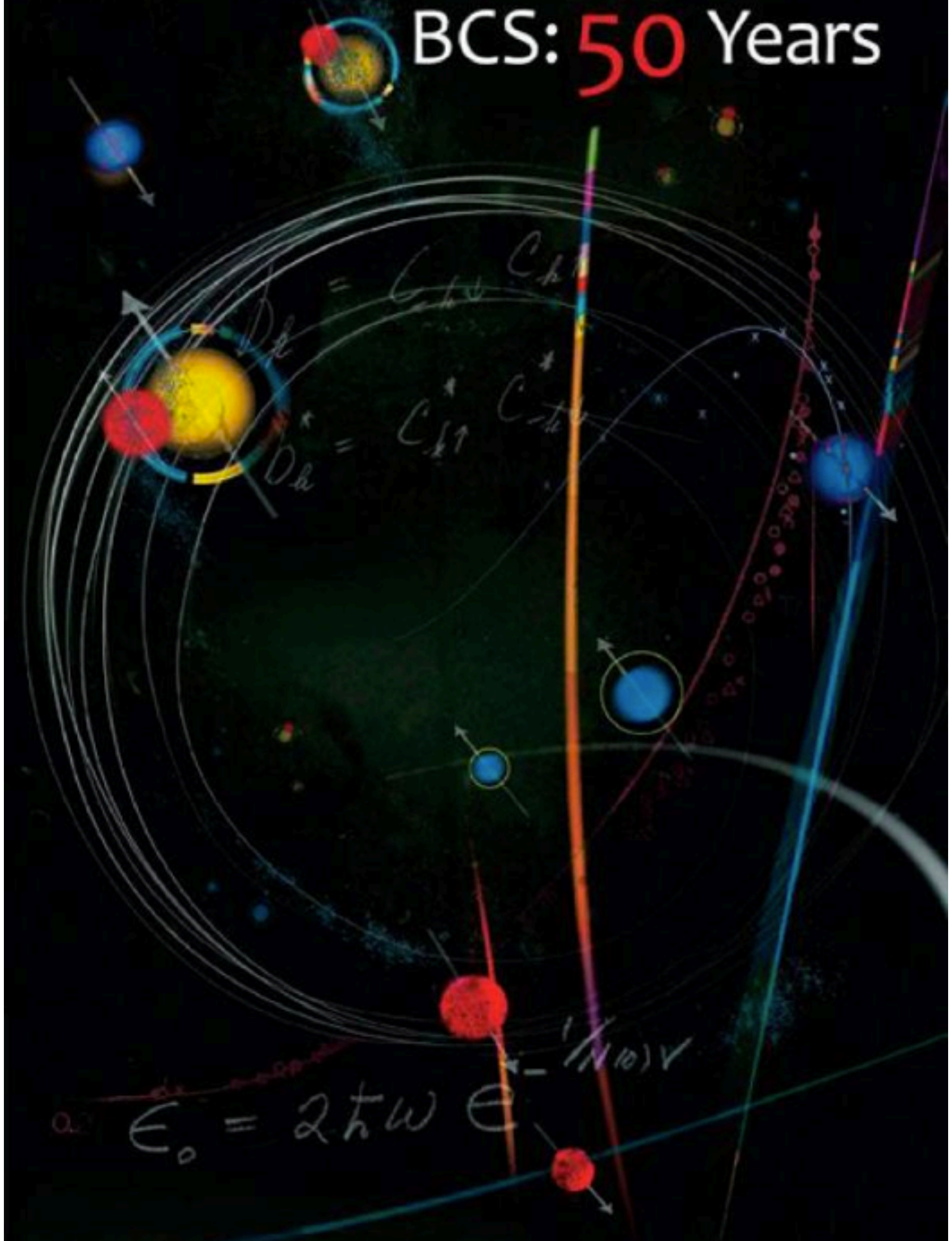
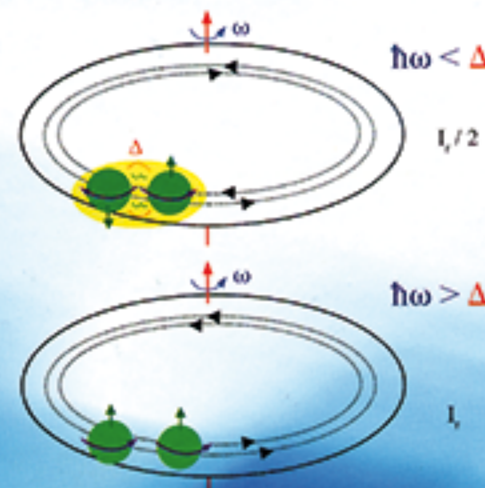
BCS: 50 Years



Edited by Leon N Cooper and Dmitri Feldman

Fifty Years of Nuclear BCS

Pairing in Finite Systems



Ricardo A Broglia
Vladimir Zelevinsky
editors

World Scientific

G. Potel

LLNL, Livermore and NSCL, East Lansing

F. Barranco

Sevilla University

A. Idini

TU Darmstadt

E. Vigezzi

INFN Milano

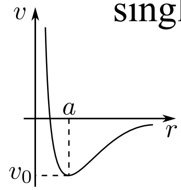
Classical localization and quantal ZPF

$\delta x \delta k \geq 1 \qquad \varepsilon = \frac{\hbar^2 k^2}{2M} \qquad \delta k = \frac{\delta \varepsilon}{\hbar v_F} \qquad (v_{F/c} \approx 0.3)$

