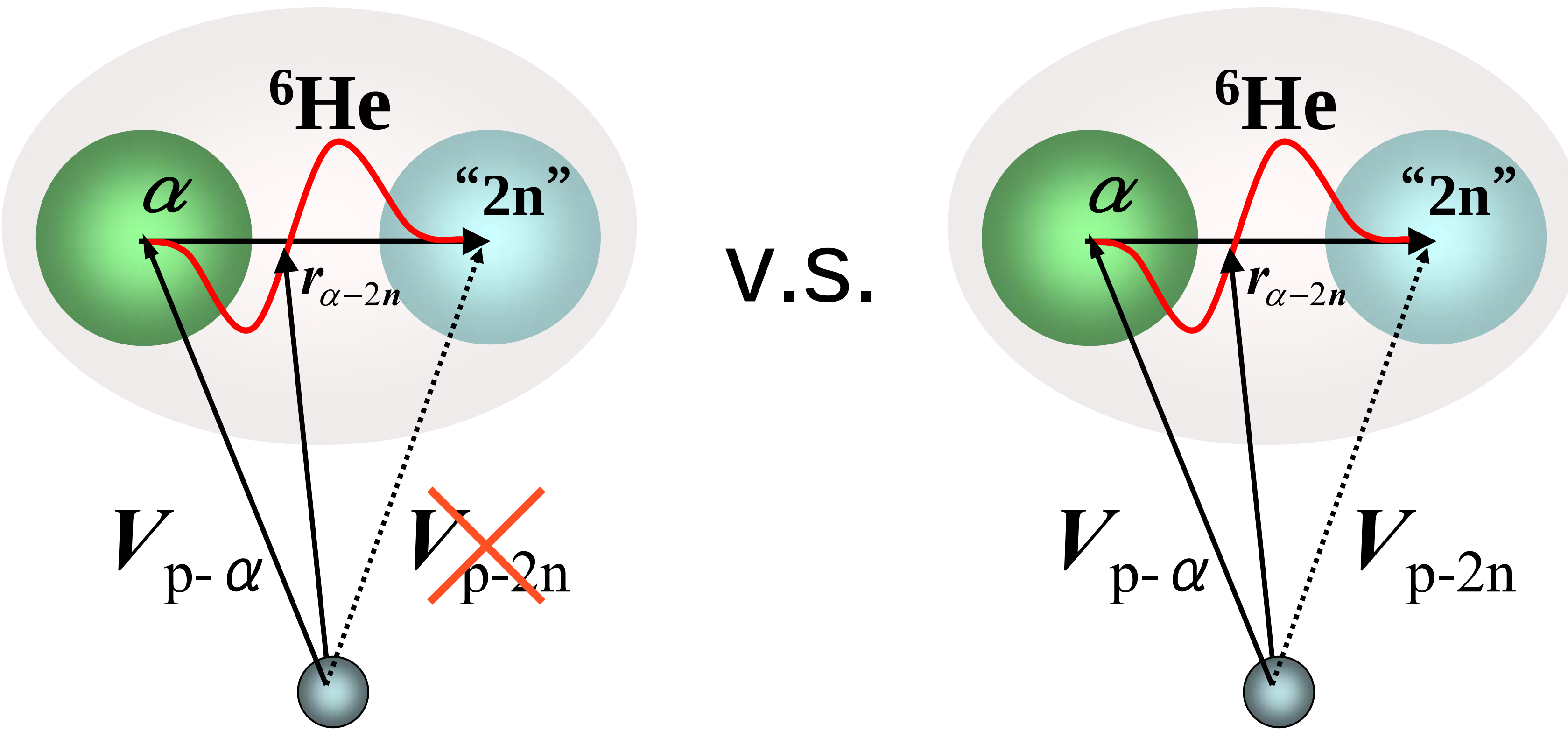
R_{2n}=2.5 fm

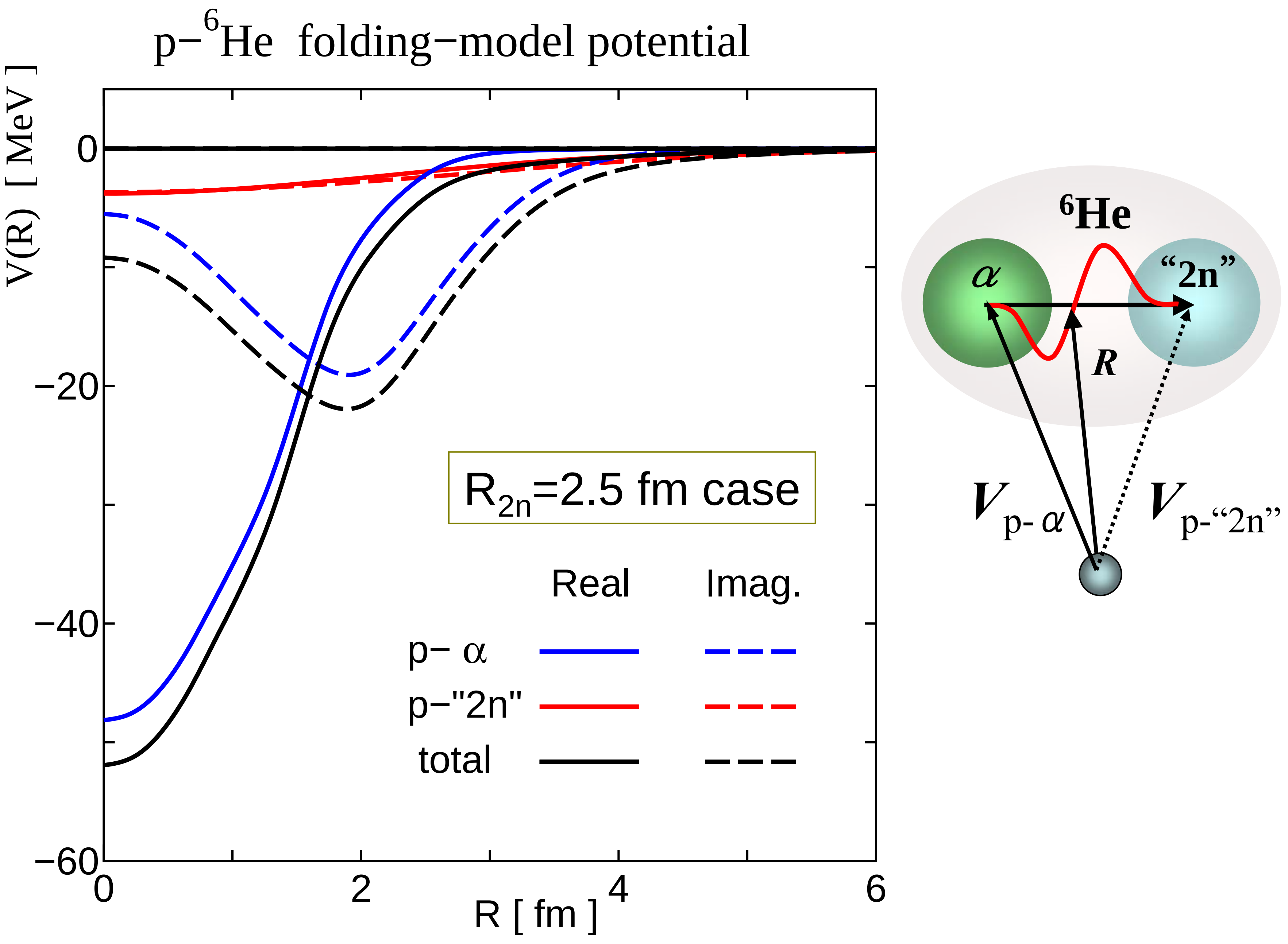
