Continuum Response in Neutron-rich Nuclei: Photo Absorption and Pair Transfer

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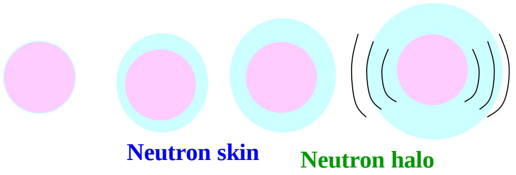
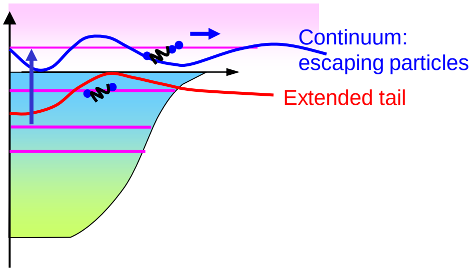
Exotic features in n-rich nuclei

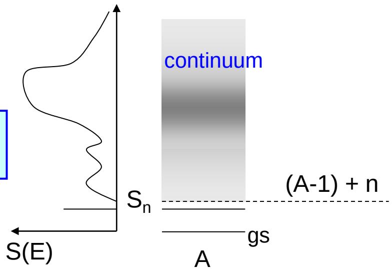


Weakly bound multiple neutrons

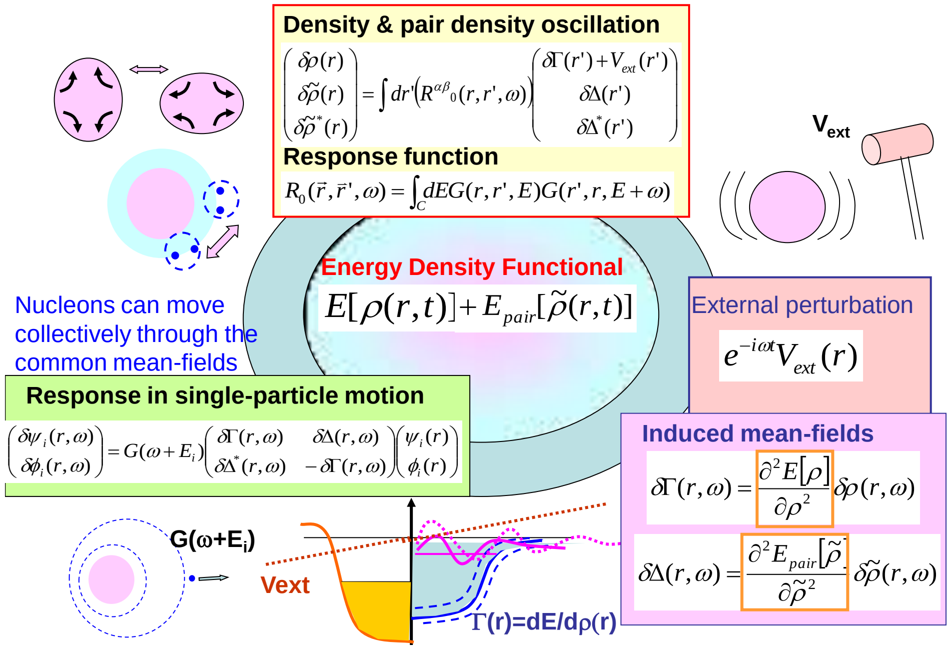


Dilute(unsaturated) matter
$\rho_n/\rho_0 << 1$ $\rho_n/\rho_p >> N/Z$

Responses/excited states in continuum & near threshold
Low neutron separation energy



QRPA: Linear Response in Density Functional Theory



Density & pair density oscillation

$$\begin{pmatrix} \delta\rho(r) \\ \delta\tilde{\rho}(r) \\ \delta\tilde{\rho}^*(r) \end{pmatrix} = \int dr' \left(R^{\alpha\beta}{}_0(r,r',\omega) \right) \begin{pmatrix} \delta\Gamma(r') + V_{ext}(r') \\ \delta\Delta(r') \\ \delta\Delta^*(r') \end{pmatrix}$$

Response function

$$R_0(\vec{r},\vec{r}',\omega) = \int_C dEG(r,r',E)G(r',r,E+\omega)$$

Nucleons can move collectively through the common mean-fields

Energy Density Functional

$$E[\rho(r,t)] + E_{pair}[\tilde{\rho}(r,t)]$$

External perturbation

$$e^{-i\omega t}V_{ext}(r)$$

Response in single-particle motion

$$\begin{pmatrix} \delta\psi_i(r,\omega) \\ \delta\phi_i(r,\omega) \end{pmatrix} = G(\omega+E_i) \begin{pmatrix} \delta\Gamma(r,\omega) & \delta\Delta(r,\omega) \\ \delta\Delta^*(r,\omega) & -\delta\Gamma(r,\omega) \end{pmatrix} \begin{pmatrix} \psi_i(r) \\ \phi_i(r) \end{pmatrix}$$