$\boxed{\text{structure}}$

Independent motion of

single nucleons



$a \approx 1$ fm

$v_0 = -100$ MeV

$\delta\varepsilon = |v_0|; \delta x \approx a$

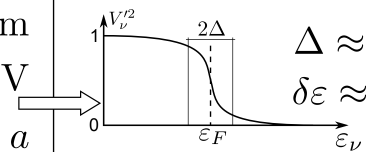
$\delta x \delta k = \frac{a|v_0|}{\hbar v_F} \geq 1$

quantality parameter

$q = \frac{\hbar v_F}{a|v_0|} \approx 0.6 \lesssim 1$

delocalization

pairs of nucleons



$\Delta \approx 1$ MeV

$\delta\varepsilon \approx 2\Delta; \delta x = \xi$

$\delta x \delta k = \frac{\xi 2\Delta}{\hbar v_F} \geq 1$

correlation length

$\xi = \frac{\hbar v_F}{2\Delta} \approx 30 \text{ fm} \gg R$

long range correlation

emergent property: generalized rigidy in

3D-space | gauge space

¿how does a short range force lead to

single-nucleon mean free paths | pairing correlations over distances

larger than nuclear dimension?

$2R \approx 20/k_F$

answer: quantal fluctuations

$\boxed{\text{reactions}}$

single particle transfer, e.g. *(p,d)*

$\frac{2R}{a} \approx 15$

absolute cross section reflects the full nucleon probability amplitude distribution, and does not depend of the specific choice of v_{np}

Cooper pair transfer, e.g. *(p,t)*

$\frac{\xi}{a} \approx 30$

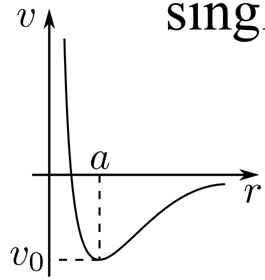
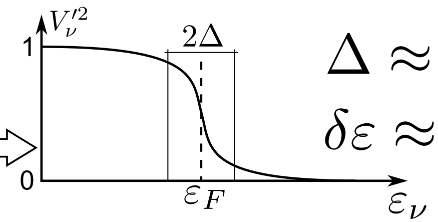
Successive and simultaneous transfer amplitude contributions to the absolute cross section carry equally efficiently information concerning pair correlations

Classical localization and quantal ZPF

$\delta x \delta k \geq 1 \qquad \varepsilon = \frac{\hbar^2 k^2}{2M} \qquad \delta k = \frac{\delta \varepsilon}{\hbar v_F} \qquad (v_{F/c} \approx 0.3)$

$\boxed{\text{structure}}$

Independent motion of

single nucleons	pairs of nucleons
	
$a \approx 1$ fm	$\Delta \approx 1$ MeV
$v_0 = -100$ MeV	$\delta\varepsilon \approx 2\Delta; \delta x = \xi$
$\delta\varepsilon = \lvert v_0 \rvert; \delta x \approx a$	
$\delta x \delta k = \frac{a \lvert v_0 \rvert}{\hbar v_F} \geq 1$	$\delta x \delta k = \frac{\xi 2\Delta}{\hbar v_F} \geq 1$
quantality parameter	correlation length
$q = \frac{\hbar v_F}{a \lvert v_0 \rvert} \approx 0.6 \lesssim 1$	$\xi = \frac{\hbar v_F}{2\Delta} \approx 30 \text{ fm} \gg R$
delocalization	long range correlation

emergent property: generalized rigidy in

3D-space	gauge space

¿how does a short range force lead to

single-nucleon mean free paths | pairing correlations over distances

larger than nuclear dimension?

$$2R \approx 20/k_F$$

answer: quantal fluctuations

$\boxed{\text{reactions}}$

single particle transfer, e.g. *(p,d)*	Cooper pair transfer, e.g. *(p,t)*
$\frac{2R}{a} \approx 15$	$\frac{\xi}{a} \approx 30$
absolute cross section reflects the full nucleon probability amplitude distribution, and does not depend of the specific choice of v_{np}	Successive and simultaneous transfer amplitude contributions to the absolute cross section carry equally efficiently information concerning pair correlations

Systematics (silent revolution)

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

A+2 = 112,114 116,118,120,122

Guazzoni et al, PRC
1999(122),2004(116),2006(112),
2008(120),2011(118,124),2012(114)

