2022.5.24 (Tue.) "Developments of Physics of Unstable Nuclei (YKIS2022b)"

Effects of quasiparticle resonance on decay spectrum of ^{21}C

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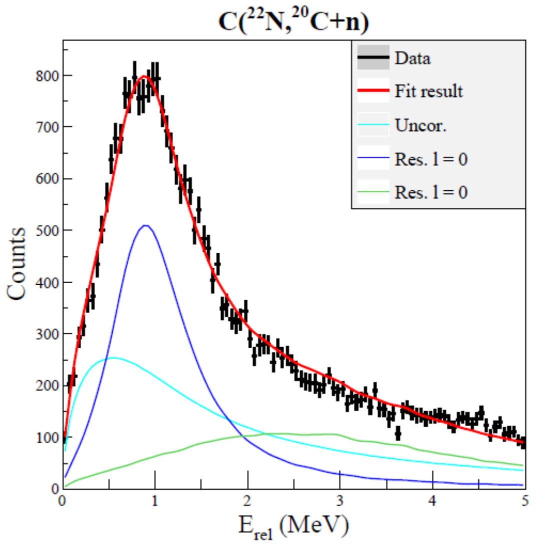
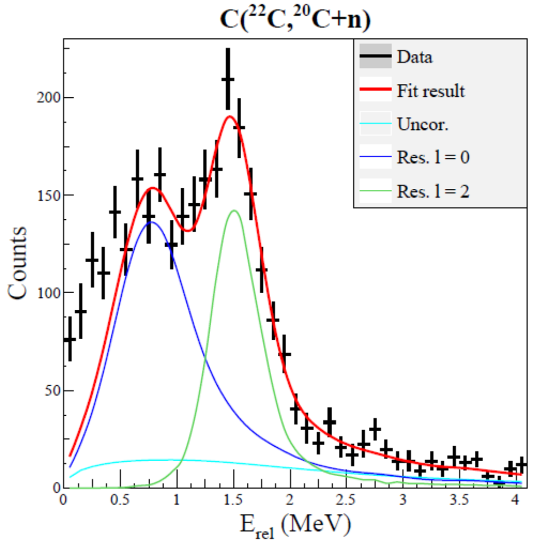
Motivation: to demonstrate the quasiparticle resonance

- Quasiparticle resonance
  - ✓ predicted by the HFB theory
  - ✓ emerged by the pairing correlation
  - ✓ occurs in even s-wave scattering
  - ✓ has not been observed yet

S. T. Belyaev et al., Sov. J. Nucl. Phys. 45, 783 (1987).
A. Bulgac, Preprint (1980); nucl-th/9907088
J. Dobaczewski, W. Nazarewicz et al., Phys. Rev.C 53, 2809 (1996).
Y. Kobayashi and M. Matsuo, Prog. Theor. Exp. Phys. 2020, 013D03 (2020).

- SAMURAI Exp.@RIBF





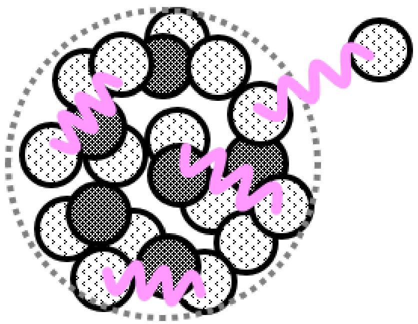
S. Leblond, PhD thesis, LPC-Caen (2015).
N. Orr, EPJ Web Conf. 113, 06011 (2016).

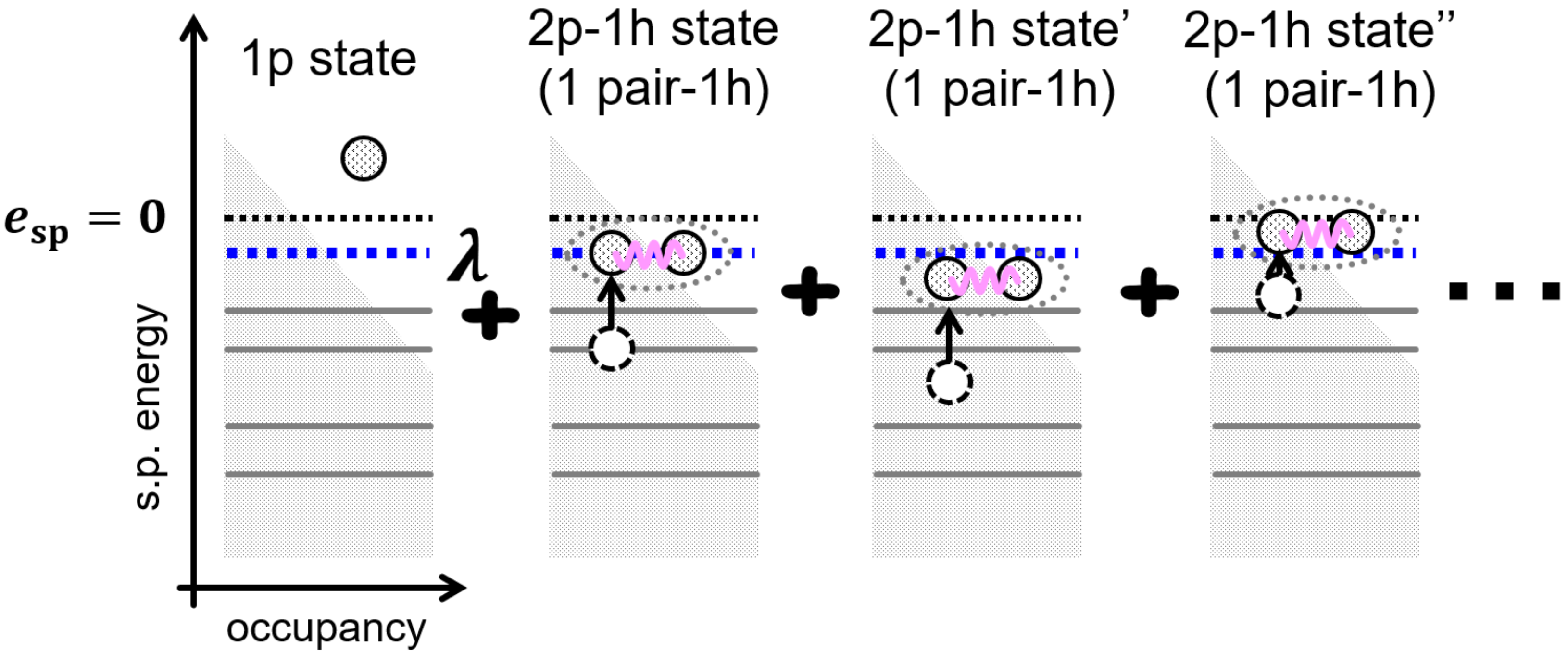
Can we explain the experimental results of SAMURAI@RIKEN by effect of the quasiparticle resonance? → **demonstration of the quasiparticle resonance**

- We analyze effects of the quasiparticle resonance in decay spectrum.
- We compare our numerical results with the experimental results.