Induced mean-fields

$$\delta\Gamma(r,\omega) = \boxed{\frac{\partial^2 E[\rho]}{\partial\rho^2}} \delta\rho(r,\omega)$$

$$\delta\Delta(r,\omega) = \boxed{\frac{\partial^2 E_{pair}[\tilde{\rho}]}{\partial\tilde{\rho}^2}} \delta\tilde{\rho}(r,\omega)$$

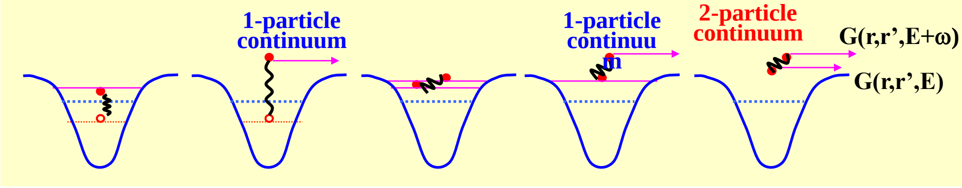
Continuum QRPA

M. Matsuo, Nucl. Phys. A696, 371 (2001)
also E. Khan et al. Phys. Rev. C66, 024309 (2002)

Nuclei near the neutron drip-line

⇒ Particle escaping in the continuum

⇒ Correlation among the continuum and weakly bound orbits



1. **Use exact single-particle Green function G(r,r’,E) with proper r→∞ asymptotics and out-going wave boundary condition**

   Belyaev’s construction 1987

   $$G(r,r',E) = \sum_{st=1,2} c^{st} \varphi^{out,s}(r_>,E)\varphi^{reg,t}(r_<,E)$$

   Regular and outgoing waves

2. **Summing up continuum states using a contour integral in the complex E-plane**

   $$R_0(\vec{r},\vec{r}',\omega) = \frac{1}{2\pi i}\int_C dEG(r,r',E)G(r',r,E+\omega) + b.w.$$

1. *Pair correlation and two-neutron transfer*

- ☐ N-rich Sn isotopes beyond A=132
- ☐ **anomalous 0_2^+ states in $^{134\text{-}140}$Sn**

Cf. Matsuo,Serizawa PRC82
024318 (2010)

Collective effect caused by weakly bound neutrons

2. *Dipole response and photo-absorption*

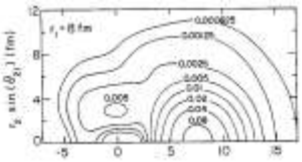
- ☐ **(γ,n)/(n,γ) cross section for r-process**
- ☐ N-rich Sn isotopes beyond A=132

Importance of continuum description

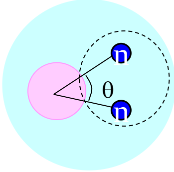
Enhancement of pairing at surface and tail in neutron-rich nuclei

1. Spatially correlated halo neutrons in ^{11}Li and ^{6}He, etc

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



Coulomb break-up exp. on 11Li



Nakamura et al.
PRL30,252502 (2006)

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

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

2. Possible “strong coupling” features in nn pairing in dilute neutron matter

$\Delta/e_F > 0.2$ & $\xi/d < 1$ at low-densities $\rho/\rho_0 = 10^{-3} \sim 10^{-1}$

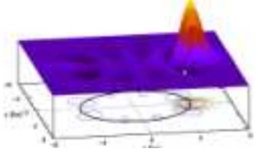
Large scattering length a_{nn}=-18.5 fm

BCS-BEC crossover

Matsuo, PRC73,044309 (2006)
Gezerlis & Carlson, PRC81 (2010)

3. Surface enhancement may be generic, but little evidence for heavy mass nuclei

Syrme-HFB for ^{84}Ni

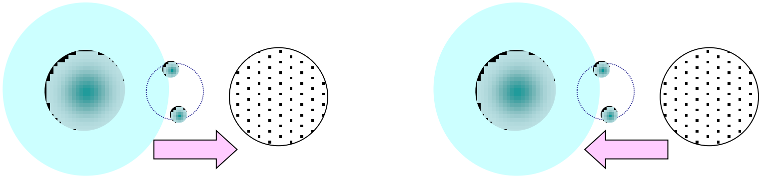


Dobaczewski et al, PTPS146,70(2002), EPJA15,21(2002
Matsuo, Mizuyama, Serizawa PRC71,064326(2005)
Pillet, Sandulescu, Schuck, PRC76, 024310 (2007)
Pankratov, et al. PRC79, 024309 (2009), etc.

Two-neutron transfer as a probe of surface pairing

Pair transfers

Bohr & Mottelson Vol.2
Broglia, Hansen, Riedel, Advances in Nucl. Phys. Vol.6, 1973
von Oertzen and Vitturi, Rep. Prog. Phys. 64, 1247 (2001)



Pair removal

Pair addition

Collectivity due to pair correlation: pair vibration & pair rotation

+ surface-enhanced spatial correlation ??

