Stati collettivi: studio delle loro proprietà e del loro ruolo nella dinamica nucleare

(Struttura nucleare a Milano)

Ex MI31:

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Strong connection
with experiment -> 50% Gr. III

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SOME KEYWORDS:

Density Functional Theory
Collective modes
Nuclear Field Theory (Particle-vibration coupling)
Nuclear superfluidity

Transfer reactions

Nuclear equation of state (symmetry energy)
Inner crust of neutron stars
Electron capture (supernovae)

I. Calculations of collective modes : HF+RPA

Fully self-consistent calculations

- Implementing new codes and devising better interactions

Connection with fundamental nuclear properties

- Symmetry energy

Sensitivity to details of the nuclear interaction

- Tensor terms

Microscopic HF plus RPA

attraction

Skyrme effective force

$$
\begin{aligned}
\hat{v}_{\mathrm{Sk}}(\boldsymbol{r}_{12}) = {}& \underline{t_0(1+x_0\hat{P}_\sigma)\delta(\boldsymbol{r}_{12})} + \frac{1}{2}t_1(1+x_1\hat{P}_\sigma)(\hat{\boldsymbol{k}}^{\dagger 2}\delta(\boldsymbol{r}_{12}) + \delta(\boldsymbol{r}_{12})\hat{\boldsymbol{k}}^2) \\
& + t_2(1+x_2\hat{P}_\sigma)\hat{\boldsymbol{k}}^\dagger \cdot \delta(\boldsymbol{r}_{12})\hat{\boldsymbol{k}} + \underline{\frac{1}{6}t_3(1+x_3\hat{P}_\sigma)\delta(\boldsymbol{r}_{12})\rho^\alpha\left(\frac{\boldsymbol{r}_1+\boldsymbol{r}_2}{2}\right)} \\
& + \mathrm{i}W_0(\hat{\sigma}_1+\hat{\sigma}_2)\cdot\hat{\boldsymbol{k}}^\dagger \times \delta(\boldsymbol{r}_{12})\hat{\boldsymbol{k}}.
\end{aligned}
$$

short-range repulsion

- After generating the HF mean-field, one is left with a residual force V_{res}.
- The residual force acts as a restoring force, and sustains collective oscillations (like GRs). Its effect is included in the linear response theory = RPA.

$$
\begin{pmatrix} A & B \\ -B^* & -A^* \end{pmatrix} \begin{pmatrix} X \\ Y \end{pmatrix} = \hbar\omega \begin{pmatrix} X \\ Y \end{pmatrix}
$$

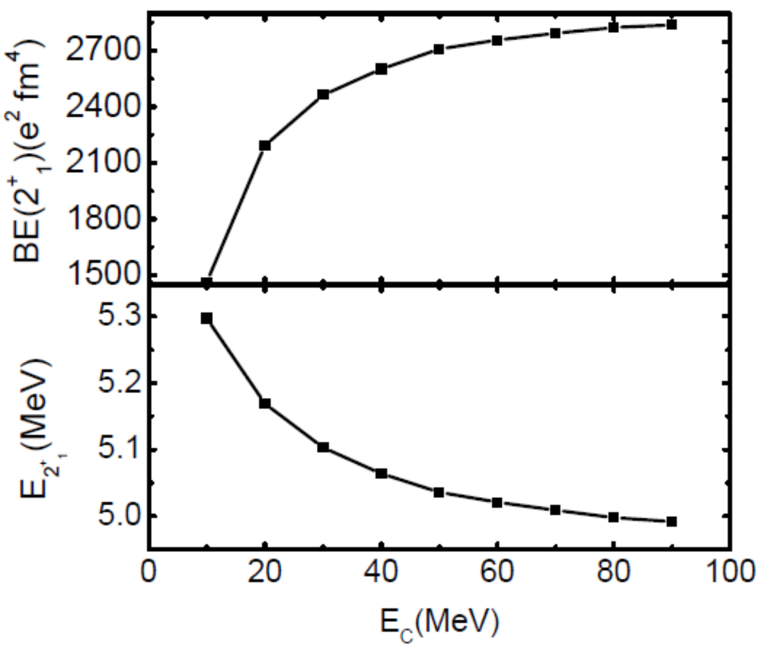
Our fully self-consistent implementation

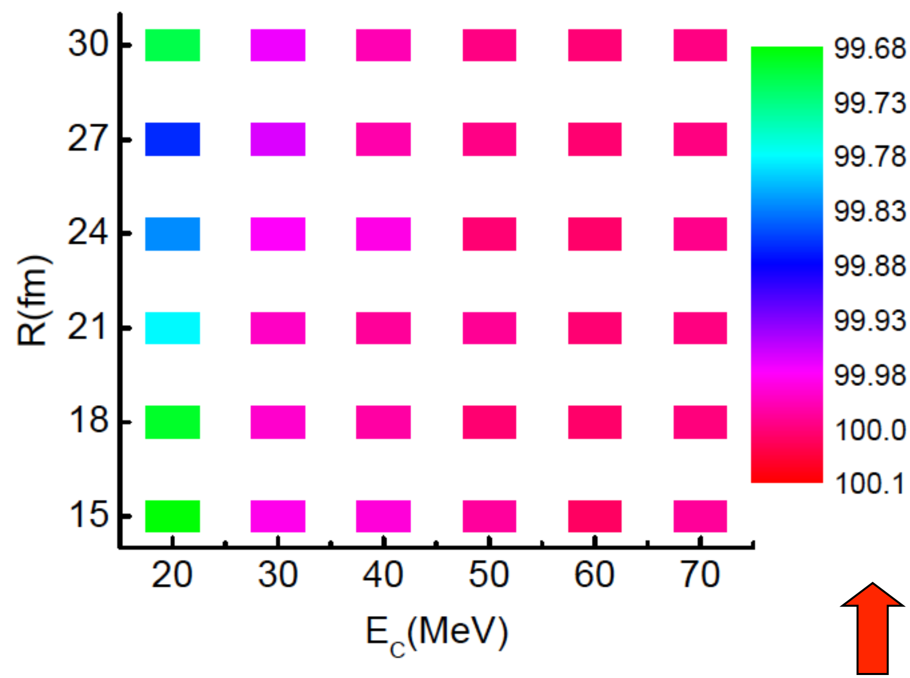
The continuum is discretized. The basis must be large due to the zero-range character of the force. Parameters: R, E_C.

The energy-weighted sum rule should be equal to the double-commutator value: well fulfilled !

$$m_1(\hat{O}) = \sum_\nu E_\nu |\langle \nu|\hat{O}|\tilde{0}\rangle|^2 = \frac{1}{2}\langle 0|[\hat{O},[H,\hat{O}]]|0\rangle$$

^{208}Pb - SGII



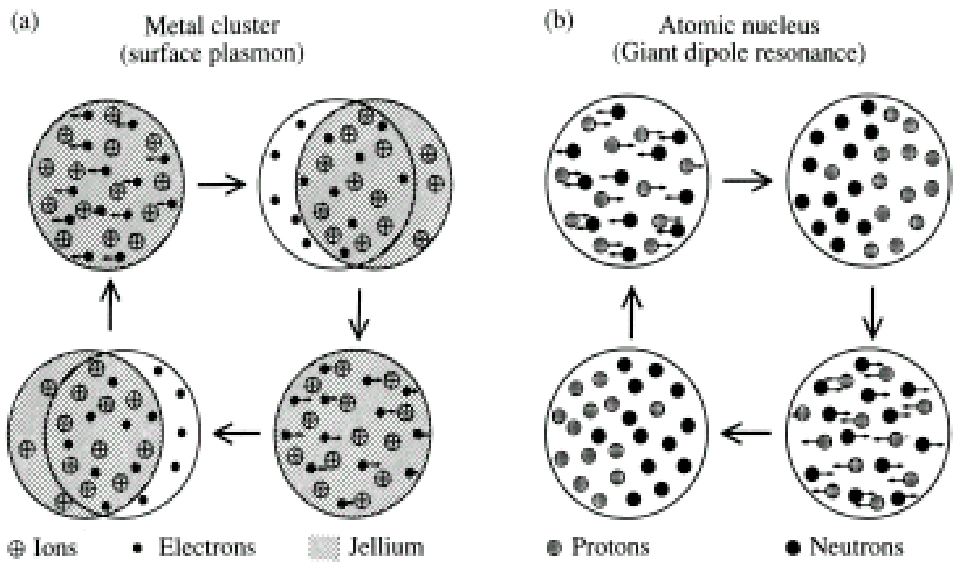


G. Colò, L. Cao, N. Van Giai, L. Capelli
Comp.phys. Comm. 184 (2013) 142

Percentages $m_1(RPA)/m_1(DC)$ [%]

Collective excitations and symmetry energy

G. Colo', U. Garg, H. Sagawa, EPJ (in press)



IV Giant Dipole Resonance (IVGDR)

Nuclear matter EOS

Symmetric matter EOS

Symmetry energy S

$$\mathcal{E}(\rho,\beta) = \mathcal{E}(\rho,\beta=0) + S(\rho)\beta^2 \qquad \beta \equiv \frac{\rho_n - \rho_p}{\rho}$$

Why should the IVGDR provide S ?

In the case in which the GDR exhausts the whole sum rule, its energy can be deduced following the formulas given by E. Lipparini and S. Stringari [Phys. Rep. 175, 103 (1989)]. Employing a simplified, yet realistic functional they arrive at

$$E_{-1} \equiv \sqrt{\frac{m_1}{m_{-1}}} = \sqrt{\frac{3\hbar^2}{m\langle r^2\rangle}\frac{b_{\text{vol}}}{\left[1+\frac{5}{3}\frac{b_{\text{surf}}}{b_{\text{vol}}}A^{-\frac{1}{3}}\right]}(1+\kappa)}.$$

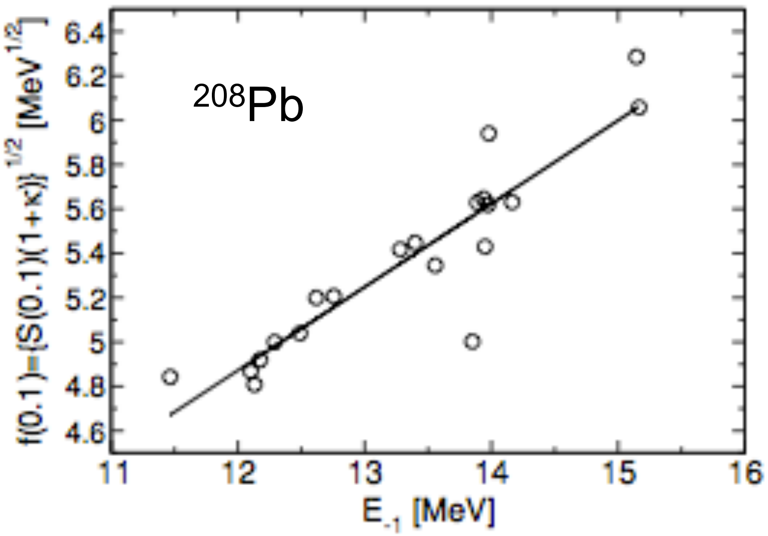
$$\approx \sqrt{\frac{6\hbar^2}{m<r^2>}\;\frac{S(\rho_0)}{1+\underbrace{\frac{5}{S(\rho_0)}[\rho\frac{dS}{d\rho}-\frac{\rho_0^2}{4}\frac{d^2S}{d\rho^2}]A^{-1/3}}_{\text{Surface effect}}}\underbrace{(1+\kappa)}_{\text{Enhancement factor}}}$$

If there is only volume, the GDR energy should scale as $\sqrt{S(\rho_0)}$ which is $\sqrt{J}$ or $\sqrt{b_{vol}}$.

The surface correction may be slightly model-dependent but several results point to $\rho_{eff} \approx 0.1$ fm^{-3} . Independent work by the Barcelona group confirms this.

ACTUAL RPA CALCULATIONS:

Centroids and symmetry energies from different Skyrme forces



Linear correlation between the centroid of GDR and the square root of S at sub-saturation density ($\rho \approx 0.1$ fm^{-3}) calculated with different Skyrme forces.