Quasiparticle resonance emerged by the pairing correlation

- Neutron-rich nuclei near the drip-line
  - ✓ weakly bound system ⇔ shallow Fermi energy
  - ✓ pairing correlation (superfluidity) is enhanced → neutron halo, di-neutron…
  - ✓ configuration mixing between weakly bound orbits and low-lying continuum
- Neutron-rich nuclei near the drip-line and one neutron system?



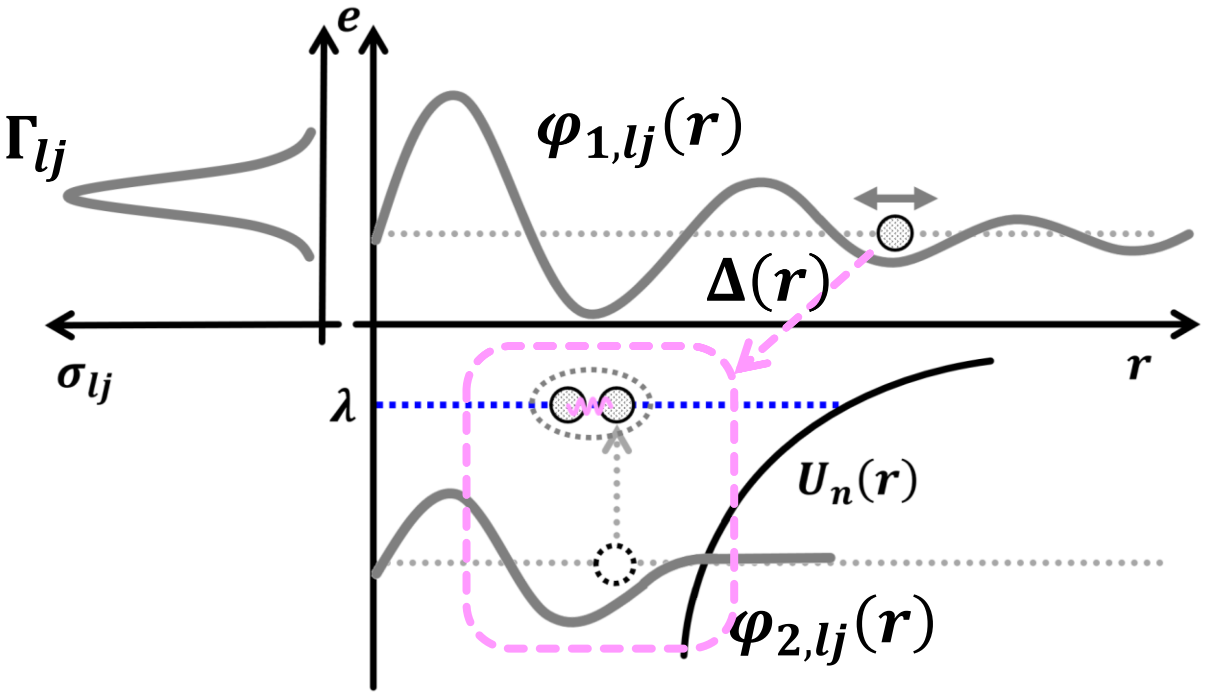


Quasiparticle resonance described by the HFB theory

- The Hartree-Fock-Bogoliubov (HFB) theory in the coordinate space.

J. Dobaczewski, H. Flocard and J. Treiner, Nuclear Physics A, 422, 103 (1984).
J. Dobaczewski, W. Nazarewicz, T. R. Werner, J. F. Berger, C. R. Chinn and J. Decharge, Phys. Rev. C 53, 2809 (1996).

$$\begin{pmatrix} h(r)-\lambda & \Delta(r) \\ \Delta(r) & -h(r)+\lambda \end{pmatrix} \begin{pmatrix} \varphi_{1,lj}(r) \\ \varphi_{2,lj}(r) \end{pmatrix} = E \begin{pmatrix} \varphi_{1,lj}(r) \\ \varphi_{2,lj}(r) \end{pmatrix}$$



<u>Bogoliubov quasiparticle</u>

$$\varphi_{lj}(r) = \begin{pmatrix} \varphi_{1,lj}(r) \\ \varphi_{2,lj}(r) \end{pmatrix}$$ "particle" component / "hole" component

- "particle" and "hole" component are coupled by the pairing correlation.
- The quasiparticle resonance can be emerged as an intermediate state.

S. T. Belyaev et al., Sov. J. Nucl. Phys. 45, 783 (1987).

Quasiparticle scattering on superfluid nucleus

Weakly bound superfluid nucleus

$$\boldsymbol{h(r), \Delta(r), \lambda}$$

Scattered quasiparticle

$$\begin{pmatrix} \varphi_{1,lj}(r) \\ \varphi_{2,lj}(r) \end{pmatrix} = C \begin{pmatrix} \cos\delta_{lj} j_l(k_1 r) - \sin\delta_{lj} n_l(k_1 r) \\ D h_l^{(1)}(k_2 r) \end{pmatrix}$$

$$k_{1,2} = \sqrt{\frac{2m}{\hbar^2}(\lambda \pm E)}$$

$$\begin{pmatrix} h(r) - \lambda & \Delta(r) \\ \Delta(r) & -h(r) + \lambda \end{pmatrix} \begin{pmatrix} \varphi_{1,lj}(r) \\ \varphi_{2,lj}(r) \end{pmatrix} = E \begin{pmatrix} \varphi_{1,lj}(r) \\ \varphi_{2,lj}(r) \end{pmatrix}$$

S. T. Belyaev et al., Sov. J. Nucl. Phys, 45 783 (1987)
M. Grasso et al., Phys. Rev. C 64 064321 (2001)
I. Hamamoto et al., Phys. Rev. C 68 034312 (2003)

- Elastic phase shifts $\delta_{lj}(E)$ and cross sections $\sigma_{lj}(E)$ have analyzed.
- Also, S-matrix S_{lj} poles have analyzed with complex wave number $k_{1,2}$ and complex energy E.

