Probing low-density pairing properties via neutron-rich nuclei

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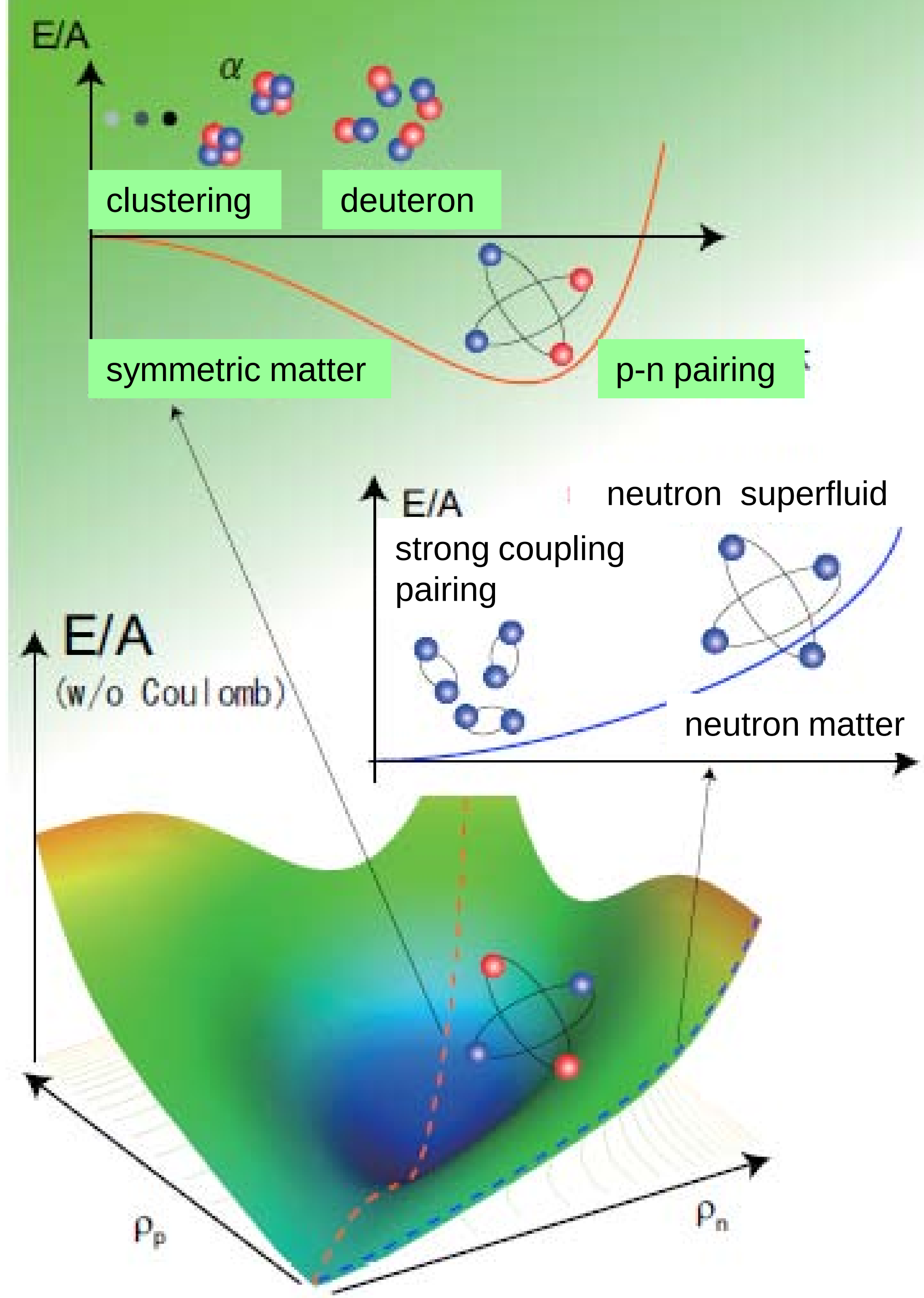
1. Dilute neutron matter

   strong-coupling pairing, BCS-BEC crossover, large scattering length

2. Are there features of strong coupling pairing in finite nuclei ?

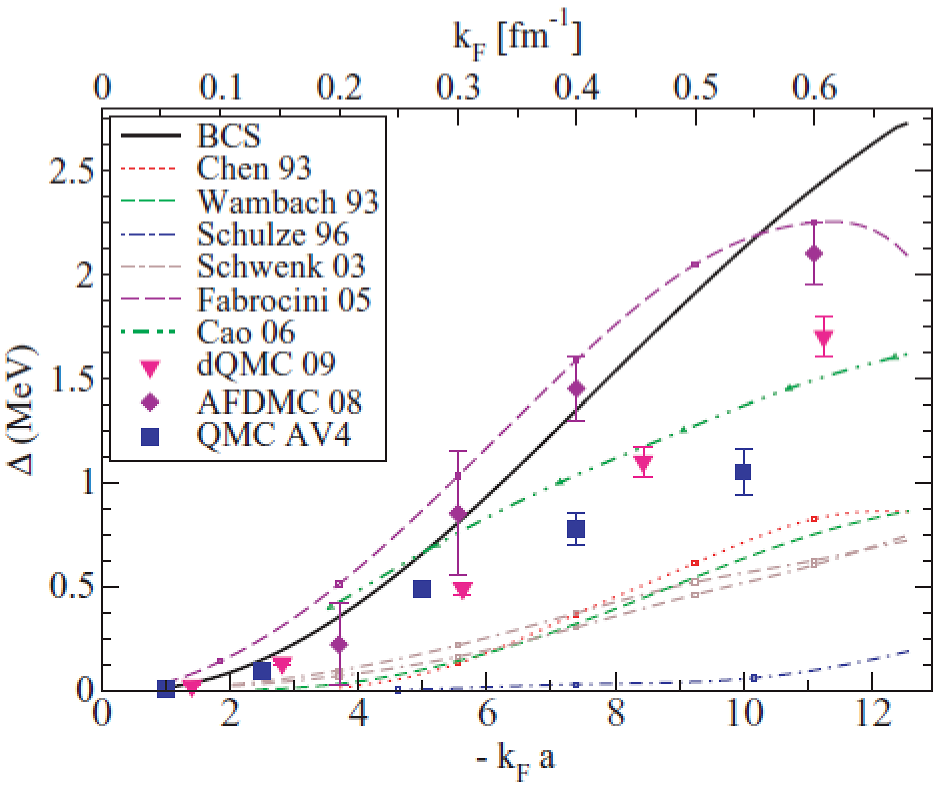
3. How do we probe?

Correlations in dilute matter

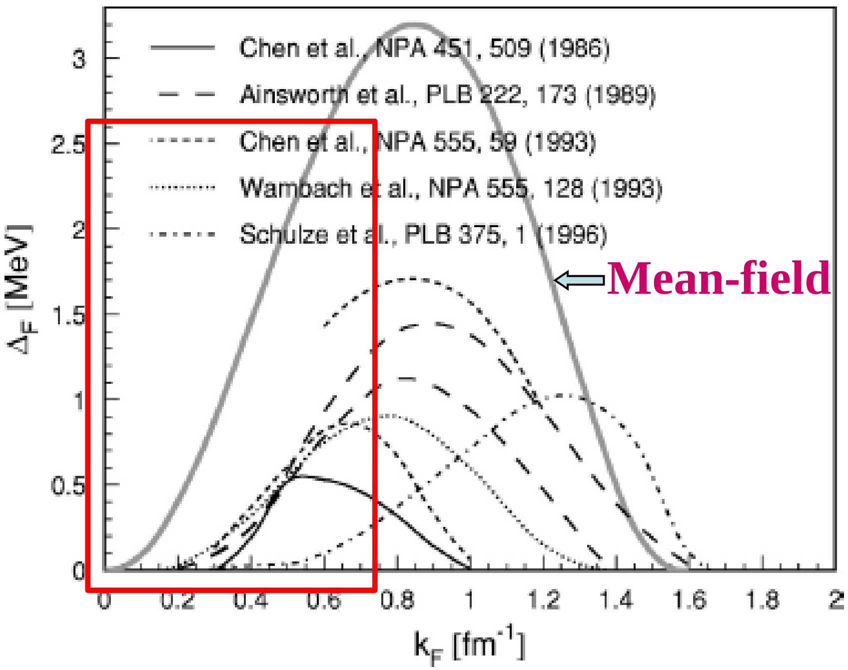


pairing gap in dilute neutron matter

$\Delta = (1 \sim 0.5)\ \Delta_{\text{mean-field}}$ in recent calculations



Gezerlis & Carlson, PRC81 (2010)



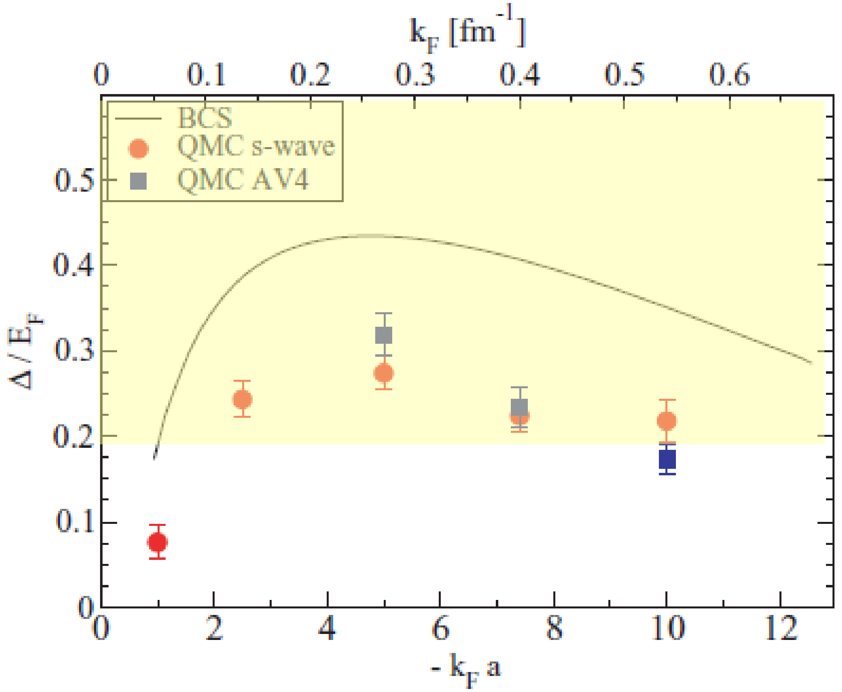
Lombardo & Schulze 2001

Strong coupling pairing & BCS-BEC crossover

"Large" pair gap vs. Fermi energy $\Delta/e_F > 0.2$ at low-densities

Monte-Carlo calculation

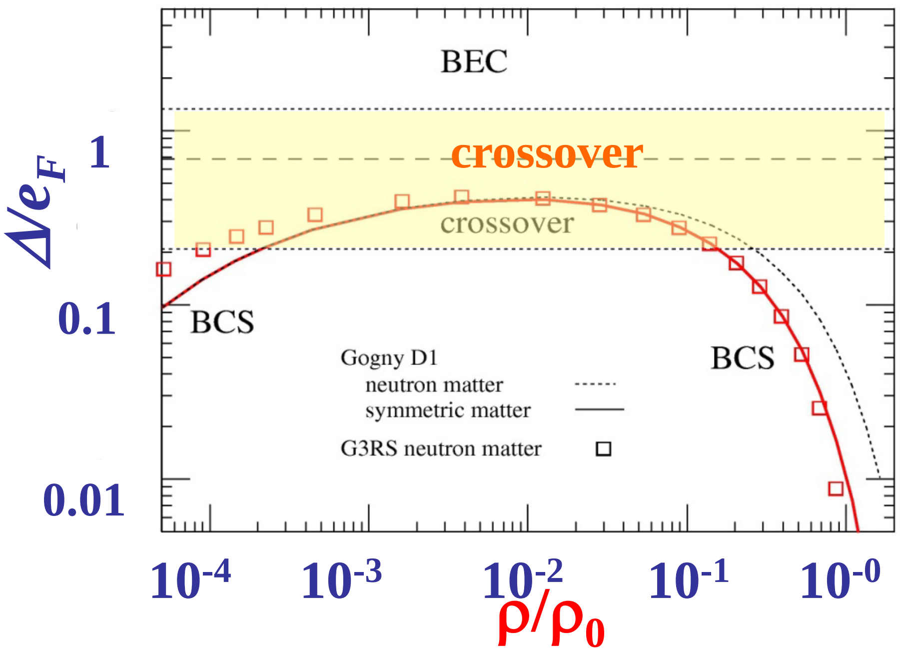
$\rho/\rho_0 = 10^{-3} \sim 0.5\times10^{-1}$



Gezerlis & Carlson, PRC81 (2010)

Mean-field calculation (BCS approx.)

