Surface di-neutron modes in multipole responses of neutron-rich nuclei

M. Matsuo & Y. Serizawa (Niigata University)

New features of pair correlation in n-rich nuclei

Strong vs. weak coupling pairing: BCS-BEC crossover

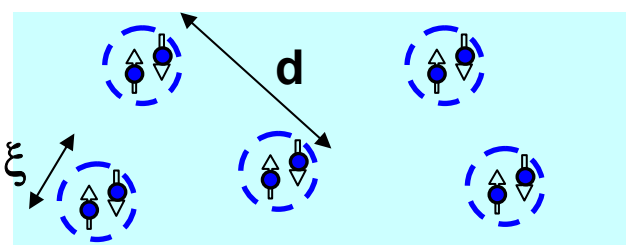
Leggett 1980, Nozieres & Schmitt-Rink 1985

BEC

Interaction: **Strong**

In free space: **Bound pair (boson) is already formed**

In medium: **Bound pairs (bosons) condensate**



$\xi/d \ll 1$, $\Delta/e_F > 1$

Crossover

Scattering length

$a \approx \pm\infty$

Δ/e_F

1.3 ~ 0.2

ξ/d

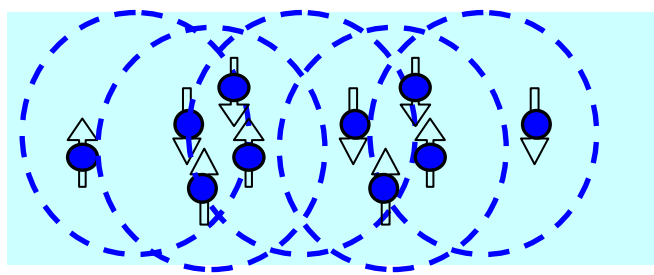
0.2 ~ 1.10

BCS

Interaction: **Weak**

In free space: **No bound pair is formed**

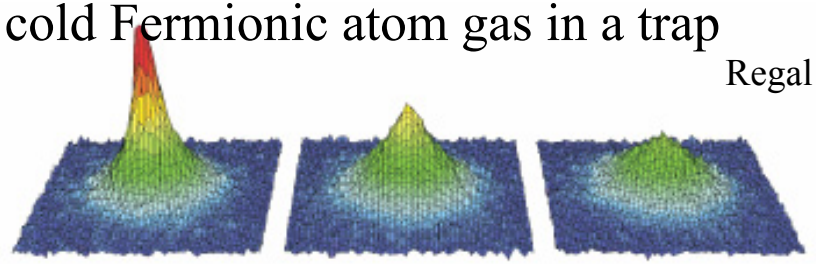
In medium: **Bound pairs (Cooper pairs) are formed, then condensate**



$\xi/d > 1$, $\Delta/e_F \ll 1$

Observed in ultra cold Fermionic atom gas in a trap

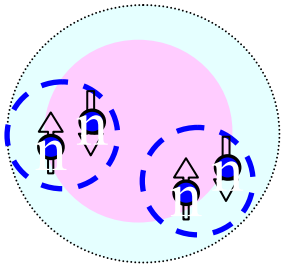
Regal et at. PRL 92(2004)040403



Di-neutron correlation as a possible signature of strong coupling pairing

Di-neutron correlation

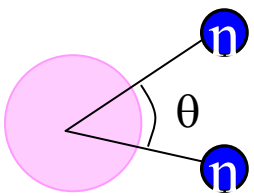
Spatially compact pair in nuclei



2n halo nuclei, eg. 11Li

Many predictions since 1990

New Coulomb break-up exp. on 11Li at RIKEN Nakamura et al. PRL30,252502 (2006)

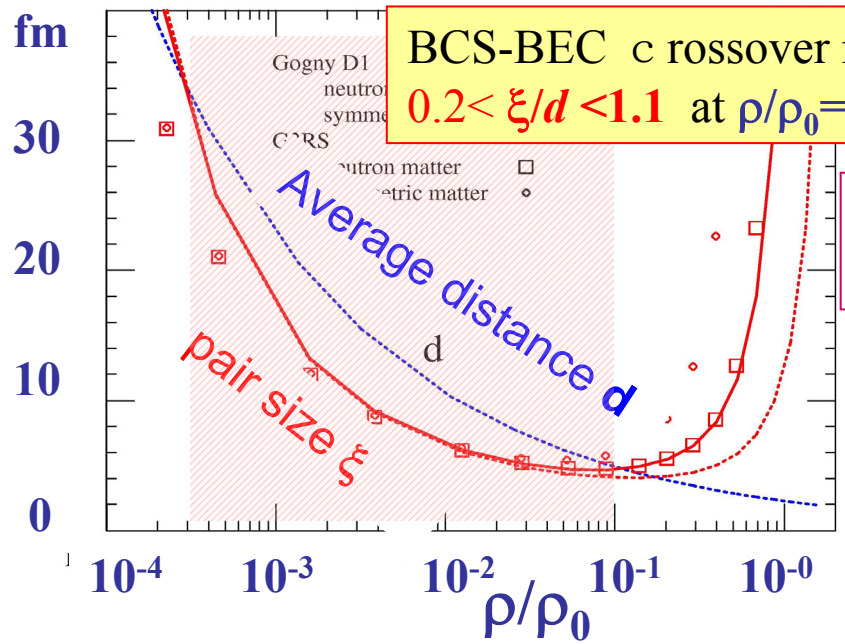


$\theta_{nn}=48^{+14}_{-18}$ deg

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

Low-density neutron/nuclear matter

Matsuo PRC73,044309(2006)



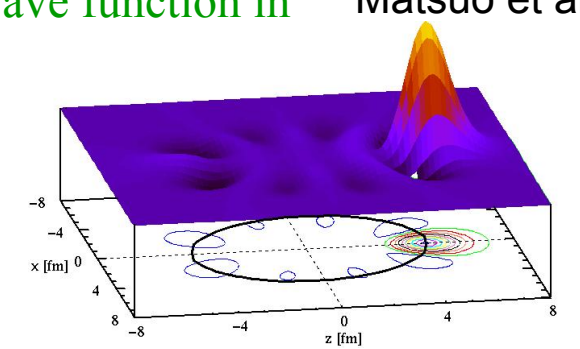
BCS-BEC crossover region
$0.2< \xi/d <1.1$ at $\rho/\rho_0=10^{-1}$-10^{-4}

BCS using a bare force

Medium-mass n-rich nuclei (skin nuclei)

pair wave function in 84Ni

Matsuo et al PRC71,064326(2005)

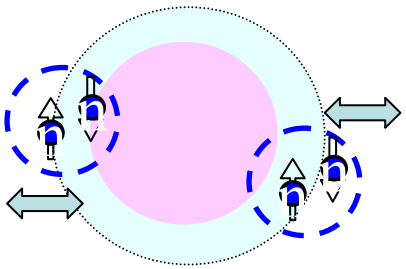


Skyrme HFB calc. (SLy4 + DDDI)

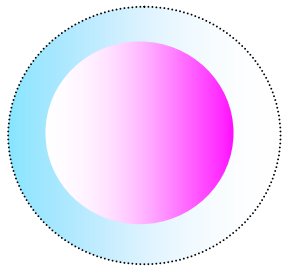
Elementary modes of excitation in systems with strong pairing

There will be new types of collective excitation arising from the “strong” pairing in n-rich nuclei.

•Motion of di-neutrons??



•Motion as a macroscopic superfluid ??



•Giant resonances?

•Low-lying surface vibrations?

Let us first visit *a paradise* to get inspirations.

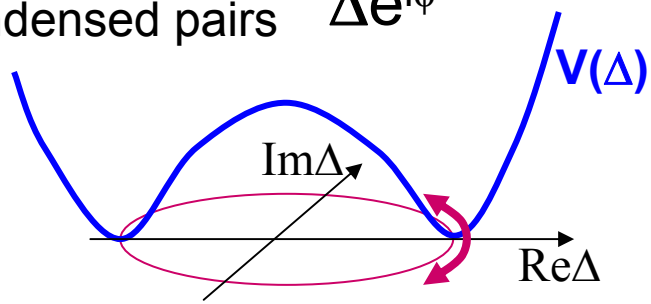
What happens? if the pairing correlation were extremely strong.

Then return to *the real life*.

How collective excitations evolve with the pairing interaction ?