Major breakthrough

$^{1}H(^{11}Li,^{9}Li)^{3}H$

Tanihata et al, PRL 2008

Spectroscopic amplitudes

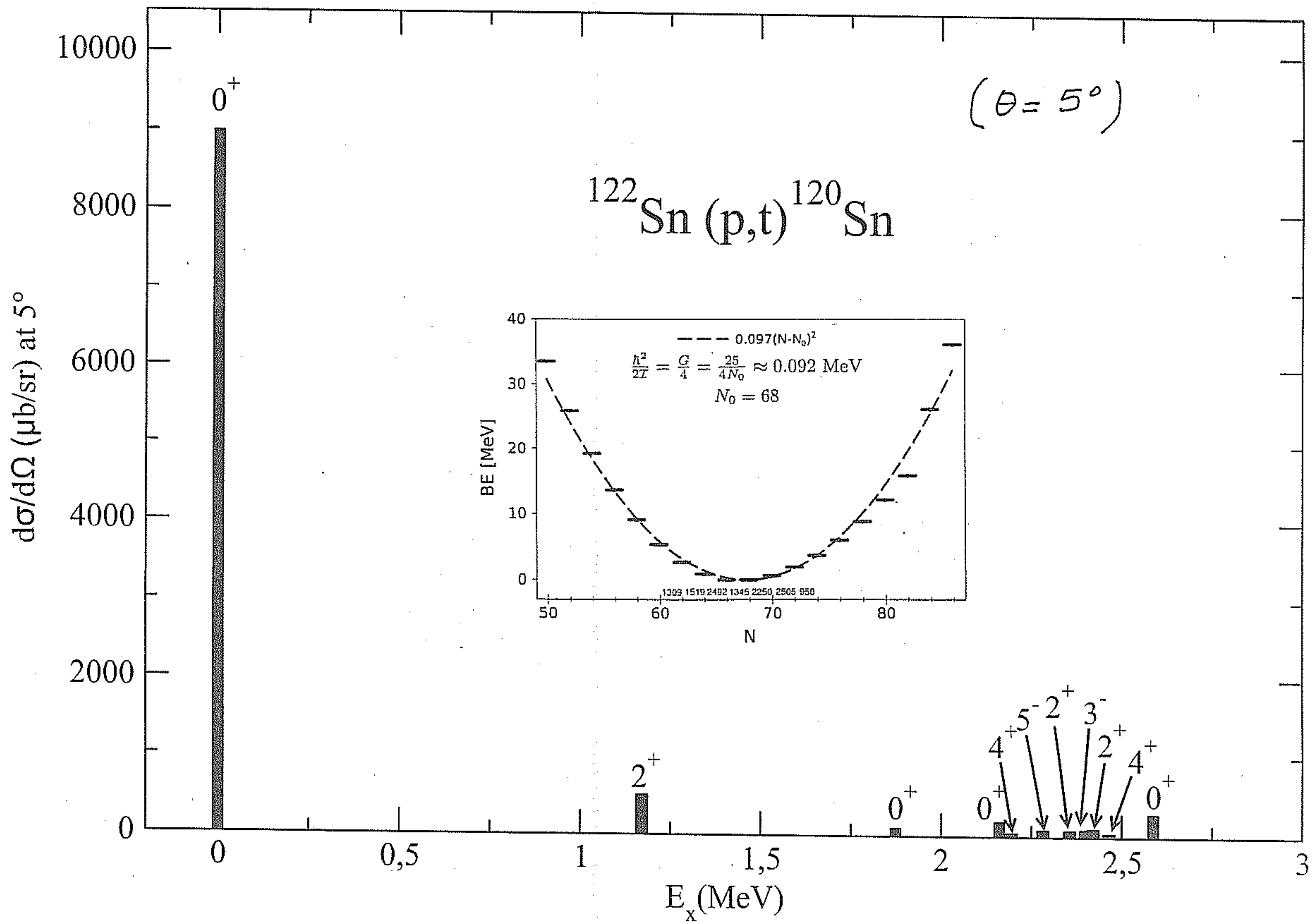
Pairing rotations $^{A+2}Sn(p,t)^{A}Sn(gs)$

U_ν V_ν (BCS)

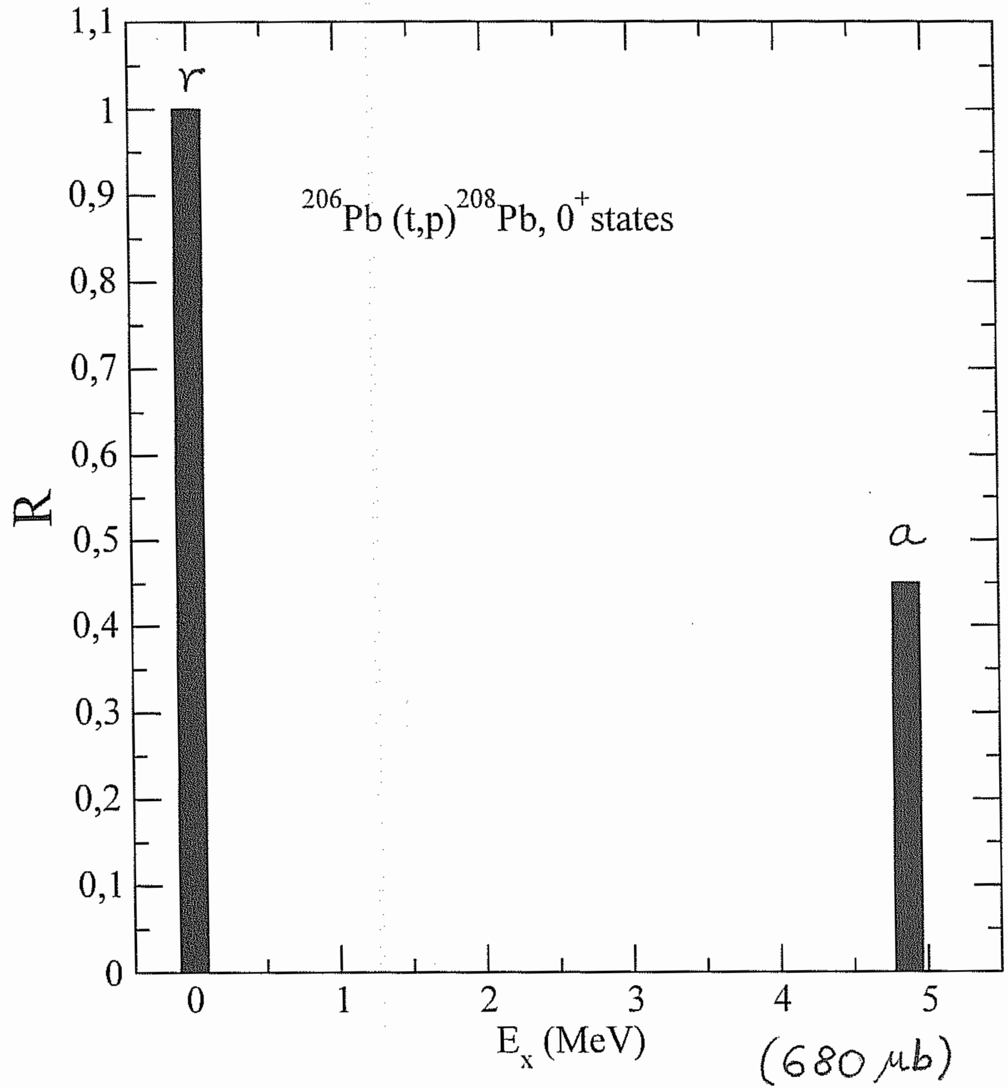
Pairing vibrations $^{208}Pb(p,t)^{206}Pb(gs)$

