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ICNT workshop "Physics of exotic nuclei: Theoretical advances and challenges"

Quasi-particle resonance near threshold in neutron drip-line nuclei

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Contents

- Introduction and motivation
- HFB equation with scattering boundary condition
- Results (elastic cross section, resonance width, etc)
- Conclusion

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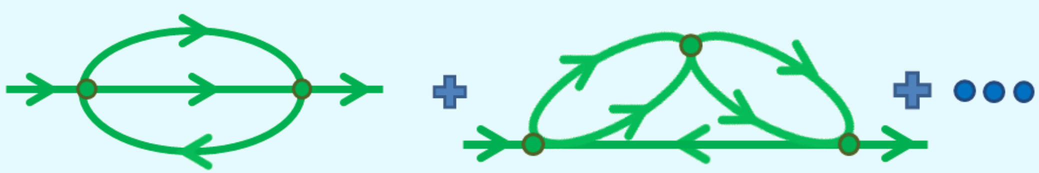
Resonance caused by pairing

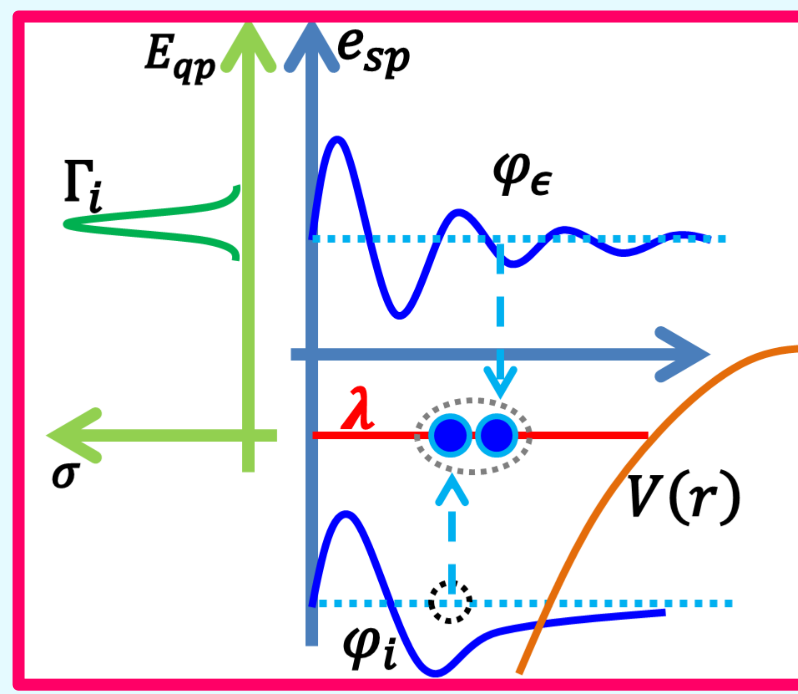
- Quasi-particle resonance is predicted to emerge in superfluid nuclei.

S. T. Belyaev et al., Sov. J. Nucl. Phys, 45 783 (1987)
A. Bulgac, Preprint(1980); nucl-th/9907088
J. Dobaczewski et al., Phys. Rev. C 53 2809 (1996)

- In Hartree-Fock-Bogoliubov (HFB) theory, an unbound nucleon can couple to a hole state by creating a Cooper pair, and resulting in a quasi-particle resonance.



Single-particle orbit	Quasi-particle resonance emerge
Deep-hole orbit in stable nuclei	in high energy region
Weakly bound orbit in drip-line nuclei	in low energy region



We expect novel property in weakly bound system.

In stable nuclei

$\lambda \cong -8.0\text{MeV}$

The q.p. resonance can emerge above $E_x \geq 8.0\text{MeV}$
(Level density is very high.)

$$(\epsilon_i - \lambda)^2 \gg \Delta^2$$

Resonance width

$$\Gamma_i = 2\pi \left| \int d^3r \varphi_i(\vec{r}) \Delta(\vec{r}) \varphi_\epsilon(\vec{r}) \right|^2 \propto |\Delta|^2$$

S. T. Belyaev et al., Sov. J. Nucl. Phys, 45 783 (1987)
A. Bulgac, Preprint(1980); nucl-th/9907088
J. Dobaczewski et al., Phys. Rev. C 53 2809 (1996)

$\Delta \nearrow \quad \Gamma_i \nearrow$

In drip-line nuclei

$\lambda \cong 0.0 \sim -1.0\text{MeV}$

The q.p. resonance can emerge in low energy region. $E_x \leq 2.0\text{MeV}$
→ maybe observe experimentally.

$$(\epsilon_i - \lambda)^2 \leq \Delta^2$$

Pairing influence weakly bound orbit and low-lying resonance strongly.

Resonance width
The perturbative equation may not be applied.

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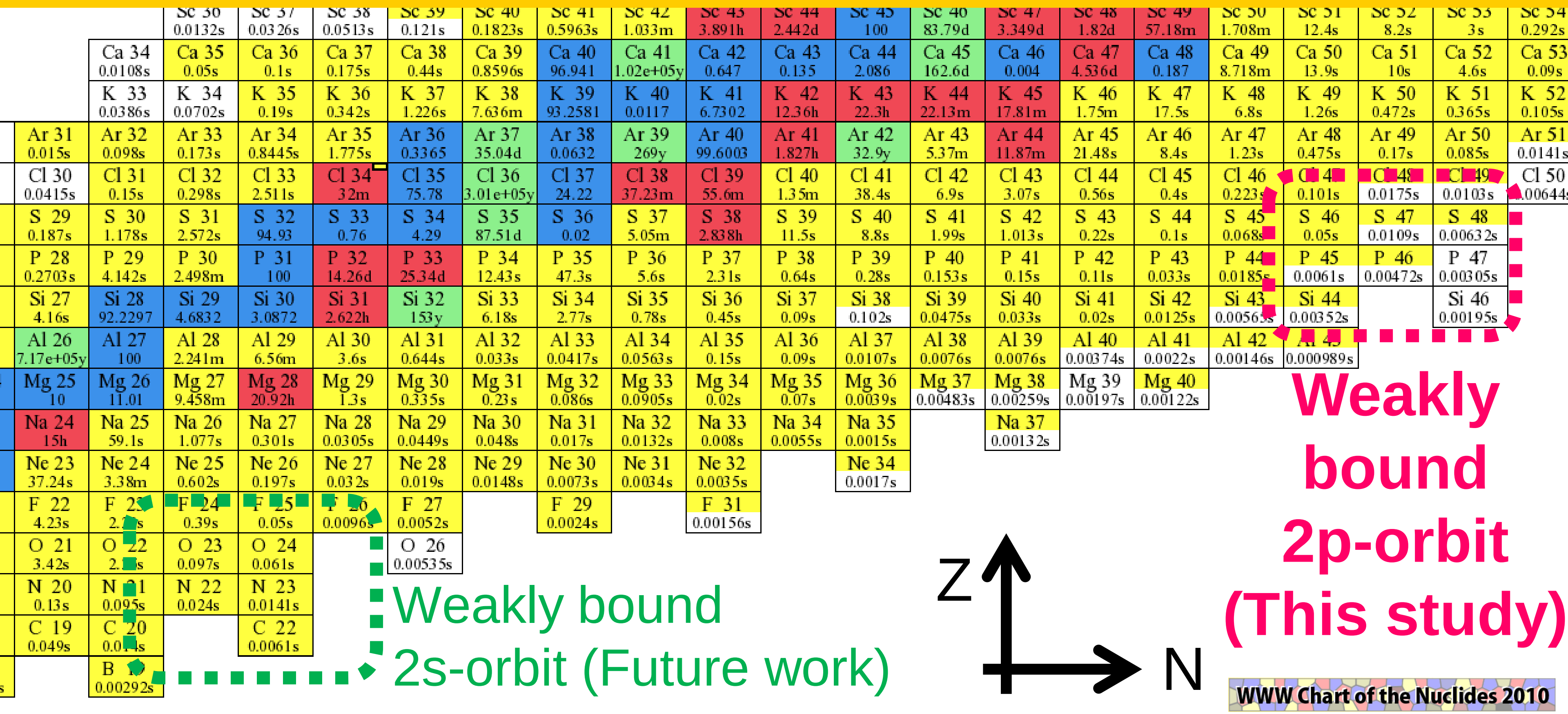
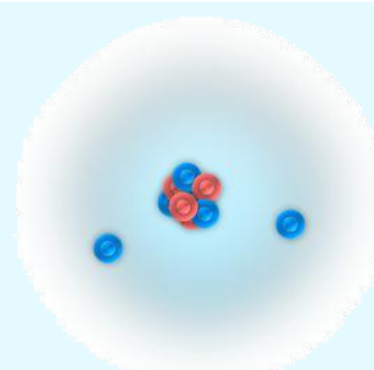
We focus on low-lying p- and s- resonance.