From experiment:

E1 = 13.46 MeV ; κ= 0.22±0.04

23.3 < S(0.1) < 24.9 MeV

L. Trippa, G. Colo', E. Vigezzi,
Phys. Rev. C77, 061304 (2008)

Main parameters that govern S:

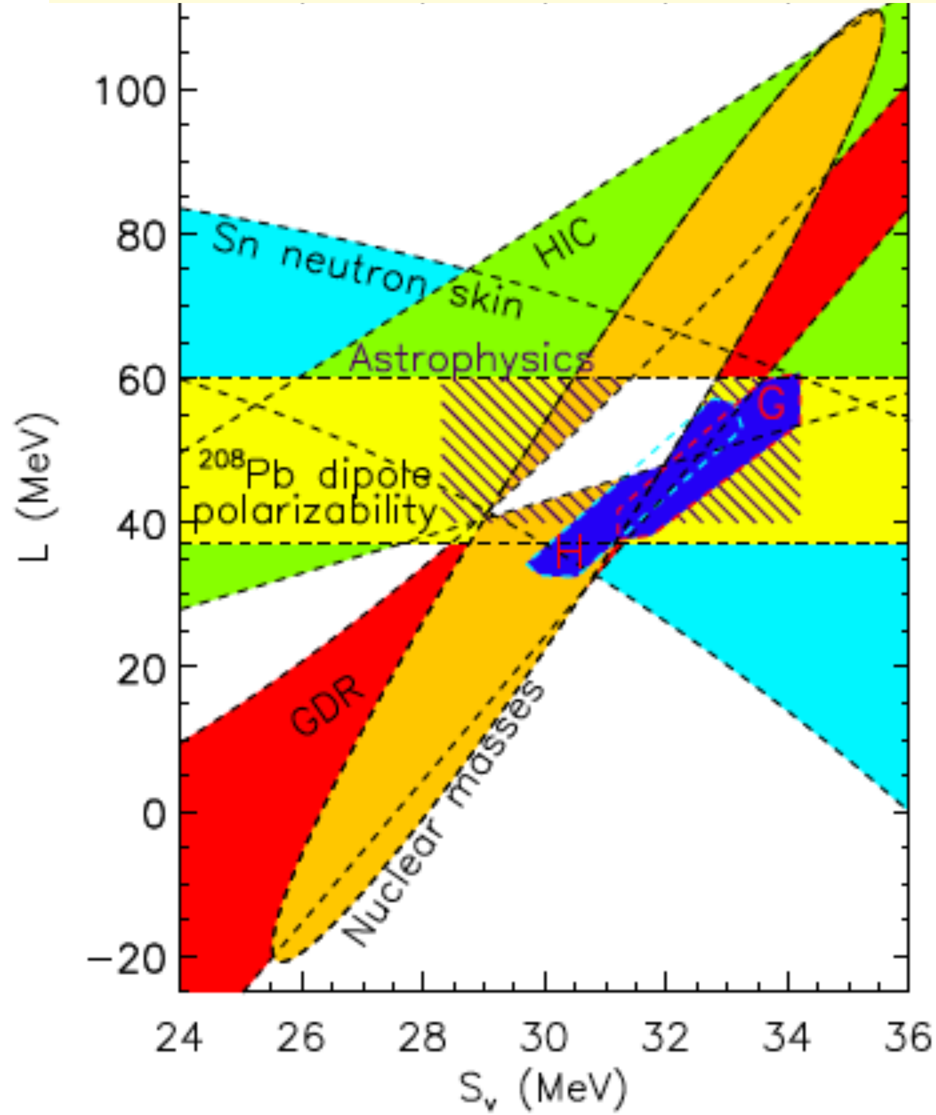
$$S(\rho_0) \equiv J$$
$$S'(\rho_0) \equiv L/3\rho_0$$
$$S''(\rho_0) \equiv K_{\rm sym}/9\rho_0^2$$

From GDR: S($\rho \approx 0.1$ fm^{-3})

Other useful information can be inferred from:

Low-lying dipole strength
IVGQR
ISGMR
Spin dipole

M.B. Tsang *et al.*, PRC 86, 015803 (2012)
J.M. Lattimer, J. Lim, arXiv:1203.4286



Tensor force

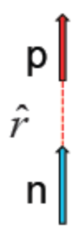
$\mathbf{S_{12}}$

$$V_T(1,2) = \left[V_{T0}(r) + V_{T\tau}(r)\vec{\tau}^{(1)}\vec{\tau}^{(2)}\right] \cdot \left[\frac{3}{r^2}(\vec{\sigma}^{(1)}\vec{r})(\vec{\sigma}^{(2)}\vec{r}) - \vec{\sigma}^{(1)}\vec{\sigma}^{(2)}\right]$$

The tensor force mixes states that have S = 1, the same value of J but ΔL = 2.

The p-n component acts in the deuteron and favours a prolate configuration. In other words, at least in the p-n channel it is known that the coefficient in front of S_{12} is negative.

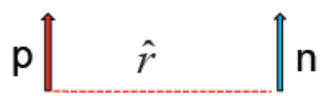
prolate



Rugby ball

$S_{12} = +2$

oblate



$S_{12} = -1$

pancake

Skyrme forces with zero-range tensor terms

T ↔ tensor even, U ↔ tensor odd

$$V_{\text{tensor}} = \frac{T}{2}\left\{[(\sigma_1\cdot \mathrm{k}')(\sigma_2\cdot \mathrm{k}') - \frac{1}{3}(\sigma_1\cdot\sigma_2)\mathrm{k}'^2]\delta(\mathrm{r}_1-\mathrm{r}_2) + \delta(\mathrm{r}_1-\mathrm{r}_2)[(\sigma_1\cdot \mathrm{k})(\sigma_2\cdot \mathrm{k}) - \frac{1}{3}(\sigma_1\cdot\sigma_2)\mathrm{k}^2]\right\}$$
$$+U\left\{(\sigma_1\cdot \mathrm{k}')\delta(\mathrm{r}_1-\mathrm{r}_2)(\sigma_2\cdot \mathrm{k}) - \frac{1}{3}(\sigma_1\cdot\sigma_2)\delta(\mathrm{r}_1-\mathrm{r}_2)[\mathrm{k}'\cdot \mathrm{k}]\right\},$$

Effect on spin-orbit potential

q= 0 -> n,
q=1 -> p

$$U^{(q)}_{s.o.}(r) = \frac{W_0}{2r}\left(2\frac{d\rho_q}{dr} + \frac{d\rho_{1-q}}{dr}\right) + \left(\alpha\frac{J_q}{r} + \beta\frac{J_{1-q}}{r}\right),$$

$$\alpha = \alpha_c + \alpha_T$$
$$\beta = \beta_c + \beta_T.$$

Exchange terms,
central interaction

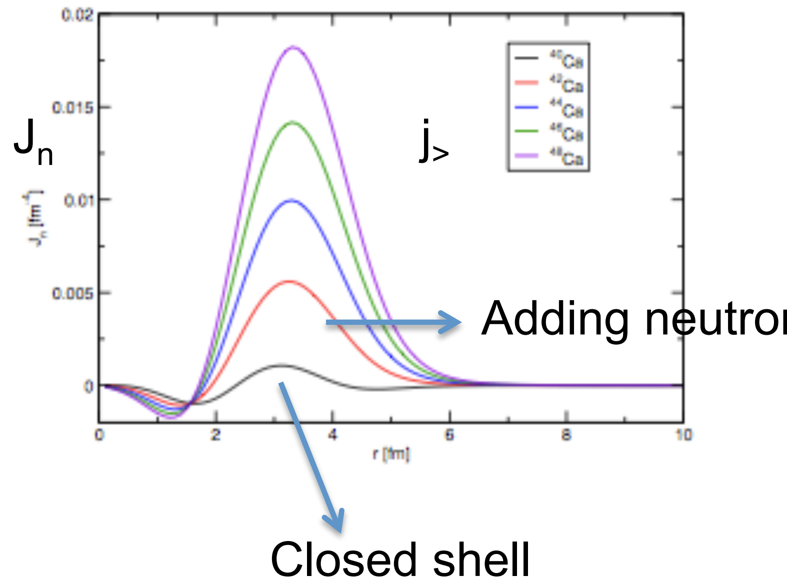
$$\alpha_C = \frac{1}{8}(t_1 - t_2) - \frac{1}{8}(t_1x_1 + t_2x_2),$$
$$\beta_C = -\frac{1}{8}(t_1x_1 + t_2x_2),$$

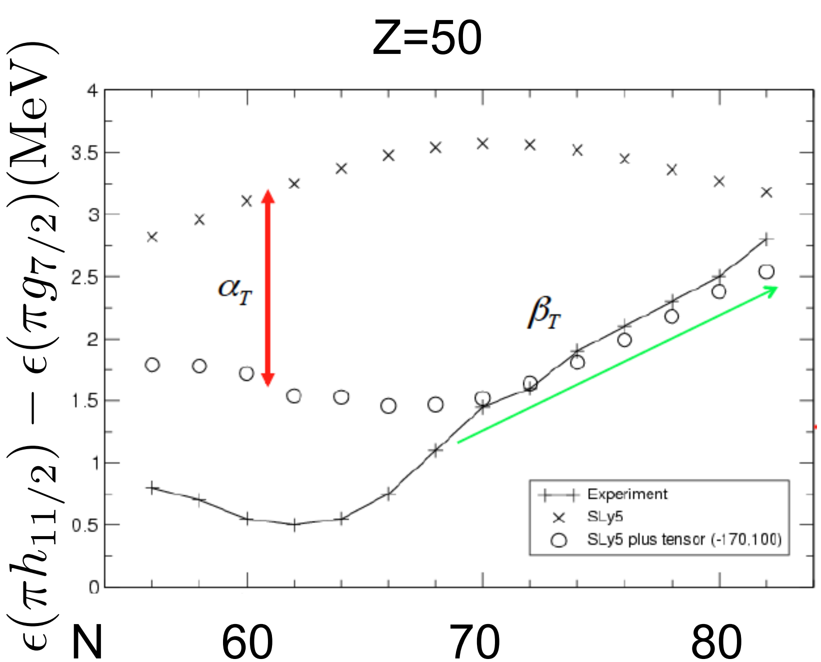
Tensor terms

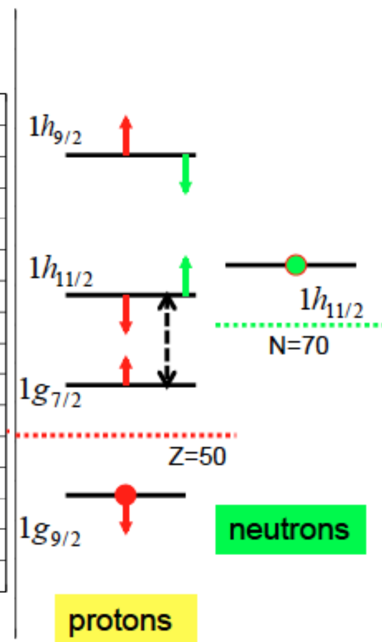
$$\alpha_T = \frac{5}{12}U,$$
$$\beta_T = \frac{5}{24}(T + U),$$

Including p-n tensor force in mean field calculations can yield single-particle energies in better agreement with experiment.