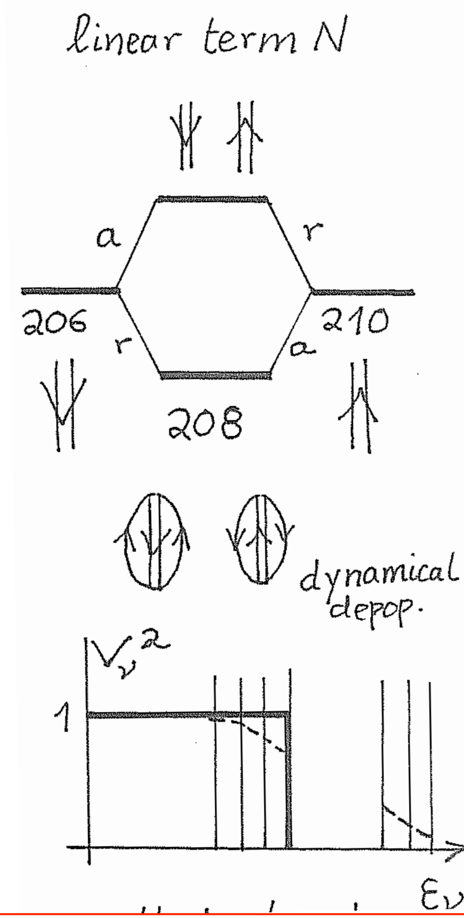
X_r Y_r (RPA)

Coherent states: essentially exact



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





Well developed vibrational nands, anharmonicities, cf. Bortignon et al., PL 76B(1978)153; Clark et al. PRL 96 (2006)032501)