Hydrodynamic mode in superfluid: Anderson-Bogliubov (AB) pairing mode

Phase degeneracy in condensed pairs $\Delta e^{i\phi}$



Phase oscillation with small energy

⇔ Density fluctuation of superfluid (k>0)

hydrodynamic phonon

In uniform case

Anderson 1958, Bogoliubov 1958

Phonon dispersion

$\omega = ck$ but $\omega < 2\Delta$, $k < 1/\xi$

strong pairing is favored

Sound velocity

$c < v_F / 3^{1/2}$

Classical, not zero sound

In trapped atoms

Baranov-Petrov 2000, Bruun-Mottelson 2001

L=1 Dipole

$\omega = \omega_{h.o}$ c.m. motion

L=2 Qudrupole

Phonon at strong pairing,

$\omega = 2^{1/2}\, \omega_{h.o}$

Phonon at moderate pairing,

- low-lying 2^+ (precursor of AB)
- high-lying 2^+ (like GR)

In nuclei

L=0 Pairing modes

- **pair rotation (AB zero mode)**
- pair vibration

Pairing modes with L=1 ? L=2 ?

AB mode with finite wave length?

soft dipole mode?

GDRs ? low-lying 2^+

Role of isospin (n & p)

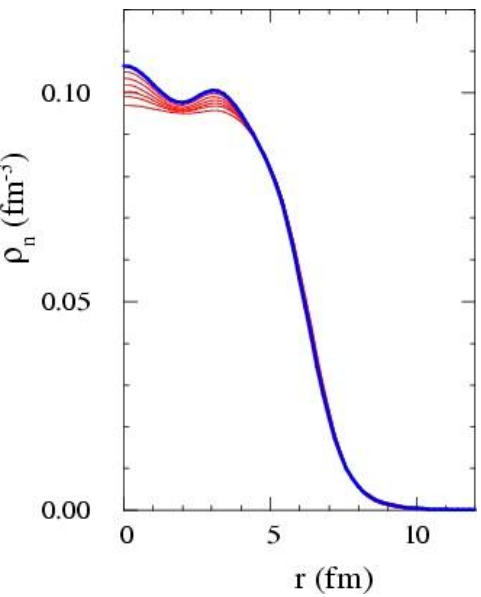
Role of shallow Fermi energy

Scheme of analysis

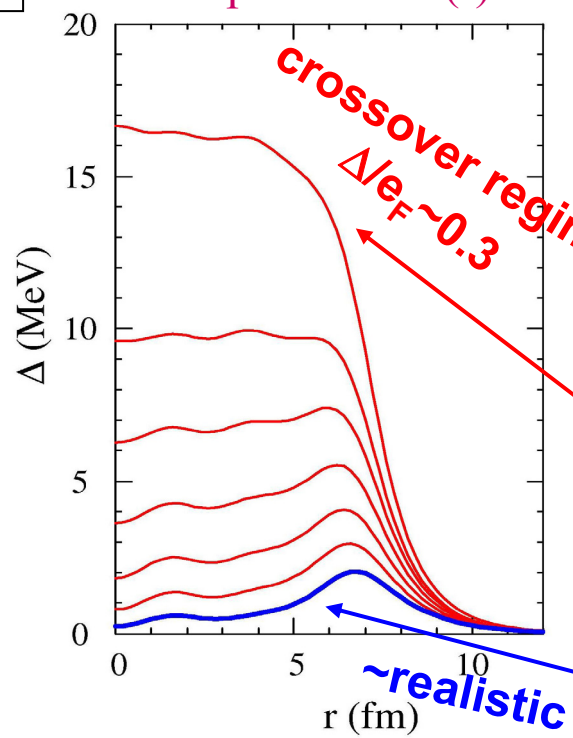
1. **Skyrme-HFB + Continuum QRPA:** **HFB/QRPA can describe the crossover and even the BEC**
2. We choose ^{120}Sn (S_n ~ 8 MeV) & ^{158}Sn (S_n ~ 1 MeV)
3. Functional/interaction: (ph) SLy4 + Landau-Migdal approx. & (pp) DDDI
4. We artificially vary the force parameters of the effective pairing interaction DDDI

^{120}Sn

Neutron density ρ(r)



Neutron pair field Δ(r)



$$V_{pair,n}(\vec{r},\vec{r}\,') = V_n[\rho_n]\delta(\vec{r}-\vec{r}\,')$$

$$V_n[\rho_n] = V_0\left(1-\eta\left(\rho_n(\vec{r})/0.08\right)^{0.59}\right)$$

$^1S_0$ scattering length a=-18fm

→ V_0=-458MeVfm^3 (Ecut=60MeV)

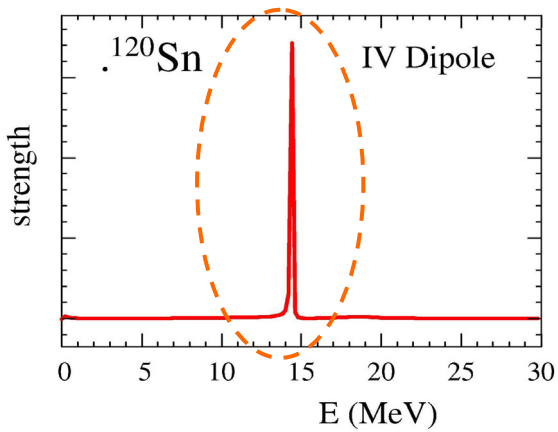
density dependence parameter

η=0	**Δ~ 15 MeV**
η=0.3	Δ~6-8 MeV
η=0.5	Δ~2-4 MeV
η=0.71	Reproduce Δ_{Sn}**~1.2MeV**
η=0.84	Reproduce $\Delta_{matter}^{\text{bare-force}}$

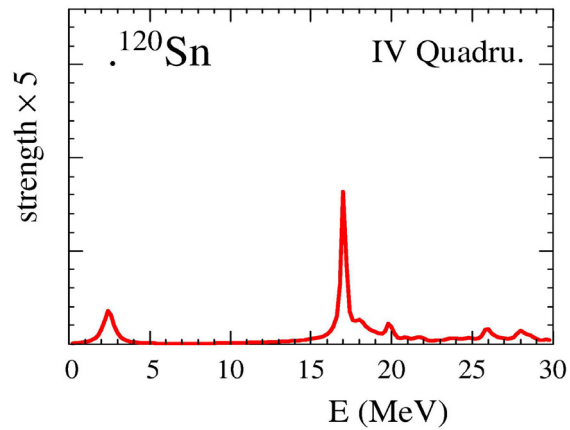
Multipole responses in "^{120}Sn" strong pairing Δ~15MeV