$\rho/\rho_0 = 10^{-4} \sim 2\times10^{-1}$

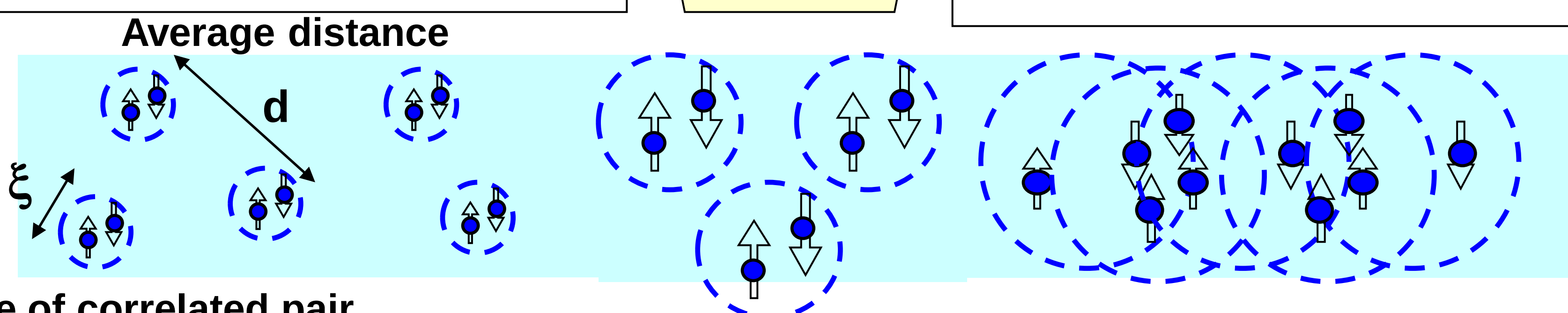


MM, PRC73,044309(2006)

Bose condensation and strong coupling pairing: BCS-BEC crossover

Leggett 1980, Nozieres & Schmitt-Rink 1985

BEC	Crossover	BCS
Interaction: **Strong**		Interaction: **Weak**
In free space: **Bound pair (boson) is already formed**		In free space: **No bound pair is formed**
In medium: **Condensate of bosons**		In medium: **Bound pairs (Cooper pairs) are formed, then condensate**



Size of correlated pair

ξ/d<<1	**ξ/d = 0.2 ~ 1.10**	**ξ/d>1**

Pairing gap

$\Delta/e_F>1$	$\Delta/e_F = 1.3 \sim 0.2$	$\Delta/e_F<<1$

$$\rho = \frac{k_F^3}{3\pi^2}$$

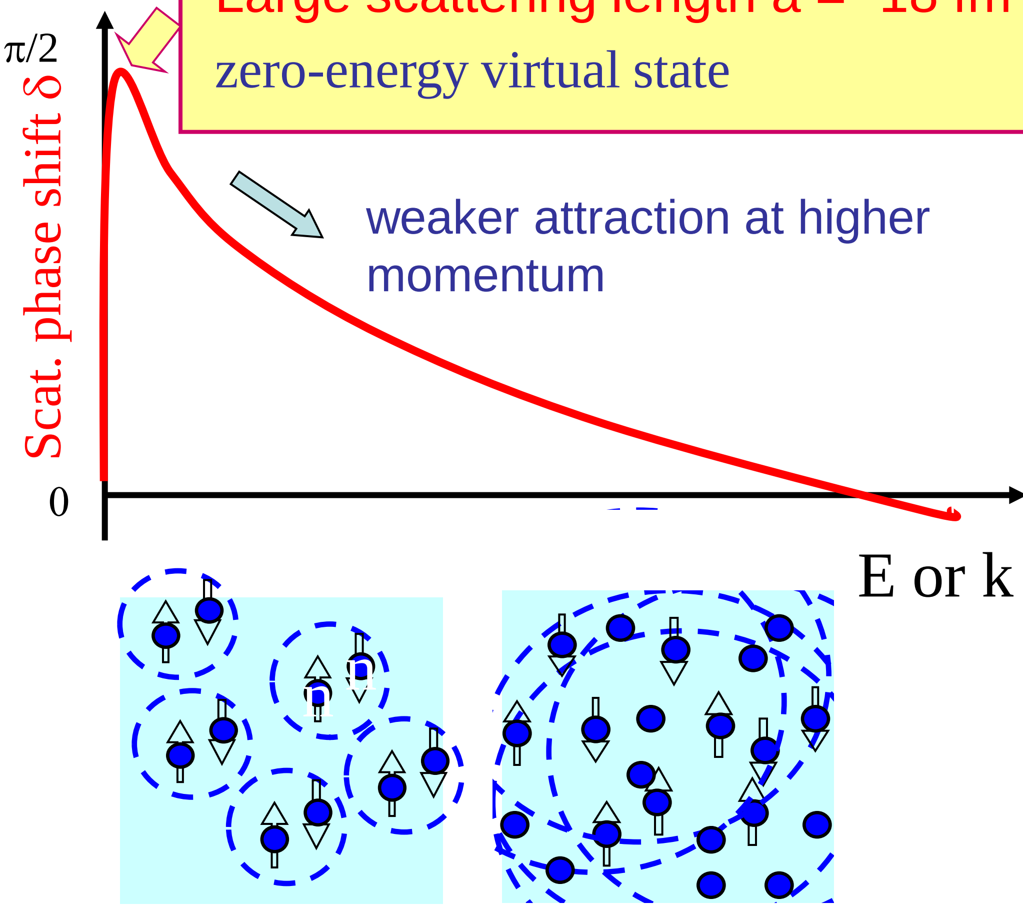
Scattering length a & density

$1/k_F a > 1$	$1/k_F a = -1 \sim 1$	$1/k_F a < -1$

nn interaction ^1S has a large scattering length at low momentum (low density)

^1S phase shift

Large scattering length a = -18 fm
zero-energy virtual state



weaker attraction at higher momentum

Strong coupling

$k_F a > -1$

may be realized for

$k_F > 0.05\ \mathrm{fm}^{-1}$

$\rho/\rho_0 > 10^{-4}$

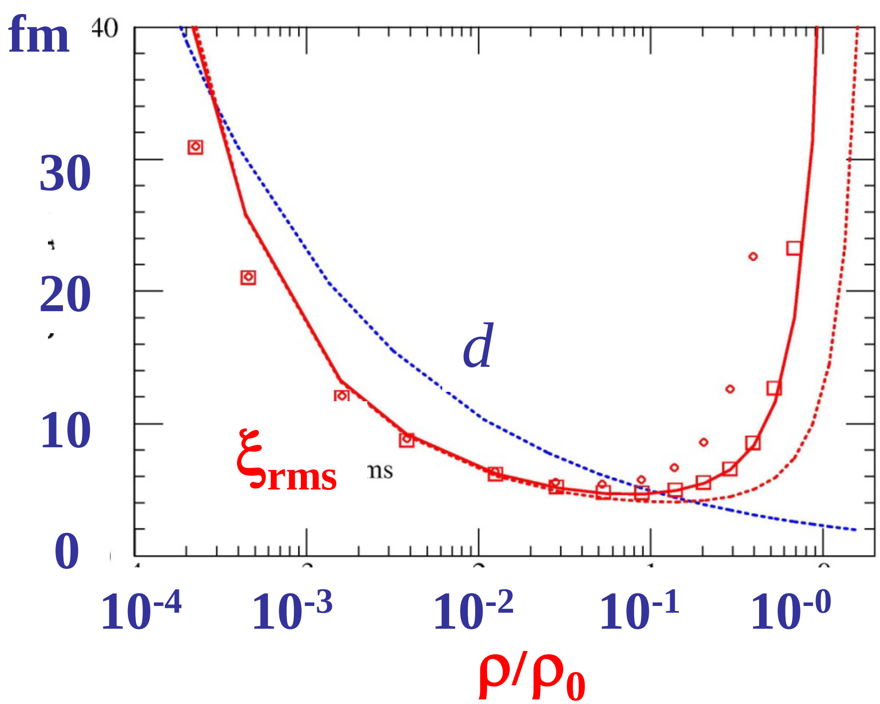
but not for

$\rho/\rho_0 \sim 1$

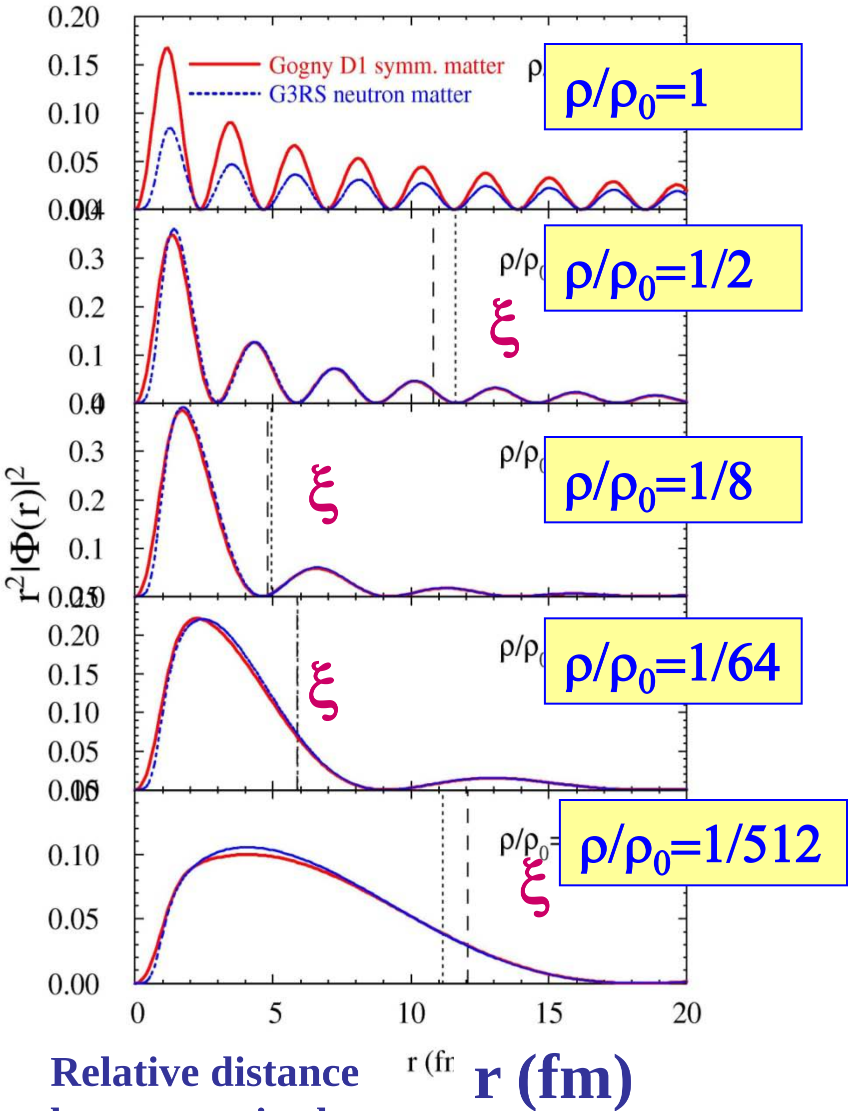
Neutron Cooper pair in dilute matter

BCS calculation using A bare force (G3RS)
Gogny force (D1)