$$P^\dagger = \sum_{\nu>0} a^\dagger_\nu a^\dagger_{\bar{\nu}}$$

$$x = \frac{2G\Omega}{D} = GN(0)$$

$$x > 1$$

$$\alpha_0 =< P^\dagger >= \frac{\Delta}{G} \approx 7$$

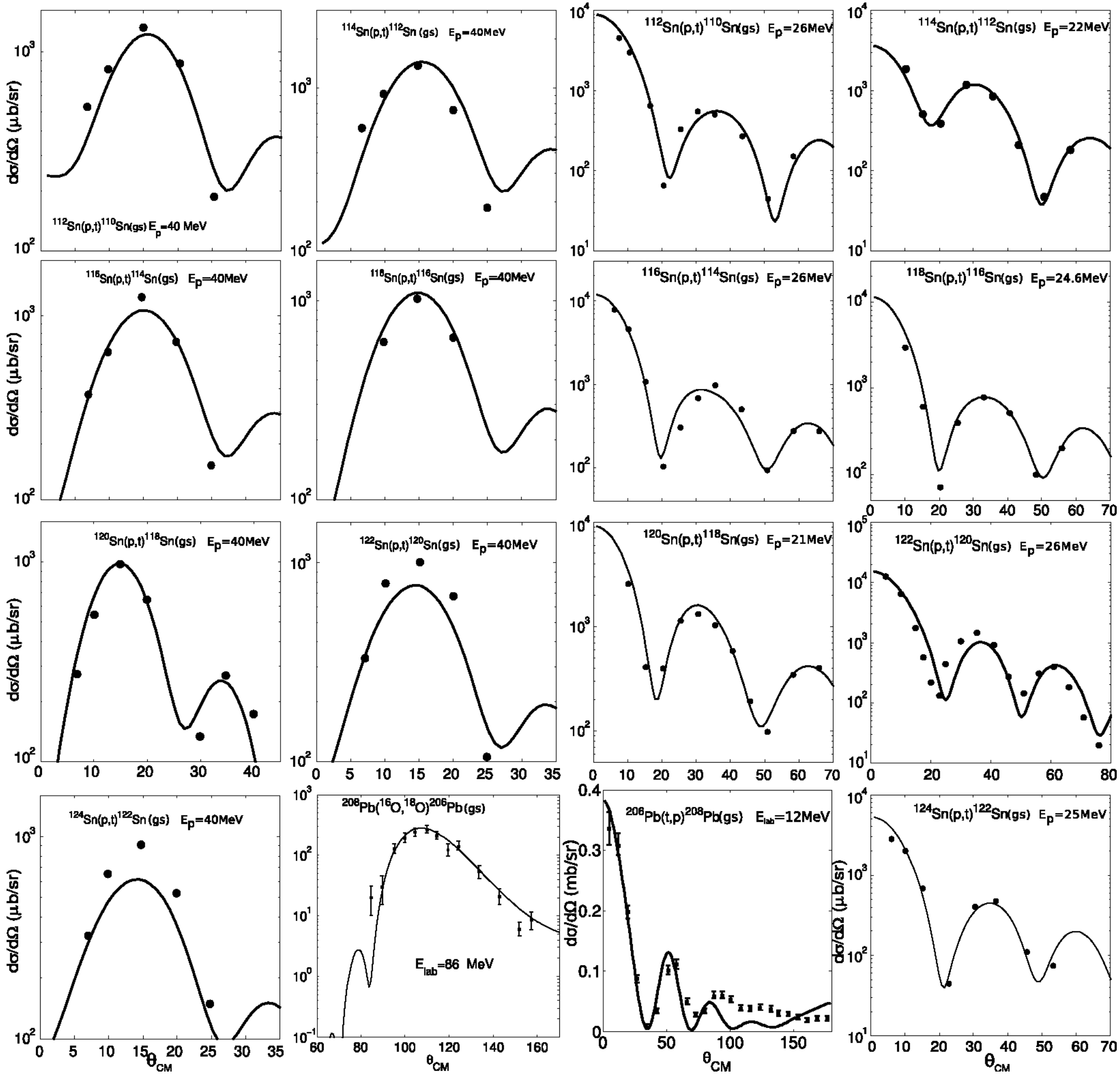
$$x < 1$$

$$\alpha_{dyn} = \frac{1}{G}\frac{<PP^\dagger>^{1/2}+<P^\dagger P>^{1/2}}{2}$$

$$\approx \quad \frac{1}{2}\left(\frac{E_{corr}(A+2)}{G} + \frac{E_{corr}(A-2)}{G}\right) \approx 10$$

$$\frac{\alpha_0}{\alpha_{dyn}} \approx 0.7$$

$$\frac{\beta_2}{(\beta_2)_{dyn}} \approx 3 - 6$$



^{112}Sn(p,t)^{110}Sn(gs) E$_p$=40 MeV
^{114}Sn(p,t)^{112}Sn (gs) E$_p$=40MeV
^{112}Sn(p,t)^{110}Sn(gs) E$_p$=26MeV
^{114}Sn(p,t)^{112}Sn(gs) E$_p$=22MeV
^{116}Sn(p,t)^{114}Sn(gs) E$_p$=40MeV
^{118}Sn(p,t)^{116}Sn(gs) E$_p$=40MeV
^{116}Sn(p,t)^{114}Sn(gs) E$_p$=26MeV
^{118}Sn(p,t)^{116}Sn(gs) E$_p$=24.6MeV
^{120}Sn(p,t)^{118}Sn(gs) E$_p$=40MeV
^{122}Sn(p,t)^{120}Sn(gs) E$_p$=40MeV
^{120}Sn(p,t)^{118}Sn(gs) E$_p$=21MeV
^{122}Sn(p,t)^{120}Sn(gs) E$_p$=26MeV
^{124}Sn(p,t)^{122}Sn (gs) E$_p$=40MeV
^{208}Pb(^{16}O,^{18}O)^{206}Pb(gs)
E$_{lab}$=86 MeV
^{206}Pb(t,p)^{208}Pb(gs) E$_{lab}$=12MeV
^{124}Sn(p,t)^{122}Sn(gs) E$_p$=25MeV
dσ/dΩ (μb/sr)
dσ/dΩ (mb/sr)
θ$_{CM}$

Evidence of the Giant Pairing Vibration in the ^{14}C and ^{15}C atomic nuclei

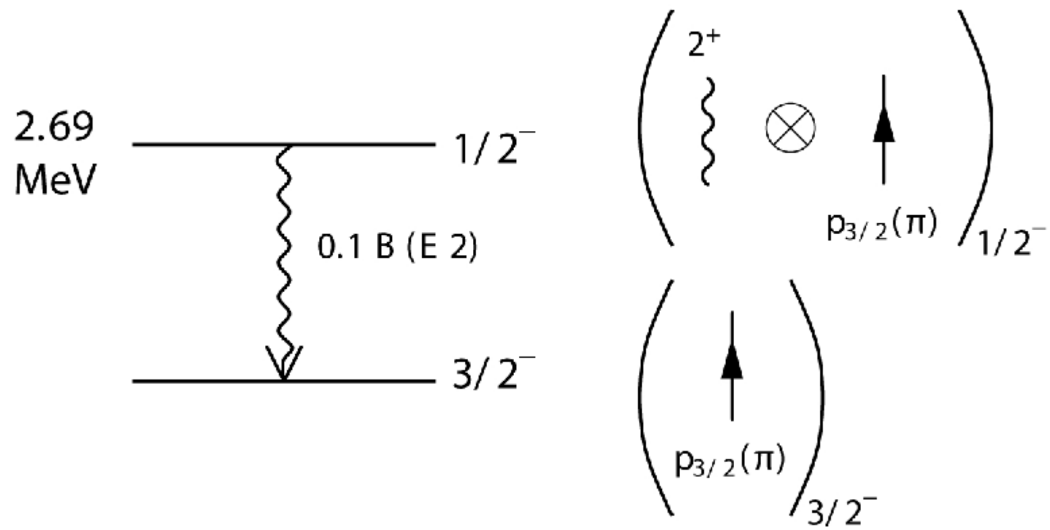
F. Cappuzzello[1,2*], D. Carbone[2], M. Cavallaro[2], M. Bondì[1,2], C. Agodi[2], F. Azaiez[3], A. Bonaccorso[4], A. Cunsolo[2], L. Fortunato[6,7], A. Foti[1,5], S. Franchoo[3], E. Khan[3], R. Linares[8], J. Lubian[8], J. A. Scarpaci[3], A. Vitturi[6,7]