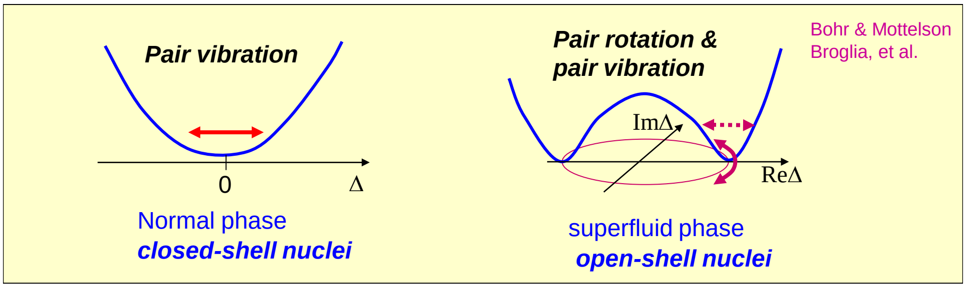
⇨ ***medium & heavy n-rich nuclei, e.g. O, Sn***

Khan et al. PRC69, 014314 (2004); ibid 80, 044328 (2009)
Avez et al. PRC78, 044318 (2008)
Matsuo, Serizawa arXiv:1007.1705

Cf. Experiments on light n-rich nuclei ^{6,8}He, ^{11}Li,

^{11}Li + $p \rightarrow$ ^{9}Li + t	I. Tanihata et al. PRL 100, 192502 (2008)
^{6}He + ^{65}Cu $\rightarrow$ ^{67}Cu* + ^{4}He	A. Chatterjee et al. PRL 101, 032701 (2008)
^{6}He+ $t \rightarrow$ ^{8}He + p, & ^{8}He+ $t \rightarrow$	M.S. Golovkov et al. PL B101, 032701 (2008)

Pairing collectivity & pair transfers



Pair vibration

Normal phase
closed-shell nuclei

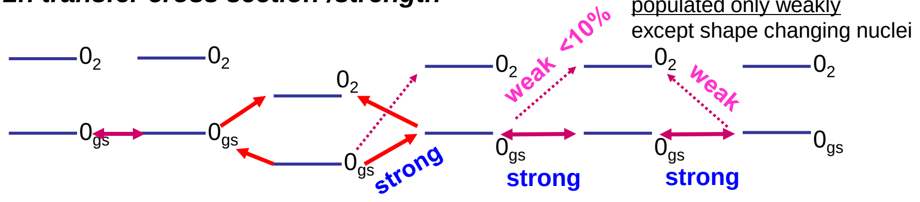
Pair rotation & pair vibration

superfluid phase
open-shell nuclei

Bohr & Mottelson
Broglia, et al.

2n transfer cross section /strength

0_2^+ pair vibrational state is populated only weakly except shape changing nuclei

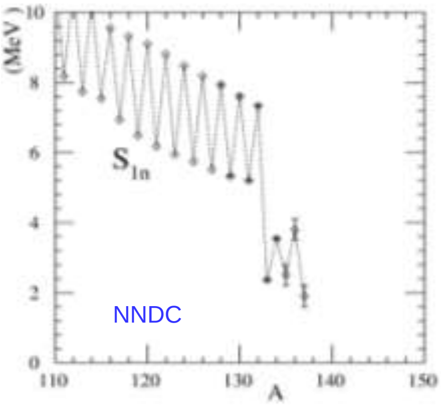


closed-shell

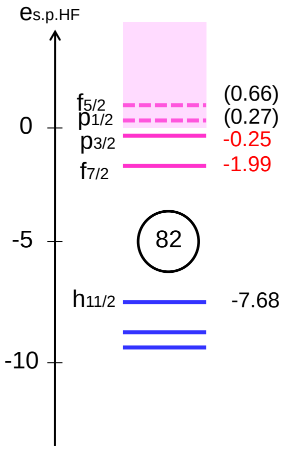
Ground-state transition
"pair rotation" dominates, prop. to Δ^2

^{132}Sn and beyond

One-neutron separation energy



Neutron orbits



Hartree-Fock for 132Sn
Skyrme SLy4

Pair transfer modes in QRPA

Given the Skyrme functional + pairing functional

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

Parameter set
SLy4
DDDI

Hartree-Fock-Bogoliubov ground state

Linear response eq. Landau-Migdal approx.

$$\begin{pmatrix}\delta\rho(r)\\ \delta\tilde{\rho}(r)\\ \delta\tilde{\rho}^*(r)\end{pmatrix} = \int dr' \left(R^{\alpha\beta}{}_0(r,r',\omega)\right)\begin{pmatrix}\delta\Gamma(r')+V_{ext}(r')\\ \delta\Delta(r')\\ \delta\Delta^*(r')\end{pmatrix}$$

Response function (ph, pp, hh)

$$R_0(\vec{r},\vec{r}',\omega) = \int_C dE\, G(r,r',E)\, G(r',r,E+\omega)$$

particle-hole density

$$\rho(r,t) = \left\langle \sum_\sigma \psi^+(r\sigma)\psi(r\sigma) \right\rangle$$

pair -addition density

$$\tilde{\rho}^*(r,t) = \left\langle \psi^+(r\downarrow)\psi^+(r\uparrow) \right\rangle$$

pair -removal density

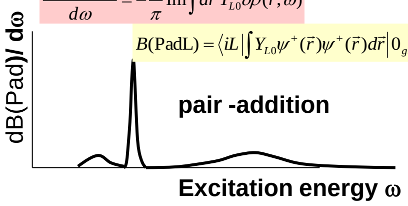
$$\tilde{\rho}(r,t) = \left\langle \psi(r\uparrow)\psi(r\downarrow) \right\rangle$$