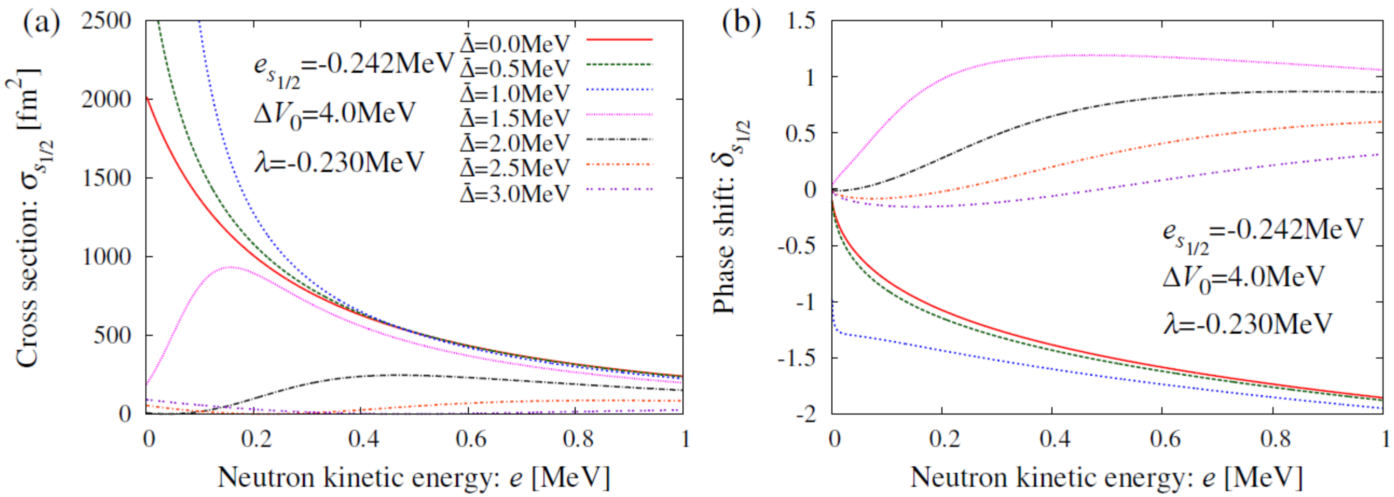
→ Even s-wave scattering, resonant behavior is appeared in elastic phase, cross section, and S-matrix due to the pairing correlation.

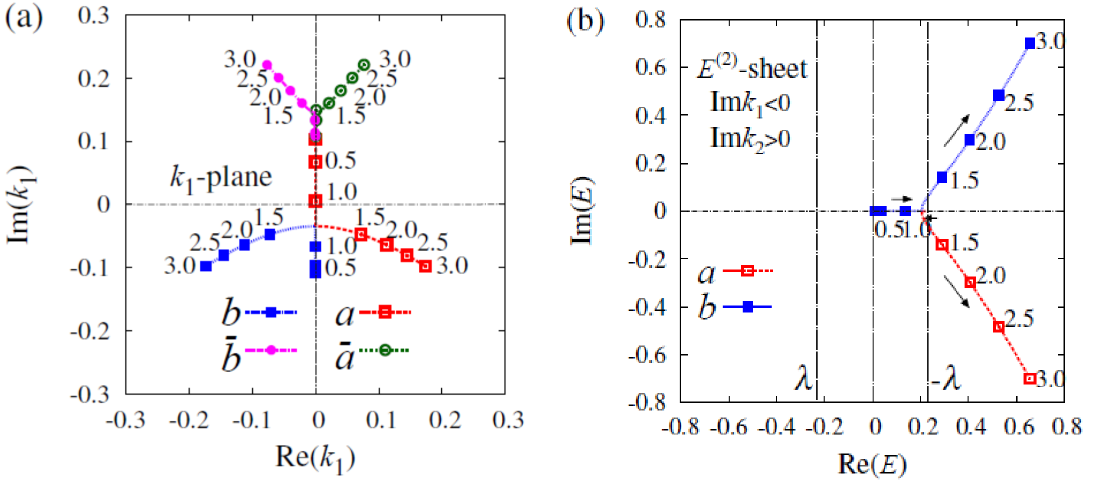
Yoshihiko Kobayashi and Masayuki Matsuo, Prog. Theor. Exp. Phys. 2016(1), 013D01, (2016).
Yoshihiko Kobayashi and Masayuki Matsuo, Prog. Theor. Exp. Phys. 2020(1), 013D03, (2020).

Our previous studies on s-wave quasiparticle resonance

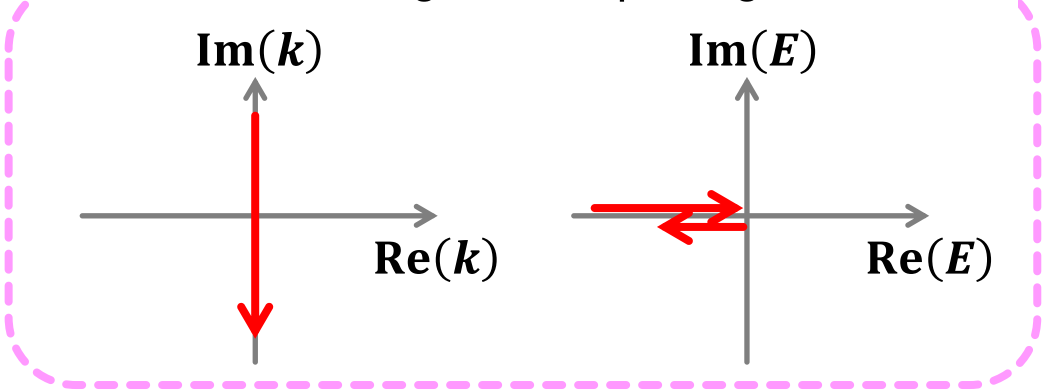
Yoshihiko Kobayashi and Masayuki Matsuo, Prog. Theor. Exp. Phys. 2016(1), 013D01, (2016).
Yoshihiko Kobayashi and Masayuki Matsuo, Prog. Theor. Exp. Phys. 2020(1), 013D03, (2020).

- pairing dependence of the s-wave quasiparticle scattering.





s-wave scattering without pairing correlation



- The S-matrix has *two pairs of poles*.
- The s-wave quasiparticle resonance emerges with a large variation depending on the pairing correlation and the position of the s-orbit.