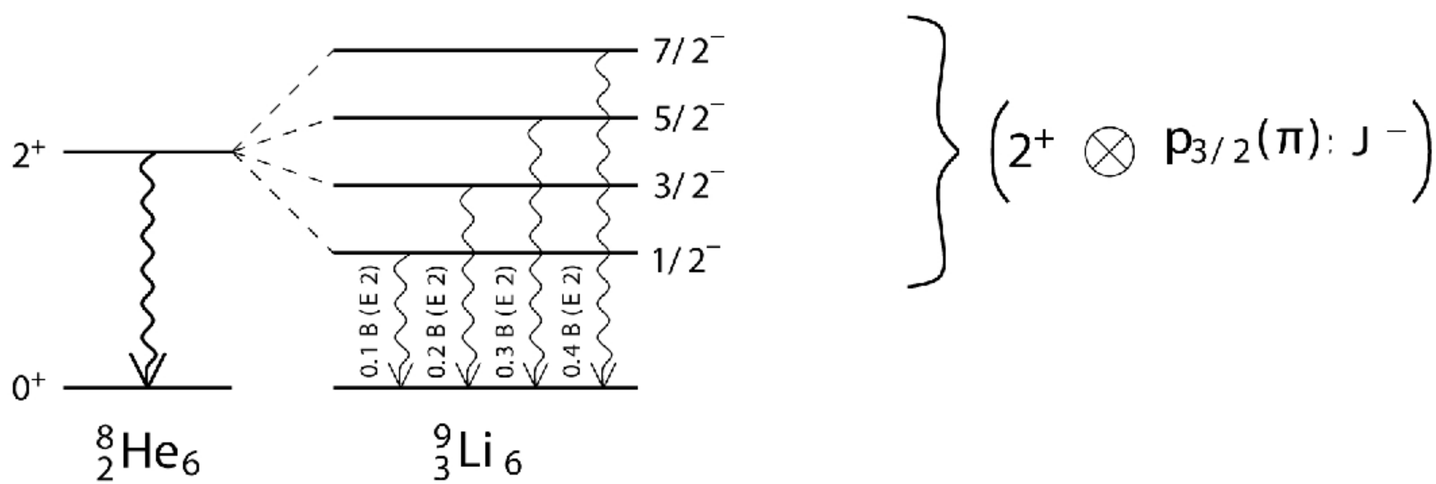
$$^{11}\mathrm{Li(i)}(^{1}\mathrm{H},^{3}\mathrm{H})^{9}\mathrm{Li(f)}$$

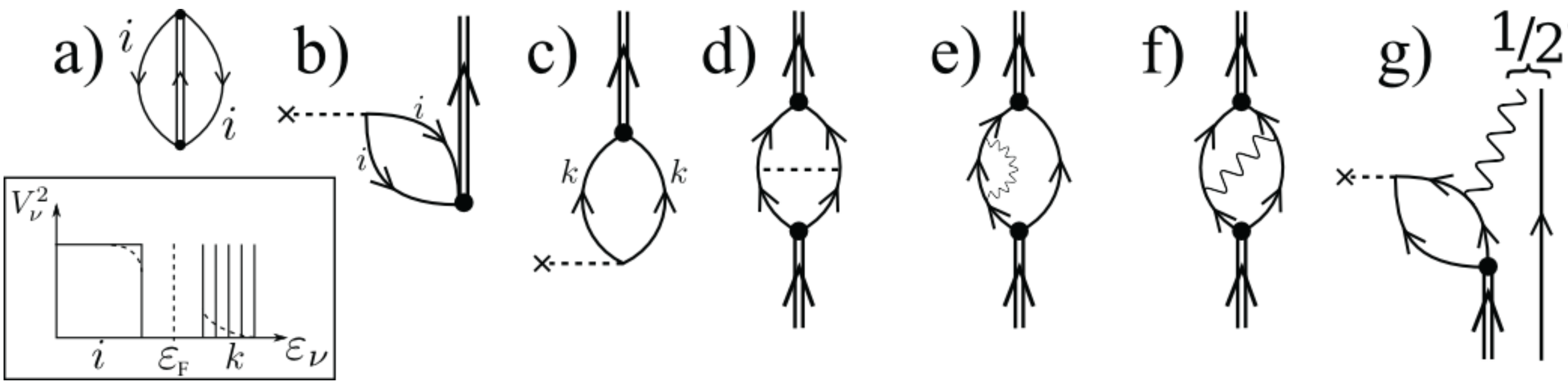
$$|i>=|gs\left(\frac{3}{2}\right)^{-}>$$