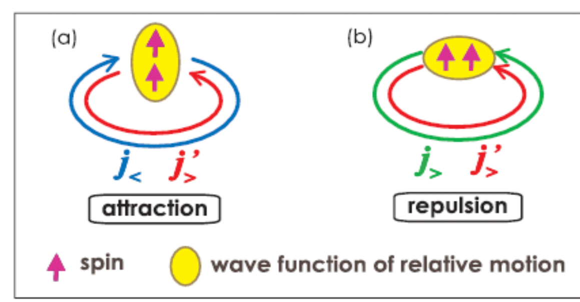
$$U^{p}_{s.o.}(r) = \frac{W_0}{2r}\left(2\frac{d\rho_p}{dr} + \frac{d\rho_n}{dr}\right) + \left(\underbrace{\alpha}_{>0}\frac{J_p}{r} + \underbrace{\beta}_{<0}\frac{J_n}{r}\right)$$







Filling the neutron h11/2 orbit

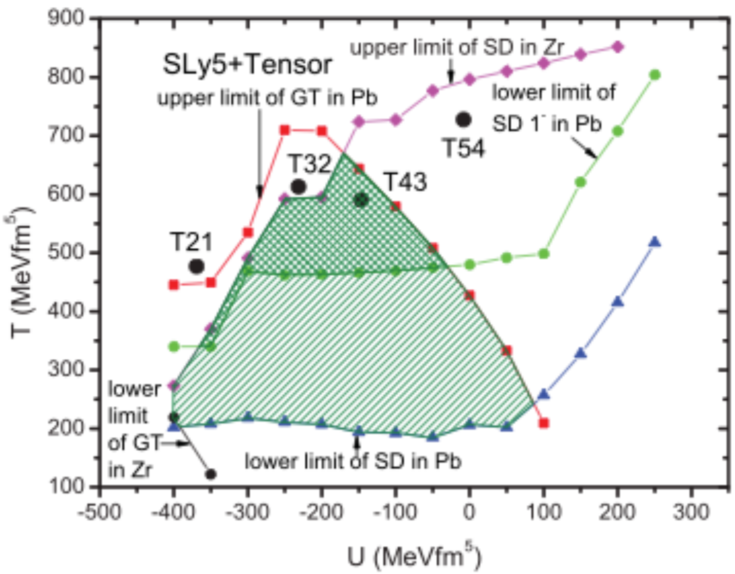


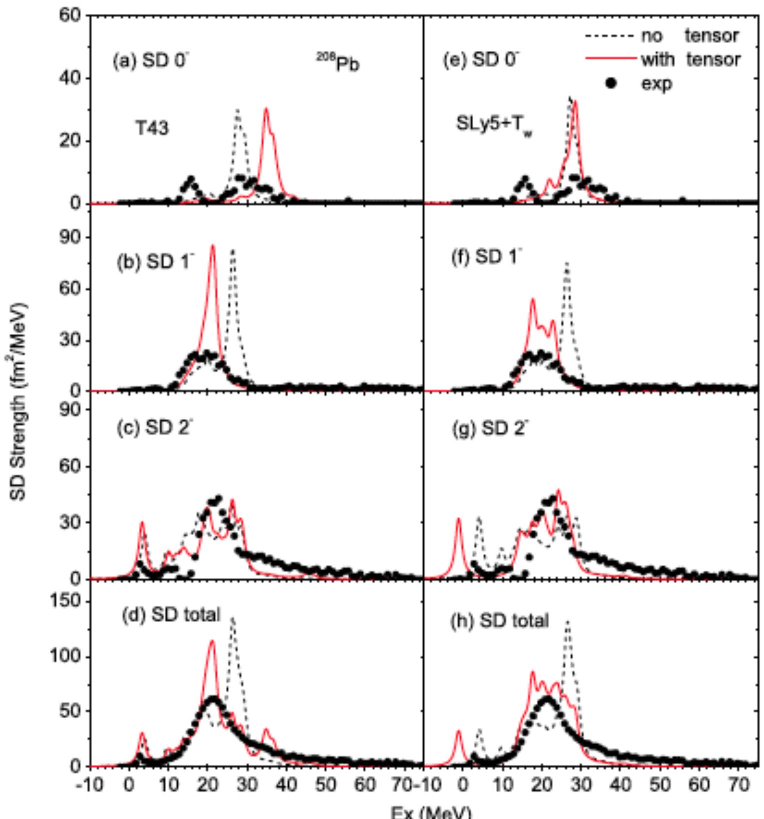
T. Otsuka et al.,
PRL 95,232502 (2005)

Gamow-Teller and spin-dipole excitations help to constrain the tensor force

THE TENSOR FORCE HAS A MULTIPOLE-DEPENDENT EFFECT AND ONLY WITH GIVEN SIGNS ONE CAN REPRODUCE THE EXPERIMENTAL FINDINGS.

T>0 is consistent with the analysis of s.-p. states and with the microscopic origin of the the tensor force



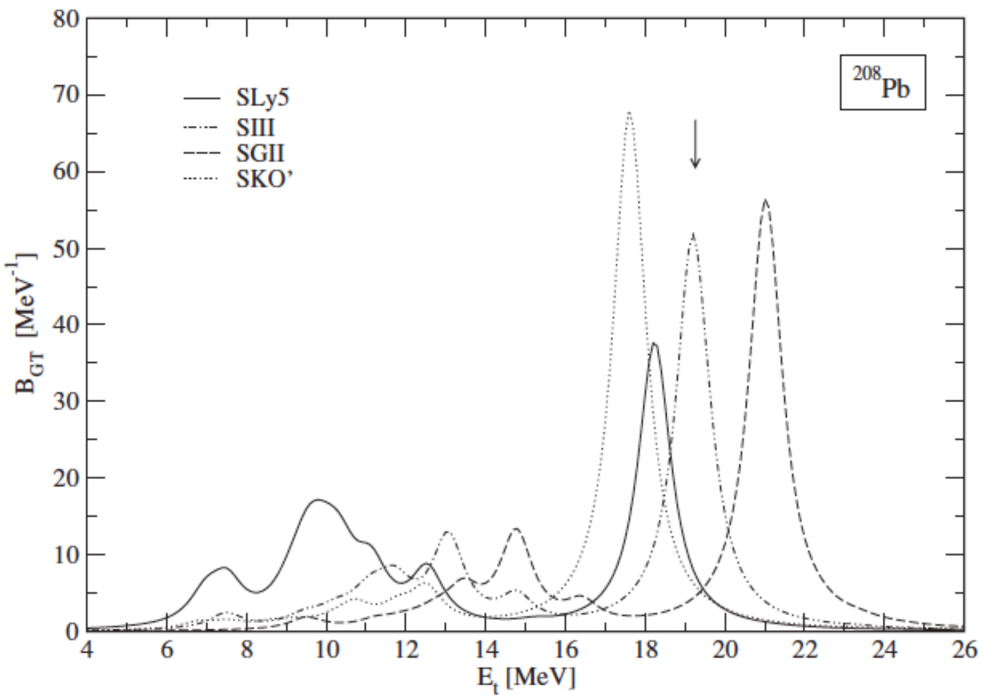


C.L. Bai et al., PRC 83, 054316 (2011)

Key point: the spin-dipole (L=1 coupled to S=1) has three components 0^-, 1^-, 2^- !

Why a new Skyrme interaction ?

We would like to single out a parameter set with the good features of the SLy* forces, but definitely better than these sets as far as the spin-isospin properties are concerned.



SLy5:

$$g_0' = -0.14$$

Fit of SAMi (Aizu-Milano)

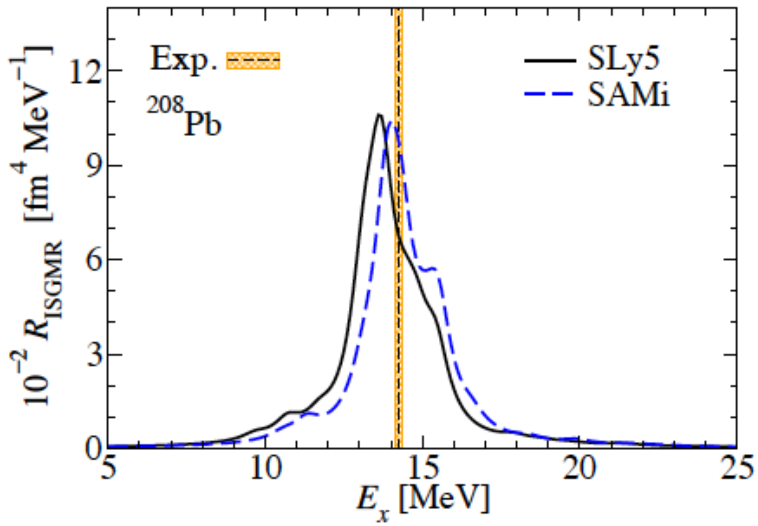
- Binding energies of $^{40,48}Ca$, ^{90}Zr, ^{132}Sn and ^{208}Pb
- Charge radii of $^{40,48}Ca$, ^{90}Zr and ^{208}Pb
- Spin-orbit splittings of 1g and 2f proton levels in ^{90}Zr and ^{208}Pb, respectively
- *Ab-initio* calculation of neutron matter between 0.07 fm^{-3} and 0.4 fm^{-3}
- g_0 and g_0' restricted around 0.15 and 0.35, respectively

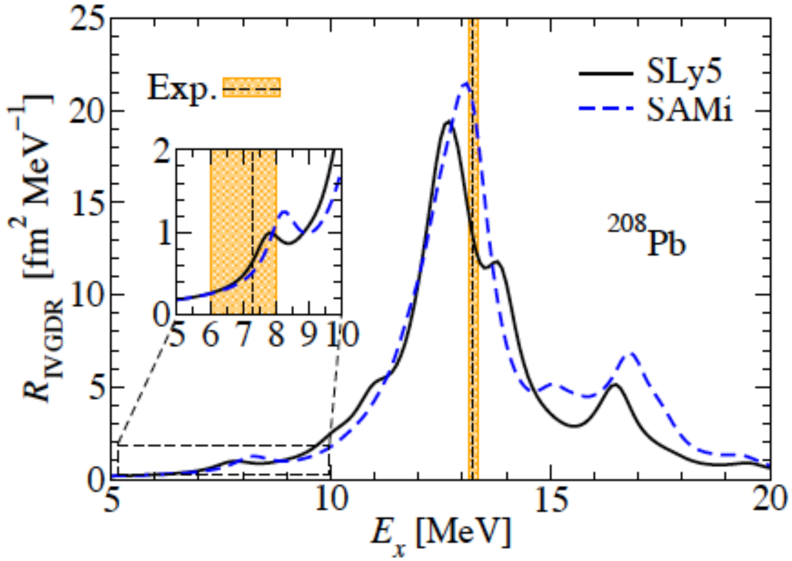
Various properties of nuclear matter, known to be correlated with GR properties, turn out to be quite reasonable

property.	value
ρ_0	0.1587
e_0	-15.9270
m^*_{IS}/m	0.675
m^*_{IV}/m	0.664
J	28.125
L	43.558
K_0	245
G_0	0.150
G'_0	0.350

X. Roca-Maza, G.Colo', H. Sagawa, PRC 86 (2012) 031306(R)

Results for the GMR and GDR





Good agreement with experiment. This is correlated with the realistic values of incompressibility, symmetry energy at saturation and its density dependence – that are, however, not imposed by means of the fit.

II. Beyond mean field: collective modes and the dynamic shell model

Coupling between quasiparticles and vibrations

- Strength functions, spectroscopic factors

Induced interaction

- Understanding nuclear superfluidity and halo nuclei

Coupling to continuum

- Absolute cross sections for inelastic scattering and transfer to excited states

Need to go beyond mean field description: one nucleon transfer experiments show that single-particle have spectroscopic factors smaller than one. This can be taken into account considering the coupling with collective vibrations (Nuclear Field Theory)

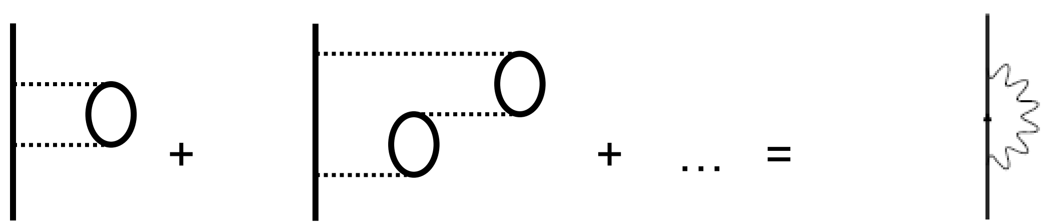
In the Dyson equation

$$[\omega - H_0]G(\vec{r},\vec{r}\,';\omega) = \delta(\vec{r}-\vec{r}\,') + \int d^3r'\,\Sigma(\vec{r},\vec{r}\,';\omega)G(\vec{r},\vec{r}\,';\omega)$$

we assume the self-energy is given by the coupling with RPA vibrations

$$\Sigma(\vec{r},\vec{r}\,';\omega) = \int d^3r_1 d^3r_2\; v(\vec{r},\vec{r}_1)\Pi^{(\mathrm{RPA})}(\vec{r}_1,\vec{r}_2;\omega)v(\vec{r}_2,\vec{r}\,')$$