Calculation of decay spectrum: breakup of ^{22}C (^{22}C, ^{20}C+n)

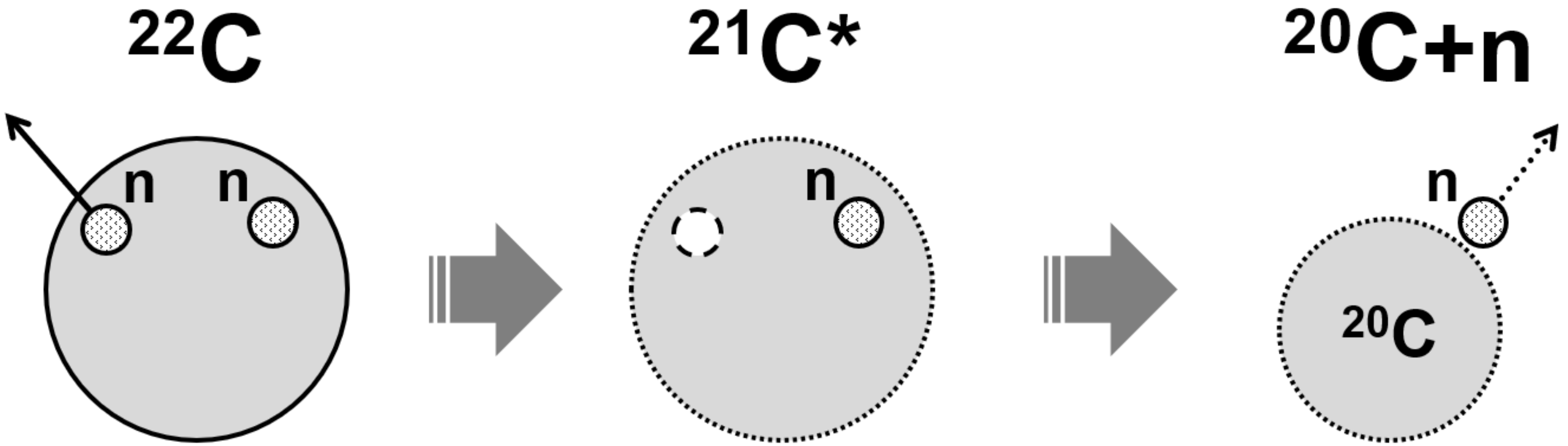
Studies of ^{25,26}O decay: K. Tsukiyama, T. Otsuka, and R. Fujimoto, Prog. Theor. Exp. Phys. 093D01 (2015).
K. Hagino and H. Sagawa, Phys.Rev. C 93, 034330 (2016).

✓ ^{21}C* immediately after the breakup: reference state $|\boldsymbol{\Phi}_{\mathbf{ref}}\rangle$ （⇔doorway state）

✓ ^{20}C+n scattering state $|\boldsymbol{\Phi}_{E}\rangle$ （⇔final state）

Y. Kobayashi and M. Matsuo, PTEP. 2016(1), 013D01, (2016).
Y. Kobayashi and M. Matsuo, PTEP. 2020(1), 013D03, (2020).

→ calculate the decay spectrum considering overlap among $|\boldsymbol{\Phi}_{\mathbf{ref}}\rangle$ and $|\boldsymbol{\Phi}_{E}\rangle$.



→ decay spectrum: $$\frac{dP(E)}{dE} = |\langle\boldsymbol{\Phi}_{\mathbf{ref}}|\boldsymbol{\Phi}_{E}\rangle|^2$$

Calculation of decay spectrum: theory towards numerical calculation

$$\frac{dP(E)}{dE} = |\langle \Phi_{\mathrm{ref}} | \Phi_E \rangle|^2$$

$$|\Phi_{\mathrm{ref}}\rangle = c^{(^{22}\mathrm{C})}_{\nu s_{1/2}} |^{22}\mathrm{C}\rangle$$

$$|\Phi_E\rangle = \left| ^{20}\mathrm{C} + n_{s_{1/2}}(E) \right\rangle = \left(\beta^{(^{20}\mathrm{C})}_{\nu s_{1/2}}(E) \right)^\dagger |^{20}\mathrm{C}\rangle$$

Yoshihiko Kobayashi and Masayuki Matsuo, Prog. Theor. Exp. Phys. 2020(1), 013D03, (2020).

$$\frac{dP(E)}{dE} = \left| \left\langle ^{22}\mathrm{C} \right| \left(c^{(^{22}\mathrm{C})}_{\nu s_{1/2}} \right)^\dagger \left(\beta^{(^{20}\mathrm{C})}_{\nu s_{1/2}}(E) \right)^\dagger \left| ^{20}\mathrm{C} \right\rangle \right|^2$$

✓ discretizing the continuum, one can calculate the equation based on the Onishi formula.

N. Onishi and S. Yoshida, Nucl. Phys. A 80, 367 (1966).
P. Ring and P. Schuck, *The Nuclear Many-Body Problem* (1980).

- To obtain continuous spectrum, we perform "diagonal approximation".

✓ The validity of the approximation has been confirmed numerically.

$$\longrightarrow \frac{dP(E)}{dE} = |\langle \Phi_{\mathrm{ref}} | \Phi_E \rangle|^2 \approx \left| \sum_\sigma \int d\vec{r} \left(\varphi^{(^{22}\mathrm{C})}_{\nu s_{1/2}} \right)^* (\vec{r}\sigma)\, \varphi^{(^{20}\mathrm{C})}_{2,\nu s_{1/2}}(\vec{r}\sigma, E) \right|^2$$

Numerical calc. with the Woods-Saxon-Bogoliubov calc.