$$|f_1>=|gs\left(\frac{3}{2}\right)^{-}>$$

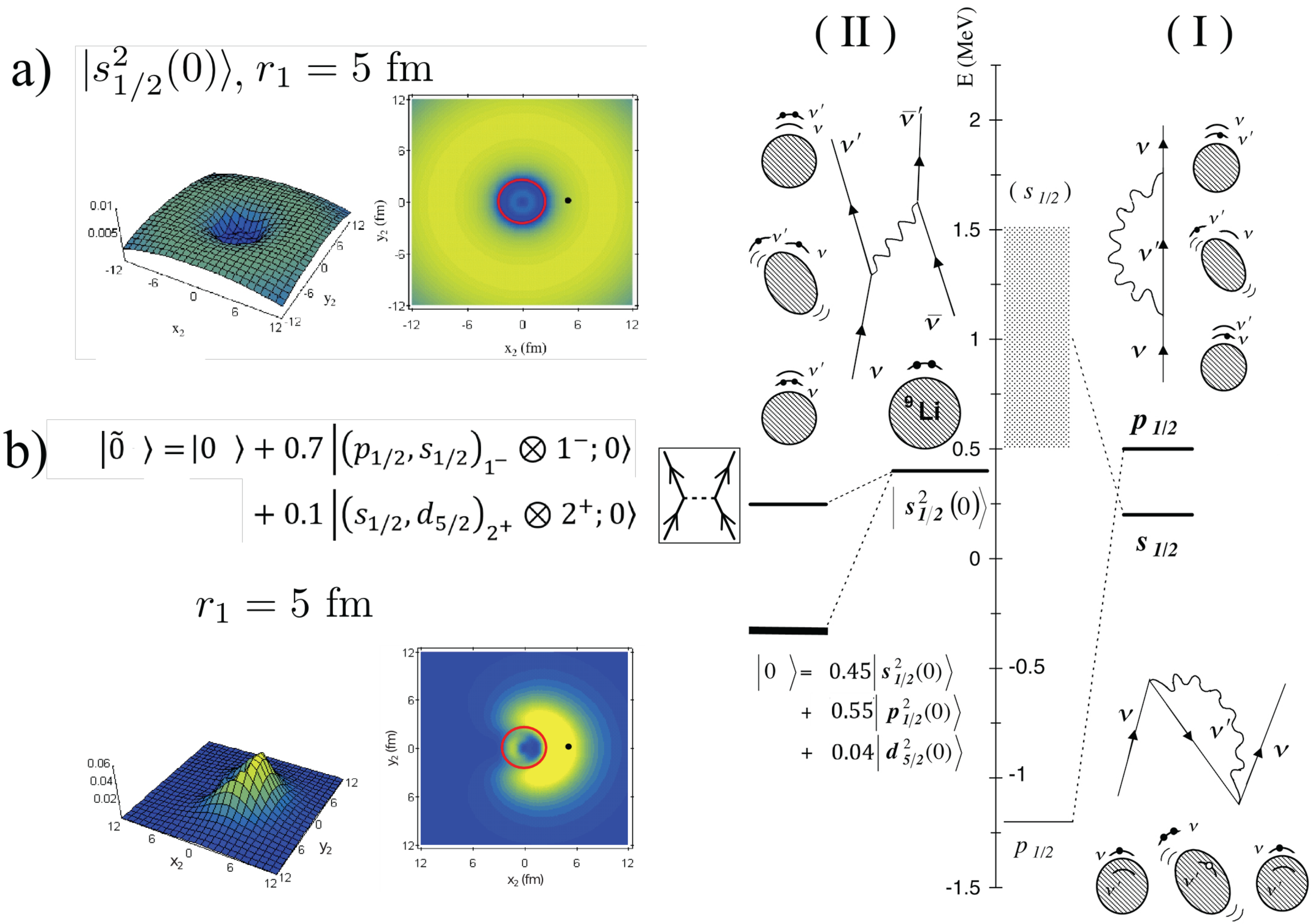
$$|f_2>=|exc\left(\frac{1}{2}\right)^{-}>$$