- Low-angular momentum wave play an important role in weakly bound nuclei.

Ex.) halo, capture etc…



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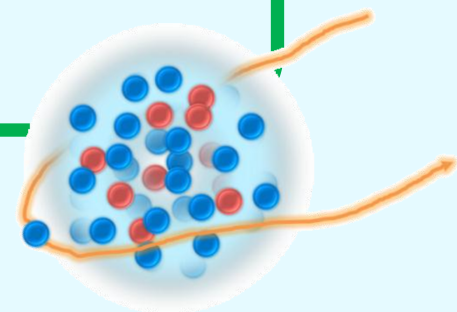
How the width is governed by the pairing ?

- Previous works of the quasi-particle resonance in drip-line nuclei.

M. Grasso et al., Phys. Rev. C 64 064321 (2001)
I. Hamamoto et al., Phys. Rev. C 68 034312 (2003)
J. C. Pei et al., Phys. Rev. C 84 024311 (2011)

- Our study:
  - ☑How the resonance width is governed by the pairing in neutron drip-line nuclei.
  - ☑What is different point from the resonance associate with deep-hole state.



- We consider,
  a neutron drip-line nucleus + one neutron
  with the HFB theory in the coordinate space (cHFB).

J. Dobaczewski et al., Nucl. Phys. A 422 103 (1984)

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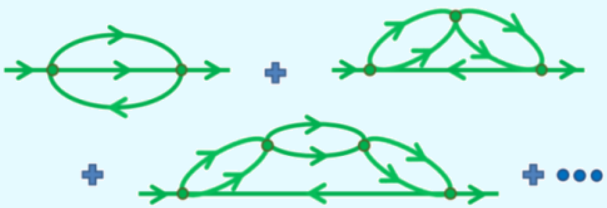
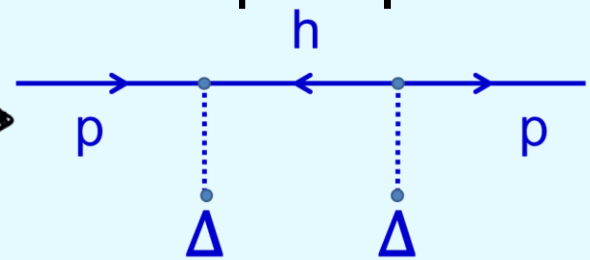
The cHFB equation for resonance

- Pairing effects describe as pair potential in cHFB.





Pair Potential
$\Delta(r)$

- The HFB equation in the coordinate space

$$\begin{pmatrix} \frac{-\hbar^2}{2m}\frac{d^2}{dr^2}+U_{lj}(r)-\lambda & \Delta(r) \\ \Delta(r) & \frac{\hbar^2}{2m}\frac{d^2}{dr^2}-U_{lj}(r)+\lambda \end{pmatrix}\begin{pmatrix}u_{lj}(r)\\ v_{lj}(r)\end{pmatrix}=E\begin{pmatrix}u_{lj}(r)\\ v_{lj}(r)\end{pmatrix}$$

$$\psi(\vec{r},\sigma)=\frac{1}{r}\begin{pmatrix}u_{lj}(r)\\ v_{lj}(r)\end{pmatrix}\left[Y_l(\theta,\phi)\chi_{\frac{1}{2}}(s_z)\right]_{jm}$$

J. Dobaczewski et al., Nucl. Phys. A 422 103 (1984)

- Scattering boundary condition of quasi-particle

$$\frac{1}{r}\begin{pmatrix}u_{lj}(r)\\ v_{lj}(r)\end{pmatrix}\xrightarrow[r\gg R]{}\begin{pmatrix}\cos\delta_{lj}j_l(k_1 r)-\sin\delta_{lj}n_l(k_1 r)\\ D h_l^{(1)}(i\kappa_2 r)\end{pmatrix}$$

$$k_1=\sqrt{\frac{2m(\lambda+E)}{\hbar^2}},\qquad \kappa_2=\sqrt{-\frac{2m(\lambda-E)}{\hbar^2}}$$

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)

→ phase shift
elastic cross section

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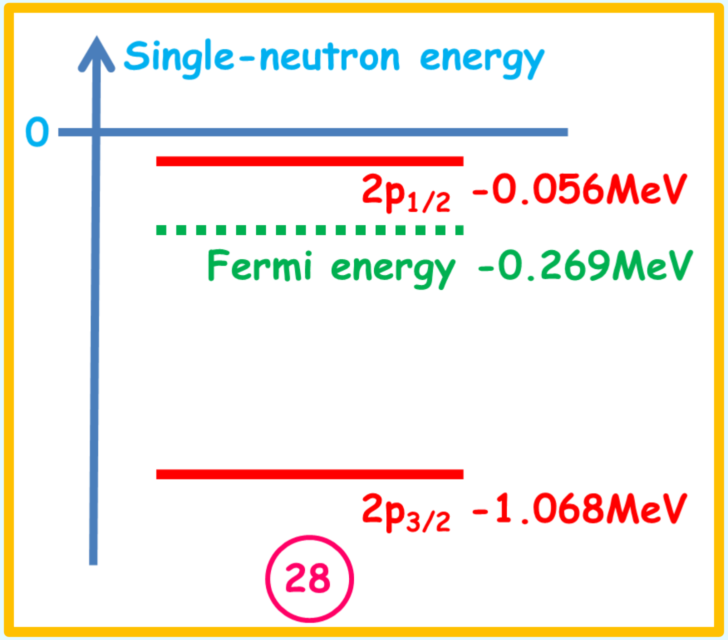
Numerical analysis with (^{46}Si + n)

● We consider the (^{46}Si + n) system.