- Hartree-Fock pot. → Woods-Saxon pot. A. Bohr and B. R. Mottelson, Nuclear Structure Vol. I (1975).

$$V_{lj}(r) = \left[V_0 + \left(\vec{l} \cdot \vec{s} \right) V_{SO} \frac{r_0^2}{r} \frac{d}{dr} \right] f(r)$$

$$f(r) = \left[1 + \exp\left(\frac{r-R}{a} \right) \right]^{-1}$$

$a = 0.67\ \mathrm{fm}$

$R = r_0 A^{1/3}\ \mathrm{fm}$

$r_0 = 1.27\ \mathrm{fm}$

→

$\Delta V_0' = V_0 - 12.0\ \mathrm{MeV}$

$a' = 1.2a = 0.804\ \mathrm{fm}$

$r_0' = 1.10\ \mathrm{fm}$

- Pair potential → DDDI-mix J. Dobaczewski, W. Nazarewicz, and P.-G. Reinhard, Nucl. Phys. A 693, 361 (2001).

$$\Delta(r) = v_0 \left(1 - \eta \left(\frac{\rho(r)}{\rho_0} \right)^{\alpha} \right) \tilde{\rho}(r)$$

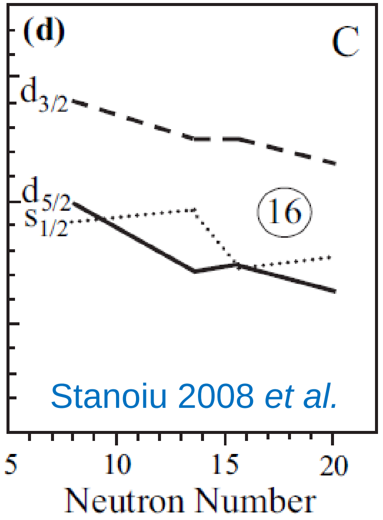
$\rho_0 = 0.32\ \mathrm{fm}^{-3}$ $\quad v_0 \sim -320.0\ \mathrm{MeV} \cdot \mathrm{fm}^3$

$\eta = 1.0, \alpha = 1.0$

- Exp. studies suggest superfluidity of ^{20}C
  - ✓ Finite occupancy of $2s_{1/2}$ orbit.
    N. Kobayashi et al., Phys.Rev. C 86, 054604 (2012).
    Y. Togano et al., Phys. Lett. B 761, 412 (2016).
  - ✓ Breaking of the N = 14 subshell closure.
    M. Stanoiu et al., Phys. Rev. C 78, 034315 (2008).

→

- ✓ ^{20}C may be superfluid
- ✓ Location among $2s_{1/2}$ and $1d_{5/2}$ is controversial.

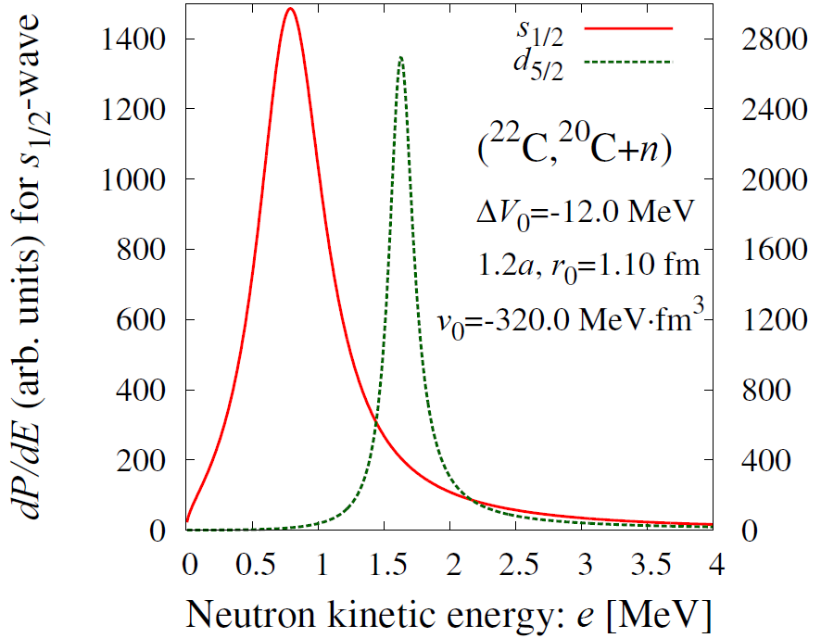


Stanoiu 2008 *et al.*

Results: decay spectrum of ^{21}C [(^{22}C, ^{20}C+n)]

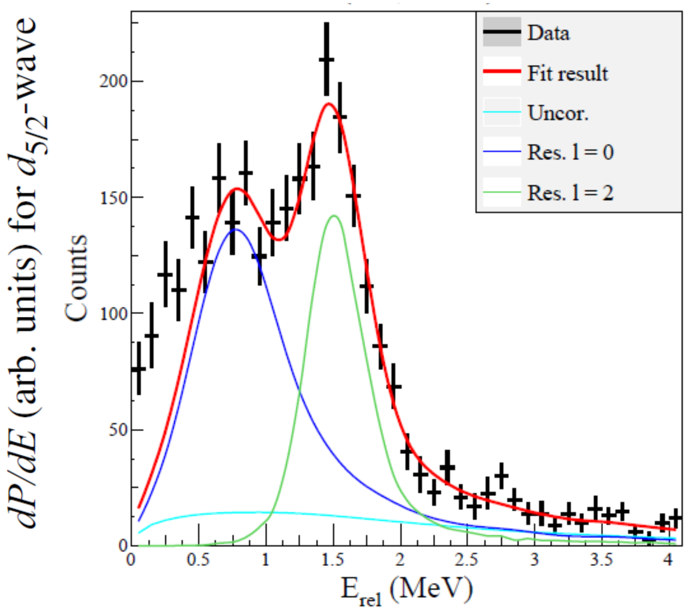
with $\boldsymbol{v_0 = -320.0}$ $\mathbf{MeV \cdot fm^3}$, $\boldsymbol{\Delta V_0 = -12.0}$ MeV, $\boldsymbol{1.2a}$, $\boldsymbol{r_0 = 1.10}$ fm

Numerical results
(Our calculation)