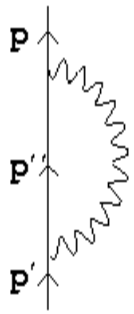
In a diagrammatic way



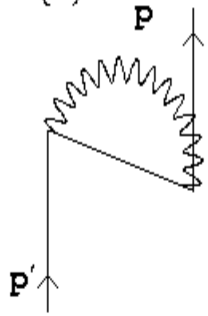
Particle-vibration coupling

SELF ENERGY RENORMALIZATION OF SINGLE-PARTICLE STATES: CLOSED SHELL

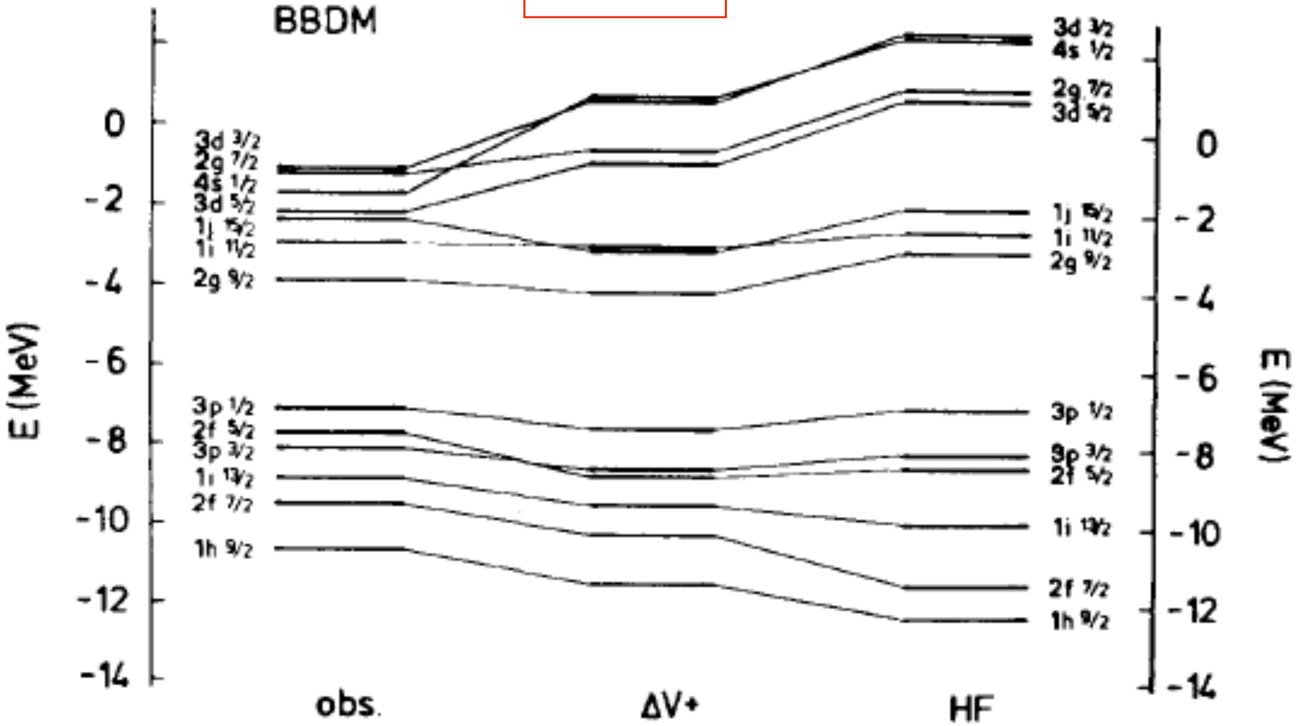
(a)



(b)



^{208}Pb



C. Mahaux, P.F. Bortignon, R.A. Broglia, C.H. Dasso and Mahaux, Phys. Rep. (1985)1 .

Proper treatment of continuum

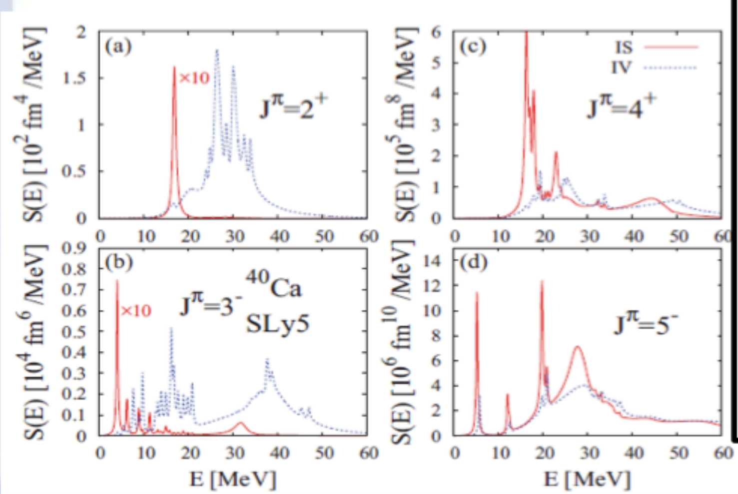
K. Mizuyama, G. Colo', E. Vigezzi, PRC 86, 034318 (2012).

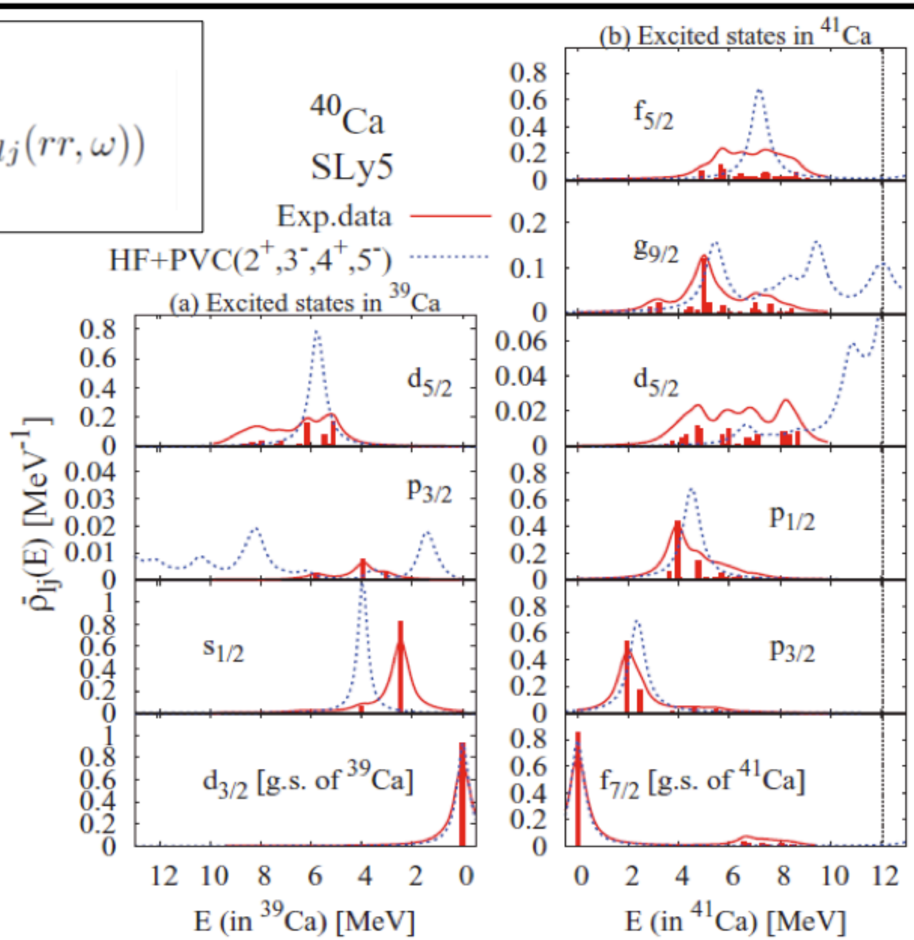
The Dyson equation is written in coordinate space with proper continuum HF wavefunctions, and phonons from continuum-RPA. Adequate for weakly-bound systems.

HF+PVC level density

$$\bar{\rho}_{lj}(\omega) = \frac{\pm 1}{\pi} \int dr \mathrm{Im}\left(G_{lj}(rr,\omega) - G_{Free,lj}(rr,\omega)\right)$$

Cross section
→ **DWBA analysis**
(With phenomenological optical pot.)
→ **Experimental Spectroscopic factor**





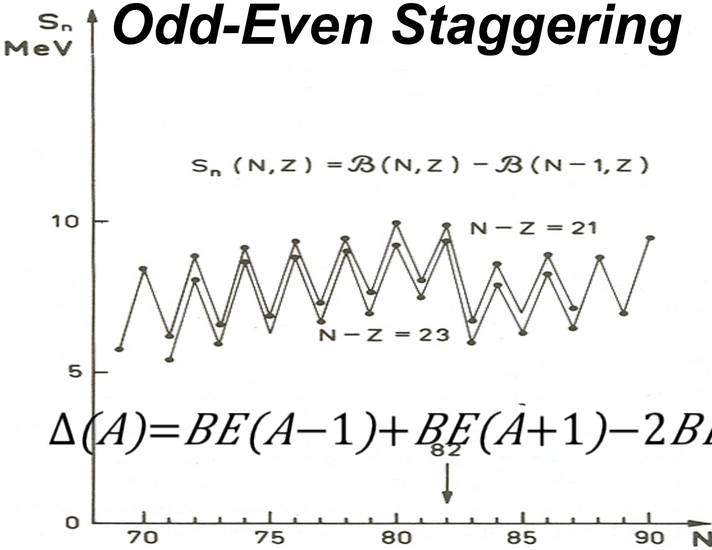
Nuclear Data Sheets 107, 225 (2006)

Nuclear Superfluidity

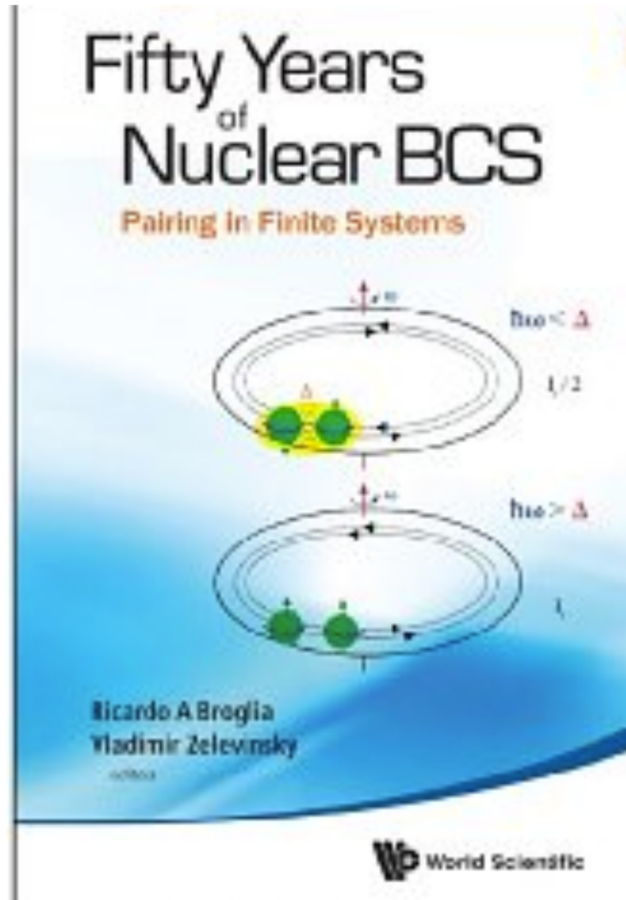
Different behaviour from **even** to **odd** open shell nuclei

__**Fermions pair together**__ in bound states (Cooper pairs): (quasi)bosons

Odd-Even Staggering



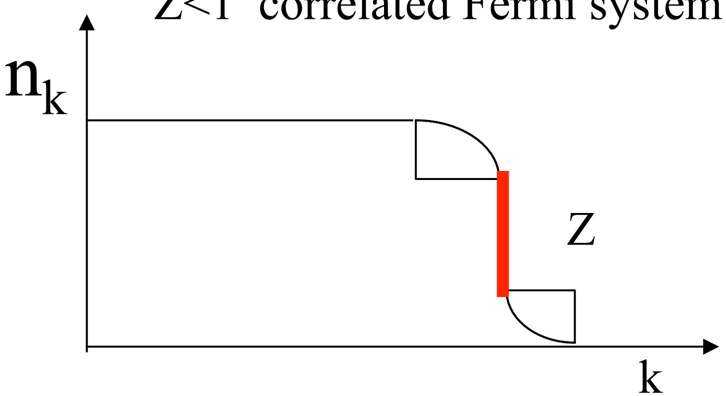
$$\Delta(A) = BE(A-1) + BE(A+1) - 2BE(A)/2$$