☑drip-line nucleus for Si isotopes.

☑deformation is small.

Ex) M. V. Stoitsov et al. PRC68. 054312 (2003)

← Energy levels of ^{46}Si
(with Woods-Saxon potential)

• Weakly bound 2p orbits

☑Fermi energy -0.269MeV

☆**Nuclear potential & pair potential = Woods-Saxon type**

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

$$\Delta(r) = \Delta_0 f_{WS}(r)$$

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

The averaged strength of the pair field

$$\bar{\Delta} = \frac{\int d\vec{r} r^2 \Delta(r) f_{WS}(r)}{\int d\vec{r}\, r^2 f_{WS}(r)}$$

I. Hamamoto, B. R. Mottelson, Phys, Rev. C 68 034312 (2003)

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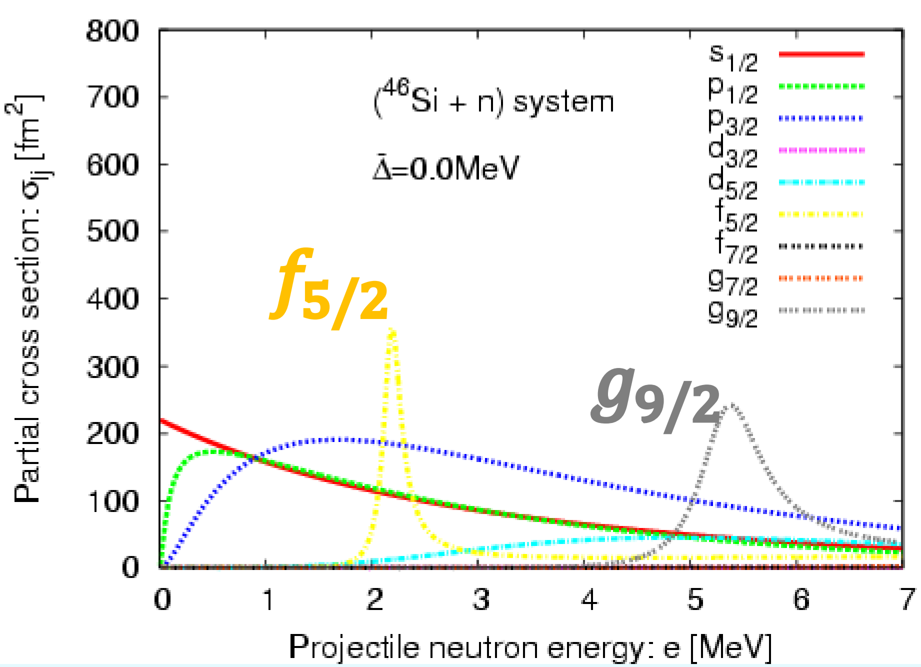
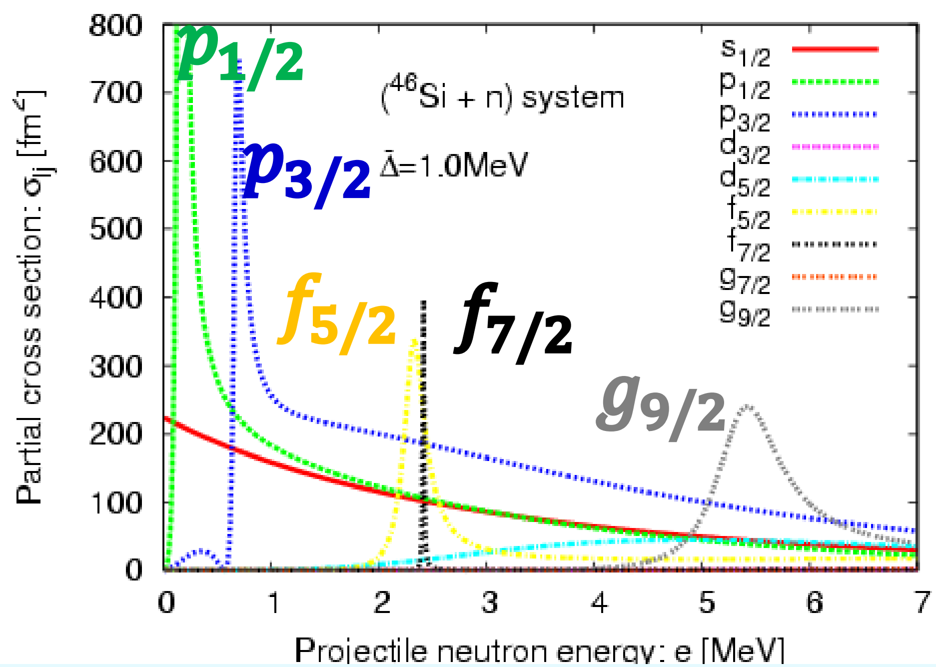
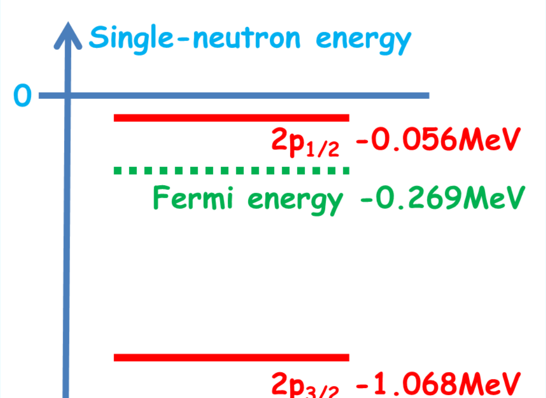
Elastic cross section