Transition density at a given ω

Strength function as a function of ω

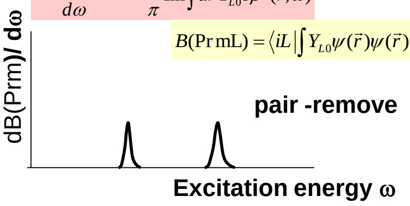
$$\frac{dB(\mathrm{PadL})}{d\omega} = -\frac{1}{\pi}\mathrm{Im}\int dr\, Y_{L0}\delta\tilde{\rho}(r,\omega)$$

$$B(\mathrm{PadL}) = \left\langle iL \middle| \int Y_{L0}\psi^+(\vec{r})\psi^+(\vec{r})d\vec{r} \middle| 0_{gs} \right\rangle^2$$



$$\frac{dB(\mathrm{PrmL})}{d\omega} = -\frac{1}{\pi}\mathrm{Im}\int dr\, Y_{L0}\delta\tilde{\rho}^*(r,\omega)$$

$$B(\mathrm{PrmL}) = \left\langle iL \middle| \int Y_{L0}\psi(\vec{r})\psi(\vec{r})d\vec{r} \middle| 0_{gs} \right\rangle^2$$

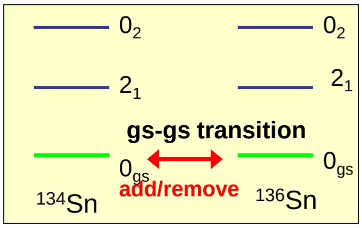


0_{gs}-0_{gs} pair transfer strength in $^{>132}$Sn

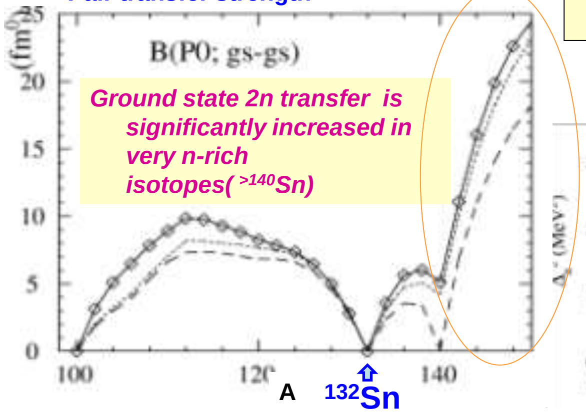
2n-add/removal transfer amplitude and strength

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

$$B(\mathrm{P0}) = \langle 0_{gs}|\int Y_{00}\psi^+(\vec r)\psi^+(\vec r)d\vec r|0_{gs}\rangle^2 = \left|4\pi\int\tilde\rho(\vec r)r^2dr\right|^2$$

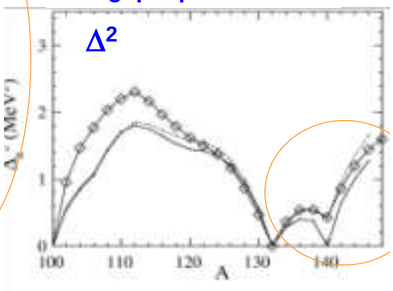


Pair transfer strength



Ground state 2n transfer is significantly increased in very n-rich isotopes($^{>140}$Sn)

Pair gap squared



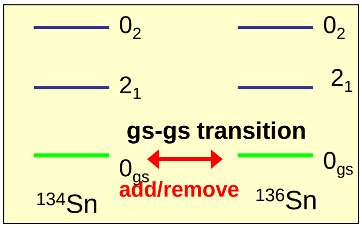
0_{gs}-0_{gs} pair transfer: enhancement mechanism

2n-add/removal : transition density and strength

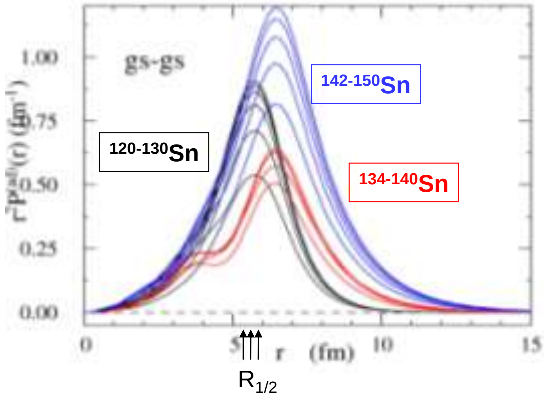
$$\langle 0_{gs}, N\pm 2|\psi^+(\vec r)\psi^+(\vec r)|0_{gs}, N\rangle \approx \langle 0_{HFB}|\psi^+(\vec r\uparrow)\psi^+(\vec r\downarrow)|0_{HFB}\rangle = \tilde\rho(\vec r)$$