Isovector

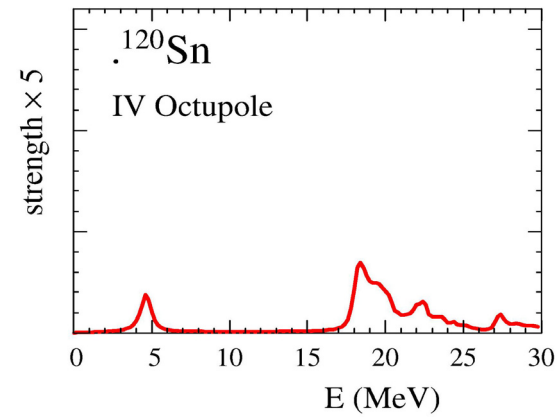
Dipole 1^-



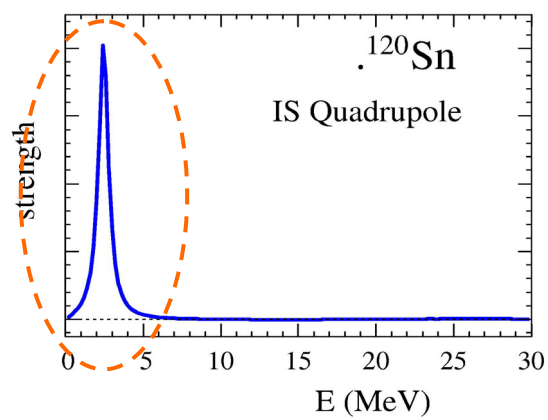
Quadrupole 2^+

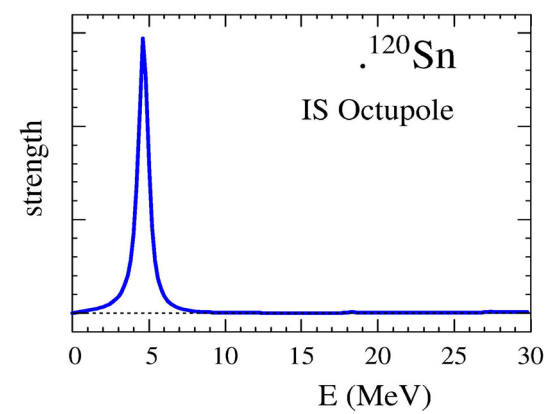


Octupole 3^-



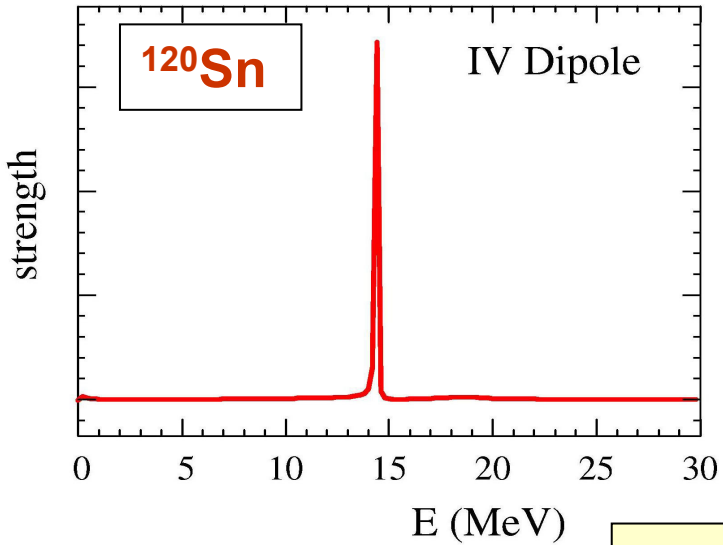
Isoscalar



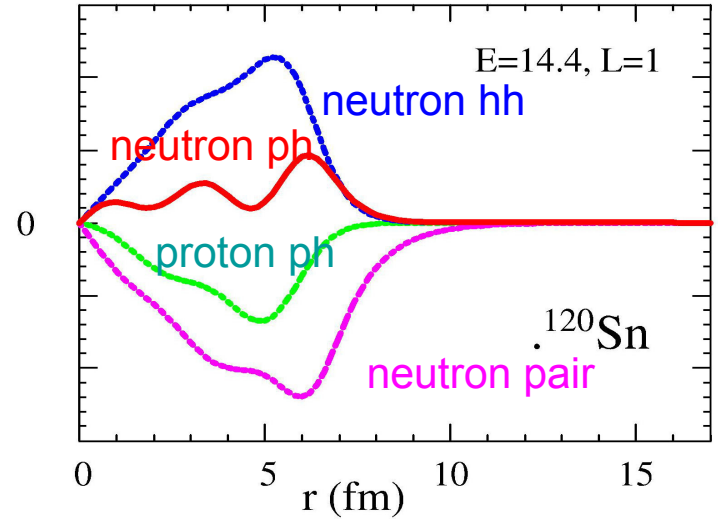


"^{120}Sn" with strong pairing: Isovector Anderson-Bogoliubov mode L=1,2,(3)

IV dipole strength



Tansition densities



Strong pairing Δ~15 MeV

Dominant particle pair (pp) and hole pair (hh) density

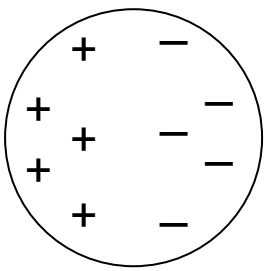
$\delta\langle\psi^*\psi^*(r)\rangle \sim -\delta\langle\psi\psi(r)\rangle \sim j_l(kr)$

opposite sign ← phase oscillation

Particle-hole density

$\delta\rho(r) \sim j_l(kr)$

Bessel form ← fluid dynamical phonon mode



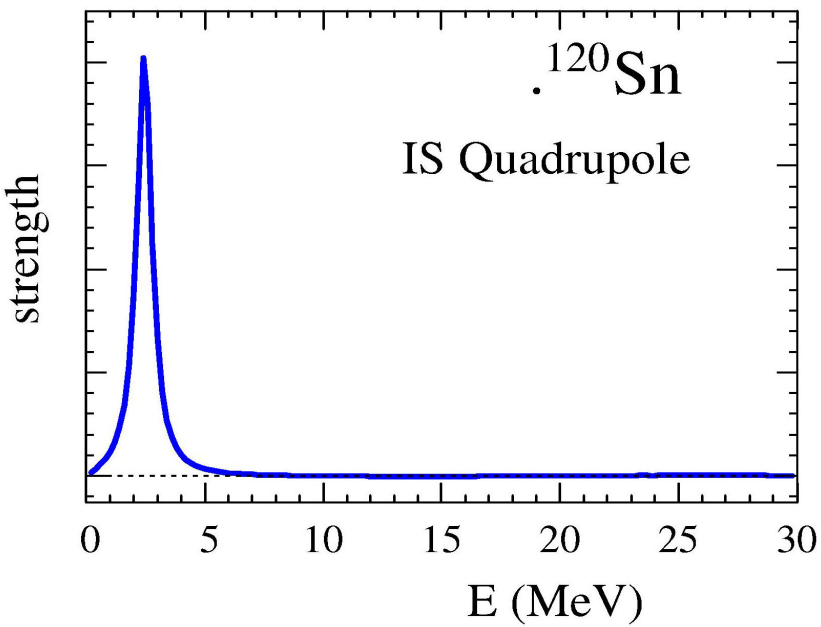
Anderson-Bogoliubov phonon mode with IV character

Volume type density fluctuation

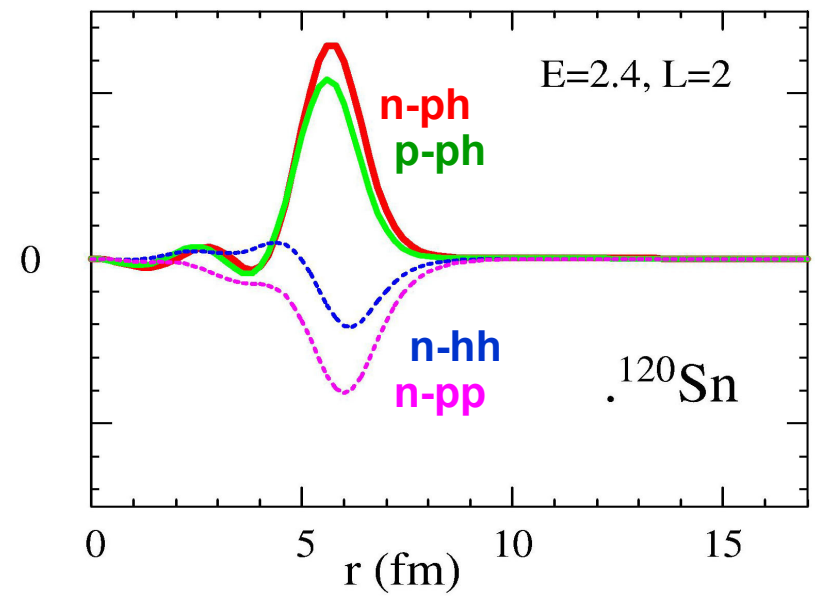
Steinwedel-Jensen mode

"^{120}Sn" with strong pairing: Isoscalar liquid drop mode; L=2,3,..