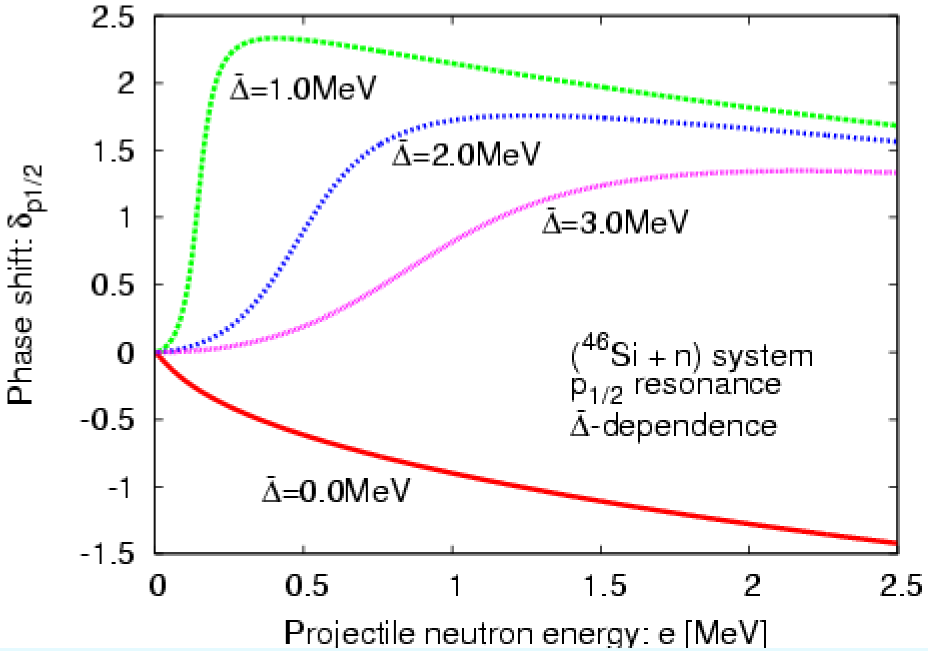


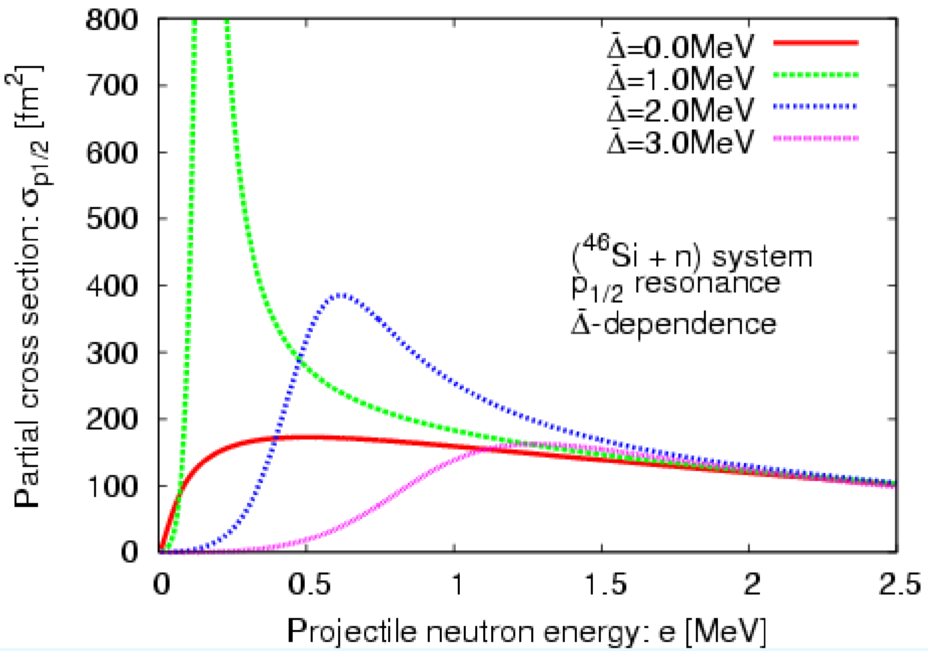
○When pairing is switched on, the $2p_{1/2}$ ($2p_{3/2}$) orbits emerges as a resonance

→ **weakly bound orbits emerge as resonances by the pairing effect**



We focus on $p_{1/2}$ resonance





- The strength of pairing.

  $\bar{\Delta} = 0.0 \sim 3.0\mathrm{MeV}$

Cf. the empirical value for ^{46}Si

$$\Delta = \frac{12.0}{\sqrt{A}}\ \mathrm{MeV} = \frac{12.0}{\sqrt{46}} \cong 1.7\ \mathrm{MeV}$$

- **Resonance energy and width depend on strength of the pairing**

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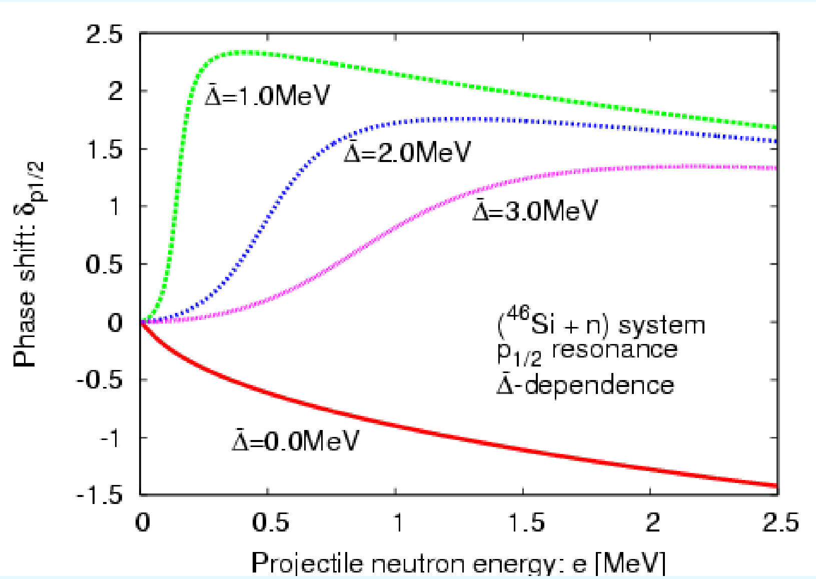
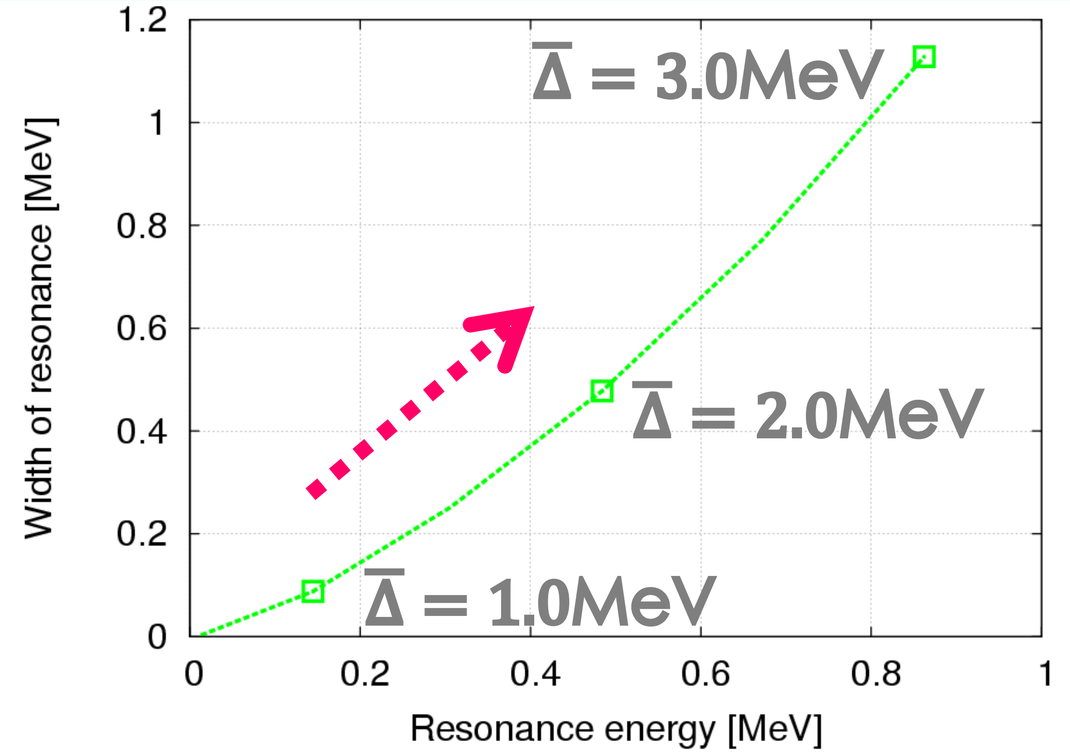
We extract the resonance width and energy