Experimental results

S. Leblond, PhD thesis, LPC-Caen (2015)



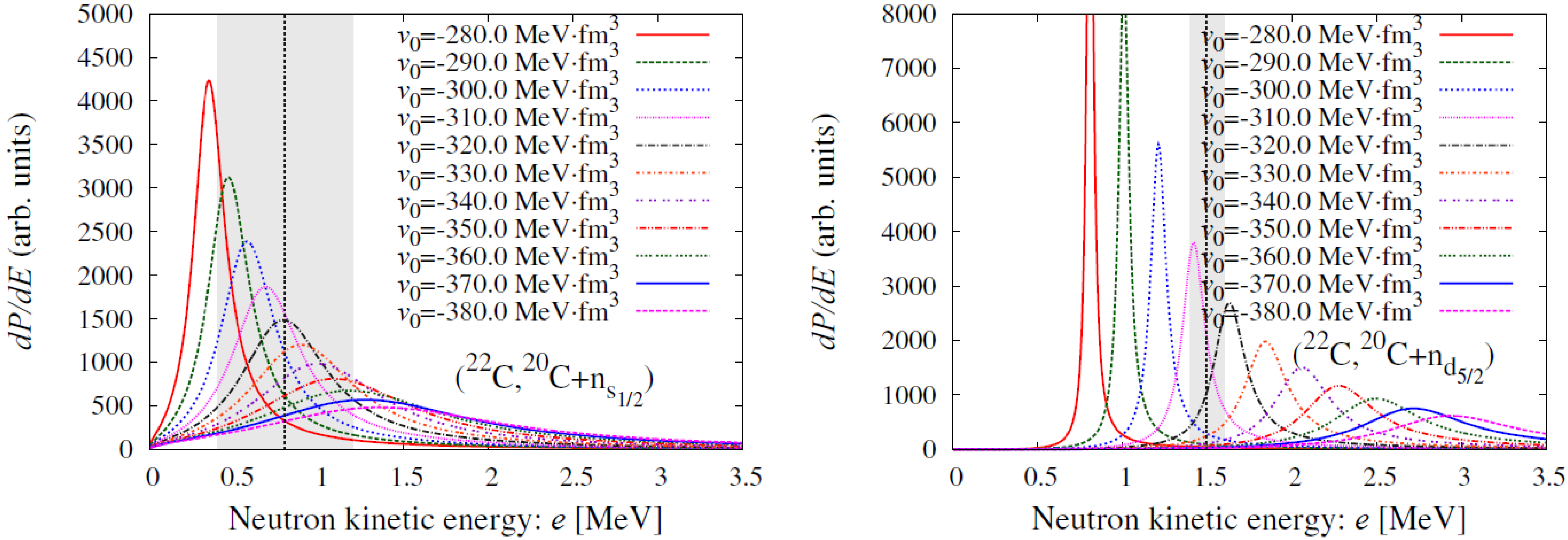
	Calc.	Exp.
$e_{R,s_{1/2}}$ [MeV]	0.773	0.8 ± 0.15
$\Gamma_{s_{1/2}}$ [MeV]	0.623	0.9 ± 0.9
$e_{R,d_{5/2}}$ [MeV]	1.625	1.5 ± 0.1
$\Gamma_{d_{5/2}}$ [MeV]	0.226	$0.2^{+0.9}_{-0.2}$

✓ We found peak structures in $s_{1/2}$ and $d_{5/2}$ decay spectrum.

✓ Numerical results of e_R and Γ were also consistent with the experiments.

Results: decay spectrum of ^{21}C [(^{22}C, ^{20}C+n)]

v_0-dependence, $\Delta V_0 = -12.0$ MeV, $1.2a$, $r_0 = 1.10$ fm



The vertical dotted line and the shaded region correspond to the experimental data of resonance energies.

S. Leblond, PhD thesis, LPC-Caen (2015)

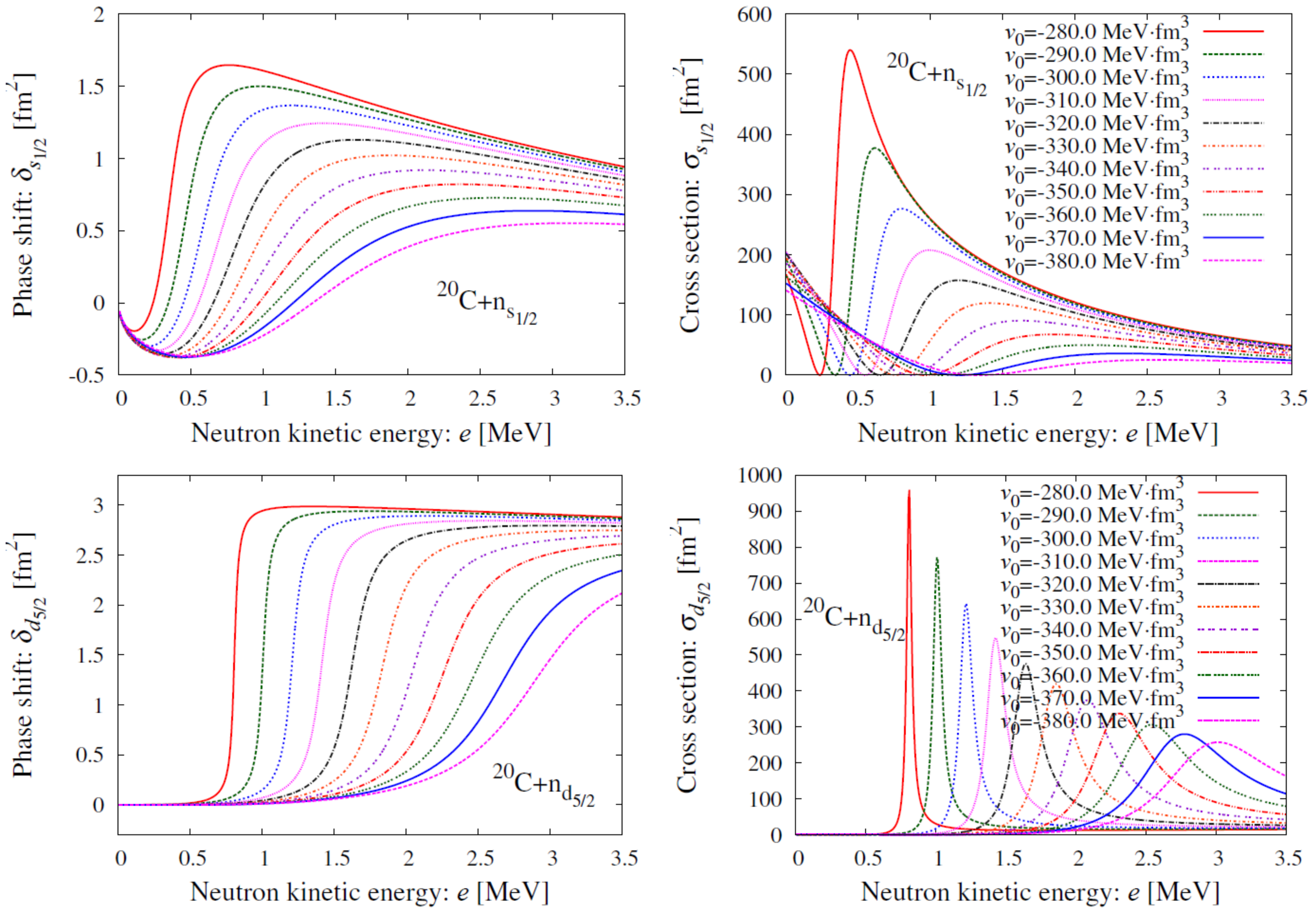
- ✓ Decay spectrums are influenced by the pairing correlation.
- ✓ Both the resonance energy e_R and the resonance width Γ increase with increasing v_0.