IS quadrupole strength



Tansition densities



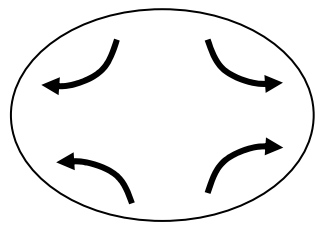
- Single mode exhausts EWSR
- scaling $\delta\rho \sim d\rho/dr$

⇨ **Irrotational and incompressible hydrodynamics = Tassie flow**

- Energy is low

⇨ not giant resonances (zero sound),

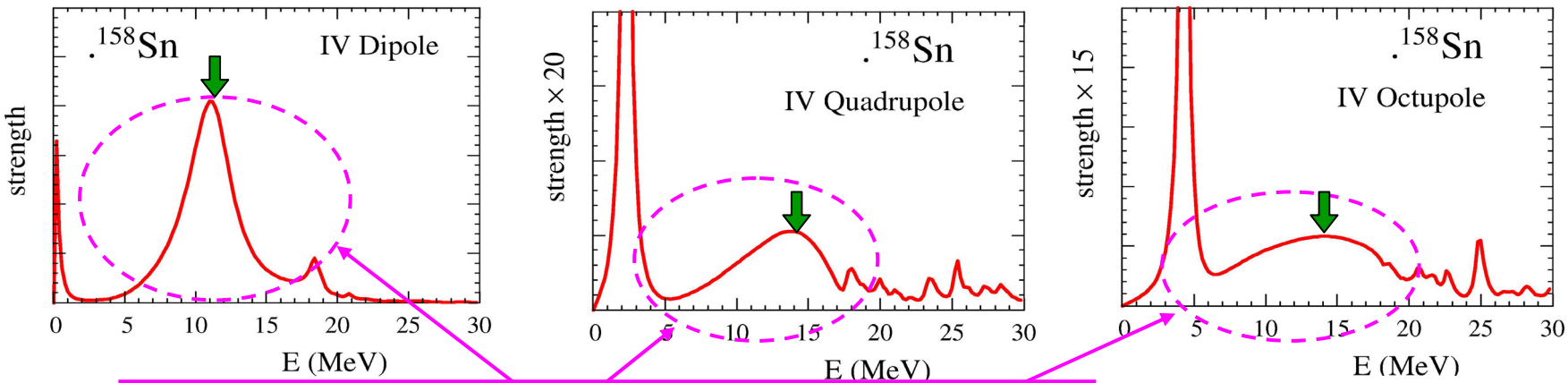
more like liquid drop (first sound)



Multipole response in near-drip-line nucleus "^{158}Sn" strong pairing Δ~15MeV

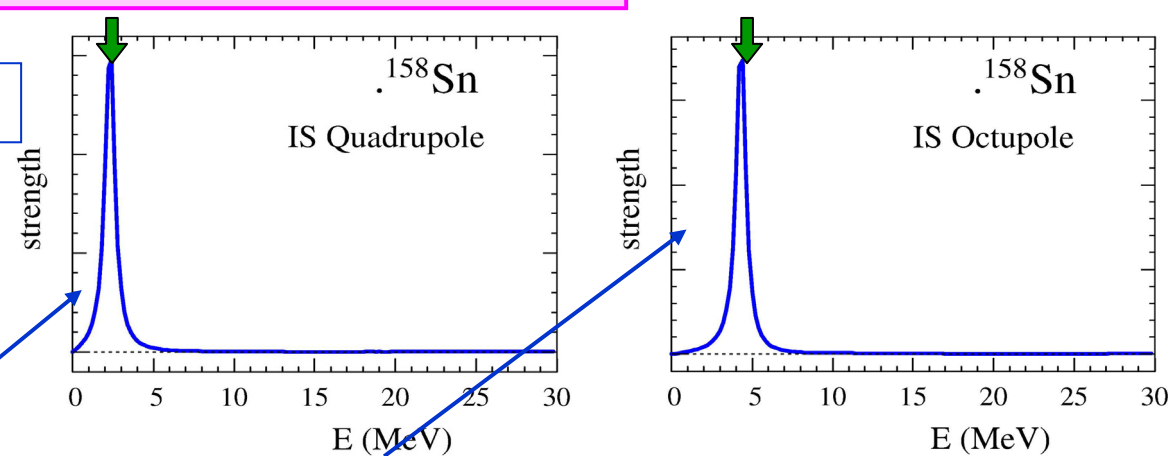
Isovector

Dipole 1^- | Quadrupole 2^+ | Octupole 3^-



Significant influence of weak binding of neutrons

Isoscalar

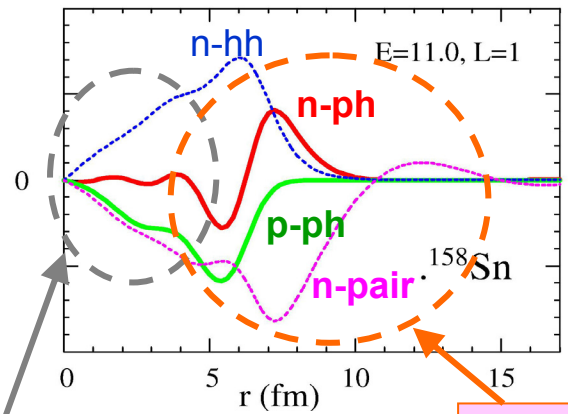


Liquid drop Tassie mode likewise in ^{120}Sn

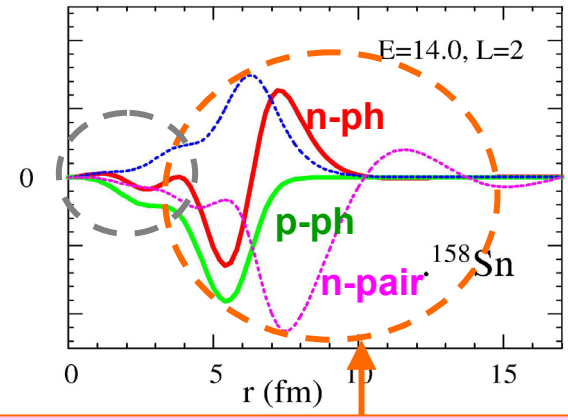
Transition densities in IV/IS modes in "^{158}Sn" strong pairing Δ~15MeV