- We calculate the width and energy from phase shifts using fitting method.

$$\delta(e) = \arctan\left(\frac{2(e - e_R)}{\Gamma}\right) + a(e - e_R) + b$$





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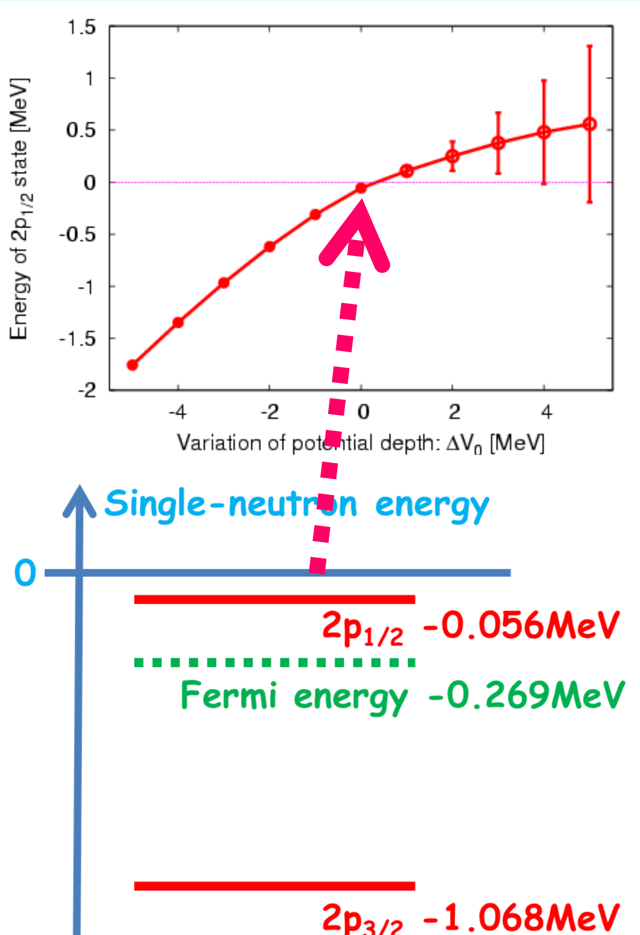
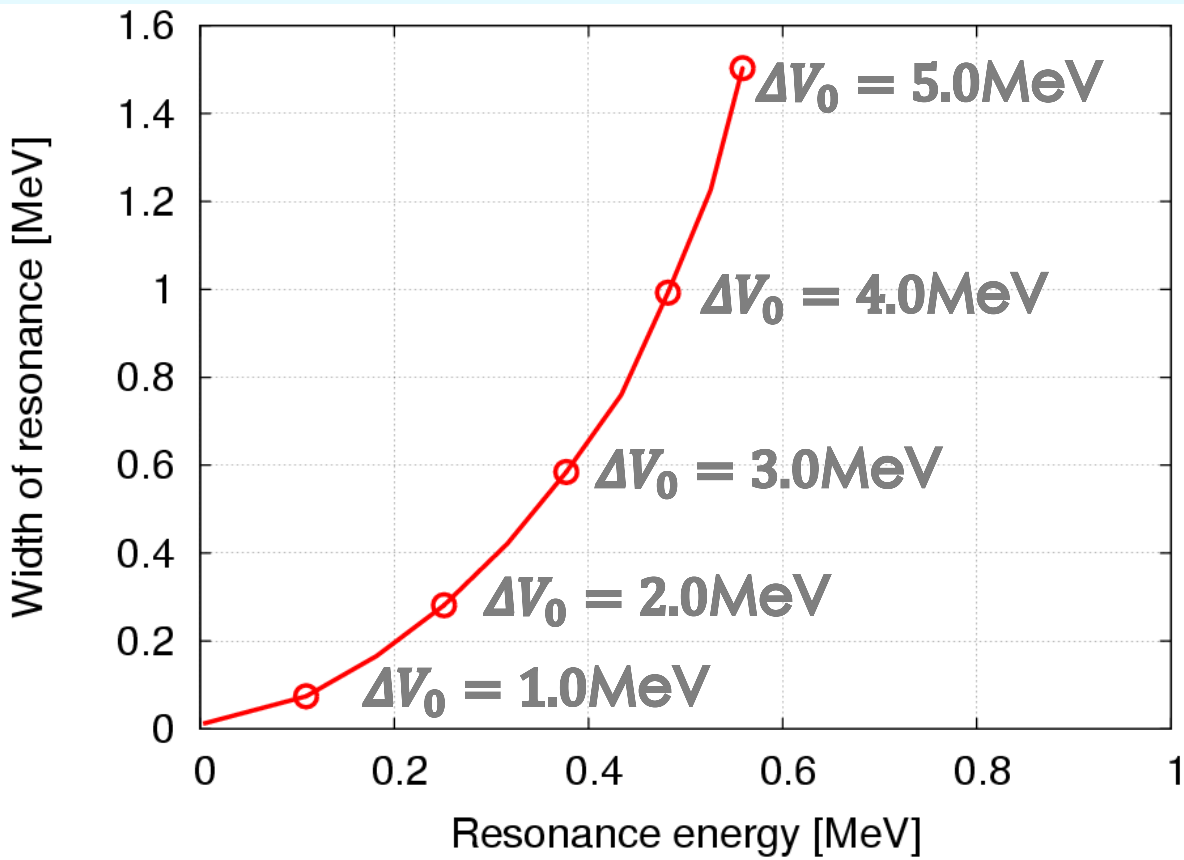
We also consider single-particle resonance

- We also calculate the width and energy for $p_{1/2}$ single-particle potential resonance.