Results: elastic phase shift and cross section of ^{20}C+n

v_0-dependence

$\Delta V_0 = -12.0$ MeV

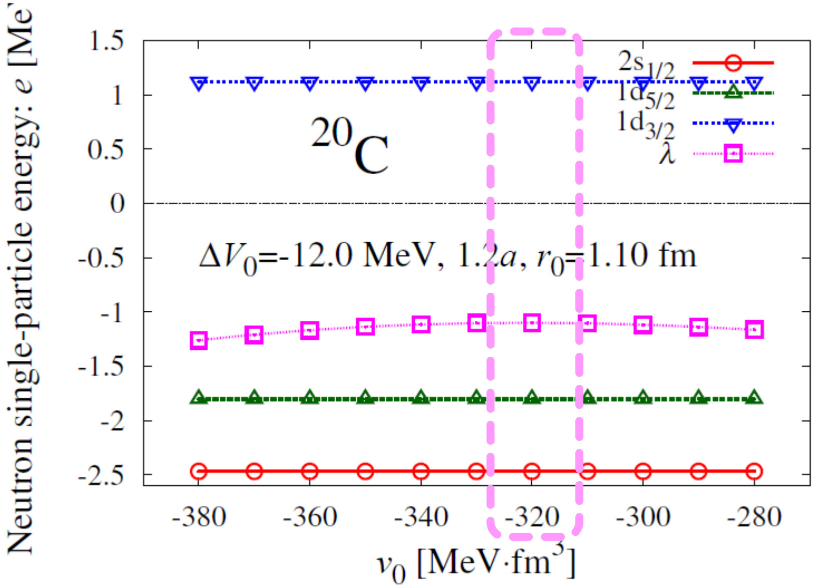
$1.2a$, $r_0 = 1.10$ fm



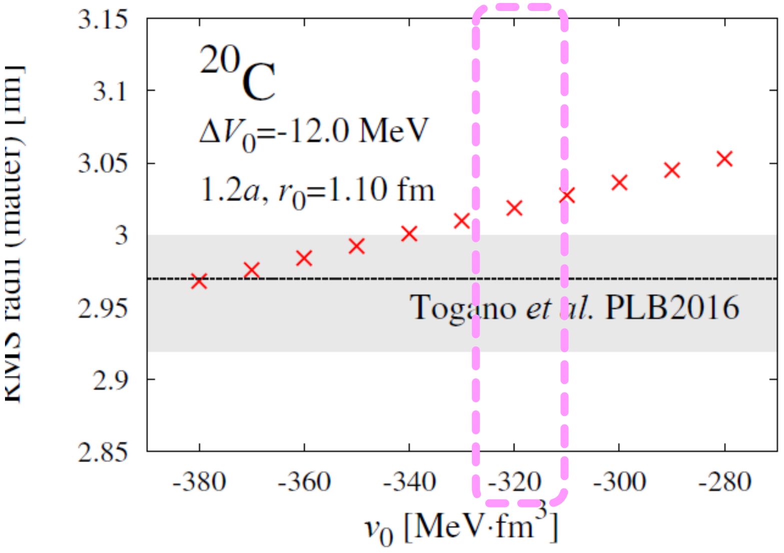
Results: ^{20}C

v_0-dependence, $\Delta V_0 = -12.0$ MeV, $1.2a$, $r_0 = 1.10$ fm

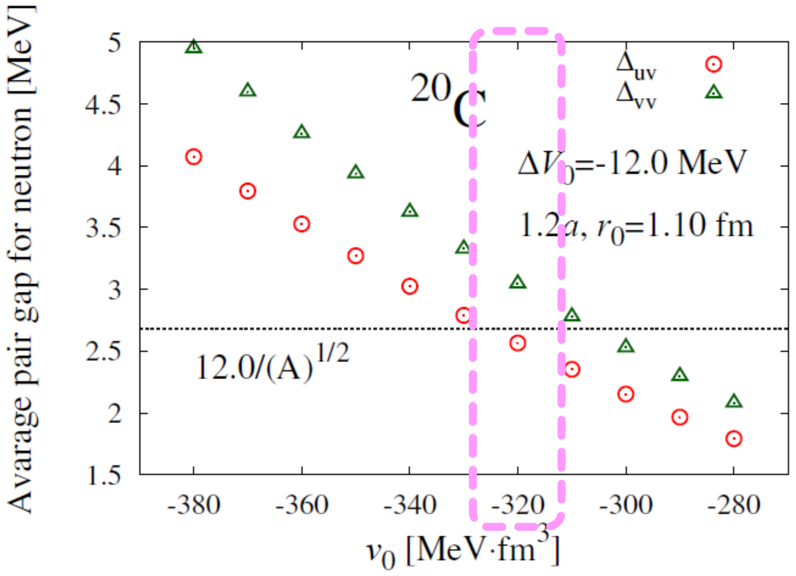
s.p. energies e_{lj}



RMS radius (matter) $\sqrt{\langle r_m^2 \rangle}$



pair gap $\boldsymbol{\Delta}$



※ RMS radius (matter)

$$\sqrt{\langle r_m^2 \rangle} = 2.97^{+0.03}_{-0.05} \text{ fm}$$

Y. Togano et al., PLB 761, 412 (2016).

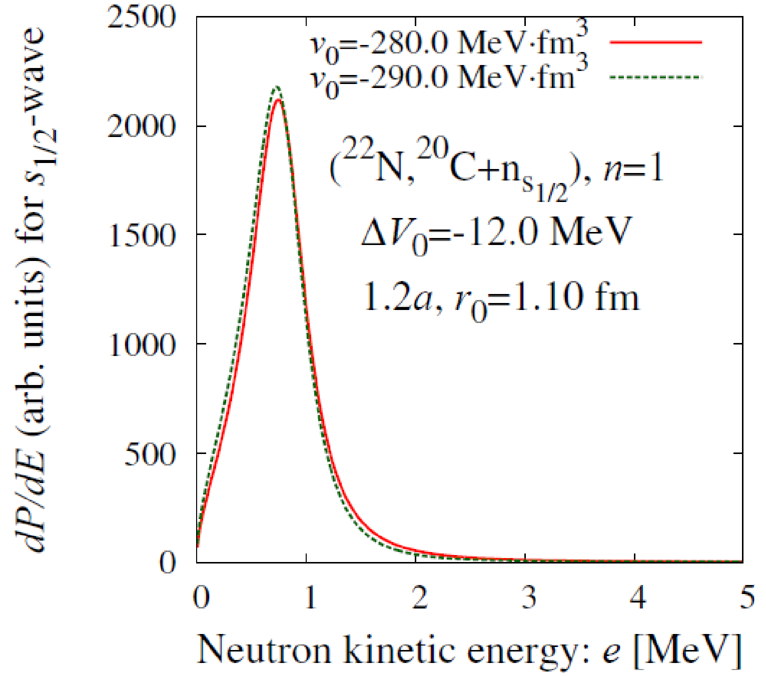
※ Empirical pair gap of ^{20}C

: $12.0/\sqrt{A} = 2.683$ MeV

Results: ^{21}C [(^{22}N, $^{20}C+n$)]