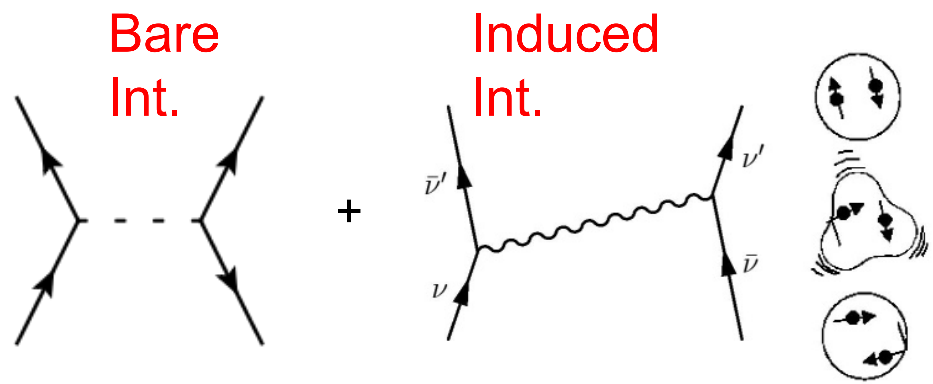
Theoretical progress in the microscopic description of superfluid nuclei beyond mean field: pairing induced interaction

By extending the Dyson equation to the case of superfluid nuclei (Nambu-Gor'kov), it is possible to consider the effects of the pairing interaction induced by the exchange of phonons:

Z=1 free Fermi gas
Z<1 correlated Fermi system



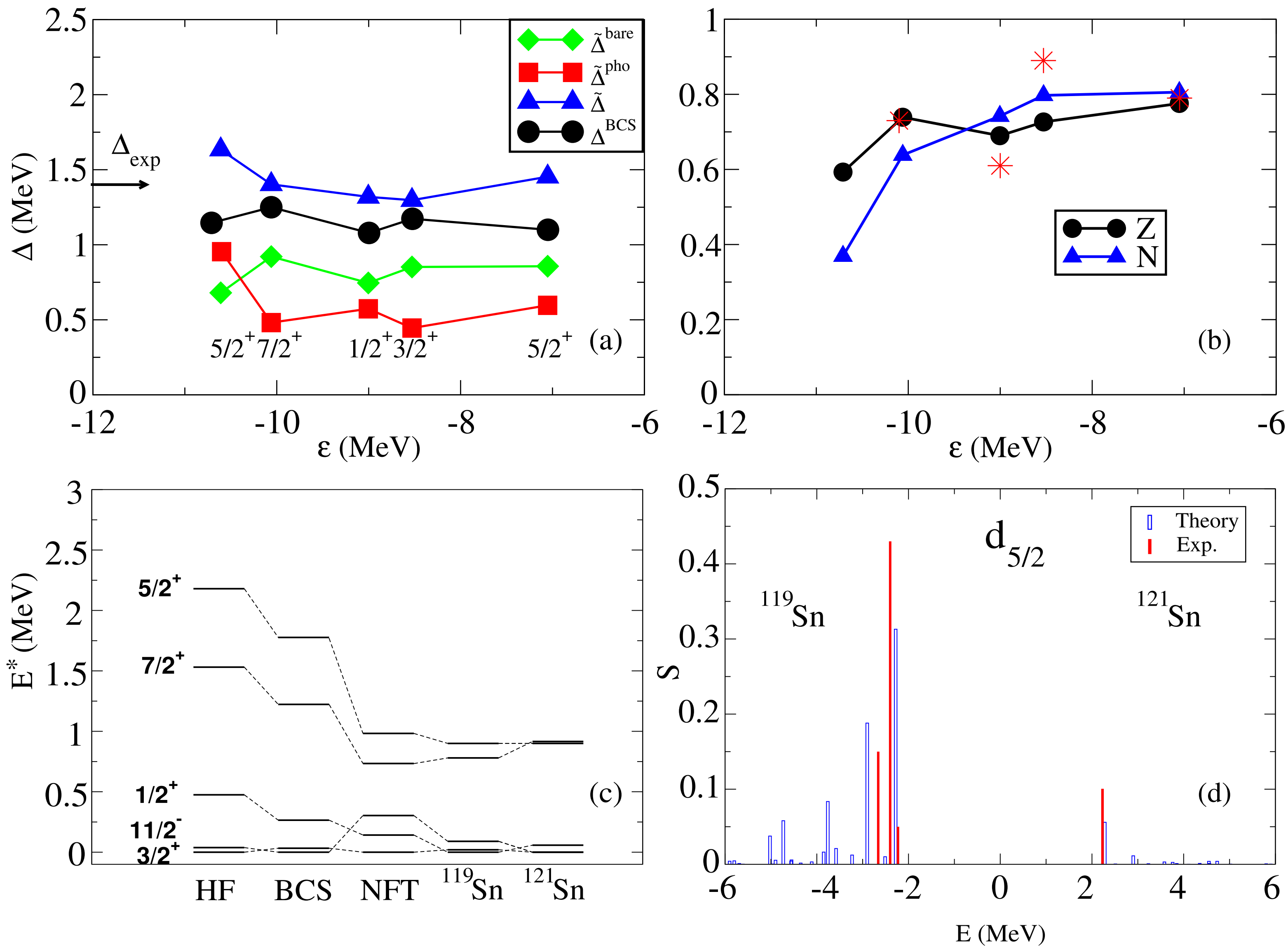
Generalized Gap Equation (schematic)



$$\Delta_k = -\frac{1}{2}\sum_{k'} \frac{Z_k [V^{bare}_{kk'} + V^{ind}_{kk'}] Z_{k'}}{\sqrt{(\tilde{\epsilon}_{k'} - \epsilon_F)^2 + \Delta^2_{k'}}} = \Delta^{bare}_k + \Delta^{ind}_k$$

Renormalized s.p. energy

A consistent picture of open shell nuclei:
pairing gaps, spectroscopic factors, spectra, strength functions



Understanding the structure of halo nuclei

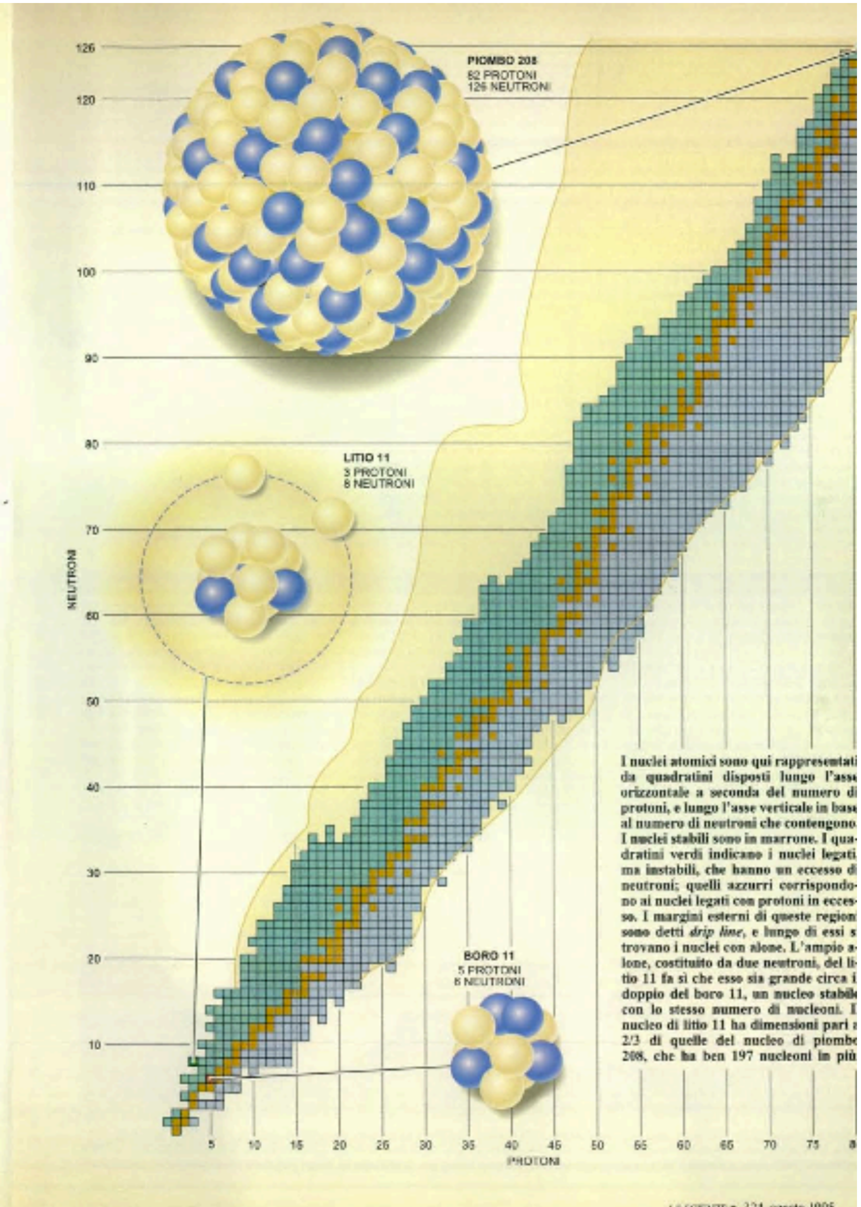


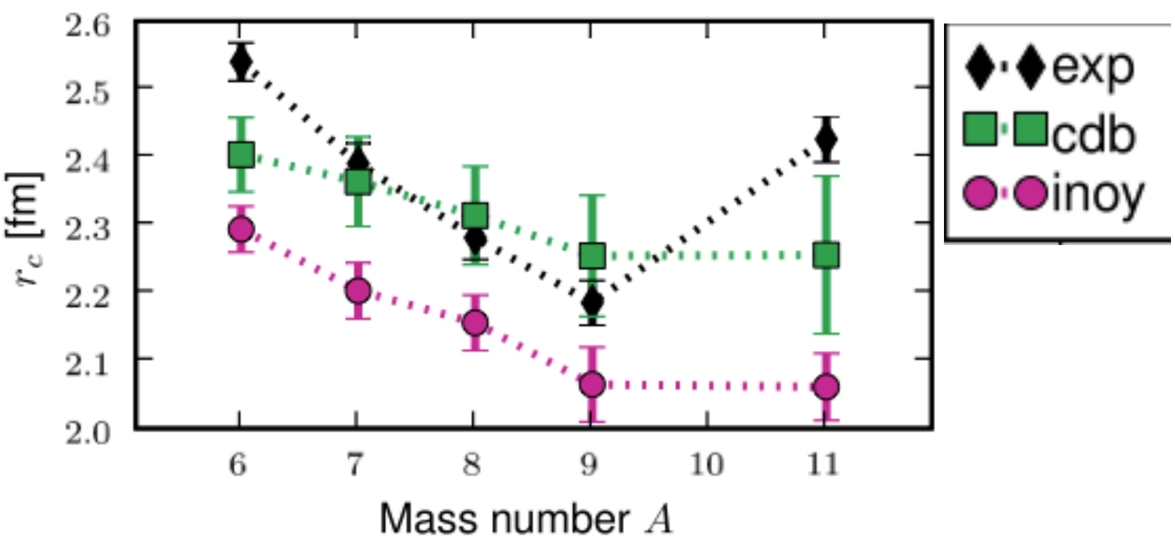
Table 2

Data	Value
S_{2n}	378 ± 5, 369.15 ± 0.65 keV
^{11}Li matter radius	3.27 ± 0.24, 3.12 ± 0.16, 3.55 ± 0.10 fm
^{9}Li matter radius	2.30 ± 0.02 fm
^{11}Li charge radius	2.467(37), 2.423(34), 2.426(34) fm
^{9}Li charge radius	2.217(35), 2.185(33) fm
$R^2_{\mathrm{ch}}(n)$	-0.1161 ± 0.0022 fm^{2*}
TMD(^{10}Li)	FWHM $= 56.1 \pm 1.2$ MeV/c, shape
Correlation c_1	$-1.03(4)$
Correlation c_2	1.41(8)
$\mu(^{11}\mathrm{Li})$	3.6673(25), 3.6712(3) n.m.
$\mu(^{9}\mathrm{Li})$	3.43678(6) n.m.
Q_9	$-30.6(2)$ mb
Q_{11}	$-35.0(49)$, $-31.5(45)$, $-33.3(5)$ mb
Q_{11}/Q_9	1.088 ± 0.015
$\sigma 264_{-2n}$	242(8), 280(30) mb
$\sigma 264_{-1n}$	144(20), 170(20) mb
$\sigma 790_R$	1040(60), 1056(30), 1060(10) mb
$\sigma 790_{-2n}$	213(21), 220(10) mb