Break-up effect

$R_{R.M.S}$=3.42420491

Effect of p-“2n” interaction

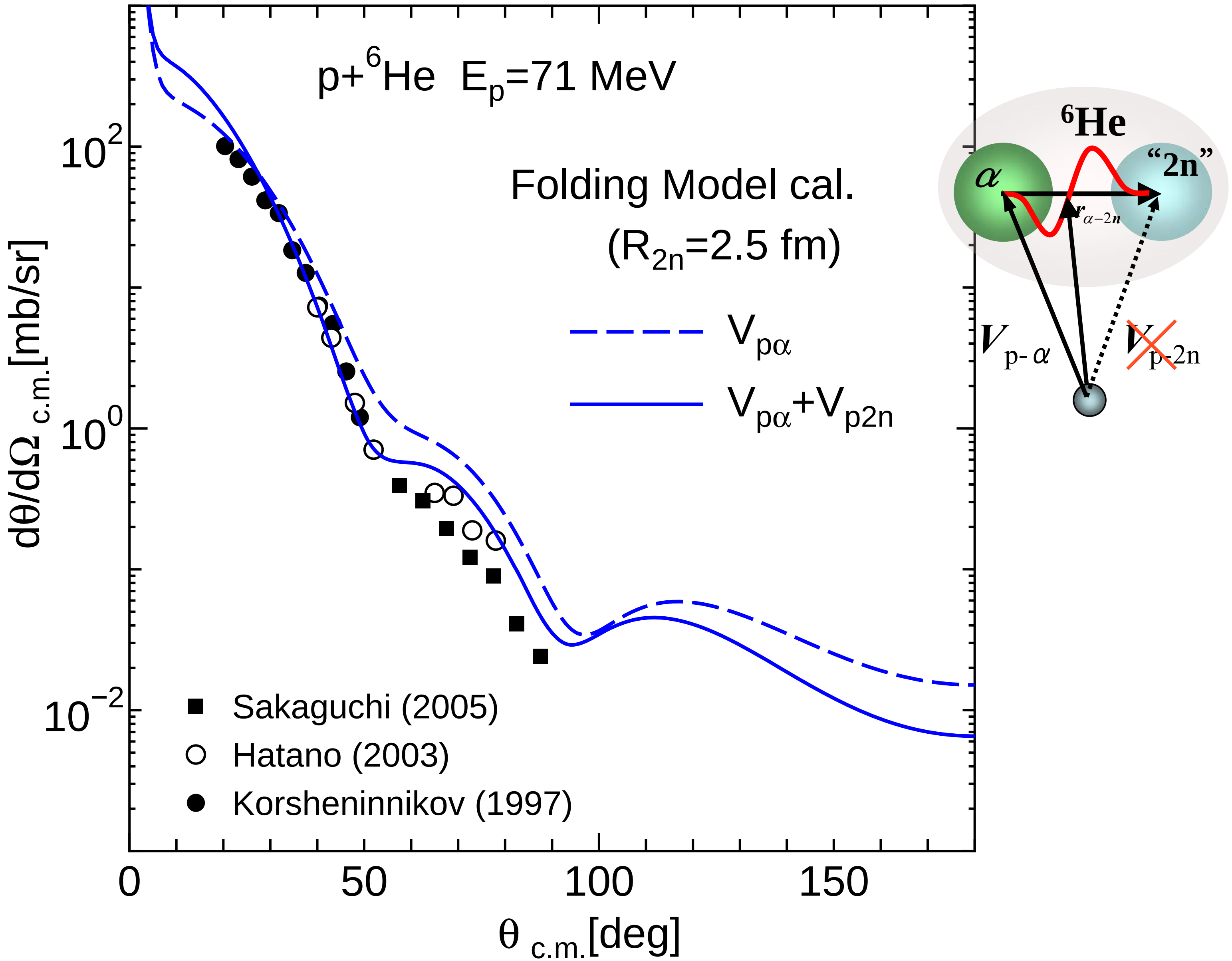
→ folding-model (no break-up effect)