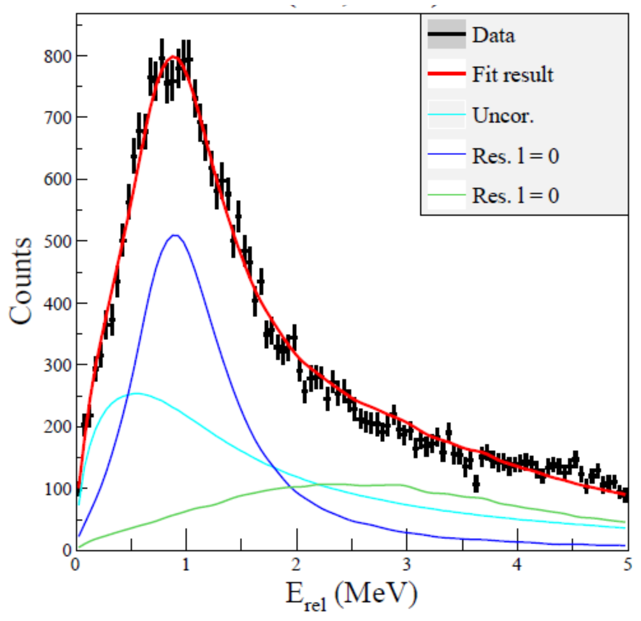
with $v_0 = -280.0, -290.0$ MeV $\cdot$ fm^3, $\Delta V_0 = -12.0$ MeV, $1.2a$, $r_0 = 1.10$ fm

Numerical results
(Our calculation)



Experimental results

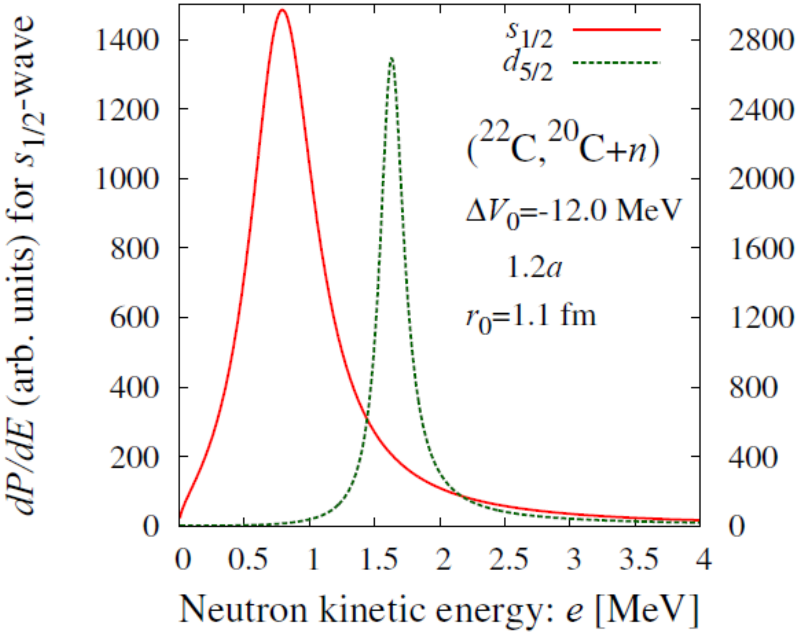
S. Leblond, PhD thesis, LPC-Caen (2015)

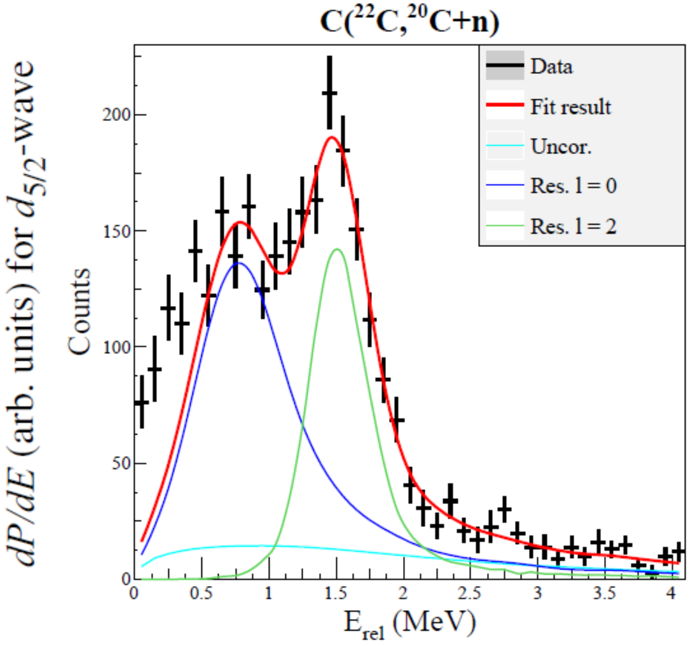


	Calc.	Exp.
$e_{R,s_{1/2}}$ [MeV]	0.773	0.8 ± 0.15
$\Gamma_{s_{1/2}}$ [MeV]	0.623	0.9 ± 0.9

Conclusion: quasiparticle resonances in the decay spectrum of ^{21}C

- The effect of quasiparticle resonances gives a peak structure to decay spectrum.
- By controlling the parameters, we obtained numerical results of (^{22}C, ^{20}C+n) and (^{22}N, ^{20}C+n) which is consistent with the experimental results.





S. Leblond, PhD thesis, LPC-Caen (2015).
N. Orr, EPJ Web Conf. 113, 06011 (2016).

<u>Future works</u>

✓ Detailed analysis by controlling parameters.

✓ Considering the relation to breakup and proton knockout cross sections.