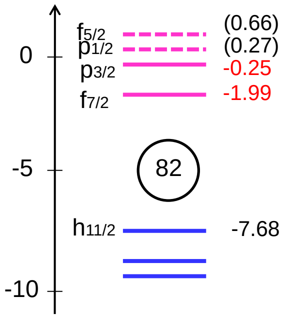
$$B(\mathrm{P0}) = \langle 0_{gs}|\int Y_{00}\psi^+(\vec r)\psi^+(\vec r)d\vec r|0_{gs}\rangle^2 = \left|4\pi\int\tilde\rho(\vec r)r^2dr\right|^2$$

Dobaczewski et al, PRC53, 2809 (1996)

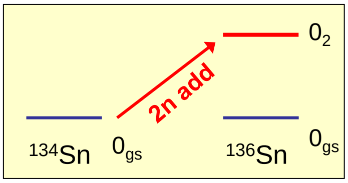


Pair transfer transition density (form factor)

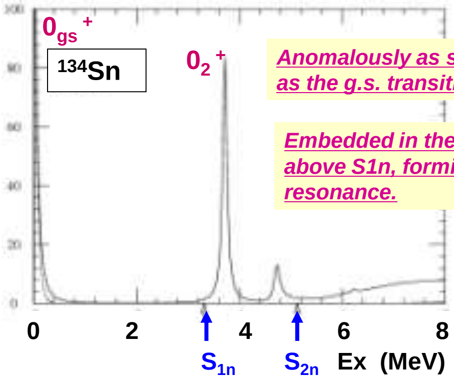




Transfer to excited 0^+ states in ^{134}Sn

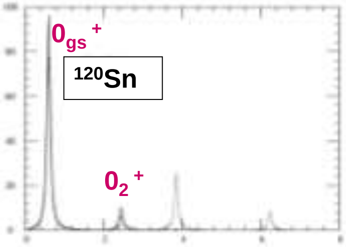


Pair-addition(removal) strength function



Anomalously as strong as the g.s. transition

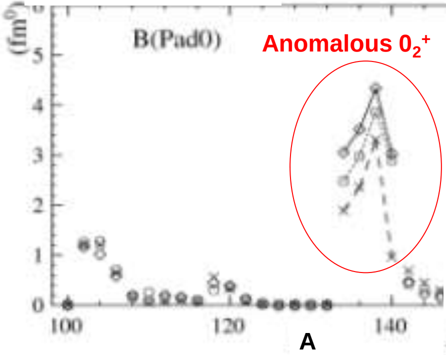
Embedded in the continuum above S1n, forming a narrow resonance.

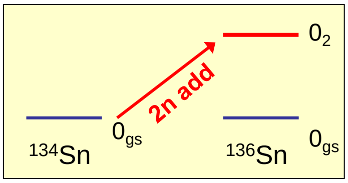


These features are very different from those of the pair vibration in stable nuclei

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

2n-addition strength

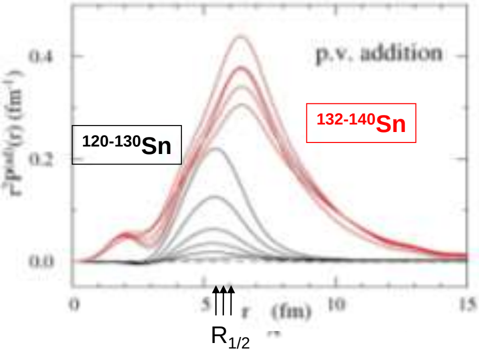




The pair-addition strength for 0_2^+ transition is significantly enhanced in $^{132\text{-}140}$Sn.

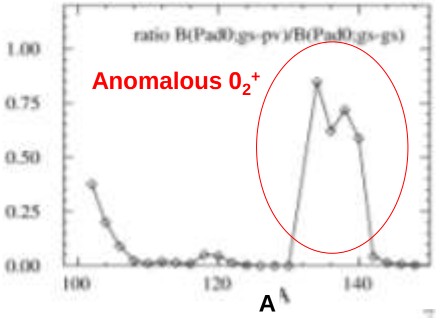
The transition density extends far outside the surface, reaching up to ~15fm.

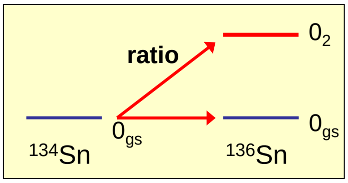
Transition density of 2n-addition



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

Strength ratio 0_2^+ / g.s.