^{11}Li: still a challenge for ab initio theories:

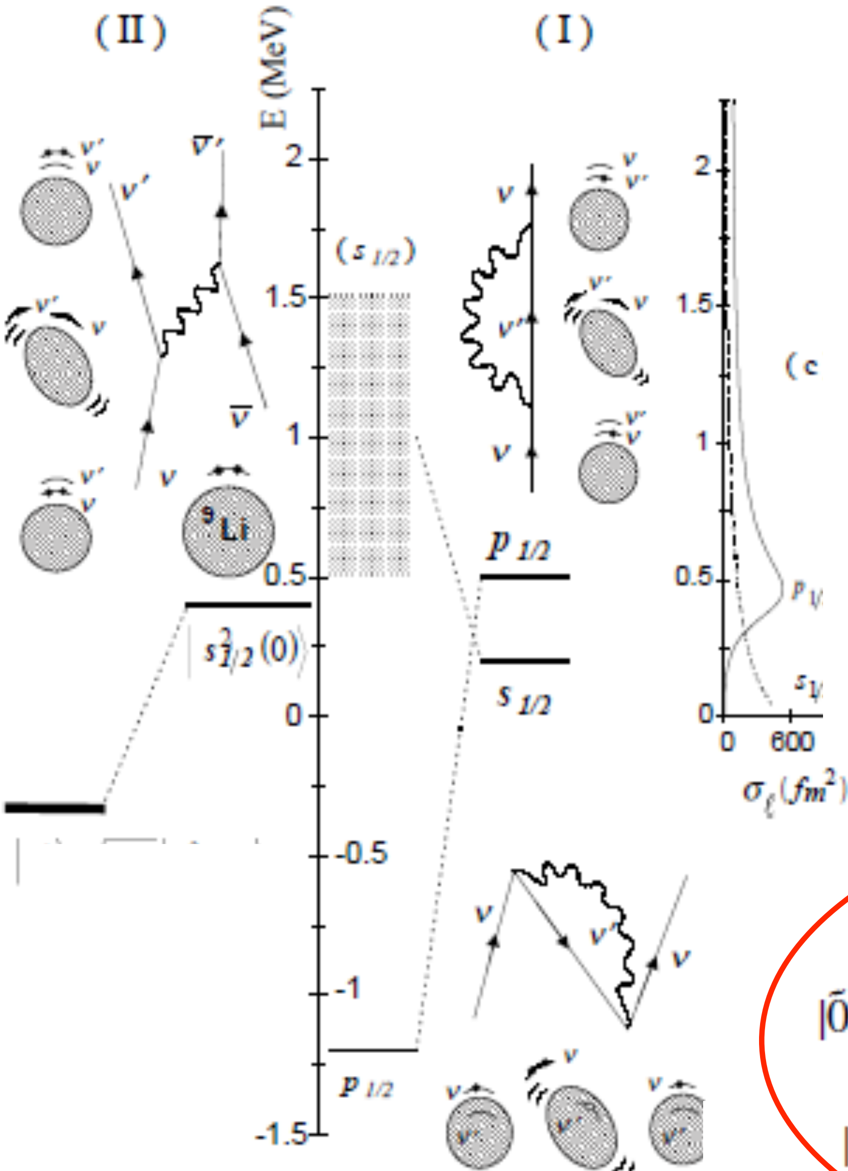
	E (MeV)			
	CDB2k	INOY		Exp.
^{6}Li	29.07(41)	32.33(19)	[32.07]	31.99
^{7}Li	35.56(23)	39.62(40)	[38.89]	39.24
^{8}Li	35.82(22)	41.27(51)	[39.94]	41.28
^{9}Li	37.88(82)	45.86(74)	[42.30]	45.34
^{11}Li	37.72(45)	42.50(95)[a]	[40.44]	45.72(1)

[a]The exponential convergence rate is not fully reached.



C. Forssen,E. Caurier, P. Navratil, PRC 79 021303 (2009)

^{10}Li and ^{11}Li results



		Exp.	Theory	
			particle-vibration +Argonne	mean field
$^{10}_{3}$Li$_7$ (not bound)	s	0.1-0.2 MeV	0.2 MeV (virtual)	~ 1 MeV (virtual)
	p	0.5-0.6 MeV	0.5 MeV (res.)	-1.2 MeV (bound)
$^{11}_{3}$Li$_8$ (bound)	S_{2n}	0.369 MeV	0.33 MeV	2.4 MeV
	s^2, p^2	50% , 50%	41% , 59%	0% , 100%
	$\langle r^2\rangle^{1/2}$	3.55±0.1 fm	3.9 fm	
	$\Delta p_\perp$	48±10 MeV/c	55 MeV/c	

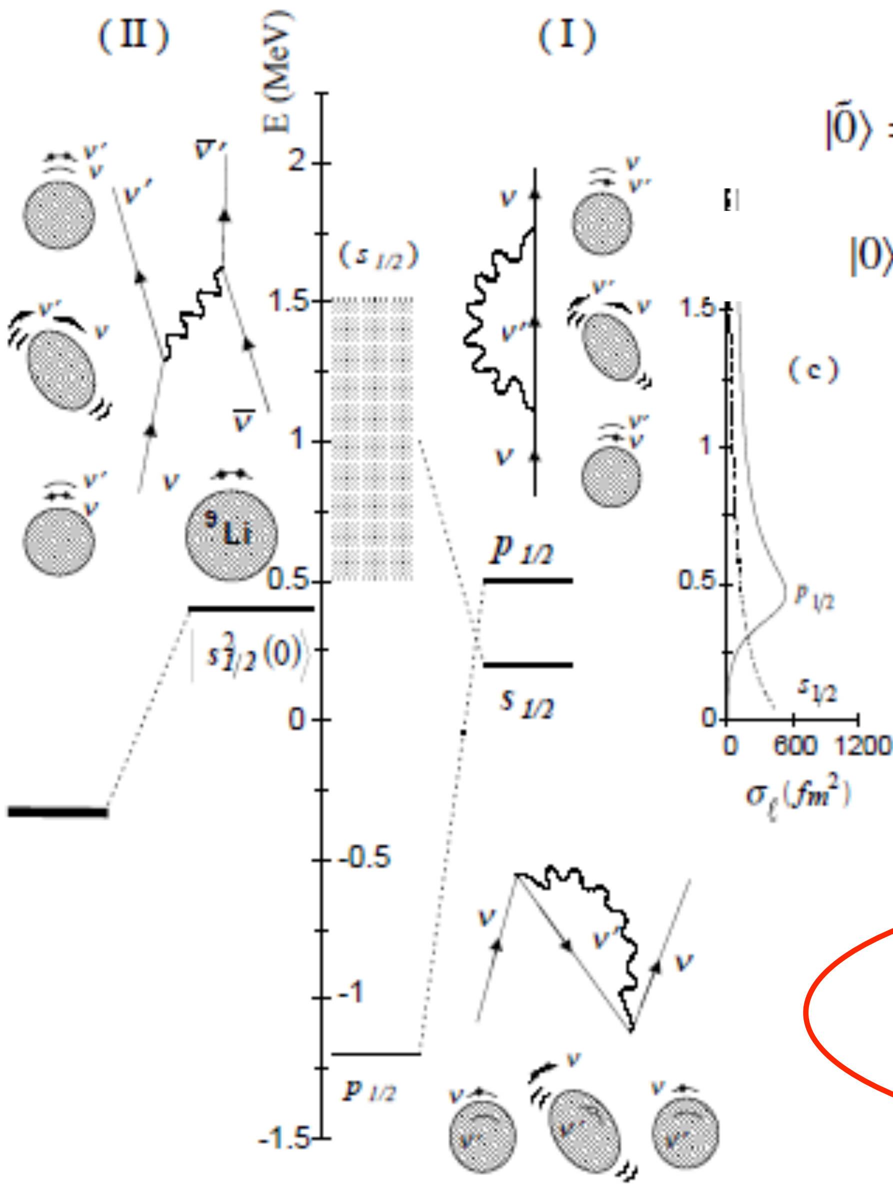
11Li correlated wave function

$$|\tilde{0}\rangle = |0\rangle + 0.7|(ps)_{1^-} \otimes 1^-; 0\rangle + 0.1|(sd)_{2^+} \otimes 2^+; 0\rangle$$

$$|0\rangle = 0.45|s^2_{1/2}(0)\rangle + 0.55|p^2_{1/2}(0)\rangle + 0.04|d^2_{5/2}(0)\rangle$$

Role of coupling to continuum

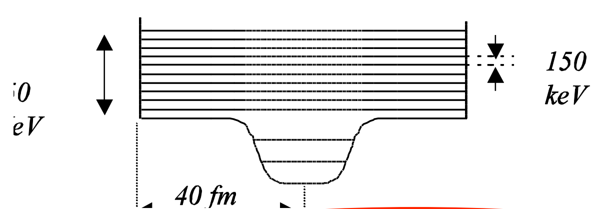
11Li correlated wave function



$$|\tilde{0}\rangle = |0\rangle + 0.7|(ps)_{1^-} \otimes 1^-;0\rangle + 0.1|(sd)_{2^+} \otimes 2^+;0\rangle$$

$$|0\rangle = 0.45|s^2_{1/2}(0)\rangle + 0.55|p^2_{1/2}(0)\rangle + 0.04|d^2_{5/2}(0)\rangle$$

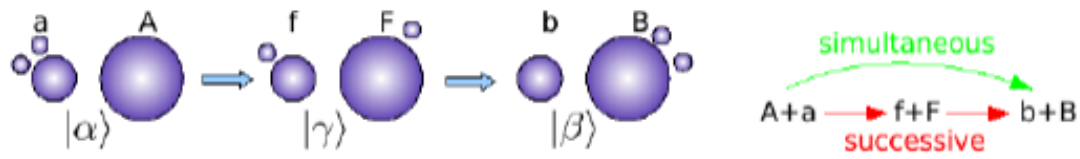
(Saxon - Woods + spin - orbit)

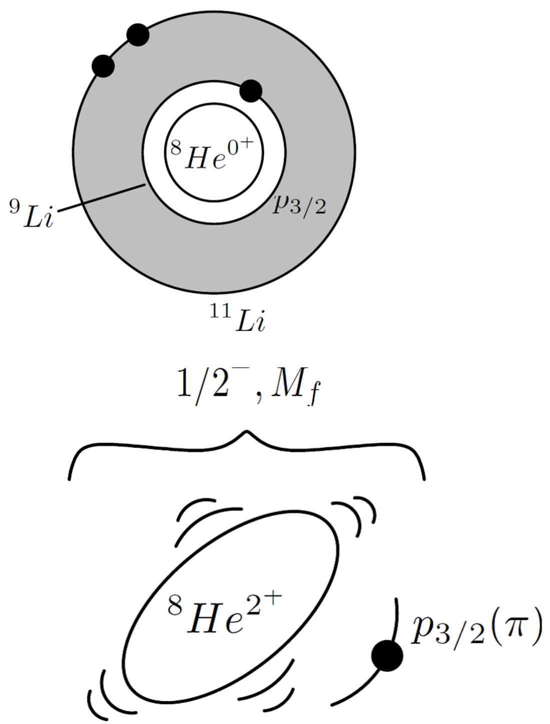


Mixing n/n' ($[\varphi_{nlj} \times \varphi_{n'lj}]0+$) in the continuum creates bound waves