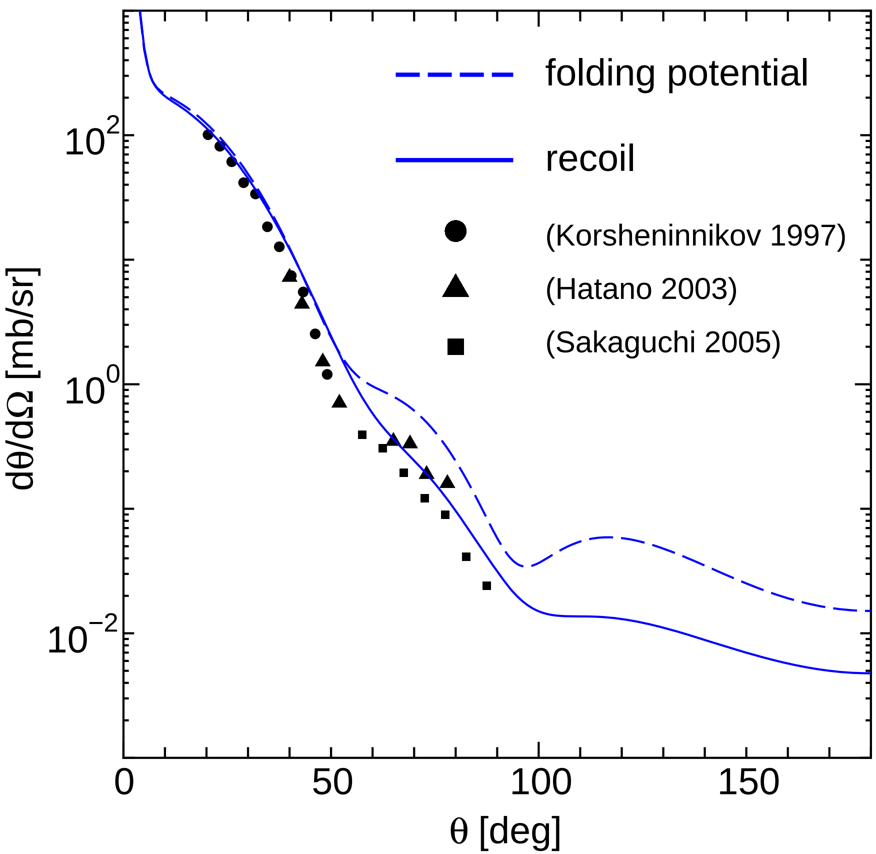


p−⁶He folding−model potential
V(R) [MeV]
0
−20
−40
−60
0
2
4
6
R [fm]
R2n=2.5 fm case
Real
Imag.
p− α
p−"2n"
total
6He
α
"2n"
R
Vp- α
Vp-"2n"

Effect of p-"2n" interaction : V_{p-2n}

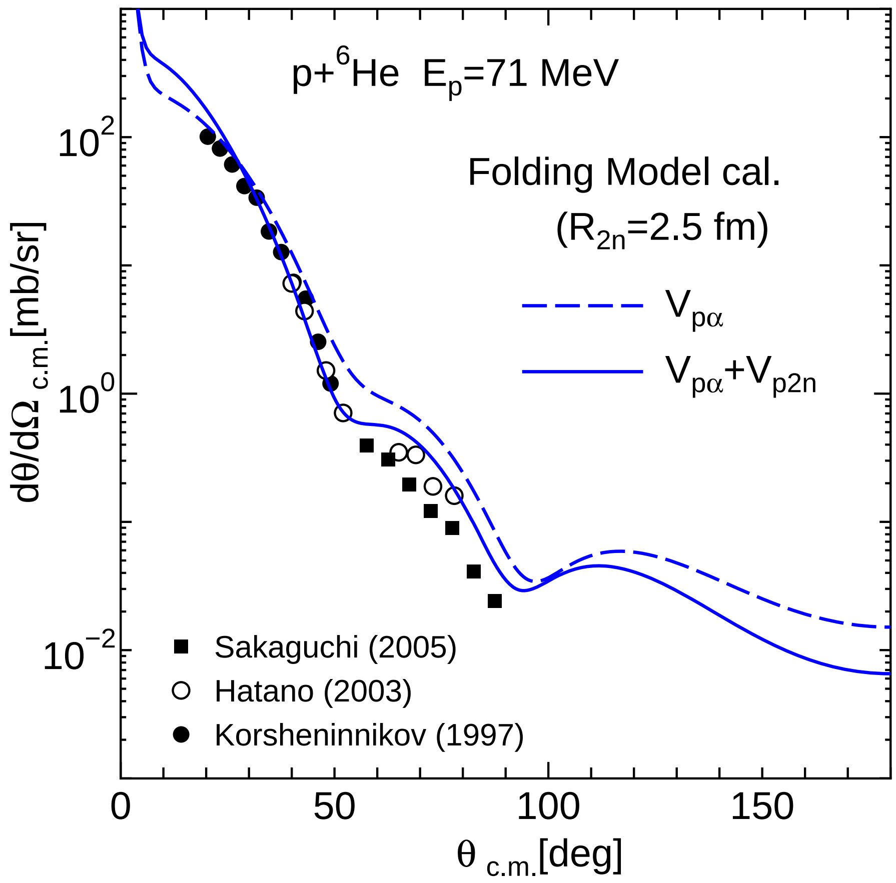


breakup effect



R_{2n}=2.5 fm $R_{R.M.S}$=3.42420491

effect of p-2n int.



Summary

- We have proposed a realistic "di-neutron" model for ^{6}He,
  - which well simulates the three-body nature of ^{6}He and
  - reproduces both ^{6}He size and binding energy simultaneously by introducing a surface barrier to 2n-α potential.
- $^6\text{He} \rightarrow \alpha +$ "2n" break-up effect is estimated by the use of adiabatic-recoil approximation (ARA)
  - the break-up effect is important at middle and backward angles of the elastic scattering by proton
  - ARA calculation gives vector analyzing power consistent to the observed ones within error bars.
- The "2n"-proton interaction, $V_{\text{p-2n}}$, neglected in the ARA calculation, has non-negligible effect
  - mainly due to small mass of the α-particle core