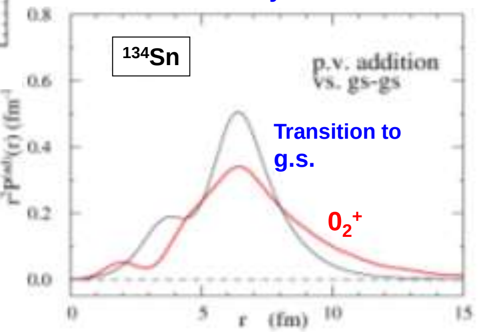




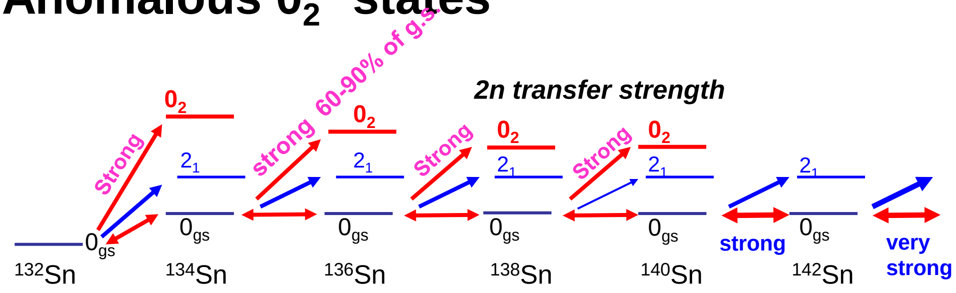
Ratio against the ground state transition is as large as 60-90 %

Usually the ratio is less than 10-20% except in nuclei with shape transition / shape coexistence

Transition density of 2n-addition



Anomalous 0_2^+ states



- Skyrme-HFB +QRPA calculations predict presence of ***anomalous 0^+ state in $^{134\text{-}140}$Sn.***
- ***Large pair-addition strength***, comparable to the ground state transition.
- It reflects both the presence of ***weakly bound orbits***, in particular *p*-orbits, above the N=82 shell gap, and the ***enhanced pairing interaction at low-density.***

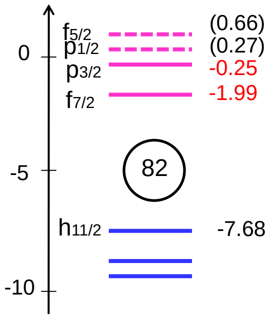


Photo-absorption for r-process

(γ,n)/(n,γ) cross section in r-process nucleosynthesis

- The environment T ∼ 10^9 K (kT ~ 100 keV)
- n-rich nuclei S_n ∼ 2MeV

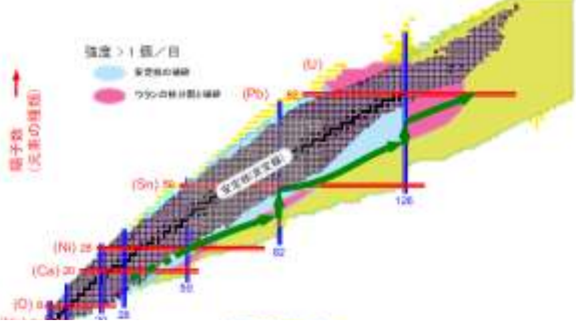
  e.g. Sn isotopes $132 < A < 150$

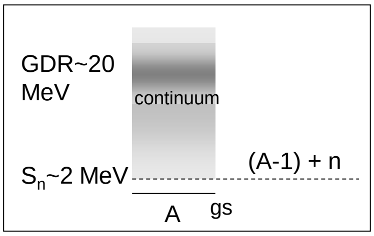
  Low threshold energy
- process (apart from β-decay)

  n+(A-1) → A* → A + γ Capture of neutron with thermal energy

  γ + A → A* → (A-1) +n Photo-absorption with neutron emission

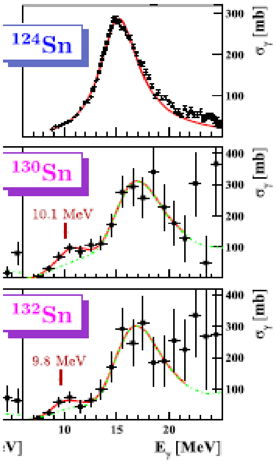
  Dipole response in the continuum





Experimental data existing up to A=132

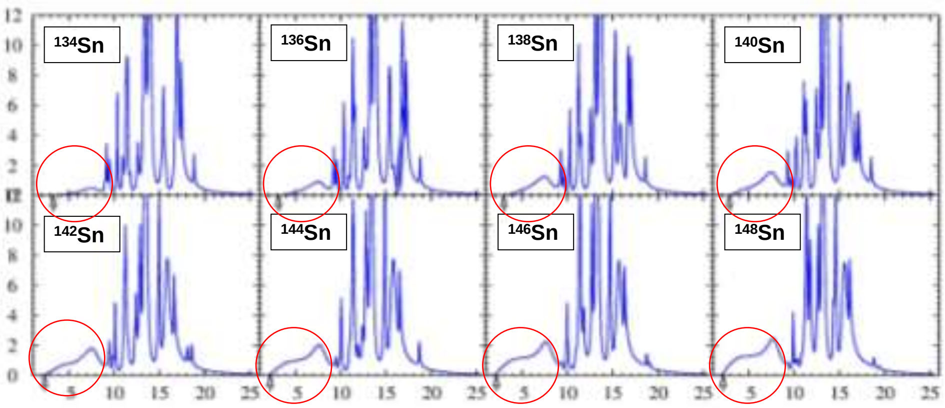
GSI data Adrich et al. PRL (2006)