Isovector

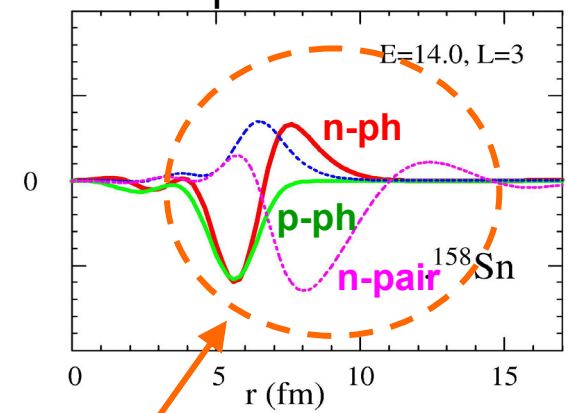
Dipole 1^-



Quadrupole 2^+



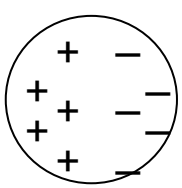
Octupole 3^-

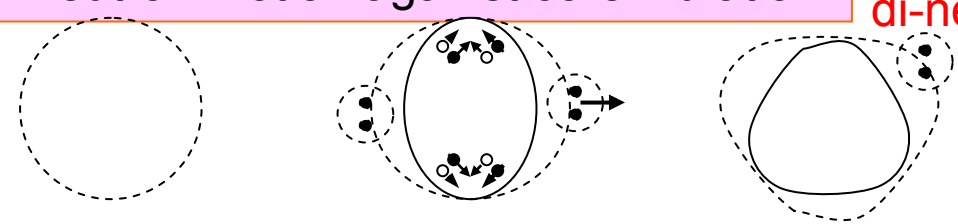


AB-phonon (SJ-phonon) in the nuclear volume

Surface di-neutron motion against core vibration

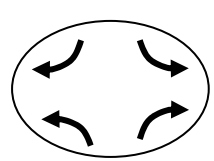
Emission of di-neutron

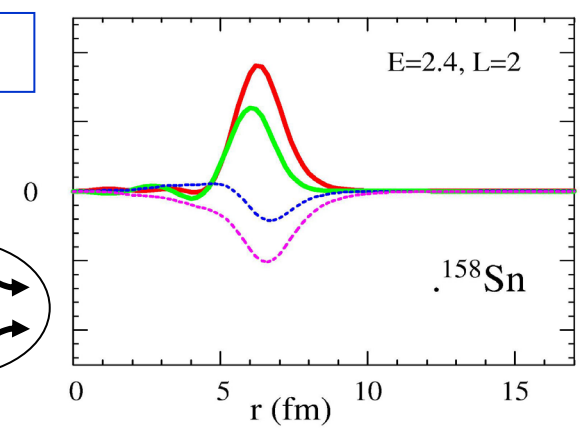


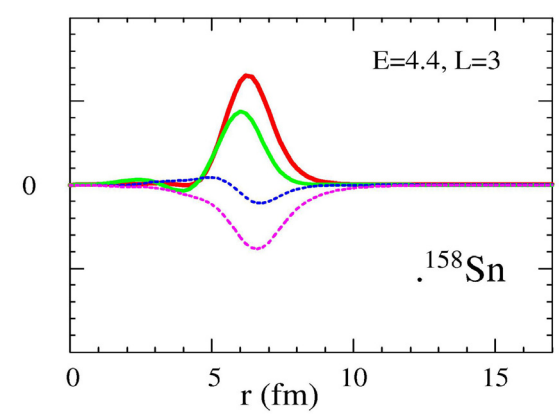


Isoscalar

Liquid drop
Tassie mode



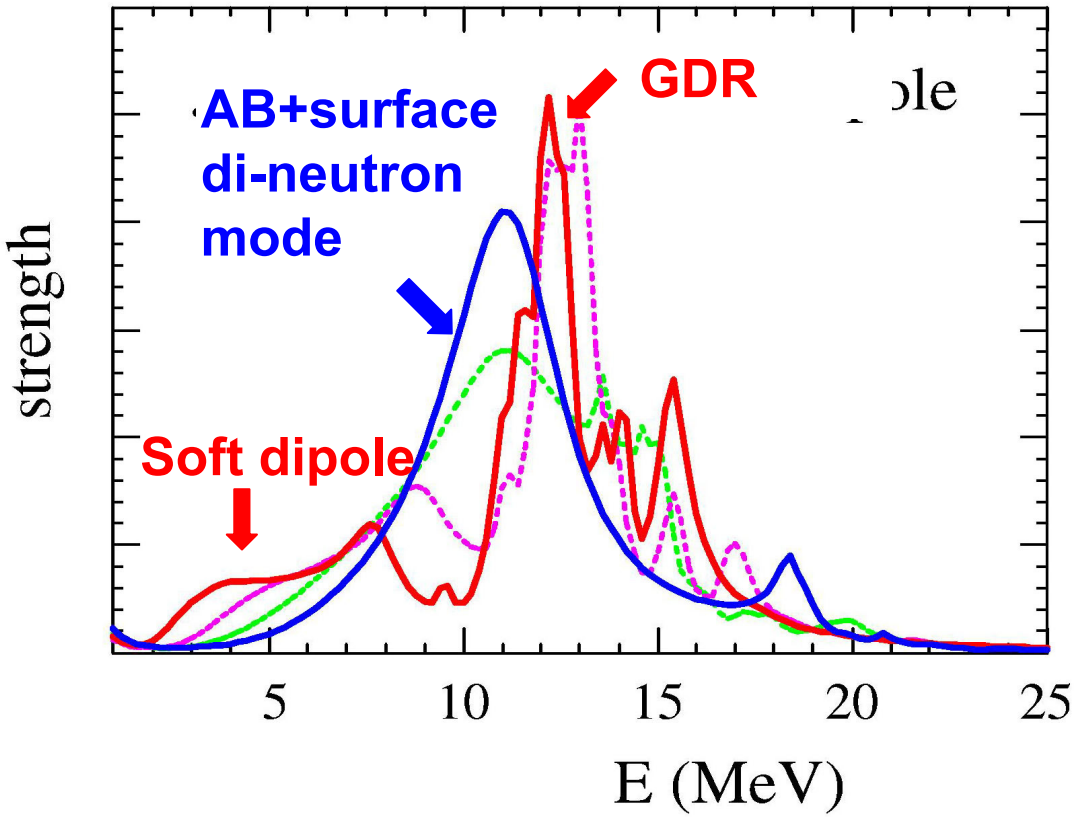




Evolution with pairing: Near-Drip-Line Nucleus ^{158}Sn

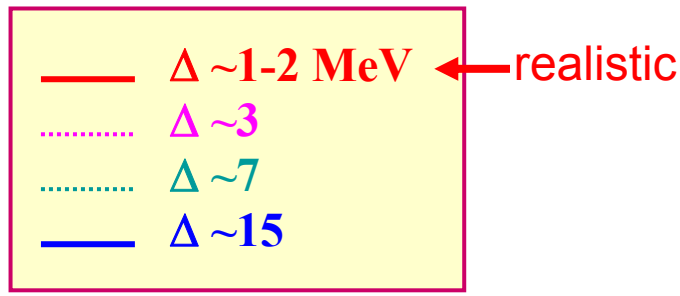
^{158}Sn

E1 strength distribution

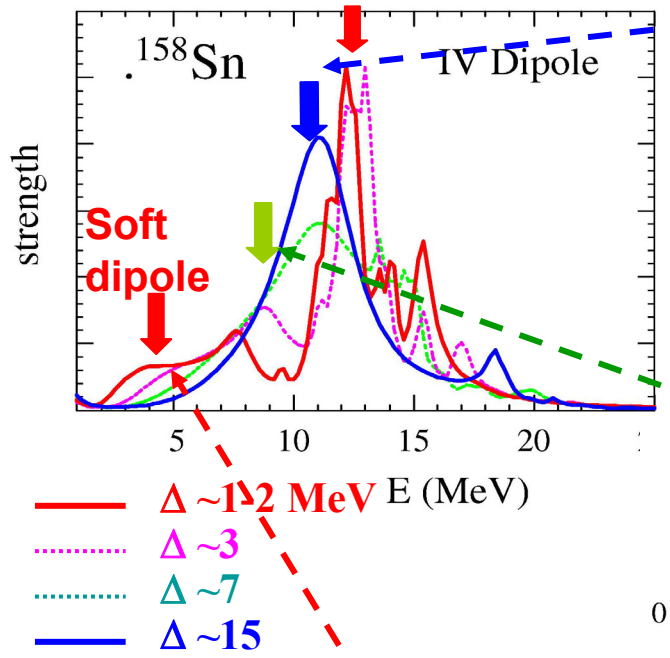


The dipole response varies with the pairing strength.

How ?