Neutron pairing gap



Cooper pair wave function



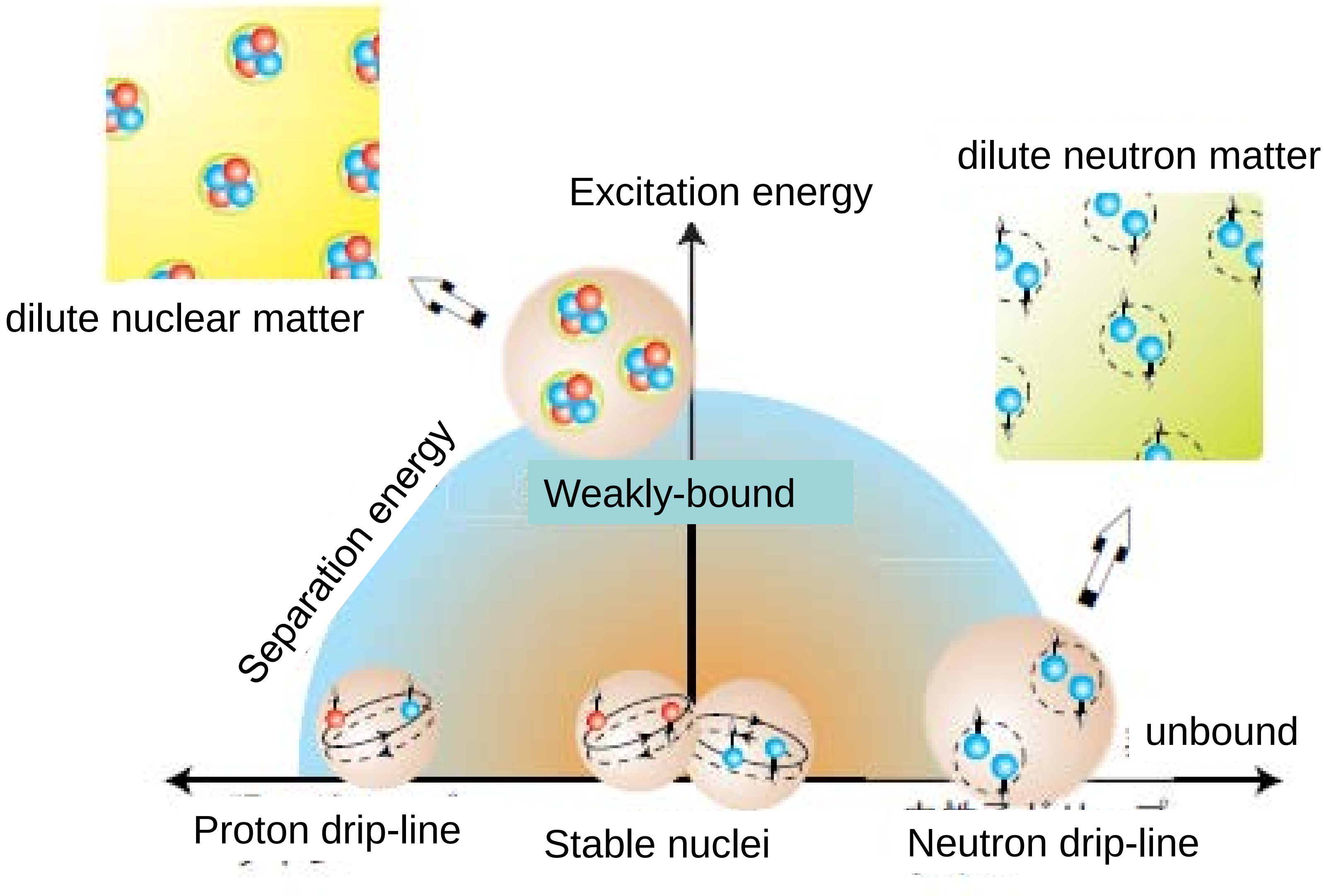
Pair wave function has large amplitude at short relative distances r∼2-3 fm

MM, PRC73,044309(2006)
Margueron et al, PRC77,054309(2008)

Question 1

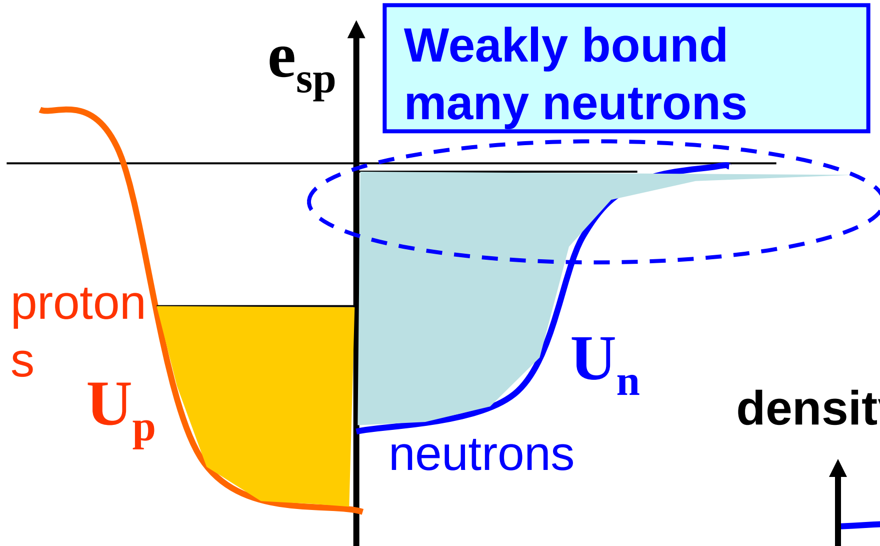
Do nuclei, in particular, neutron-rich nuclei exhibit features of the strong-coupling, e.g., the spatial correlation in Cooper pairs?

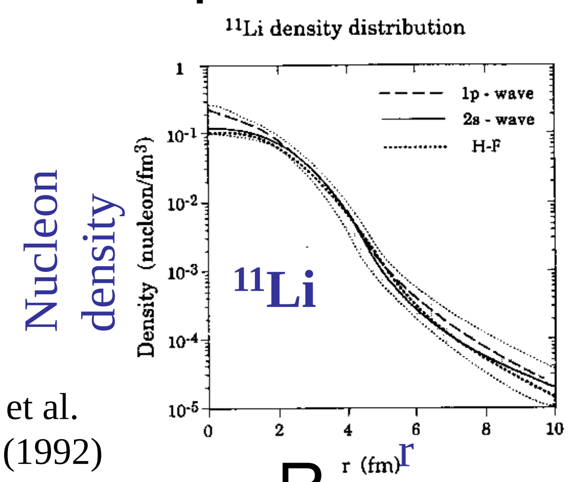
Dilute matter vs. Weakly-bound nuclei / excited states near separation energies



"Dilute matter" in n-rich nuclei

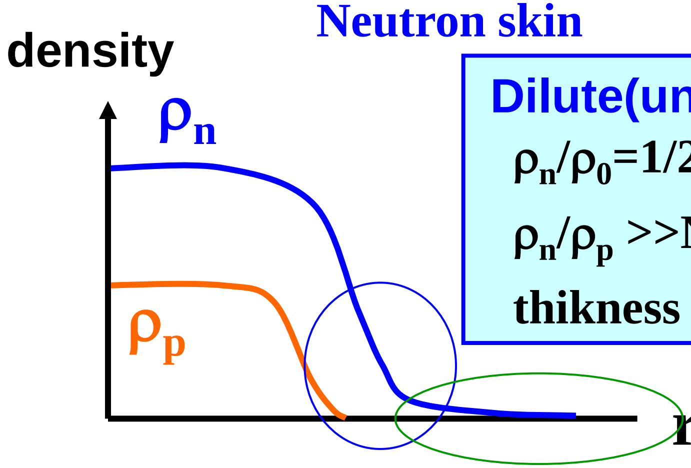
Weakly bound many neutrons





Tanihata et al.
PLB287 (1992)

Neutron skin



Dilute(unsaturated) matter

ρ_n/ρ_0=1/2 – 10^{-2}(?)

ρ_n/ρ_p >>N/Z

thikness < 1-2fm(?)

Neutron halo

Long tail

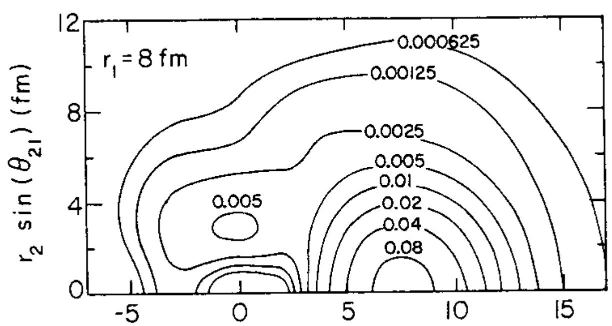
$\rho_n/\rho_0 < 10^{-2}$(?)

Spatial pair correlation & surface-enhanced pairing in n-rich nuclei

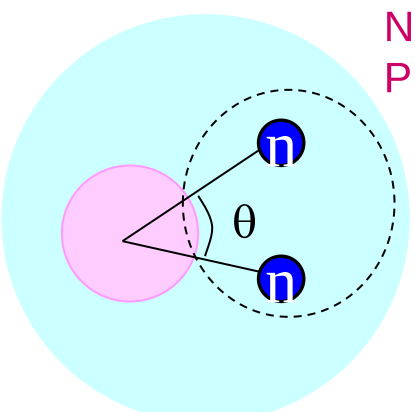
Spatially compact pair in nuclei

2n-halo nucleus ^{11}Li

G.F.Bertsch, H.Esbensen, Ann. Phys. 209(1991) 327



Recent Coulomb break-up exp.