- Bump around Ex ~ 10 MeV
- “Pygmy Dipole Resonance”

Skyrme HFB + Continuum QRPA

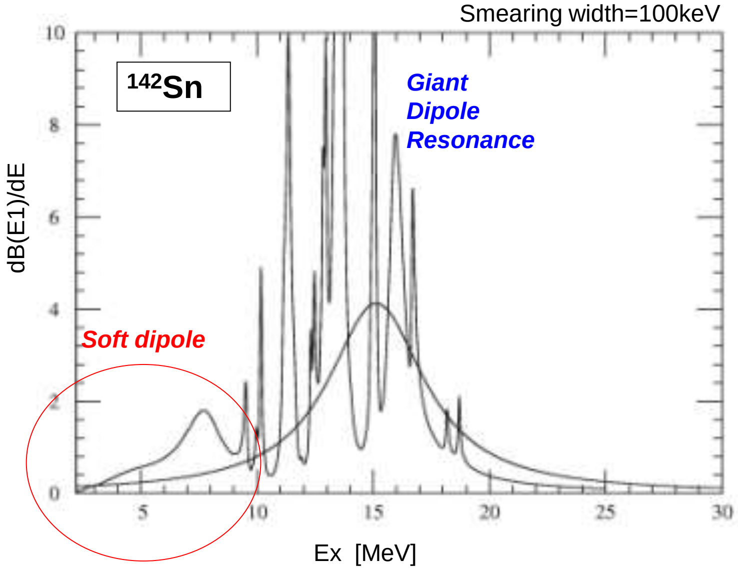
Parameter set: SLy4 DDDI-mix
Landau-Migdal approx.



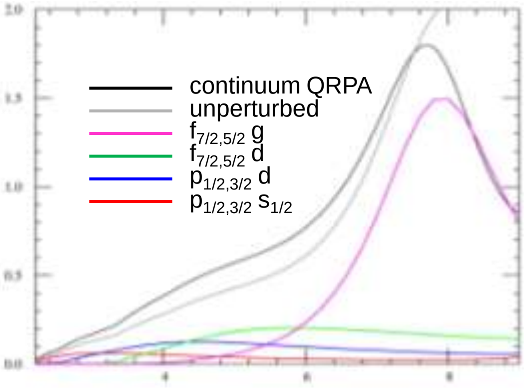
Arrows: neutron separation energy S_n ~ 2-3 MeV