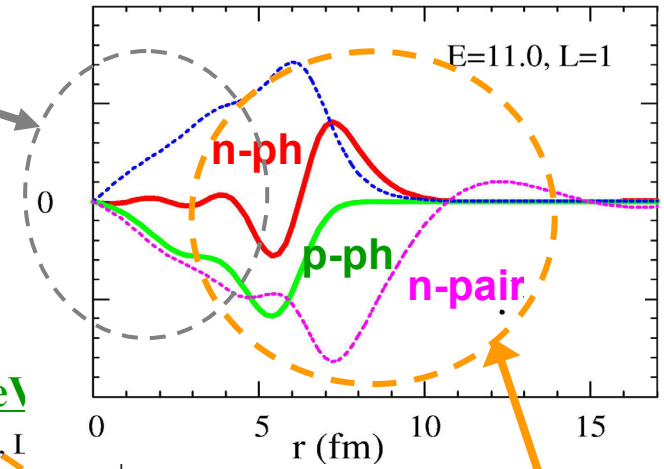


Soft dipole as surface di-neutron mode

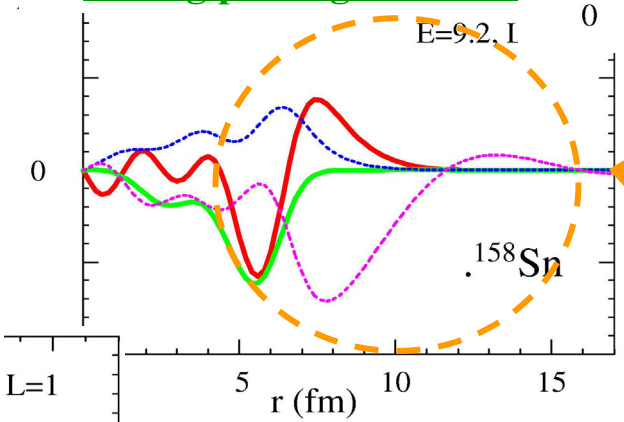


unitarity pairing Δ~15 MeV

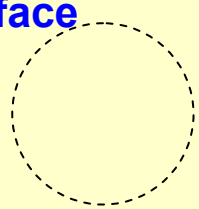
AB-phonon in the nuclear volume



Strong pairing Δ~7 MeV

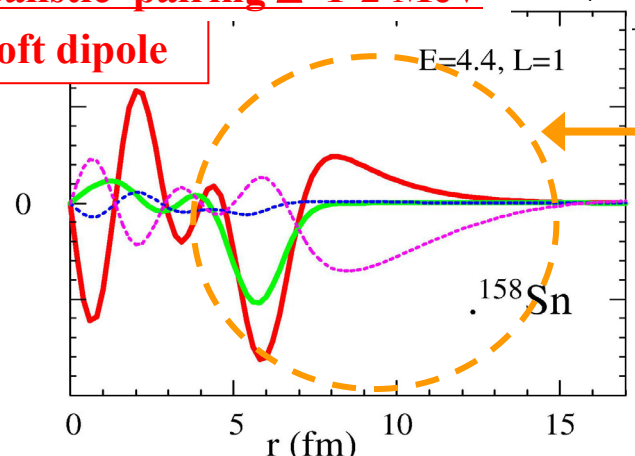


core-vs-di-neutron collective mode at surface



realistic pairing Δ~1-2 MeV

Soft dipole



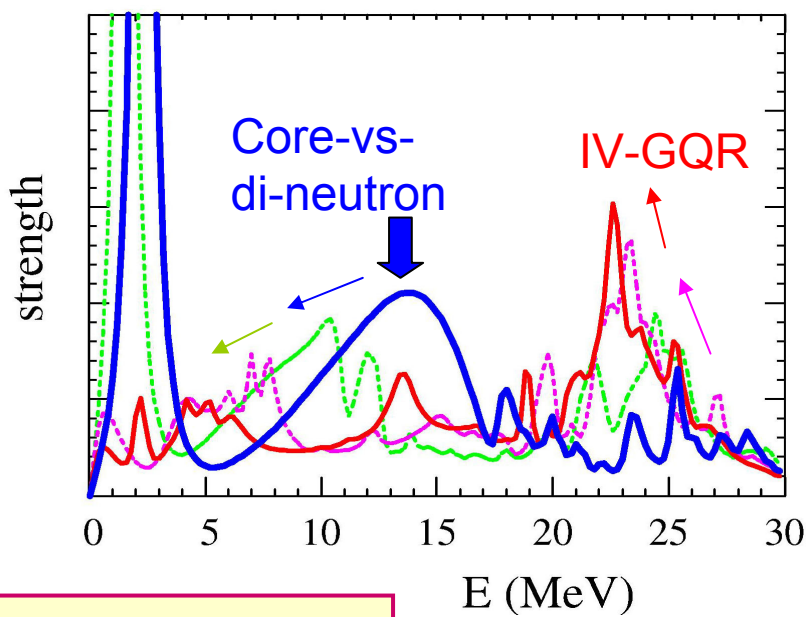
It persists down to the normal pairing case.

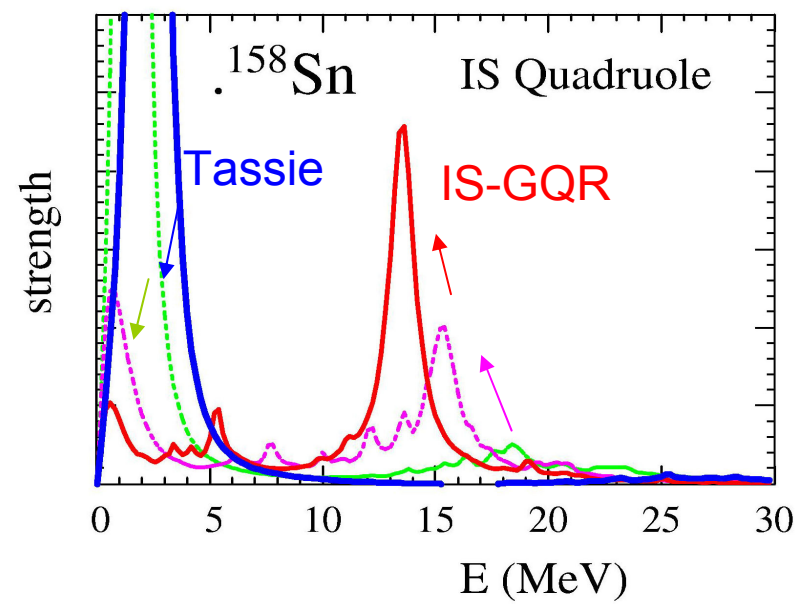
This is because the pairing is naturally strong in the external low-density region

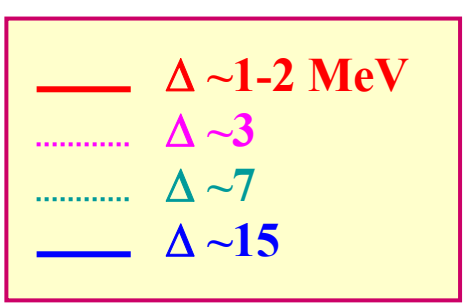
Absence of surface di-neutron mode in L=2 response

Decreasing the pairing gap down to the realistic value

- **The surface di-neutron mode with L=2 disappears at the realistic pairing.**
- **The liquid-drop Tassie mode resolves into low-lying 2+ and ISGQR. The IVGQR emerges**





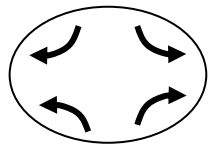


Different from the L=1 response due to shell effects

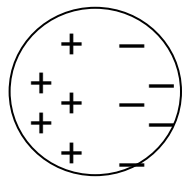
Conclusions

Three collective modes in “superfluid” nuclei in the unitarity regime

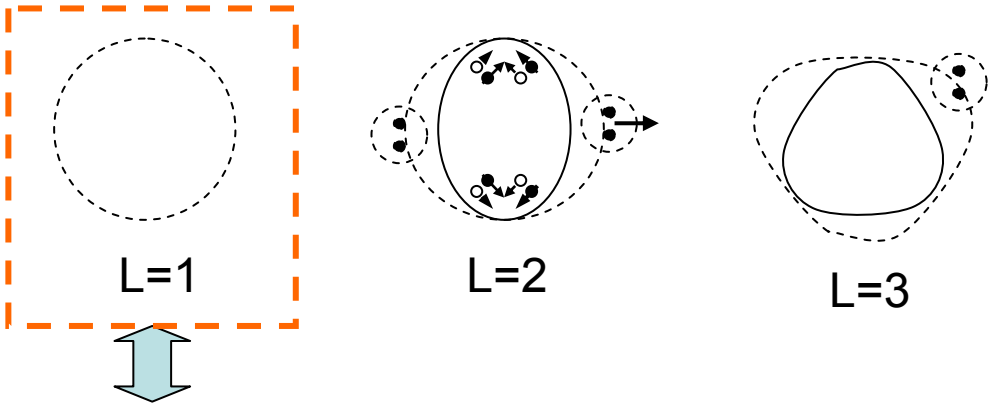
1. Isocalar liquid drop modes L=2,3, … :
   =Tassie modes