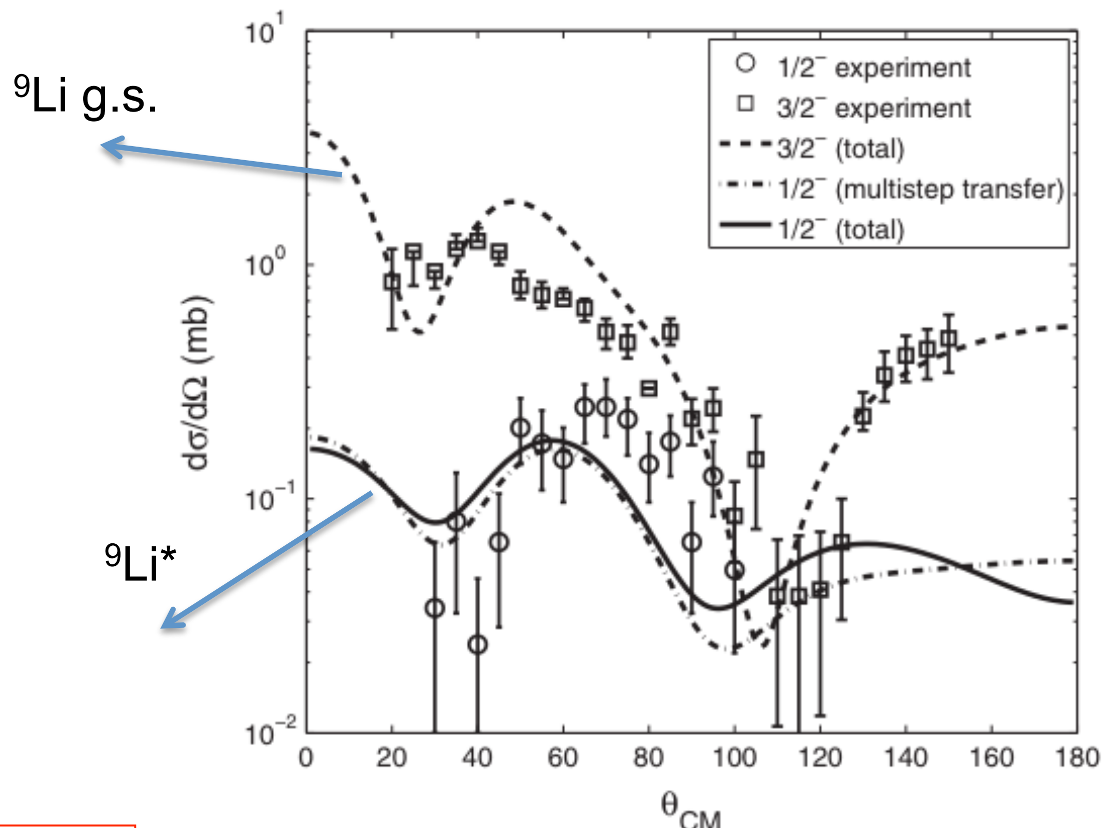
Testing our wavefunction with the $^{11}Li(p,t)^{9}Li$ reaction

simultaneous and successive contributions



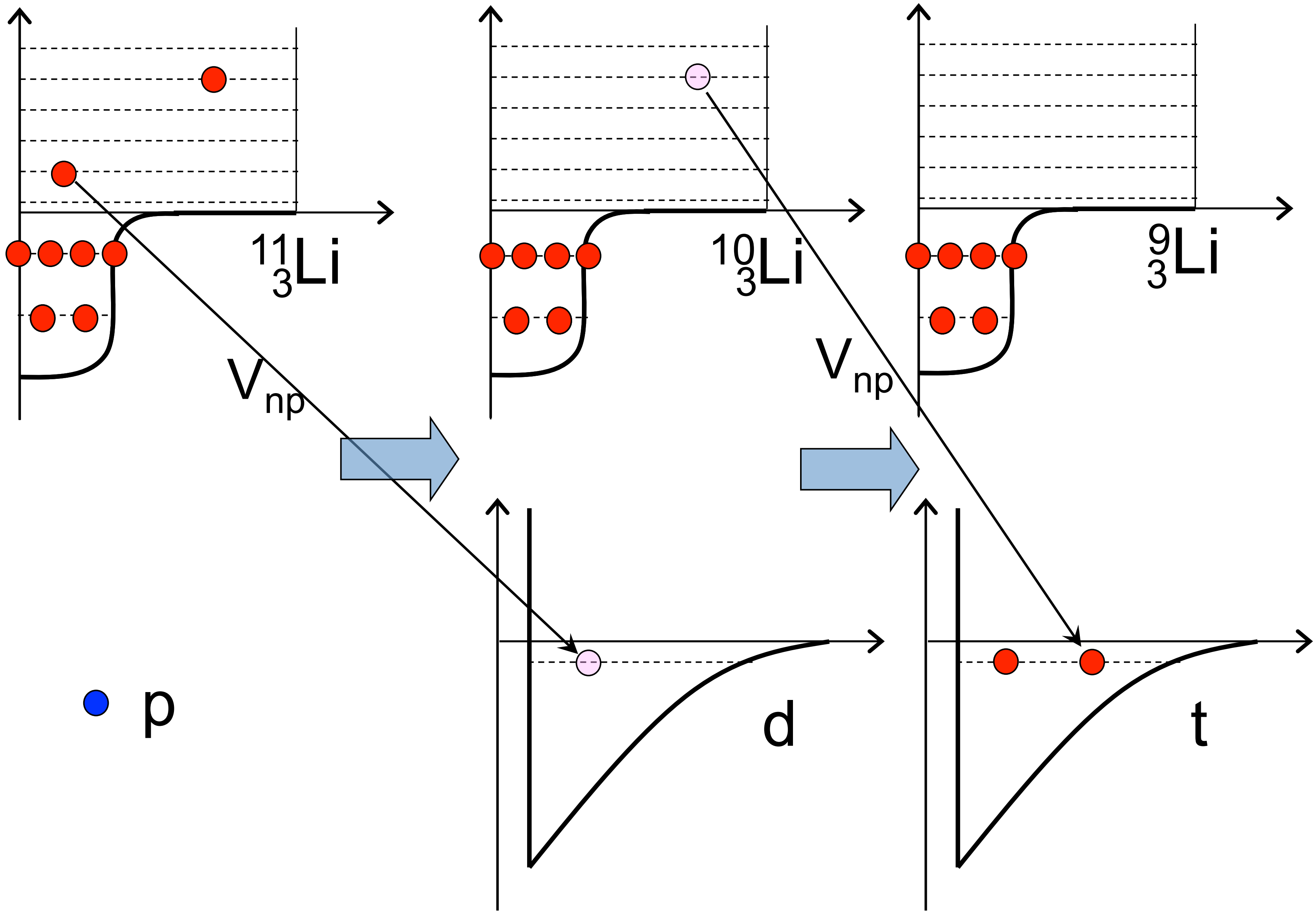


First excited state of ^{9}Li

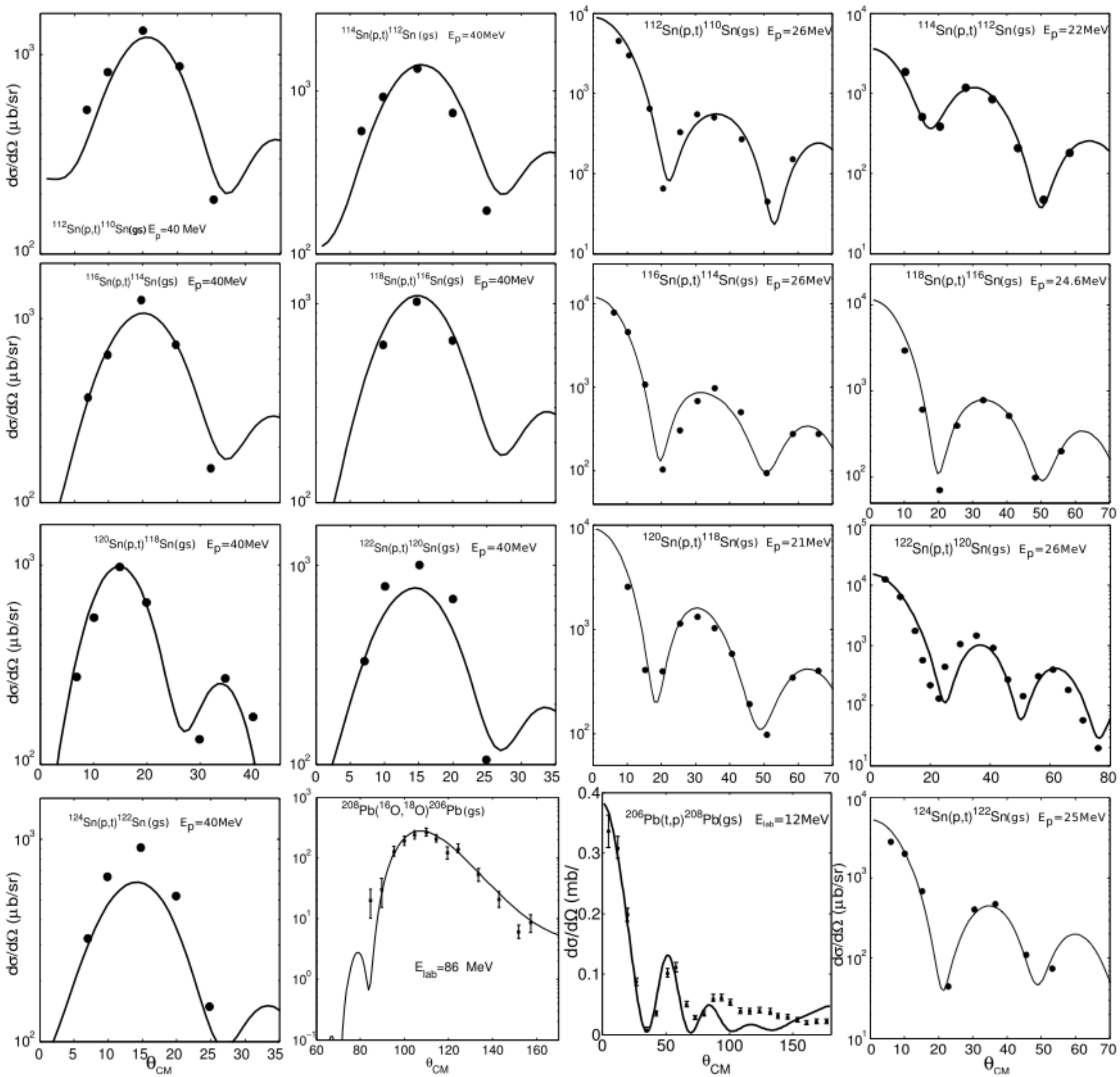


G. Potel et al., PRL 105 (2010) 172502

$$\sum_{n_1,n_2} a_{n_1,n_2}[\psi_{n_1}(r_1)\psi_{n_2}(r_2)]_{00}$$



Success of second order DWBA in the calculation of absolute two-nucleon transfer cross sections: the best probe of pairing correlations

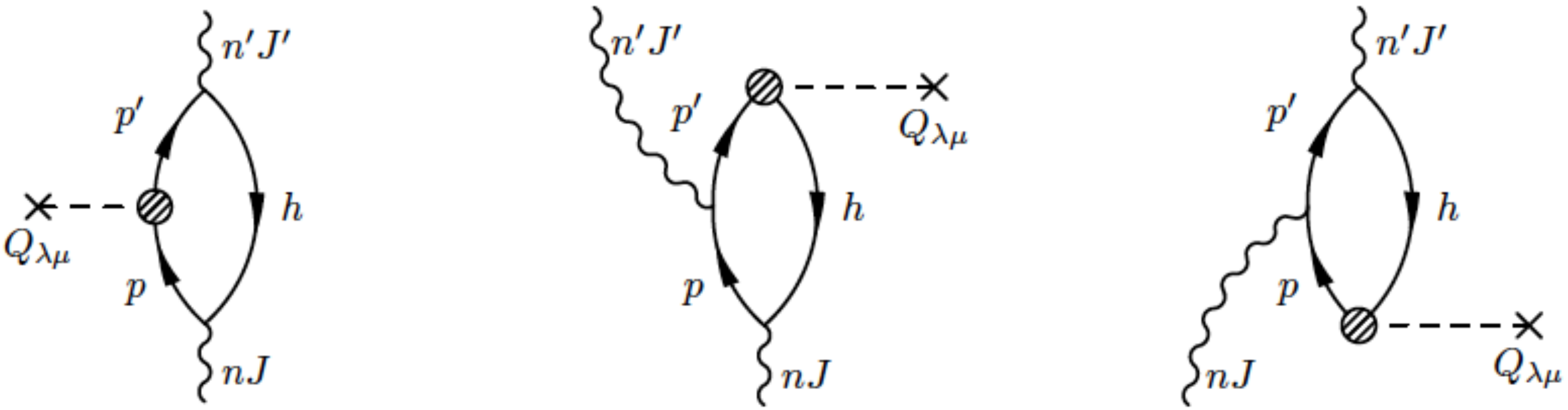


$^{N+2}Sn(p,t)^{N}Sn$

G. Potel et al., Rep. Prog. Phys. 76, 106301 (2013)

γ-decay to excited states

By definition the transitions from excited states to excited states are outside RPA.