E1 strength function in Continuum QRPA

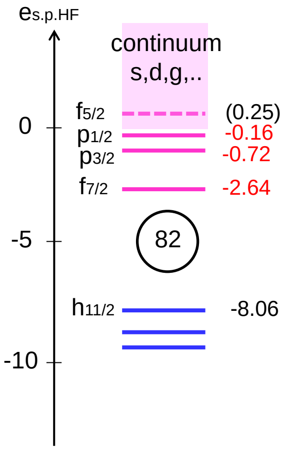
Smearing width=100keV



Soft dipole mode of continuum single-particle transitions

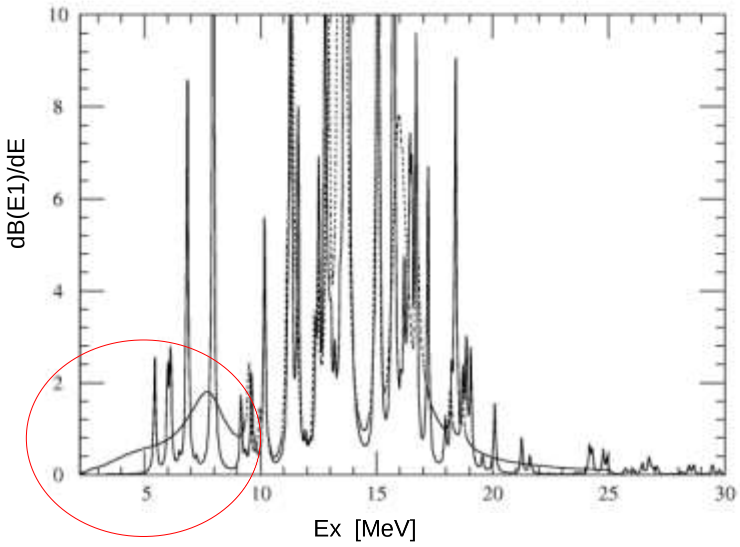


Neutron orbits

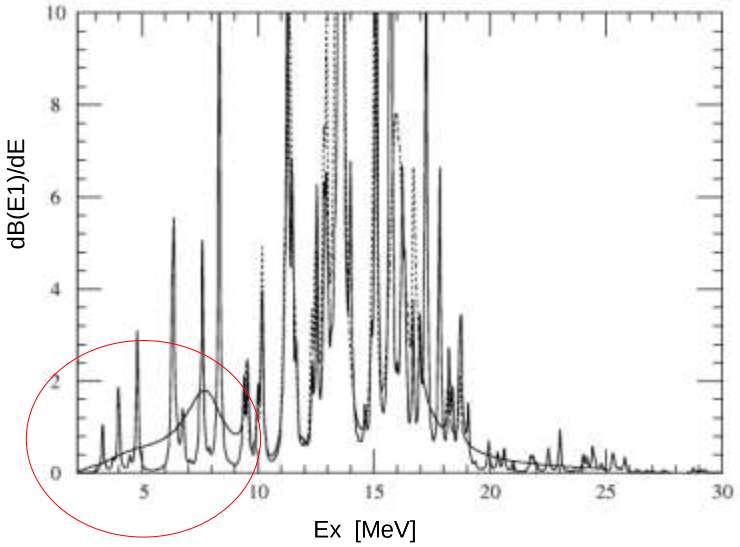


Hartree-Fock for 140Sn
Skyrme SLy4

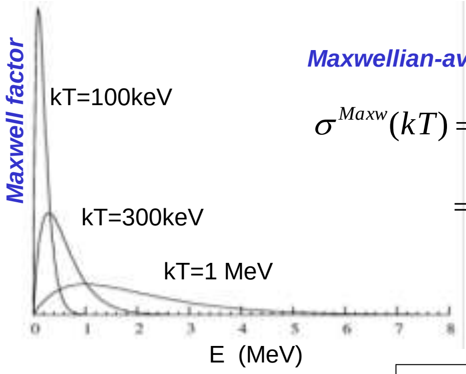
Continuum QRPA vs discretized QRPA in box（R_{box}=14 fm)



Continuum QRPA vs discretized QRPA in box（R_{box}=20 fm)



Nucleosyntehsis (γ,n)(n,γ) cross section



Maxwellian-averaged cross section (MACS)

$$\sigma^{Maxw}(kT) = \frac{\langle \sigma v \rangle}{v_T} = \frac{2}{\sqrt{\pi}(kT)^2}\int_0^\infty \sigma(E) E \exp\left(-\frac{E}{kT}\right) dE$$

Neutron energy $E = E_x - S_n$

Temperature range：

$T_9 = 0.1 \sim 10$ K

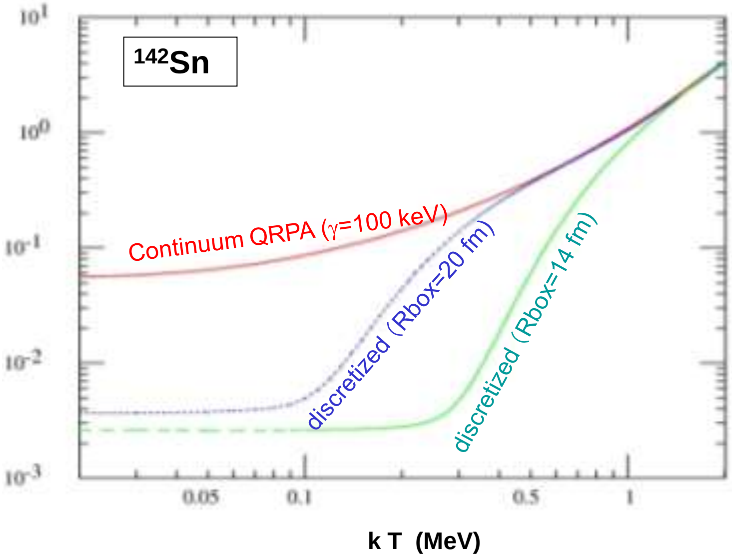
kT= 10 keV ~ 1 MeV

(γ, n) (n,γ) cross section *E1 strength function*

$$\sigma(E) = \frac{16\pi^3 e^2}{9\hbar c} E_x \frac{dB(E1)}{dE_x} \Leftarrow \text{QRPA}$$

⇨ ***Fine resolution of 10-100 keV is required***

Maxwellian-averaged cross section (MACS)



Discretization does not work for the box sizes adopted broadly

(γ,n)(n,γ) cross section for r-process

- Accurate description of ***continuum E1 response near the threshold*** is required.
- ***Continuum QRPA*** provides a useful scheme for this purpose. Discretization of continuum orbits is dangerous.

For further developments

- Due to a large computation time needed for continuum QRPA calculations, it is hard to use small smearing width ~10 keV. (Achieved resolution is ~100 keV so far).
- Continuum QRPA description of deformed nuclei. (Spherical nuclei so far.)
- Coupling more complex configurations --- eg phonon coupling --- need to be included for nuclei near the stability line.
- Need to find better Skyrme density functional for quantitative description of existing data and reliable predictions useful for astrophysical applications.

1. Pair correlation and two-neutron transfer

☐ N-rich Sn isotopes beyond A=132

☐ **anomalous 0_2^+ states in $^{134\text{-}140}$Sn**

Collective effect caused by weakly bound neutrons

2. Dipole response and photo-absorption

☐ **(γ,n)/(n,γ) cross section for r-process**

☐ N-rich Sn isotopes beyond A=132

Importance of continuum description