2. Isovector Anderson-Bogoliubov hydrodynamic modes L=1,2,… :
   =Steinwedel-Jensen modes.



3. Core-vs-di-neutron surface mode: in nuclei near drip-line



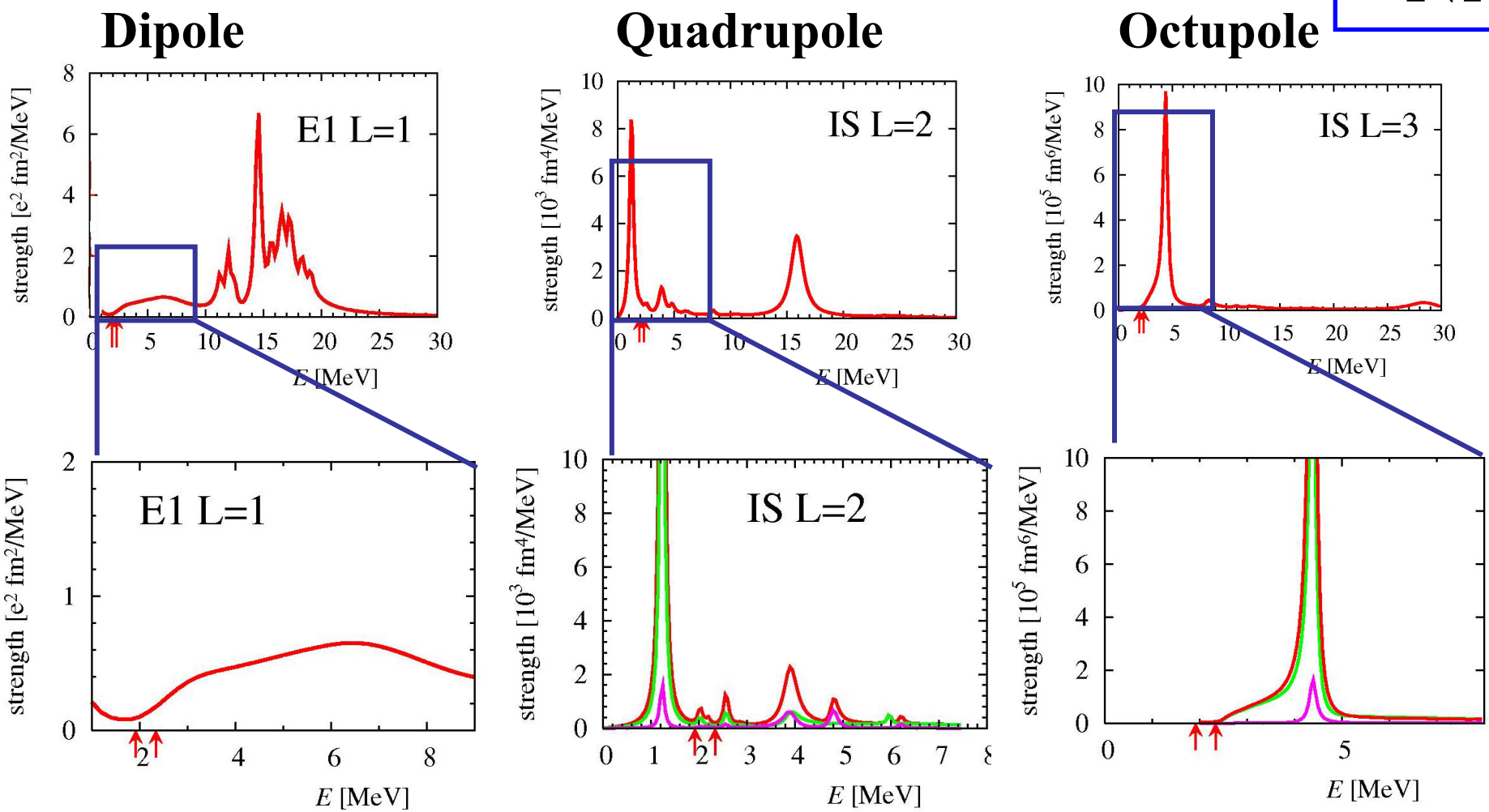
L=1 mode survives in the realistic pairing case, as the soft dipole excitation in nuclei near the neutron drip line. (Cf. Also L=3, but not L=2)

Multipole responses in ^{84}Ni

Skyrme-HFB + Continuum QRPA calc.
with SLy4 (Landau-Migdal approx) & mix-type DDDI