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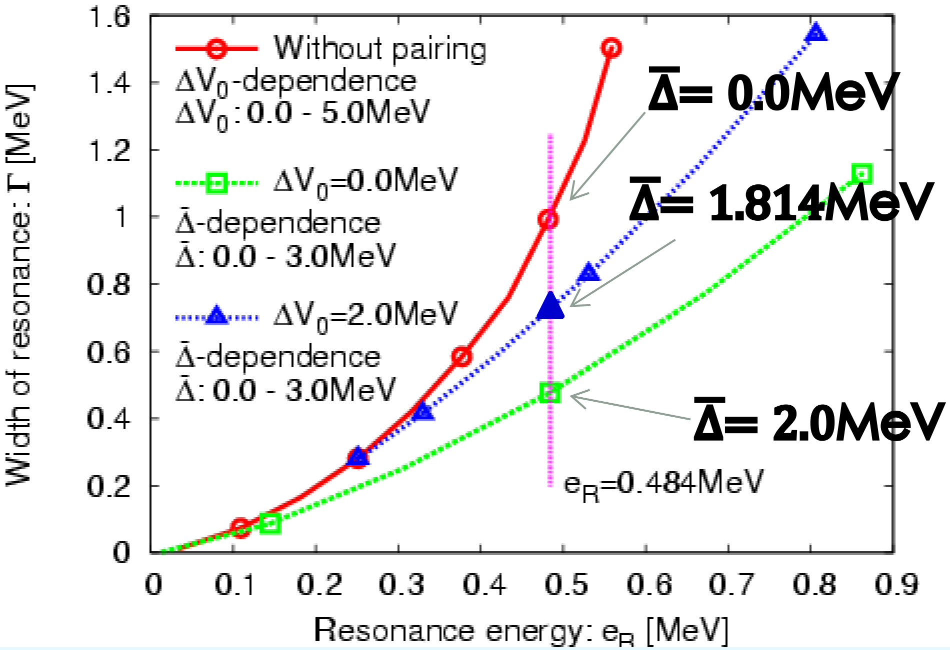
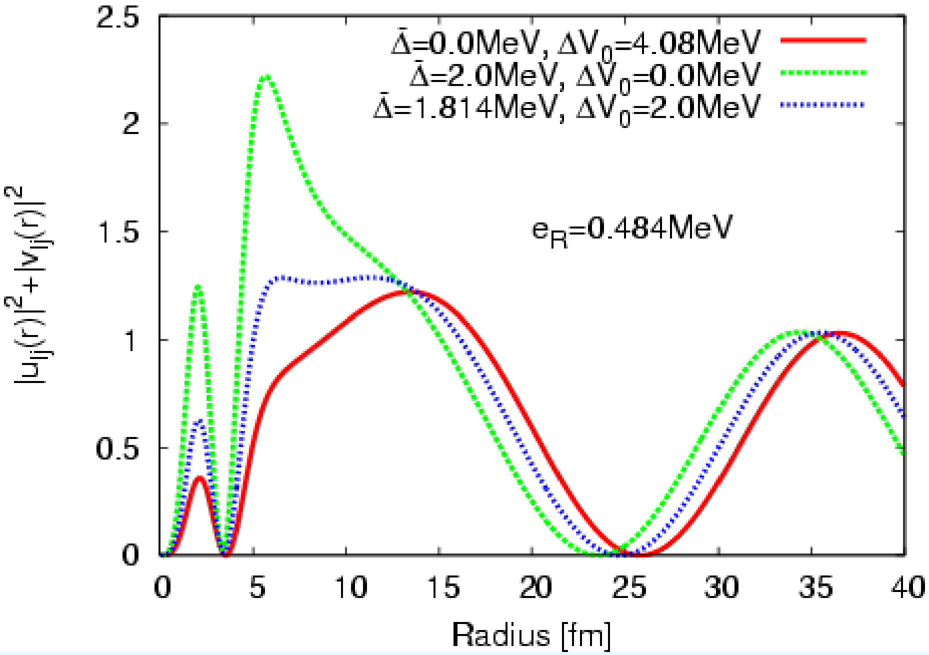
q.p. resonance vs s.p. resonance





- If we compare these results at the same resonance energy, we found that **the width of quasi-particle resonance is narrower than the width of single-particle potential resonance.**
- Pairing decrease the resonance width.

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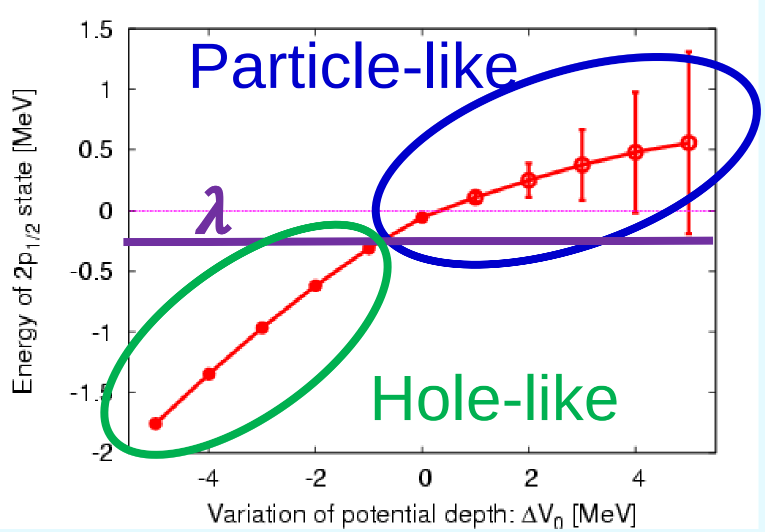
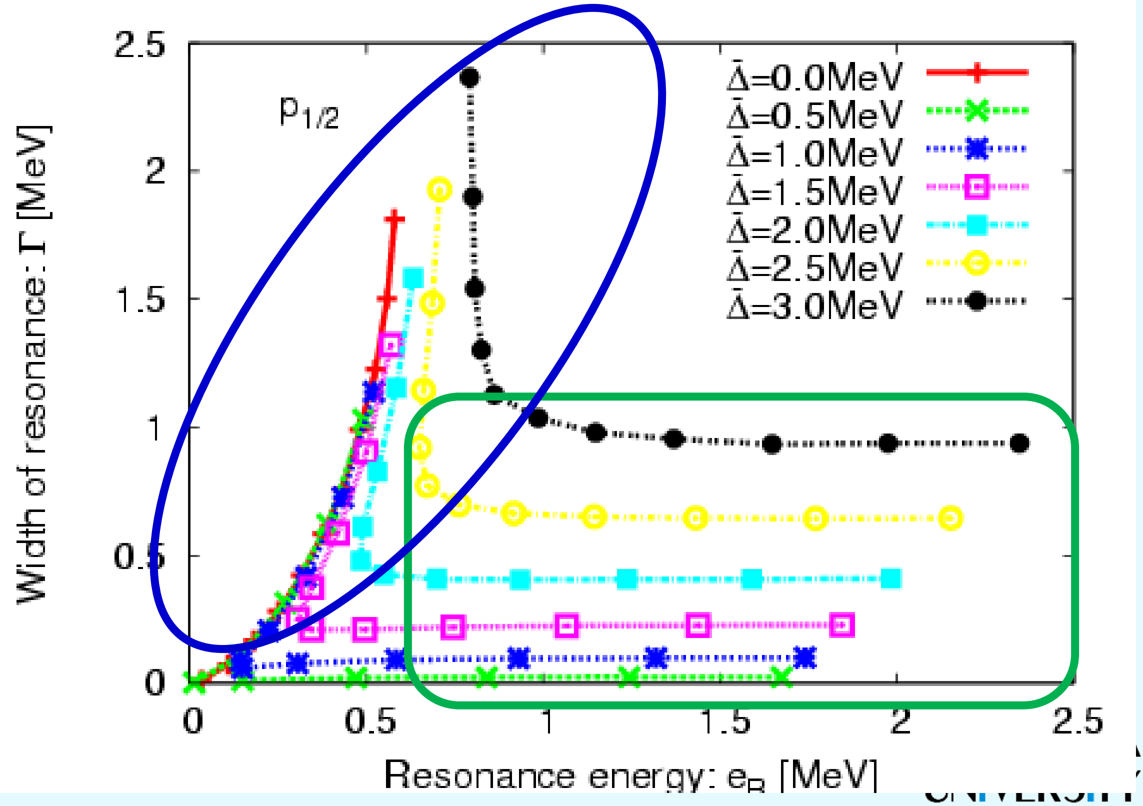
The width with various condition