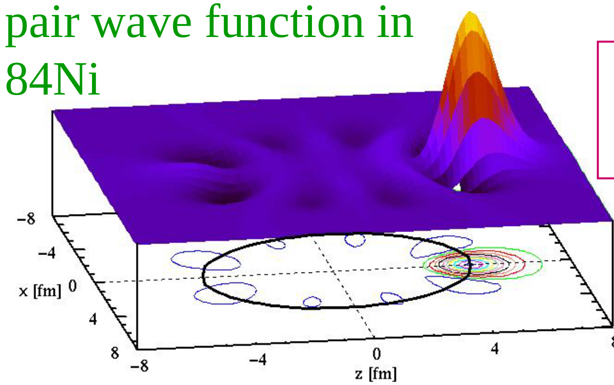
Nakamura et al.
PRL30,252502 (2006)

$\theta_{nn}=48^{+14}_{-18}$ deg

$R_{c,2n}$=5.01+-0.32 fm

neutron skin nuclei in medium mass region

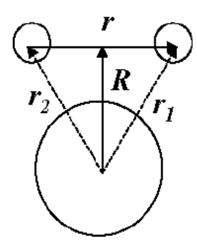
pair wave function in 84Ni

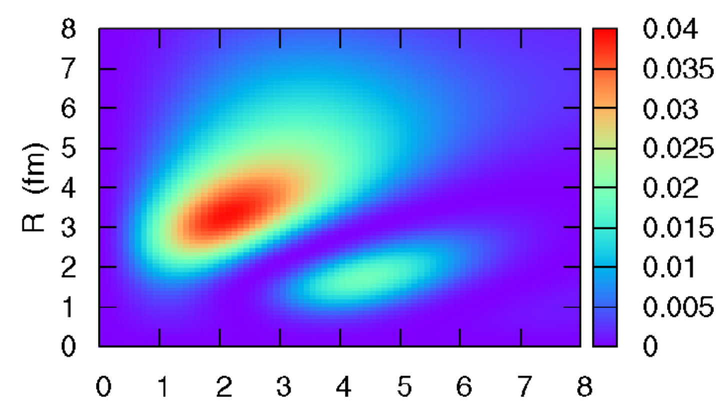


HFB calc.
Using DDDI

Matsuo et al PRC71,064326(2005)
Pillet, Sandulescu, Schuck, PRC76, 024310 (2007)

K.Hagino et al., Phys.Rev. Lett.99, 022506(2007)





Strong coupling pairing & Spatial correlation in Cooper pair

Closed-core + 2N e.g. ^{210}Pb

Ibarra et al. NPA288, (1977)
Janouch & Liotta PRC27 (1983)
etc

Slab

Kanada-En'yo et al. PRC79, (2009)

Semi-infinite matter

Pankratov et al. PRC79, (2009)

pn pairing in symmetric matter

Alm et al. NPA551, (1993)
Baldo et al. PRC52, (1995)
etc

Density functional theories: a link between matter and nuclei

The Skyrme functional　　　Pair correlation energy functional

$$E = E_{Skyrme}[\rho, \vec{\nabla}\rho, \Delta\rho, \tau, \vec{j}, \vec{s}, \overleftrightarrow{J}] + E_{pair}[\rho, \tilde{\rho}, \tilde{\rho}^*]$$

A simple functional DDDI (density-dependent delta interaction)

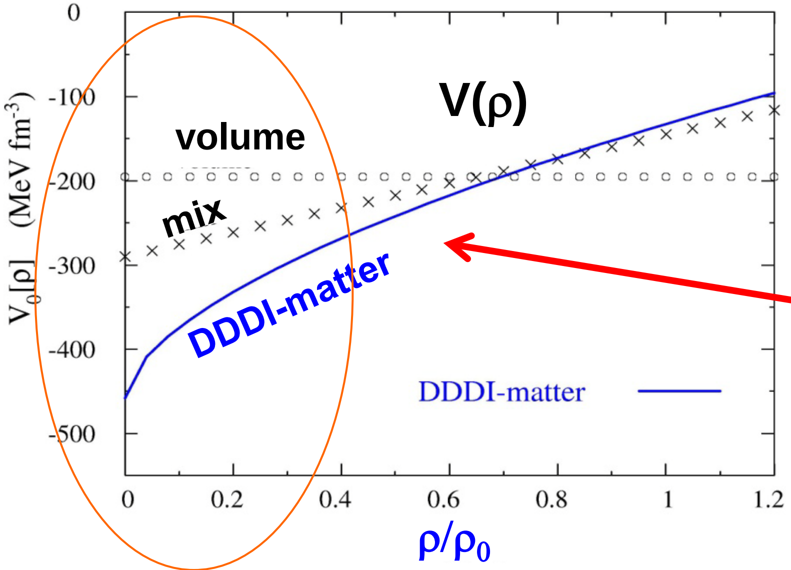
Esbensen-Bertsch 1
Garrido etal 1999,
Matsuo 2006

$$E_{pair}[\rho, \tilde{\rho}, \tilde{\rho}^*] = \int d\vec{r} V_q[\rho_n, \rho_p] \tilde{\rho}(\vec{r}) \tilde{\rho}^*(\vec{r})$$

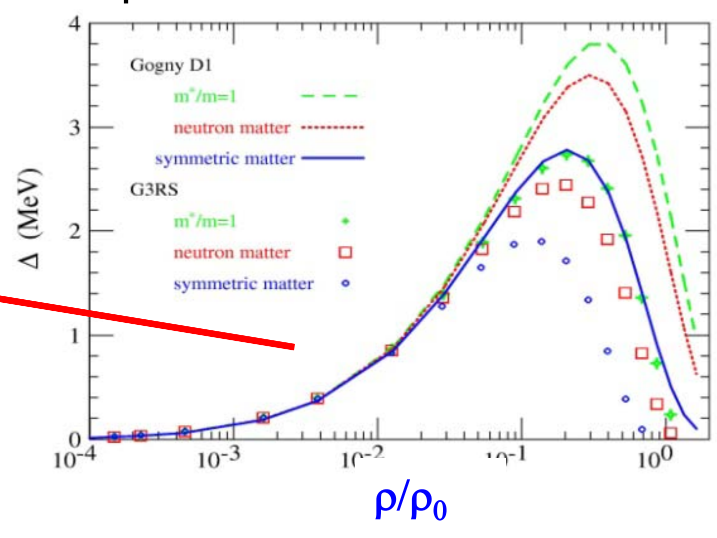
Pair density

$$\tilde{\rho}(\vec{r}) = \langle HFB | \psi^+(\vec{r}\uparrow)\psi^+(\vec{r}\downarrow) | HFB \rangle$$

Density dependence is flexibly incorporated as a simple functional



Gap in neutron matter



Pairing functional at work

DDDI-matter, reproducing matter pair gap Δ_{matter}(BCS)

DDDI a-18

$$V_n[\rho_n] = v_0\left(1 - 0.845\left(\rho_n / 0.08\right)^{0.59}\right)$$

0.71

DDDI-mix Linear weak dependence on density

$$V_n[\rho_n, \rho_p] = v_0\left(1 - 0.5\left(\rho_n + \rho_p / 0.16\right)^1\right)$$

DIDI-volume No density dependence

vol a-1

$$V_n[\rho_n, \rho_p] = v_0$$

v_0= -458.4 ← a_{nn}= -18.5 fm

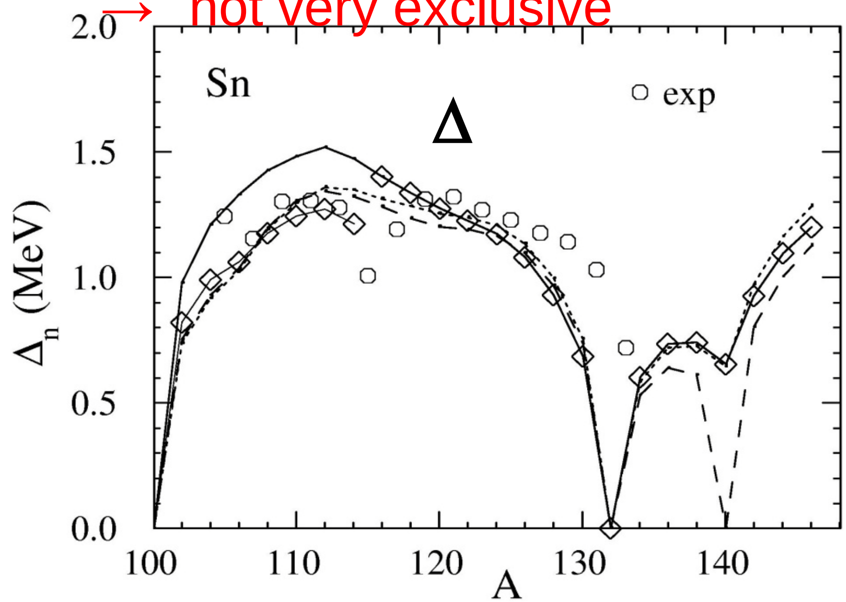
v_0= -292 ← a_{nn} = -1.4 fm

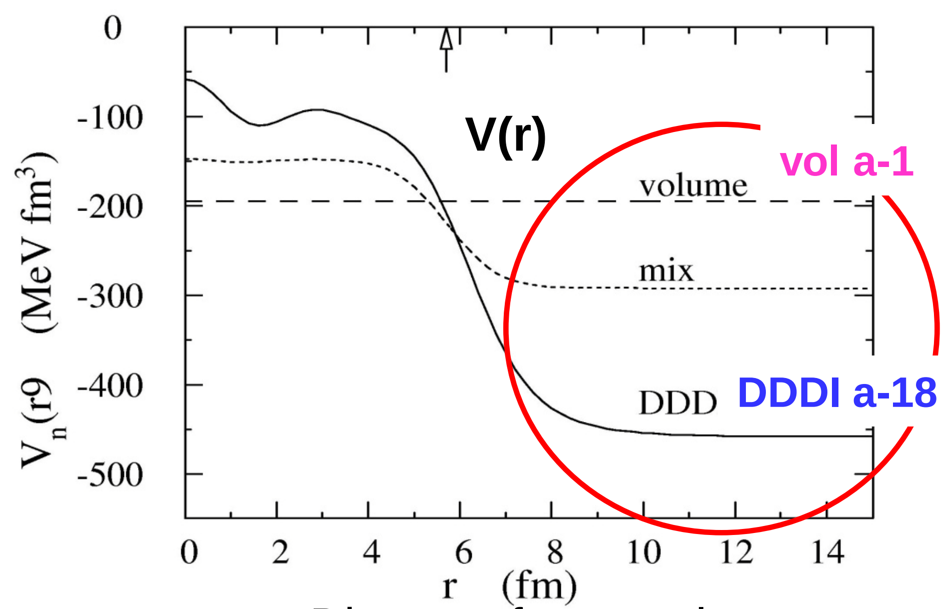
v_0= -195 ← a_{nn} = -0.63 fm

Different low-density limit

average pair gap in Sn istopes

→ not very exclusive





Distance from nuclear center

Spatial correlation at surface of n-rich nuclei

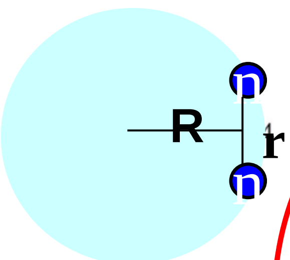
Cooper pair wave function $\Psi_{pair}(\vec{r}_1,\vec{r}_2)=\langle HFB|\psi^+(\vec{r}_1\uparrow)\psi^+(\vec{r}_2\downarrow)|HFB\rangle$