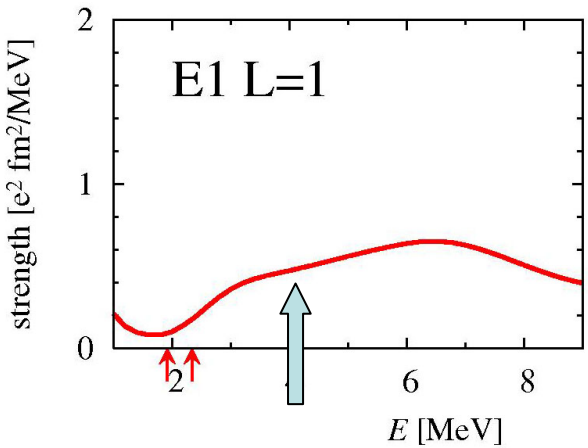
^{84}Ni

Multipole strength function

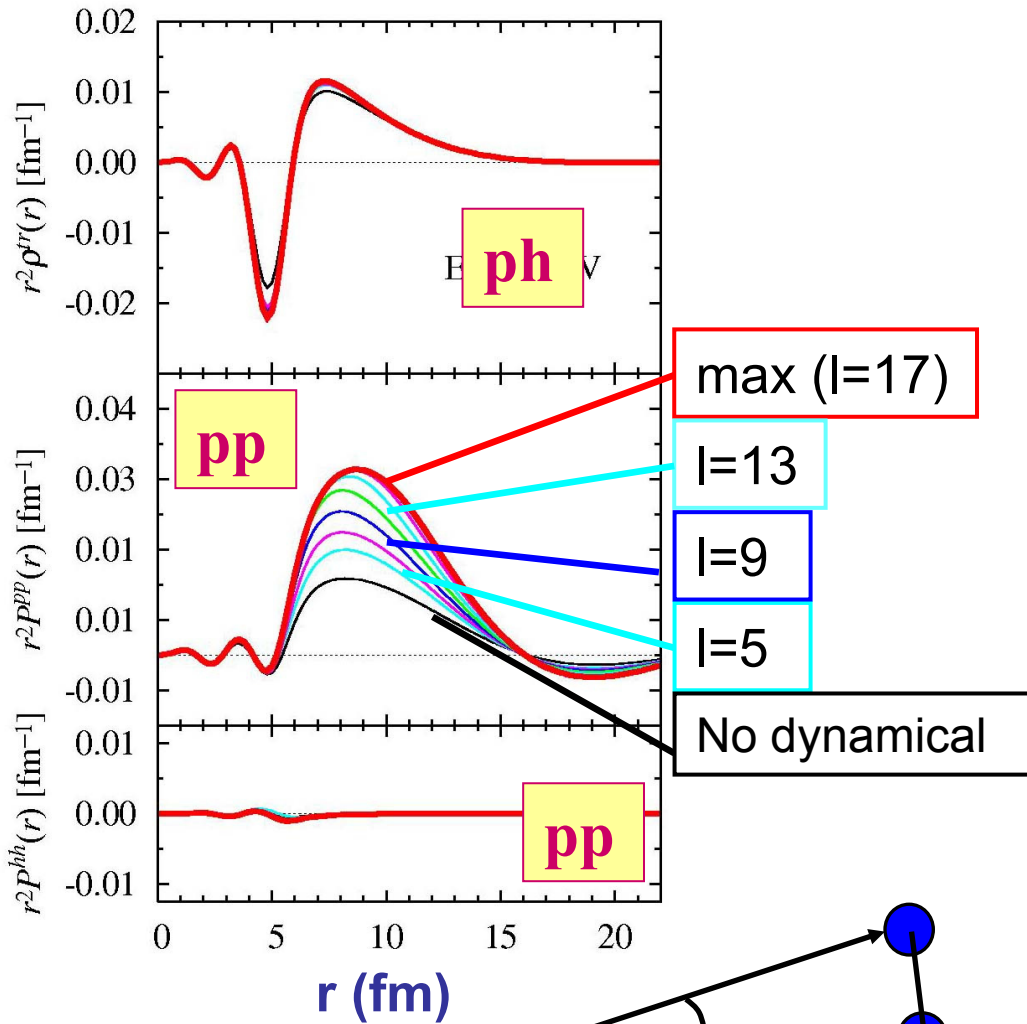


^{84}Ni Soft dipole : Surface di-neutron mode

Strength function



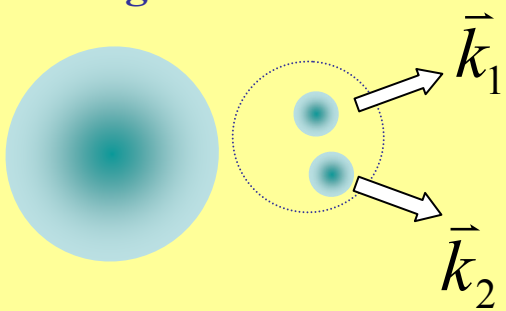
Neutron transition densities @ E=4.0MeV

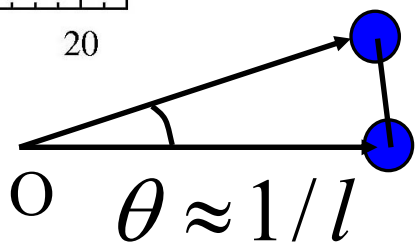


Emission of di-neutrons

pp ≫ ph, hh

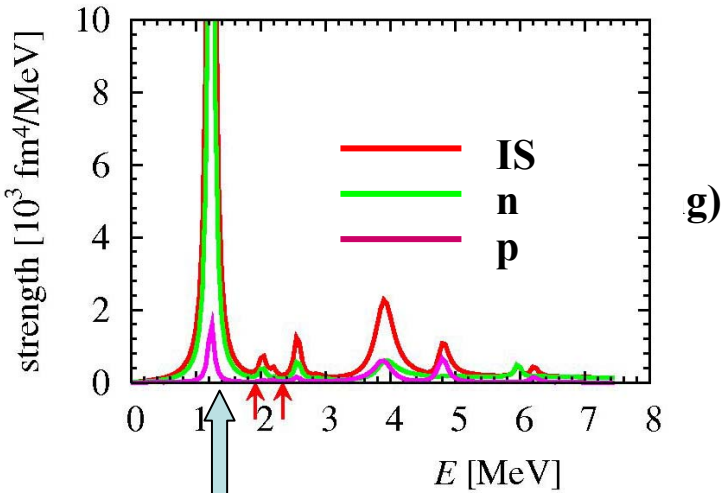
High-L orbits





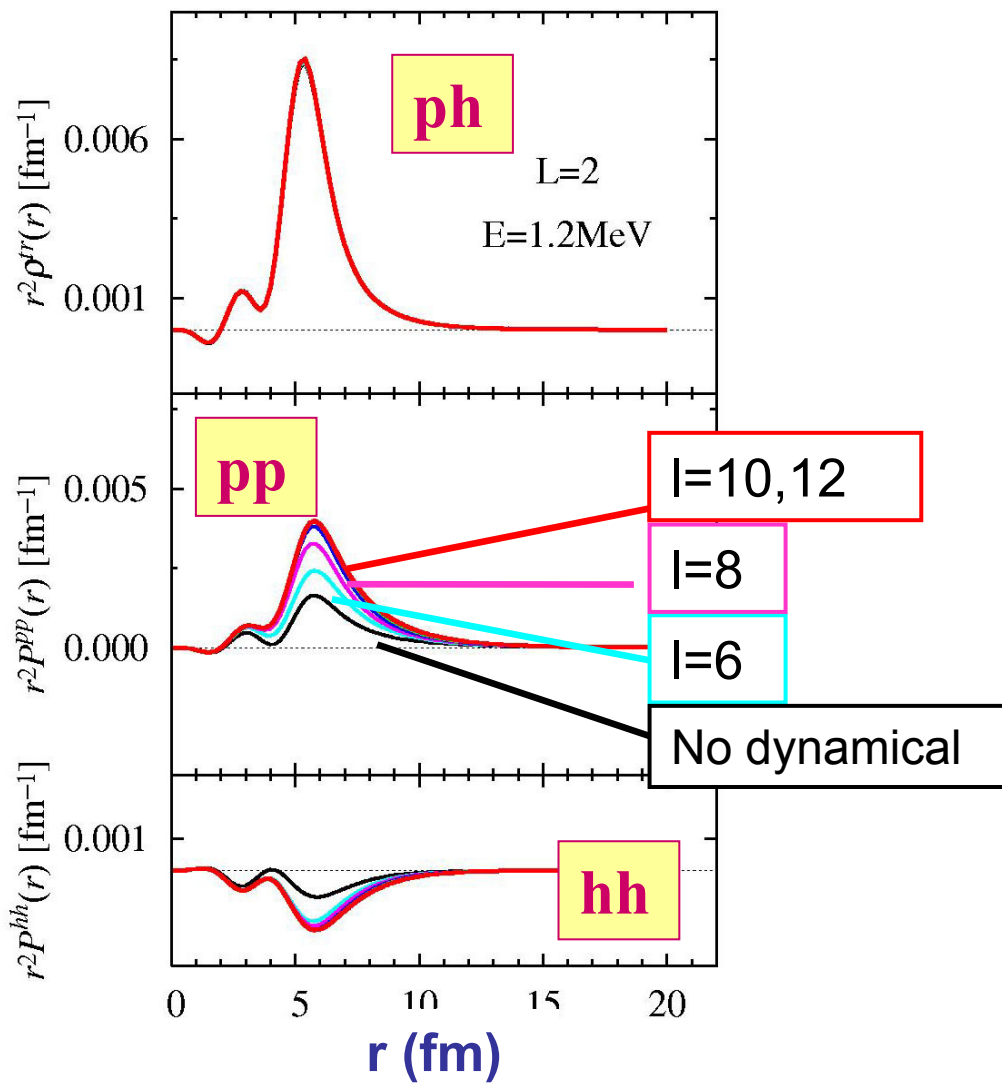
^{84}Ni low-lying 2^+ : surface vibration

Strength function



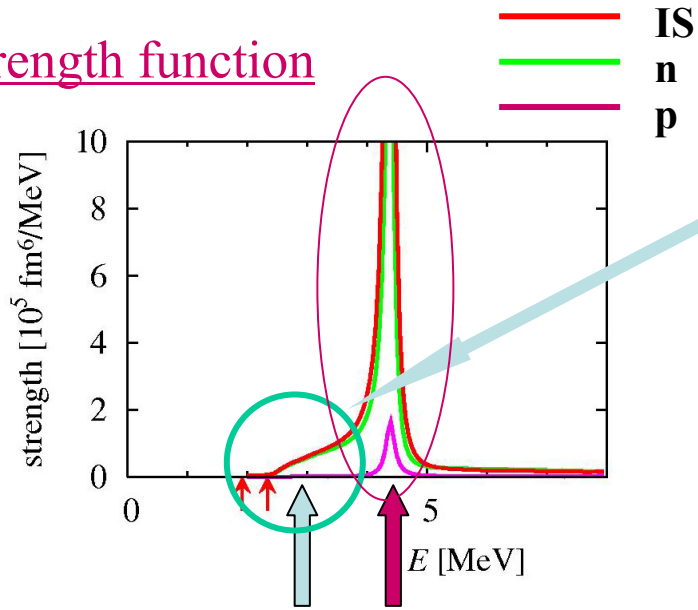
1. **Pronounced 2_1^+ state below E_{th}**
2. Surface vibration of ph-character
3. **No pair emission**
   (few emission even in the resonance case)
4. Some pairing effect,
   but di-neutron feature is weak.

Neutron transition densities @ E=1.2MeV

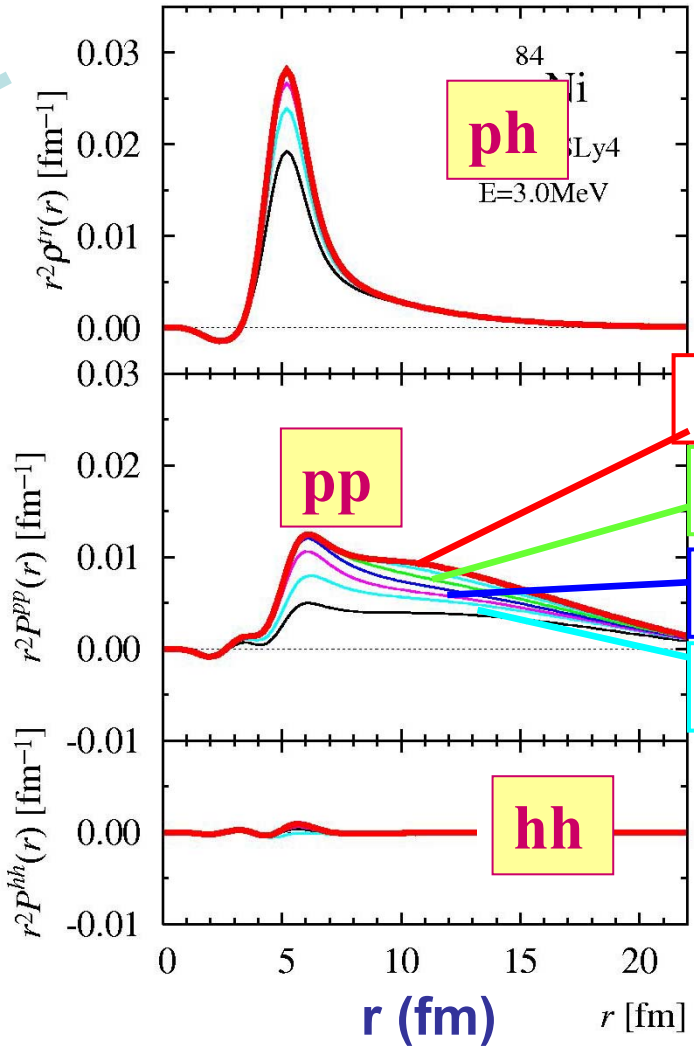


^{84}Ni There are two octupole modes

Strength function



Neutron transition densities @ E=3.0MeV



Max(l=17)

l=13

l=11

l=7

There are two modes

A. Surface vibration of ph character
- **Similar to 2_1^+**
- **Sharp resonance even above E_{th}**

B. Continuum surface di-neutron mode
- **emission of di-neutron**
- **Similar to soft dipole,**

but the di-neutron feature is slightly weaker