- <u>We change</u>
- the strength of pairing $\bar{\Delta} = 0.0\sim3.0\text{MeV}$
- the depth of nuclear potential $\Delta V_0 = -6.0\sim4.0\text{MeV}$

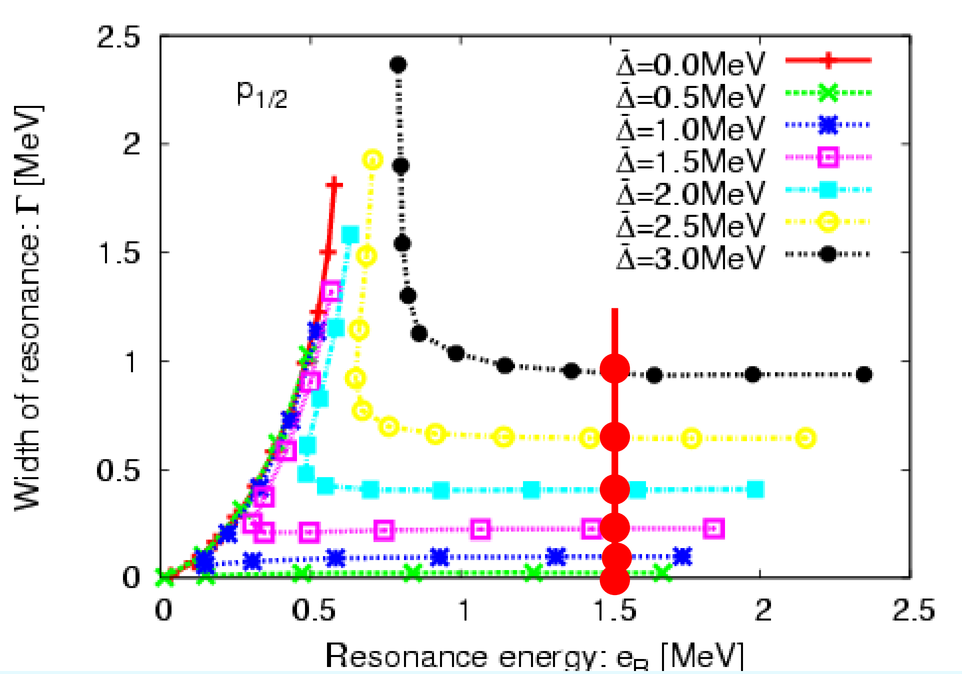
☑We fix the Fermi energy (=-0.269MeV)

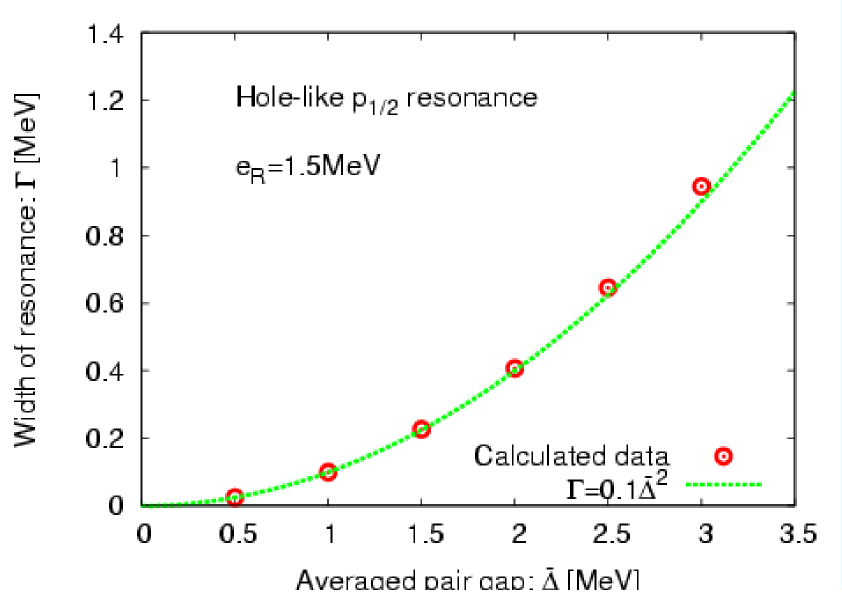


Single-particle energy of $2p_{1/2}$ and ΔV_0



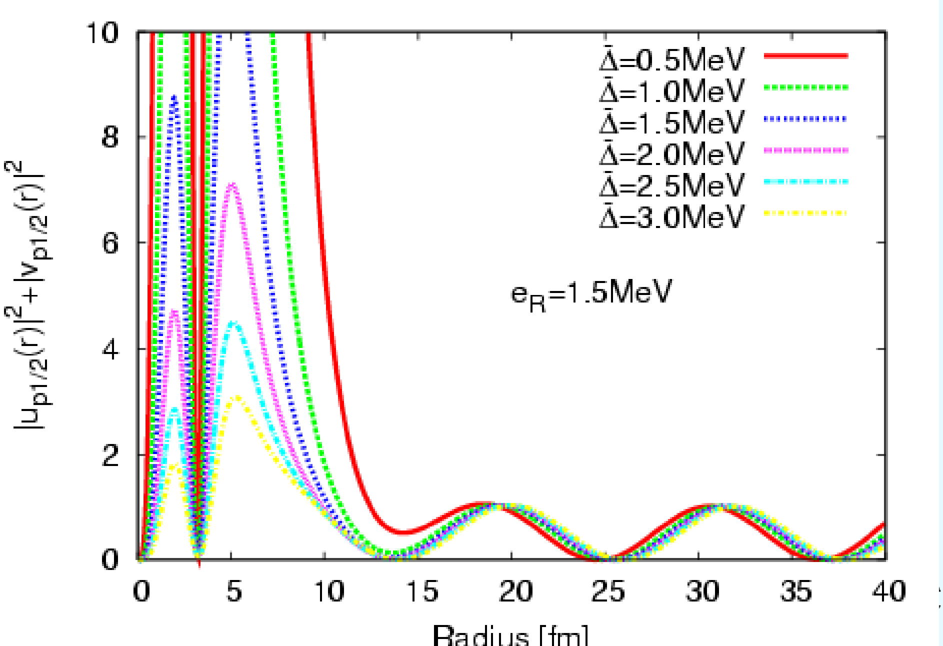
The width of hole-like quasi-particle resonance





- We focus on e_R=1.5MeV.
- The width ∝ $\bar{\Delta}^2$.