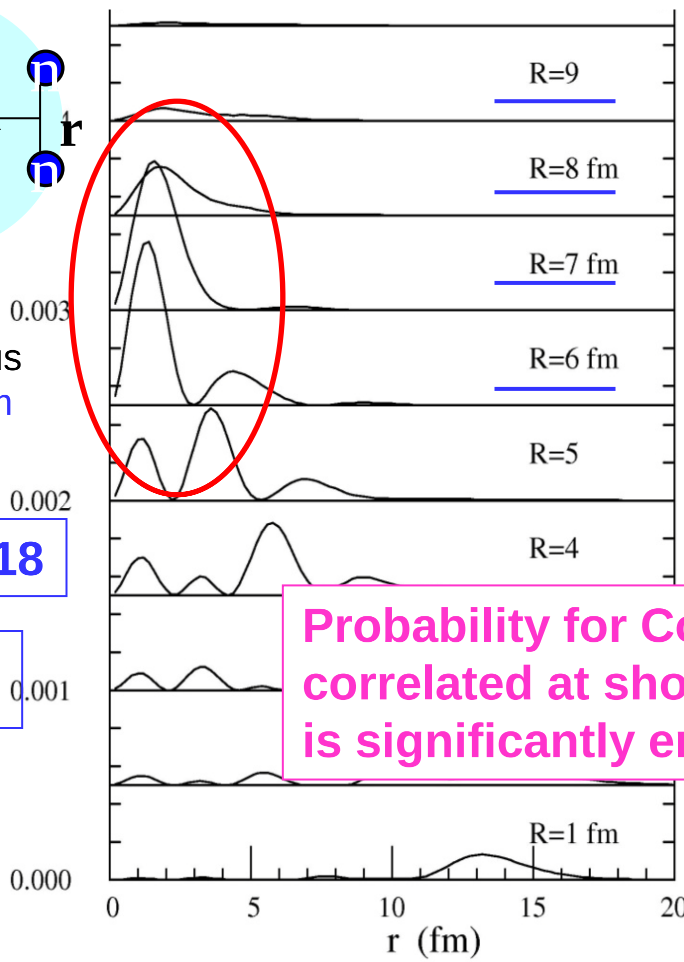
Probability distribution 1

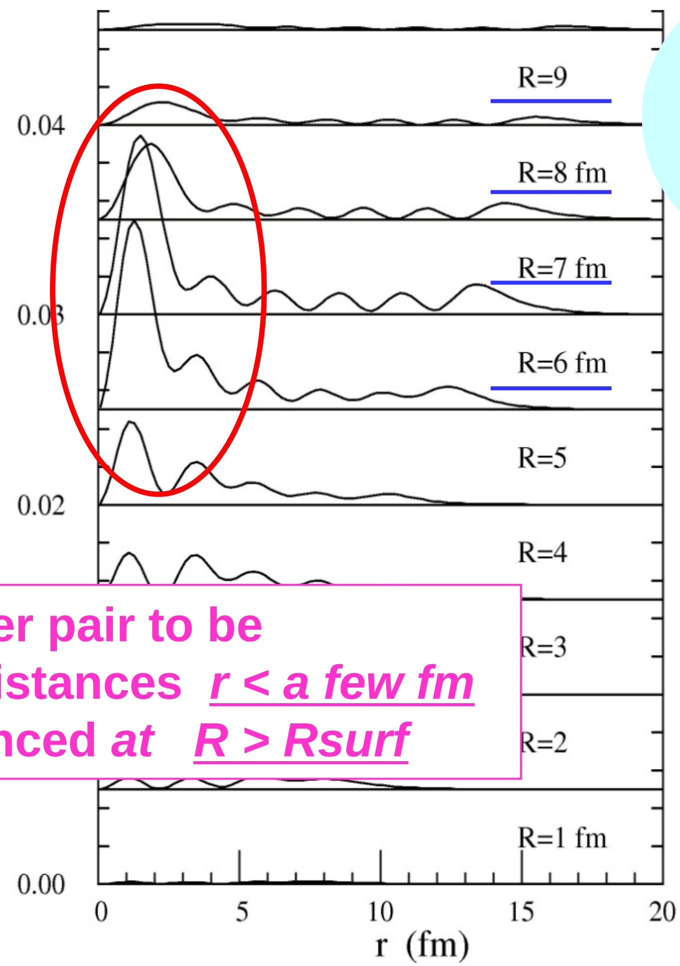
$$P_c(R,r)=R^2r^2\int d\Omega\,|\Psi_{pair}(\vec{R}-\tfrac{\vec{r}}{2},\vec{R}+\tfrac{\vec{r}}{2})|^2$$

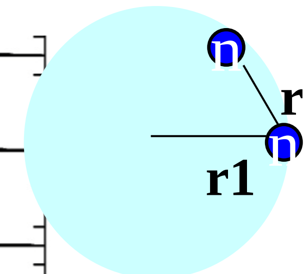
Probability distribution 2

$$P_1(r_1,r)=r_1^{\,2}r^2\int d\Omega\,|\Psi_{pair}(\vec{r}_1,\vec{r}_1+\vec{r})|^2$$









surface radius
R_{surf}= 5.8 fm

DDDI a-18

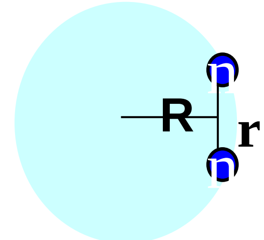
^{142}Sn

Probability for Cooper pair to be correlated at short distances *r < a few fm* is significantly enhanced *at R > Rsurf*

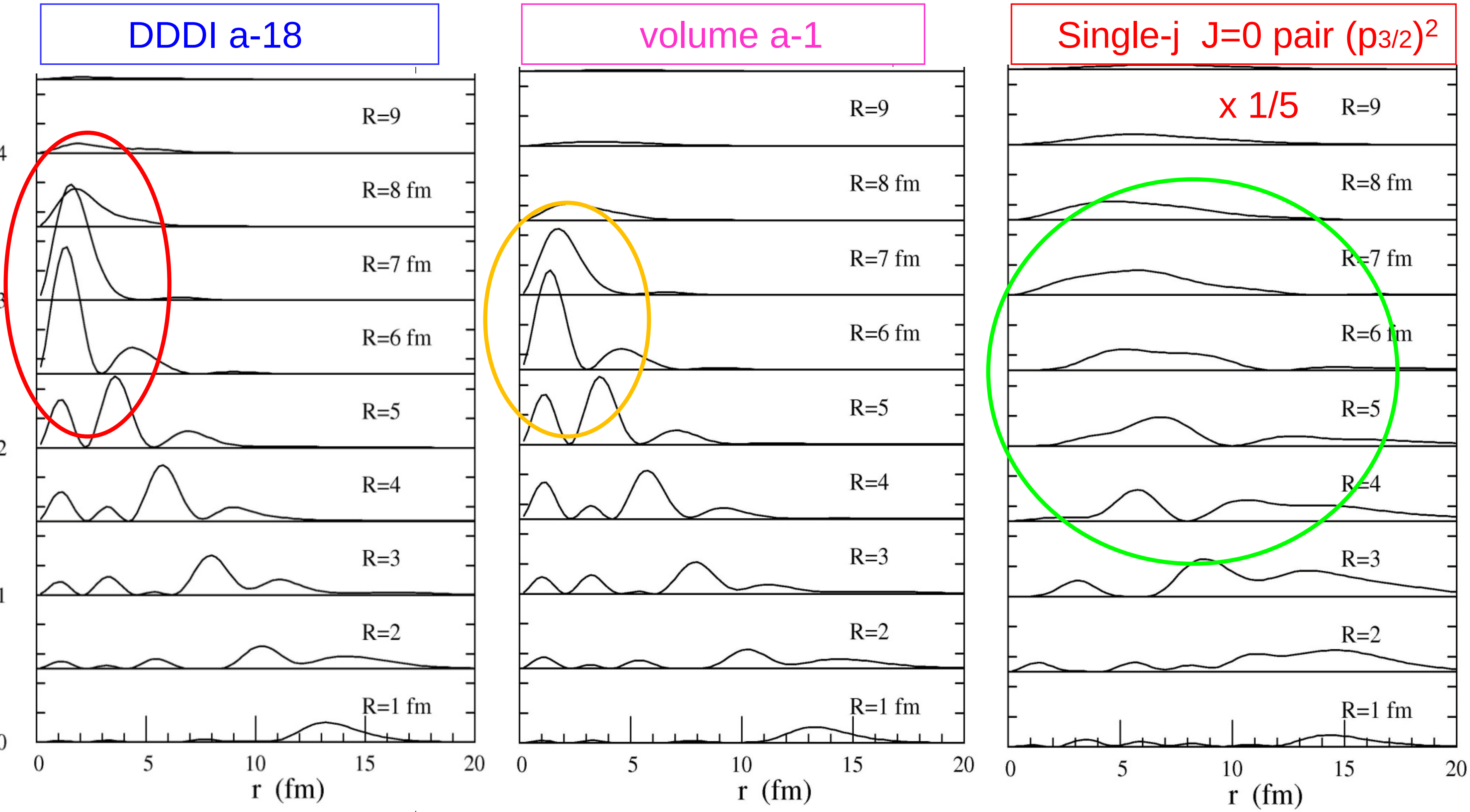
Sensitivity to the low-density pairing

Probability distribution 1

$$P_c(R,r) = R^2 r^2 \int d\Omega \, |\Psi_{pair}(\vec{R} - \tfrac{\vec{r}}{2}, \vec{R} + \tfrac{\vec{r}}{2})|^2$$