γ-decay of the GQR in ^{208}Pb to g.s. and 3^-_1:

M. Brenna, G.C., P.F. Bortignon, PRC 85, 014305 (2012).

Decay to the 3^- state

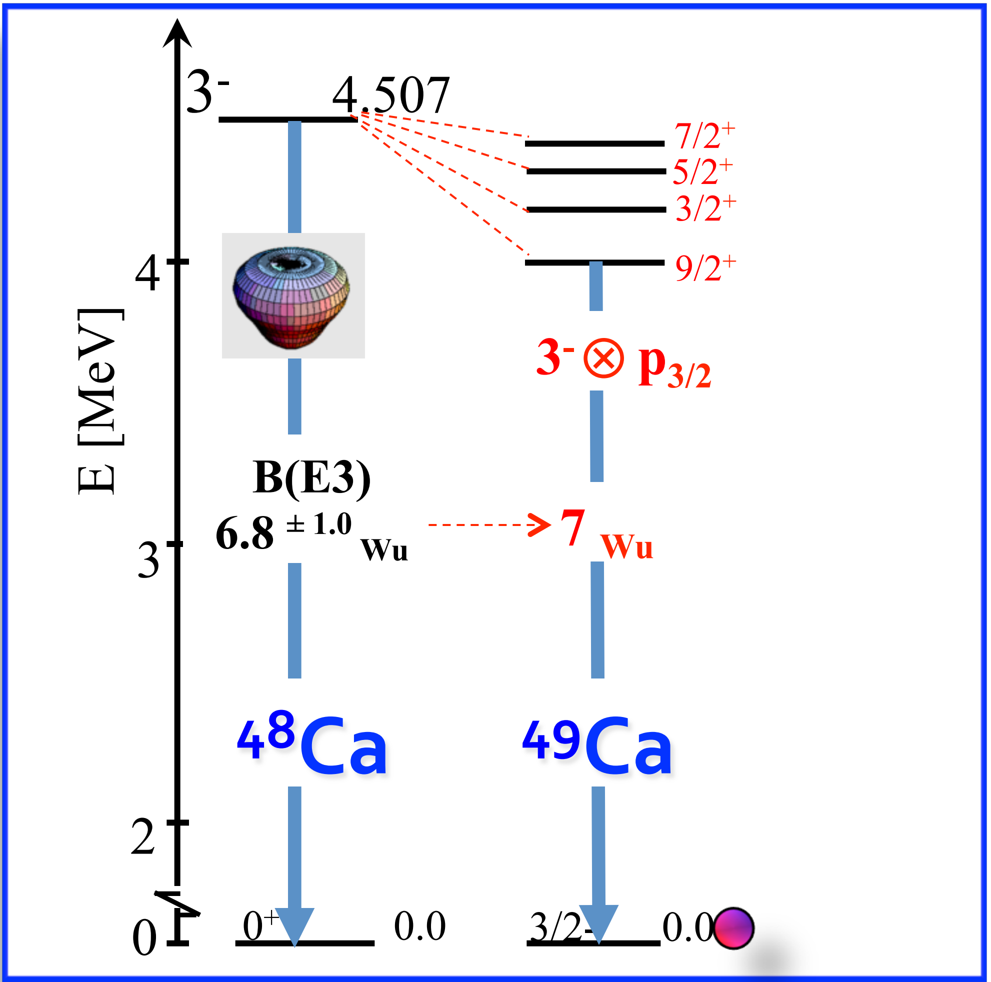
Interaction	E_{tran} [MeV]	Γ_γ [eV]
SLy5	8.66	3.39
SGII	8.58	29.18
SkP	6.99	8.34
LNS	8.90	39.87
Speth et al.,*PRC* **85**, 2310 (1985)	7.99	4.00 – *theor.*
Bortignon et al.,*PLB* **148**, 20 (1984)	8.59	3.50 – *theor.*
Beene et al.,*PRC* **39**, 1307 (1989)	7.99	5.00±5.00 – *exp.*

Theory works at the eV level !

There are several quenching mechanisms acting, since the typical s.p. p-h transition has a width of ≈ 10^3 eV.

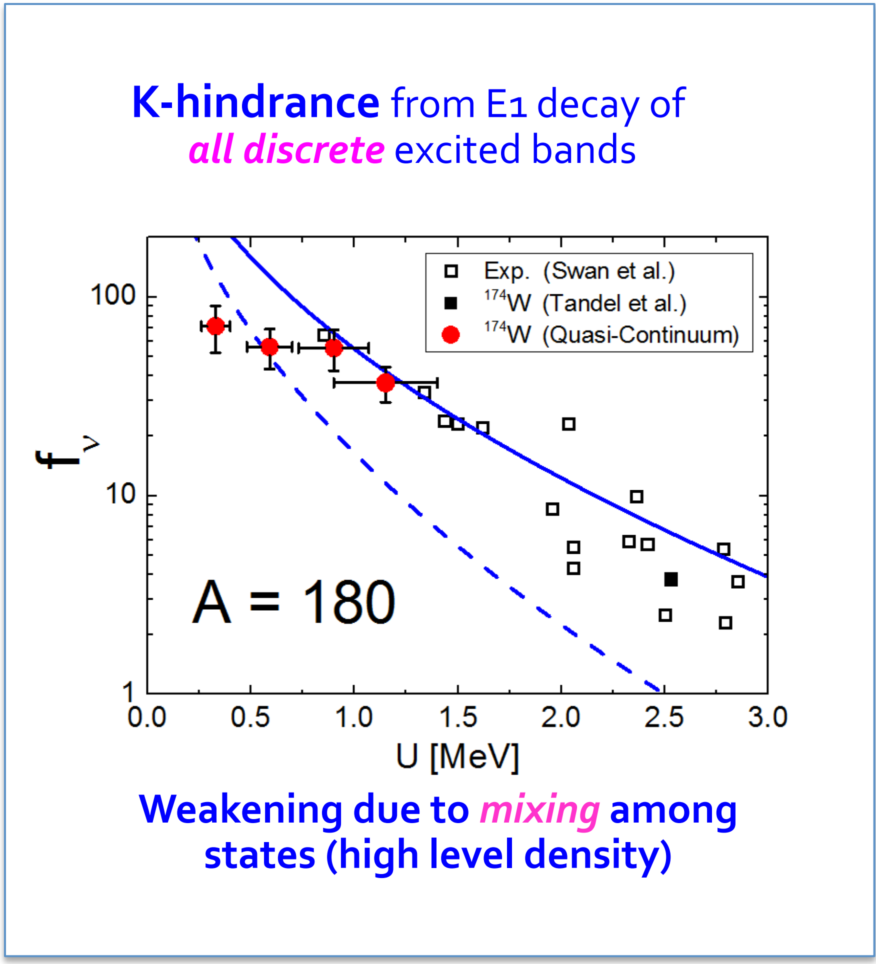
An important point:
cooperation with the experimental gamma-spectroscopy group

Particle-vibration coupling



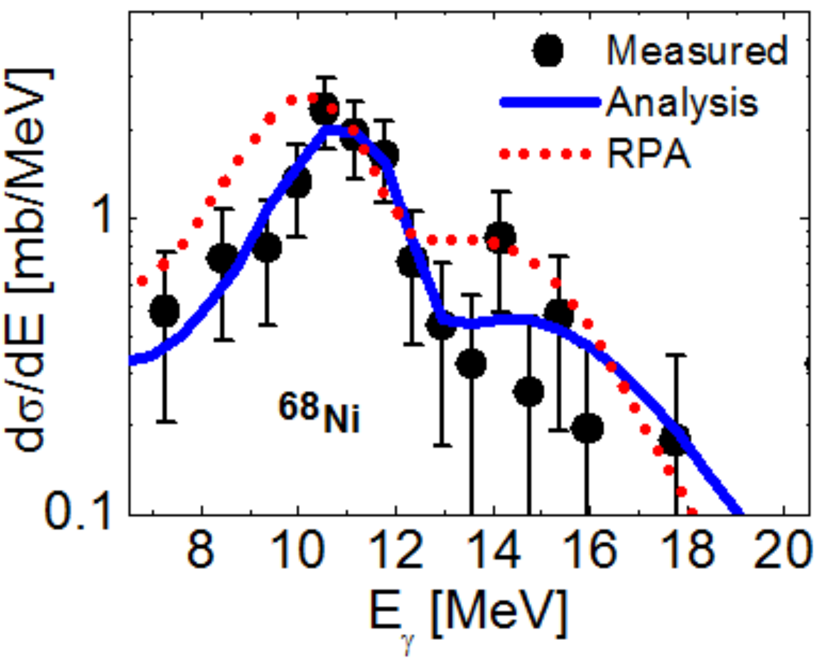
D. Montanari, S. Leoni et al.,
PLB697(2011)288

Order and chaos in rotating nuclei



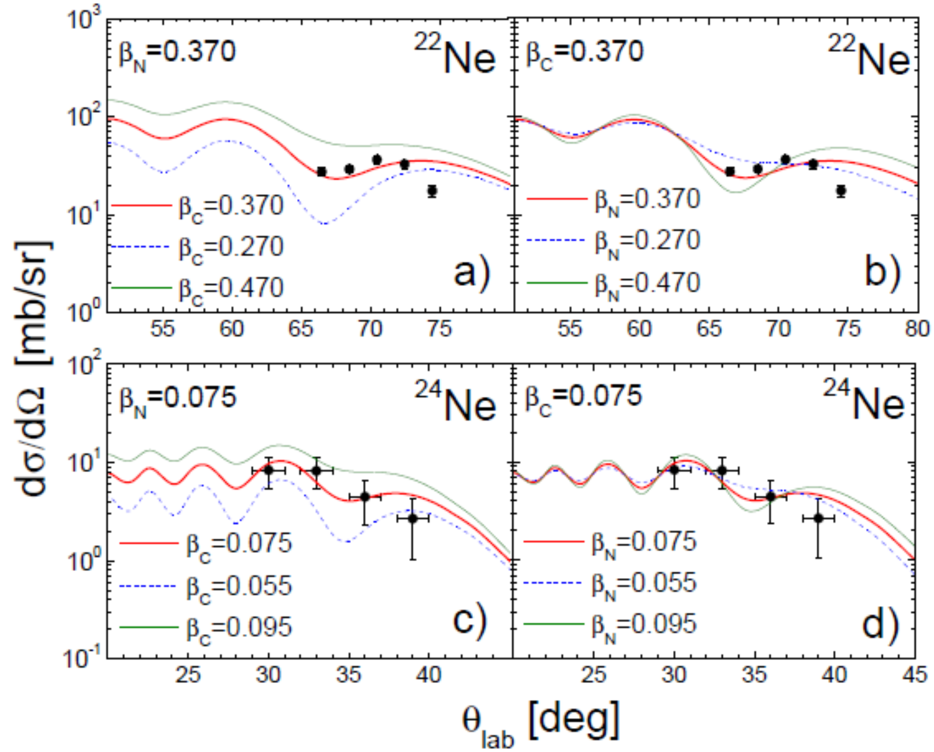
V. Vandone et al.,
PRC88(2013) 034312

Study of low-lying dipole strength



O.Wieland et al.,
PRL 102, 092502 (2009)

Inelastic scattering of exotic nuclei



S. Bottoni et al.,
PRC 85, 064621 (2012)