→ Pairing increase the width for hole-like quasi-particle resonance.

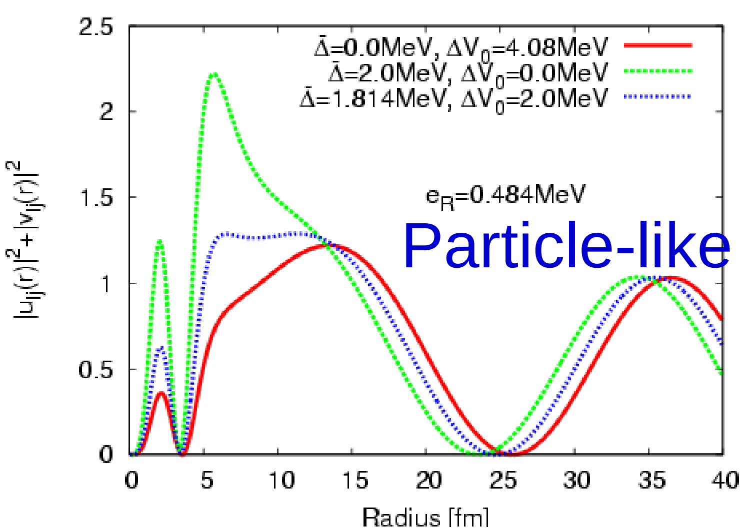


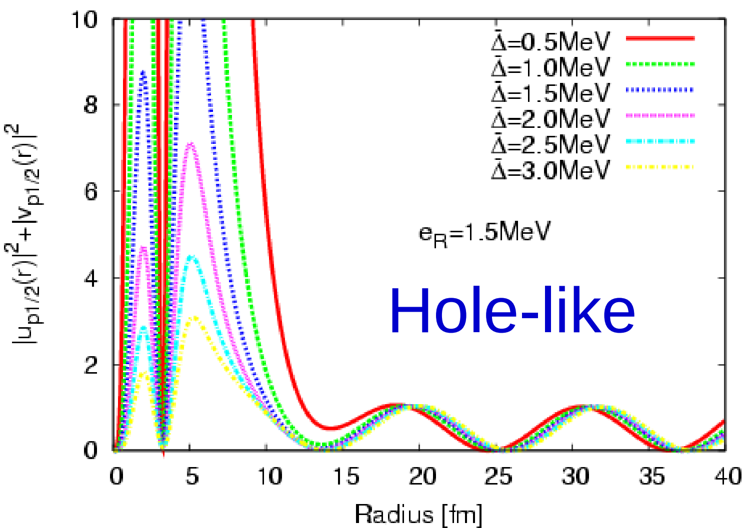
Particle-like vs hole-like

- We analyze the different point between particle-like q.p resonance & hole-like q.p. resonance with BCS formula.

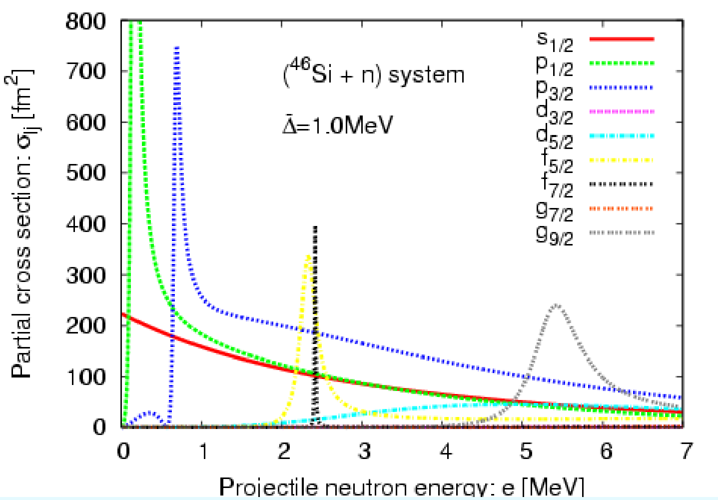
$$v_j^2 = \frac{1}{2}\left(1 - \frac{\epsilon_j - \lambda}{\sqrt{(\epsilon_j - \lambda)^2 + \Delta^2}}\right) \qquad u_j^2 = \frac{1}{2}\left(1 + \frac{\epsilon_j - \lambda}{\sqrt{(\epsilon_j - \lambda)^2 + \Delta^2}}\right)$$

Original $p_{1/2}$ orbit	When pairing increase	v^2 and u^2	Width of resonance
Particle-like	$\Delta \nearrow$	$v^2 \nearrow$	$\Gamma \searrow$
Hole-like	$\Delta \nearrow$	$u^2 \nearrow$	$\Gamma \nearrow$

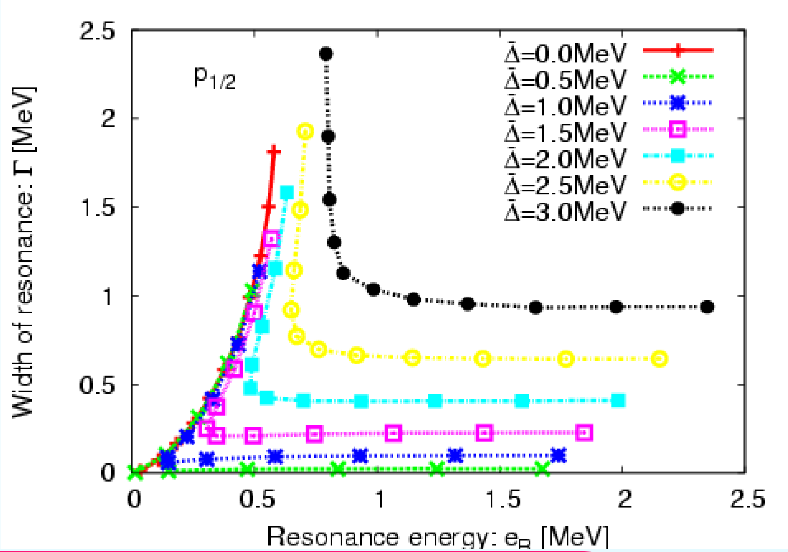




Conclusion



- Weakly bound orbits emerge as low-lying quasi-particle resonances when pairing is switched on in drip-line nuclei.



- The width of quasi-particle resonance is influenced by the pairing.

<u>The pairing effect on the width of quasi-particle resonance</u>

- For particle-like ： *<u>decrease the width</u>*
- For hole-like ： increase the width

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