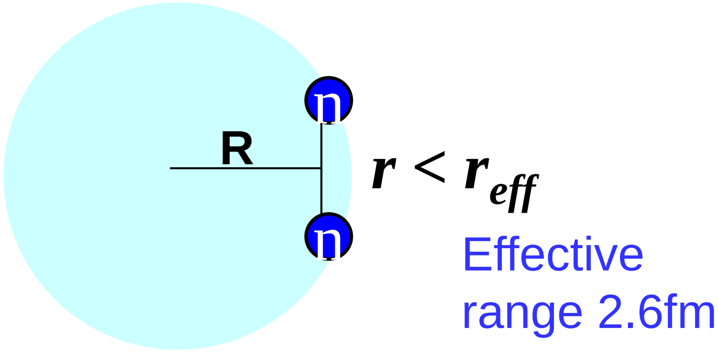
^{142}Sn

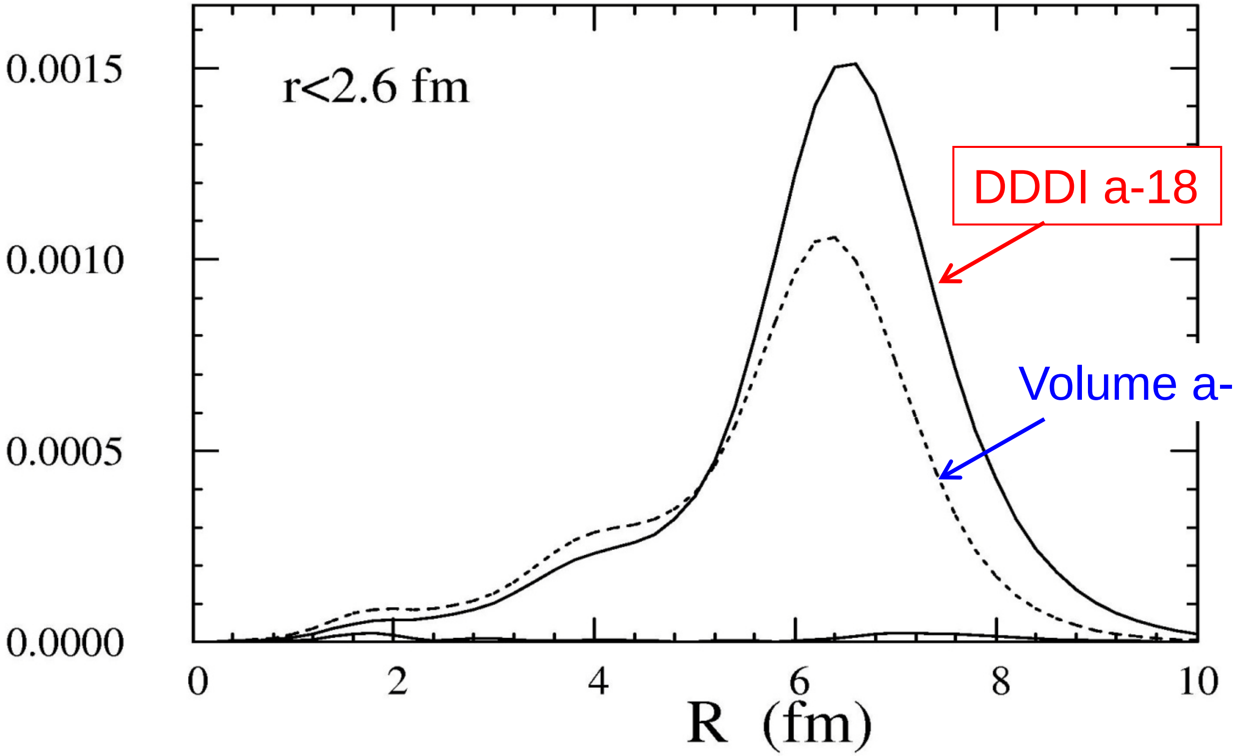


Pair contact probability r < 2.6 fm

Probability of pair at short relative distances within the interaction range

$$p(R) = \int_0^{r_{eff}} P_c(R, r)\,dr$$

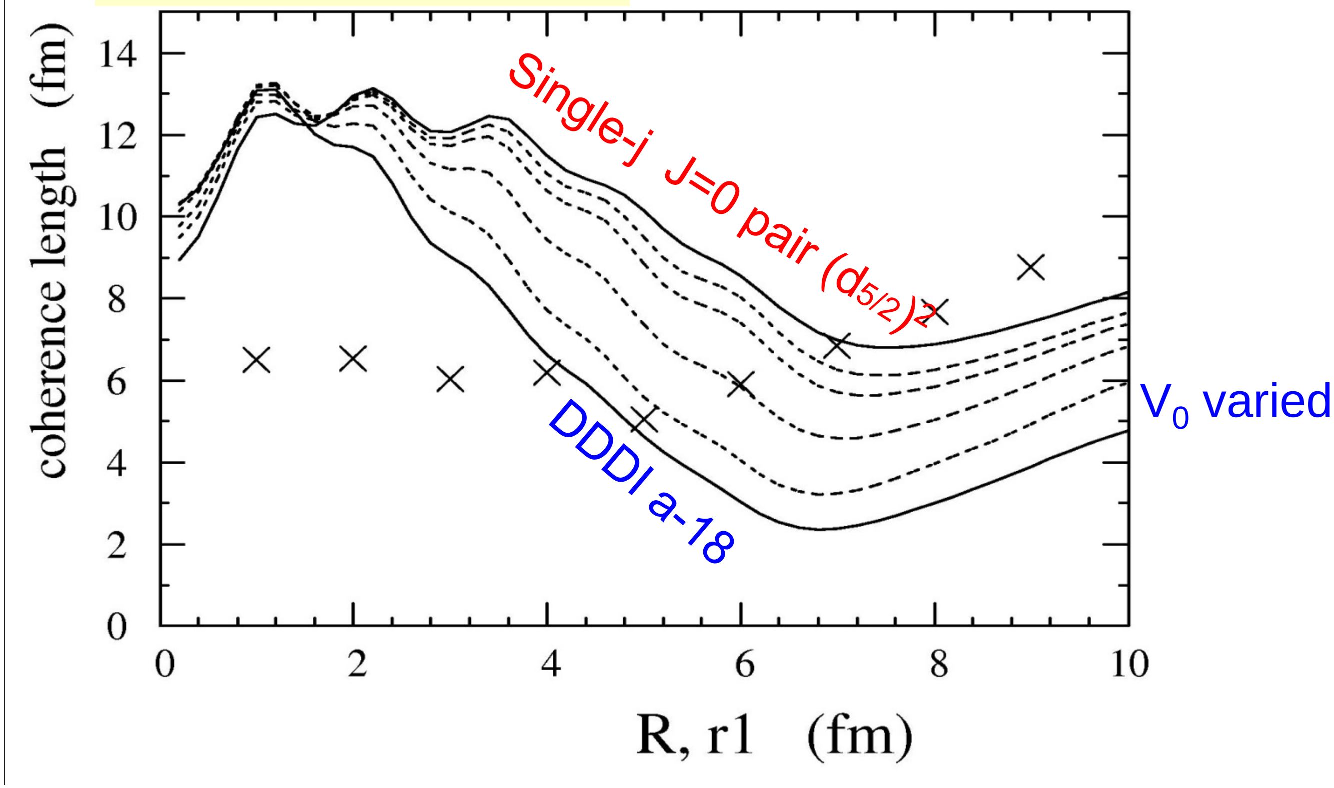


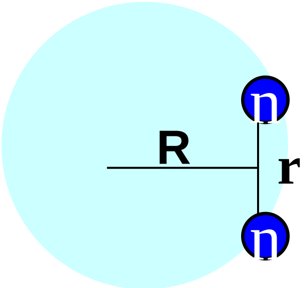


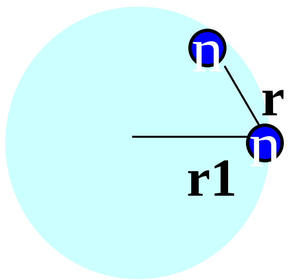
Comment on coherence length

Rms radius of ‘Cooper pair’ as a function of R

$$\xi = \langle r^2 \rangle = \frac{\int r^2 P_c(R,r)dr}{\int P_c(R,r)dr}$$







1. It is influenced by the finite size effect

2. And also depends on choices of coordinate.

3. But still it reflects the spatial correlation to some extent.

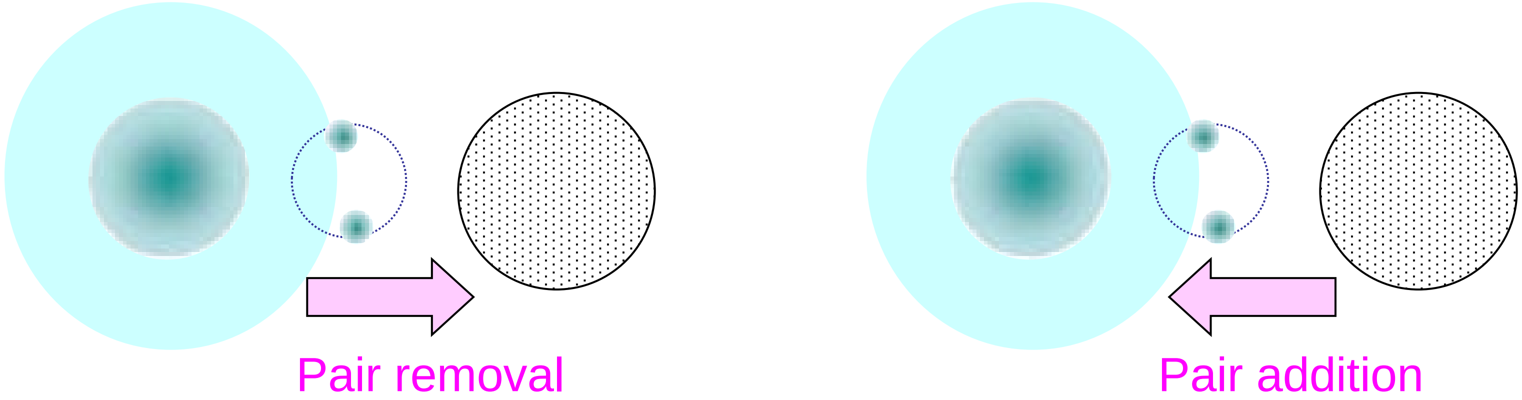
[1] Pillet, Sandulescu, Schuck, Berger, PRC81 (2010)

[2] Hagino et al J Phys.G37 (2010)

Question 2

How can we probe the features of the strong coupling pairing in the surface? the strong spatial correlation in the surface?

Pair transfers in neutron-rich nuclei

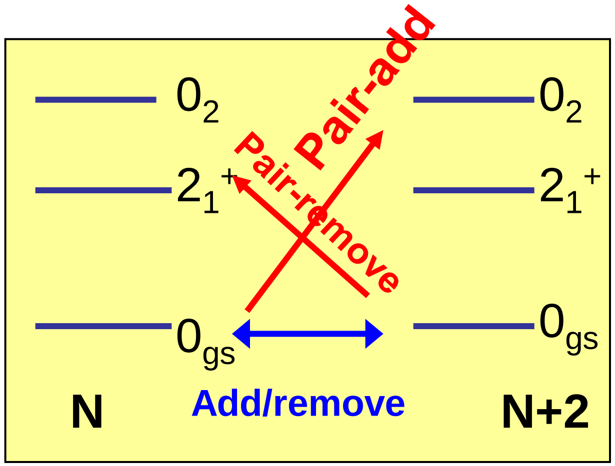


Pair transfer process, for Sn istopes, **132Sn~**

Anomalous 0+ state, **a new kind of pair vibration**

Pair correlation and pair transfer in heavier n-rich nuclei: Skyrme HFB + QRPA approach

Khan, Grasso, Margueron, PRC80, 044328 (2009)
Matsuo, Serizawa, arXiv:1007.1705
Shimoyama, Matsuo, in preparation



1. ground–ground pair transfer

0_{gs}-0_{gs} pair-add/remove transition density

Hartree-Fock-Bogoliubov mean-field calc.

$$\left\langle 0_{gs}, N \pm 2 \left| \psi^+(\vec{r}\uparrow)\psi^+(\vec{r}\downarrow) \right| 0_{gs}, N \right\rangle \approx \left\langle 0_{gs} \left| \psi^+(\vec{r}\uparrow)\psi^+(\vec{r}\downarrow) \right| 0_{gs} \right\rangle = \tilde{\rho}(\vec{r})$$

Pair density in the ground state

2. Pair transfer to excited 0^+,2^+ states

0_{gs}-2^+ pair-add transition density

$$\left\langle 2^+, N+2 \left| Y_{2M}\psi^+(\vec{r})\psi^+(\vec{r}) \right| 0_{gs}, N \right\rangle$$

0_{gs}-2^+ pair-remove transition density

$$\left\langle 2^+, N-2 \left| Y_{2M}\psi(\vec{r})\psi(\vec{r}) \right| 0_{gs}, N \right\rangle$$

QRPA calc. of excitation modes

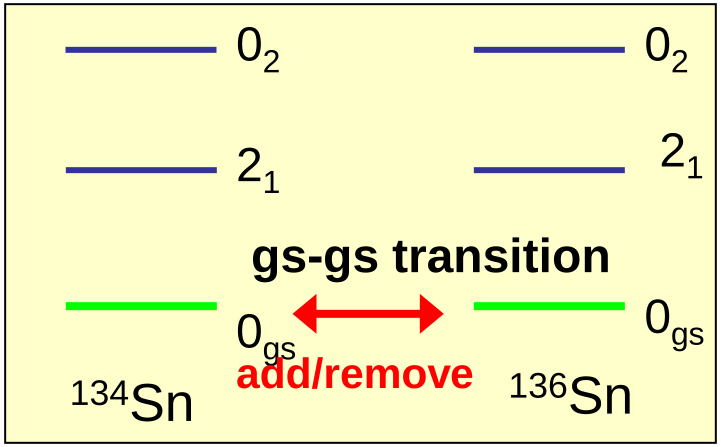
The same Skyrme, but Landau-Migdal approximation to residual ph int.

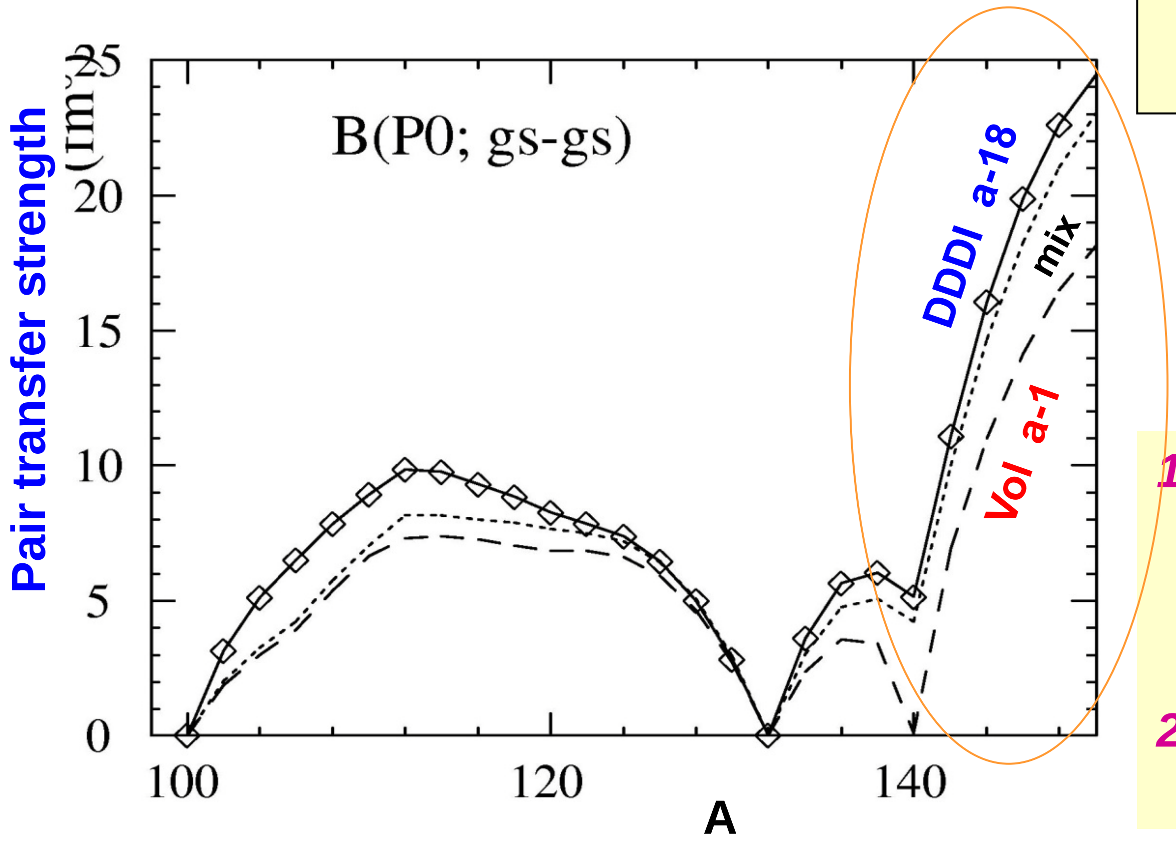
0_{gs}-0_{gs} pair transfer strength in $^{>132}$Sn

2n-add/removal transfer strength

$$B(\mathrm{P0}; 0_{gs} N \rightarrow 0_{gs} N \pm 2) = M_{gg}^2$$

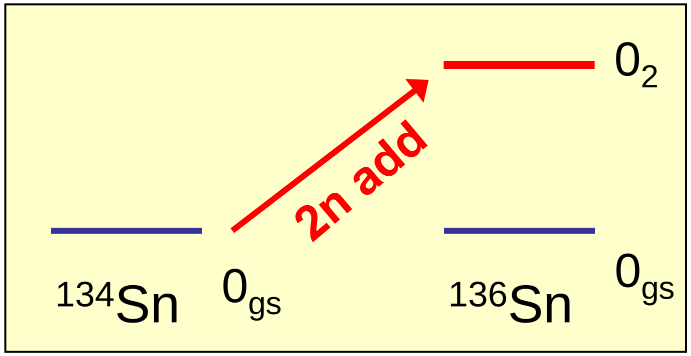
$$M_{gg} = \left\langle 0_{gs} \left| \int Y_{00} \psi^+(\vec{r}) \psi^+(\vec{r}) d\vec{r} \right| 0_{gs} \right\rangle = 4\pi \int \tilde{\rho}(\vec{r}) r^2 dr$$



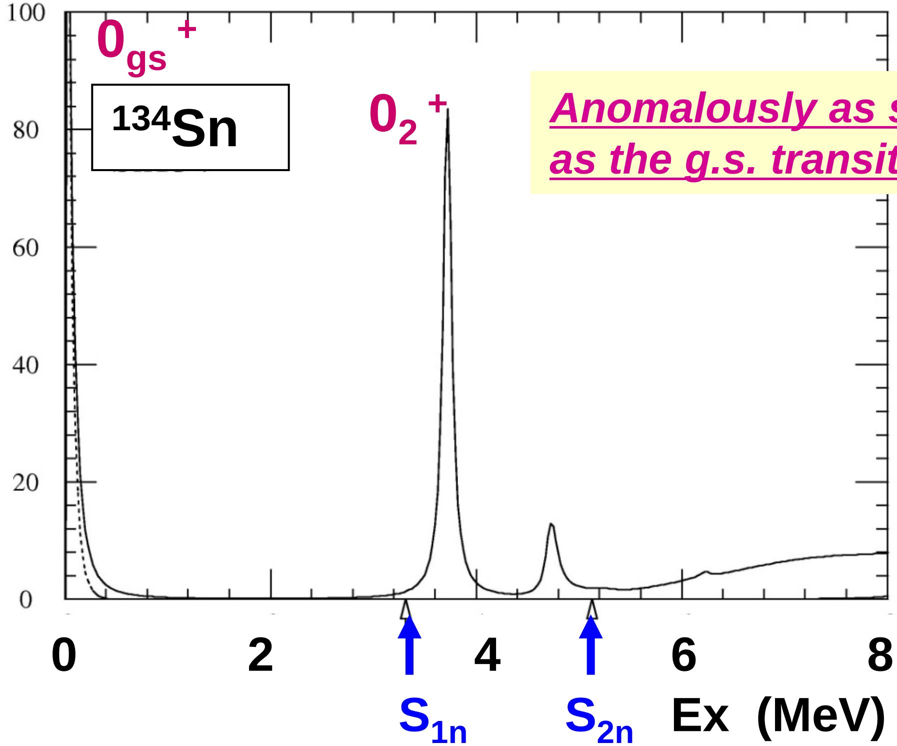


1. *Ground-ground 2n transfer is significantly increased in very n-rich isotopes($^{>140}$Sn)*
2. *Sensitivity to the correlation at R>Rsurf*

Anomalous 0_2^+ pair transfer in $^{132-140}Sn$

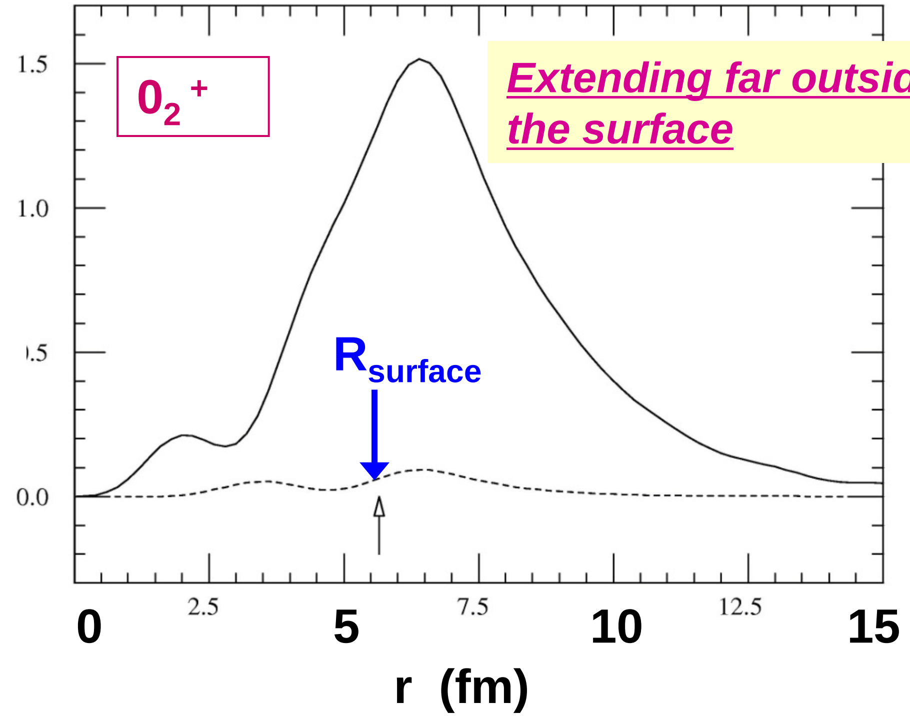


Pair-addition strength function



Anomalously as strong as the g.s. transition

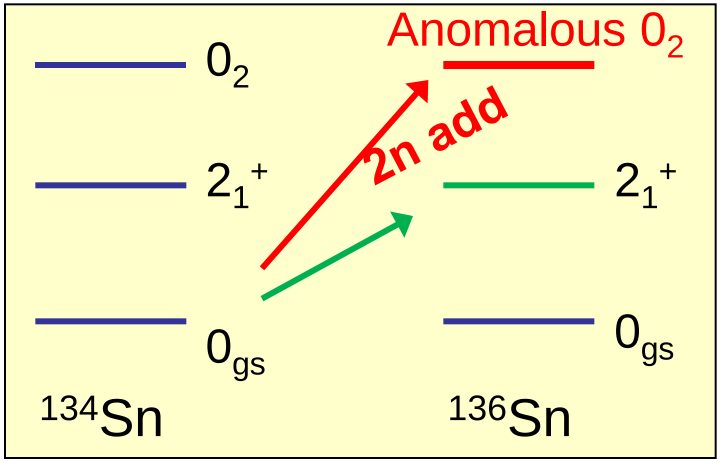
Pair-addition transition density

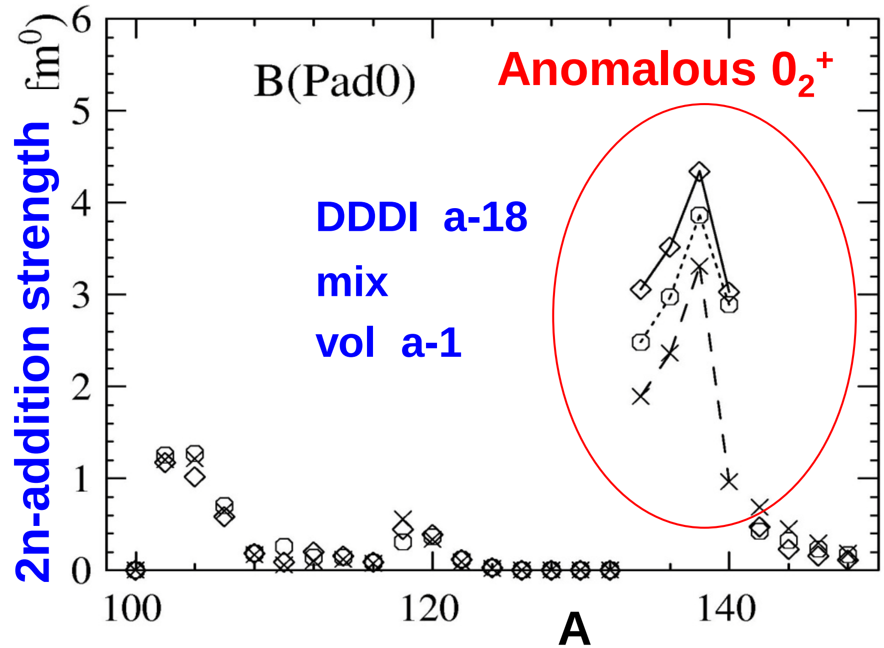


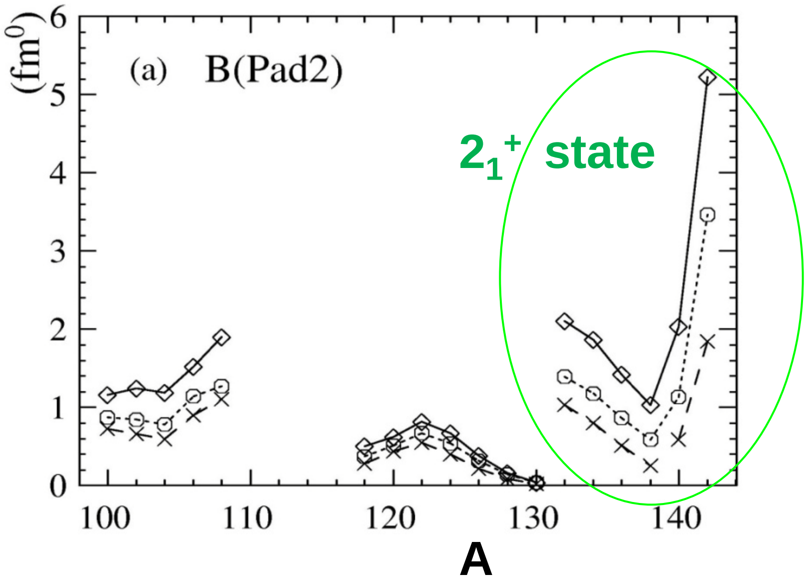
Extending far outside the surface

These features are very different from those of the pair vibration in stable nuclei

Pair-addition transfers to 0_2 and 2_1 states in $^{132\text{-}140}$Sn may provide probes





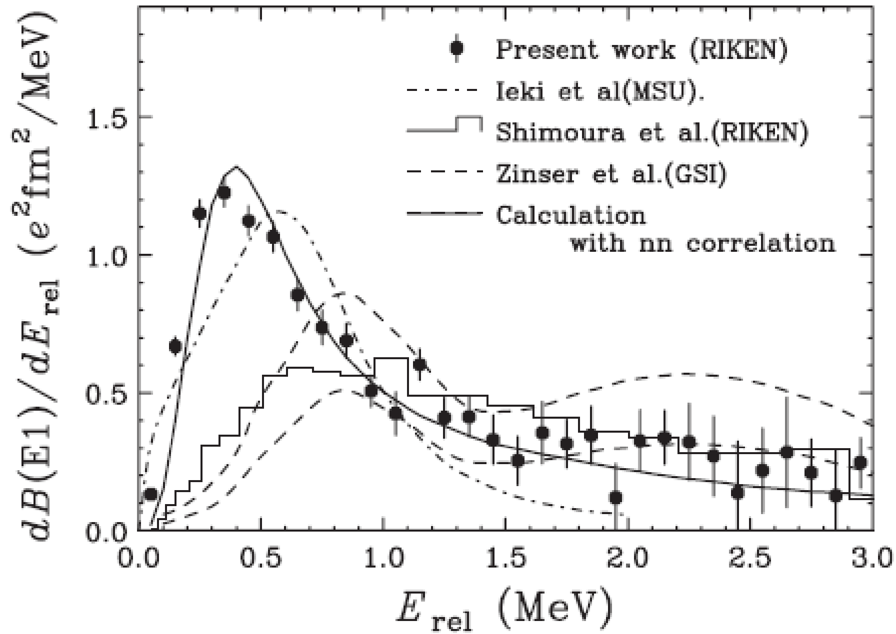


2n-add transfer to the anomalous 0+ and 2+ provides is sensitive to the surface correlation

Another probe?
Soft neutron modes above S_{2n}

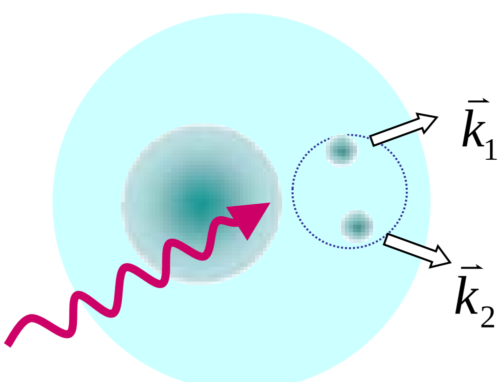
RIKEN exp. Nakamura et al.
PRL30,252502 (2006)

2n break-up through soft dipole excitation in nuclei near n-drip line



2n-halo nuclei

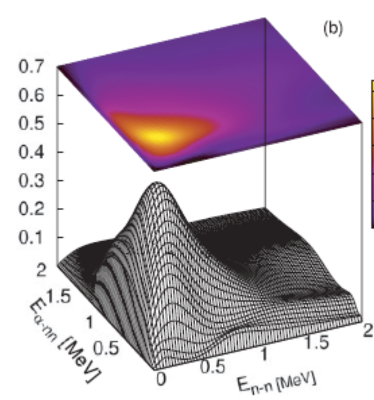
^{11}Li, ^{6}He, etc.



2n correlation ??

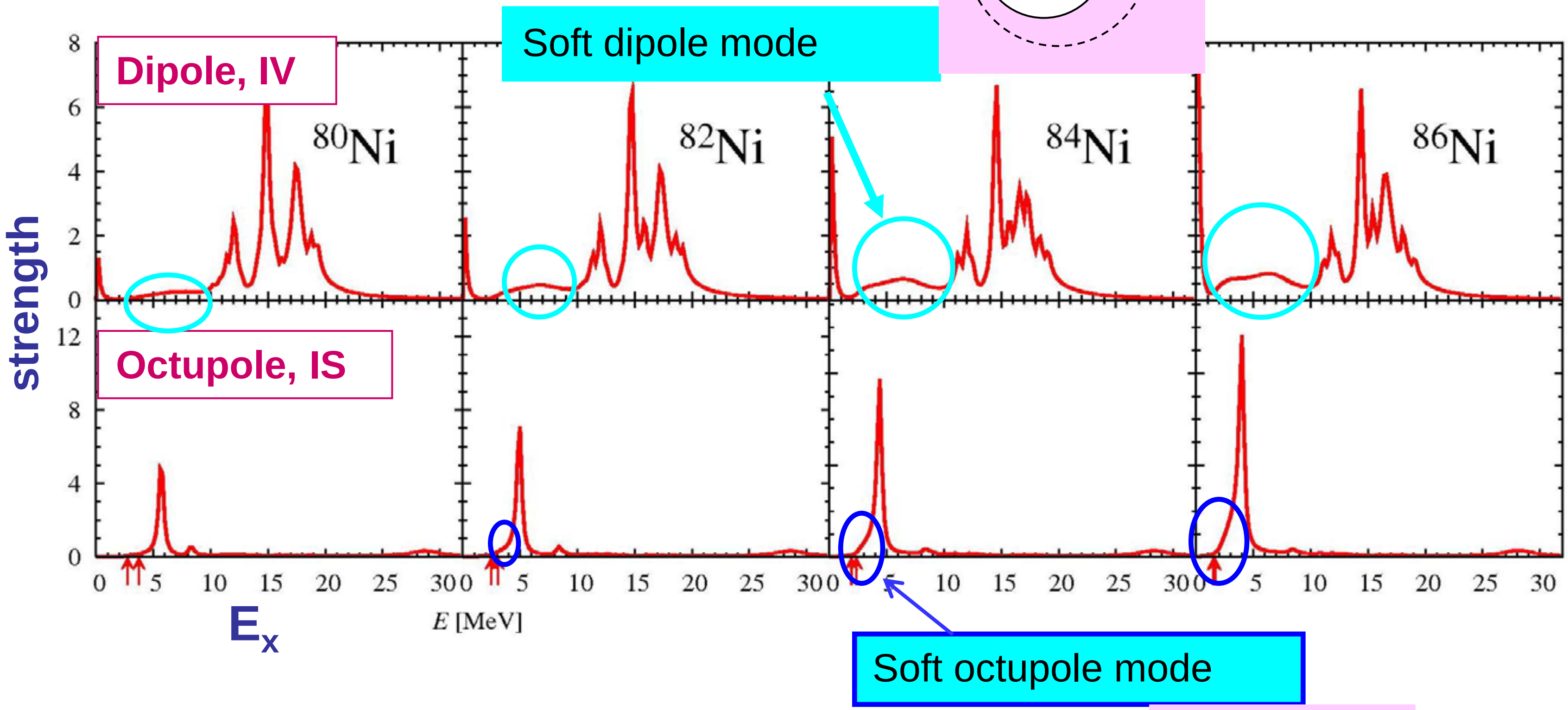
Hagino et al., PRC80, 031301 (2009)

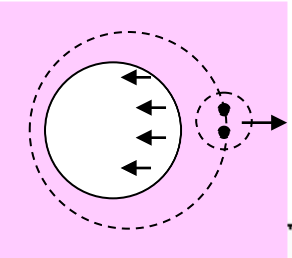
Kikuchi et al., PRC81, 044308 (2010)

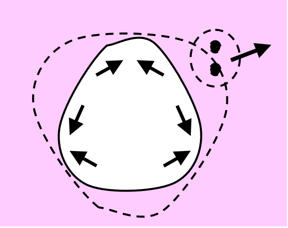


Soft neutron modes above S_{2n} in skin nuclei

S_{1n}~S_{2n} ~< 2-3 MeV







Continuum QRPA with SLy4 & mix pairing

Serizawa, Matsuo, PTP121 (2009)

Conclusions

- ***Pairing properties of dilute neutron matter*** are interesting.

- Neutron rich-nuclei appear to share those properties to some extent, especially in ***neutron correlations in the surface region***.

  Spatial correlation of Cooper pair at short distances,
  e.g. the pair contact probability.

- There exist a few ideas to probe them via neutron-rich nuclei.

  - ***Two neutron transfers*** in neutron-rich **$^{>132}$Sn** isotopes.
    - ***Anomalous 0_2^+ states*** in $^{134\text{--}140}$Sn.
    - ***2_1^+ states*** in $^{134\text{--}140\text{--}}$Sn.
    - ***Enhanced gs-gs transfer*** in $^{132\text{--}140\text{--}}$Sn.

  - 2n correlation in 2n break-up via soft modes → on the way

- ***We await experimental data***