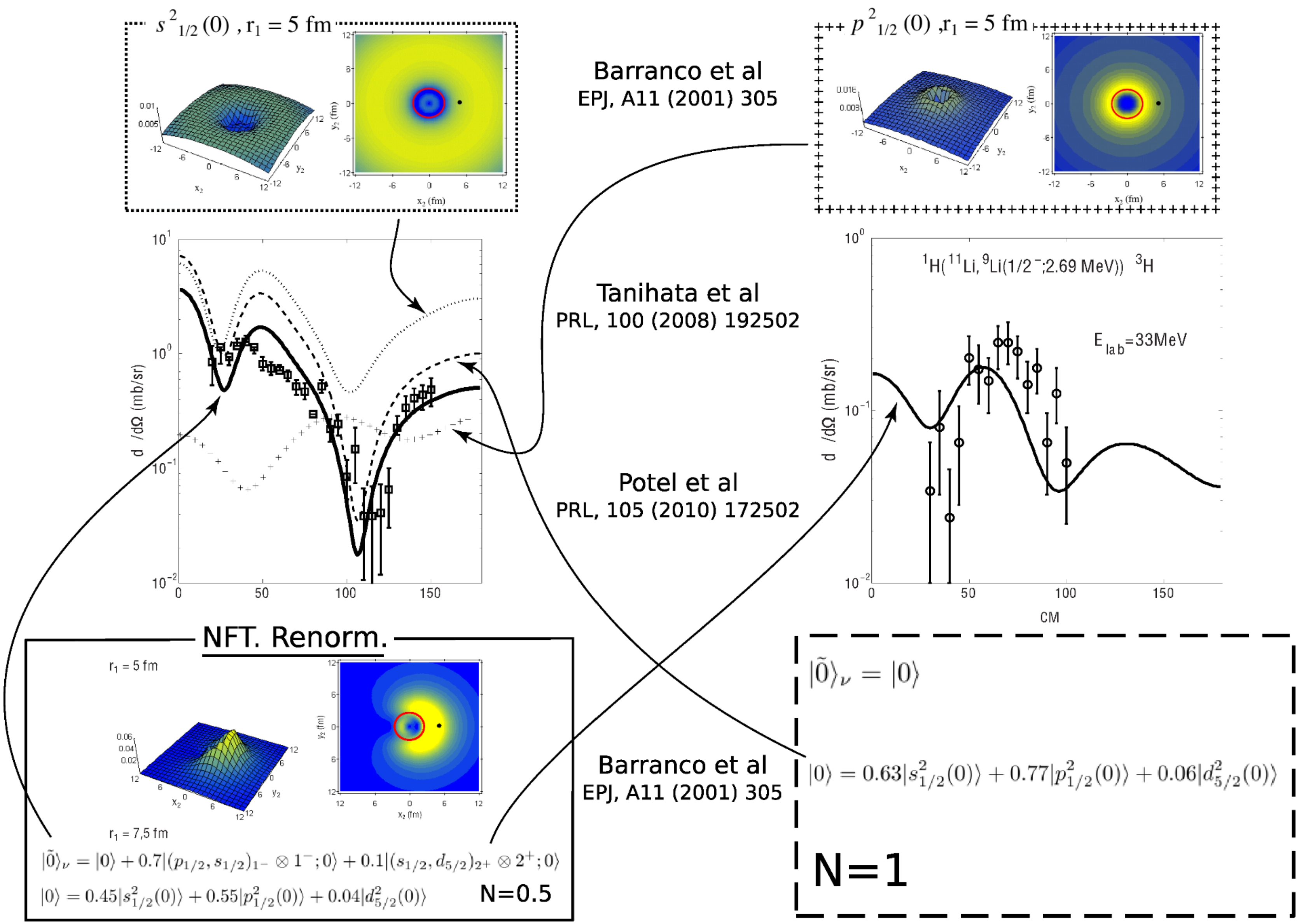




a)
i
i
V_ν^2
i
ε_{F}
k
ε_ν
b)
i
i
c)
k
k
d)
e)
f)
g)
1/2

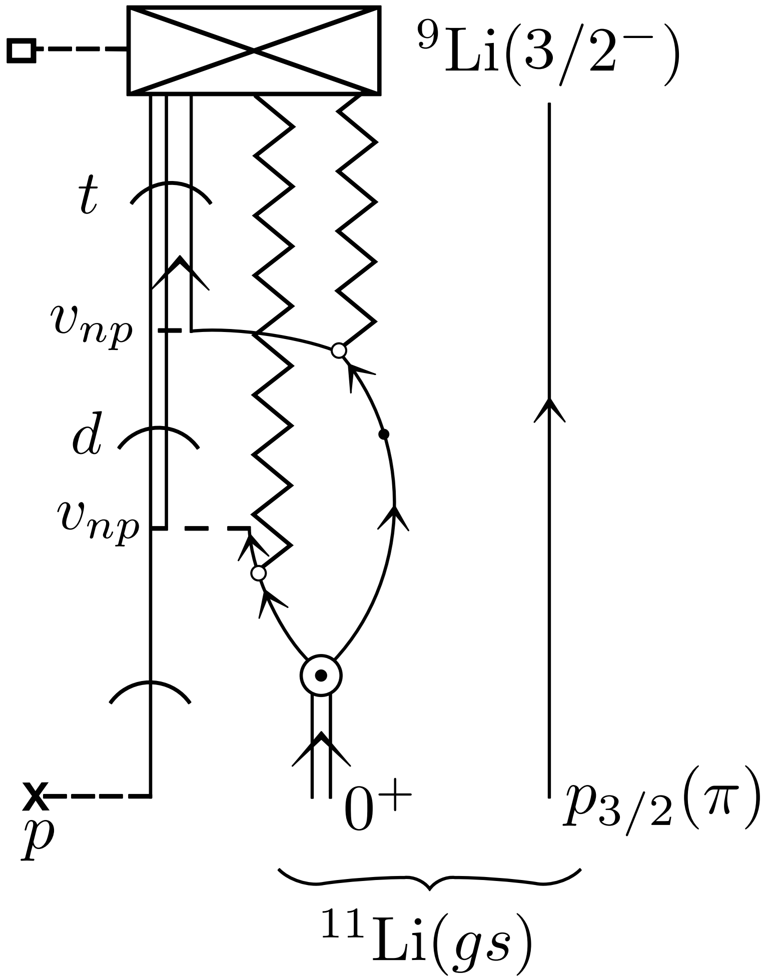


a) $|s^2_{1/2}(0)\rangle$, $r_1 = 5$ fm
b) $|\tilde{0}\rangle = |0\rangle + 0.7\,|(p_{1/2}, s_{1/2})_{1^-} \otimes 1^-; 0\rangle + 0.1\,|(s_{1/2}, d_{5/2})_{2^+} \otimes 2^+; 0\rangle$
$r_1 = 5$ fm
y2 (fm)
x2 (fm)
x2
y2
(II)
(I)
E (MeV)
^{9}Li
$(s_{1/2})$
$p_{1/2}$
$s_{1/2}$
$|s^2_{1/2}(0)\rangle$
$|0\rangle = 0.45\,|s^2_{1/2}(0)\rangle + 0.55\,|p^2_{1/2}(0)\rangle + 0.04\,|d^2_{5/2}(0)\rangle$
$p_{1/2}$



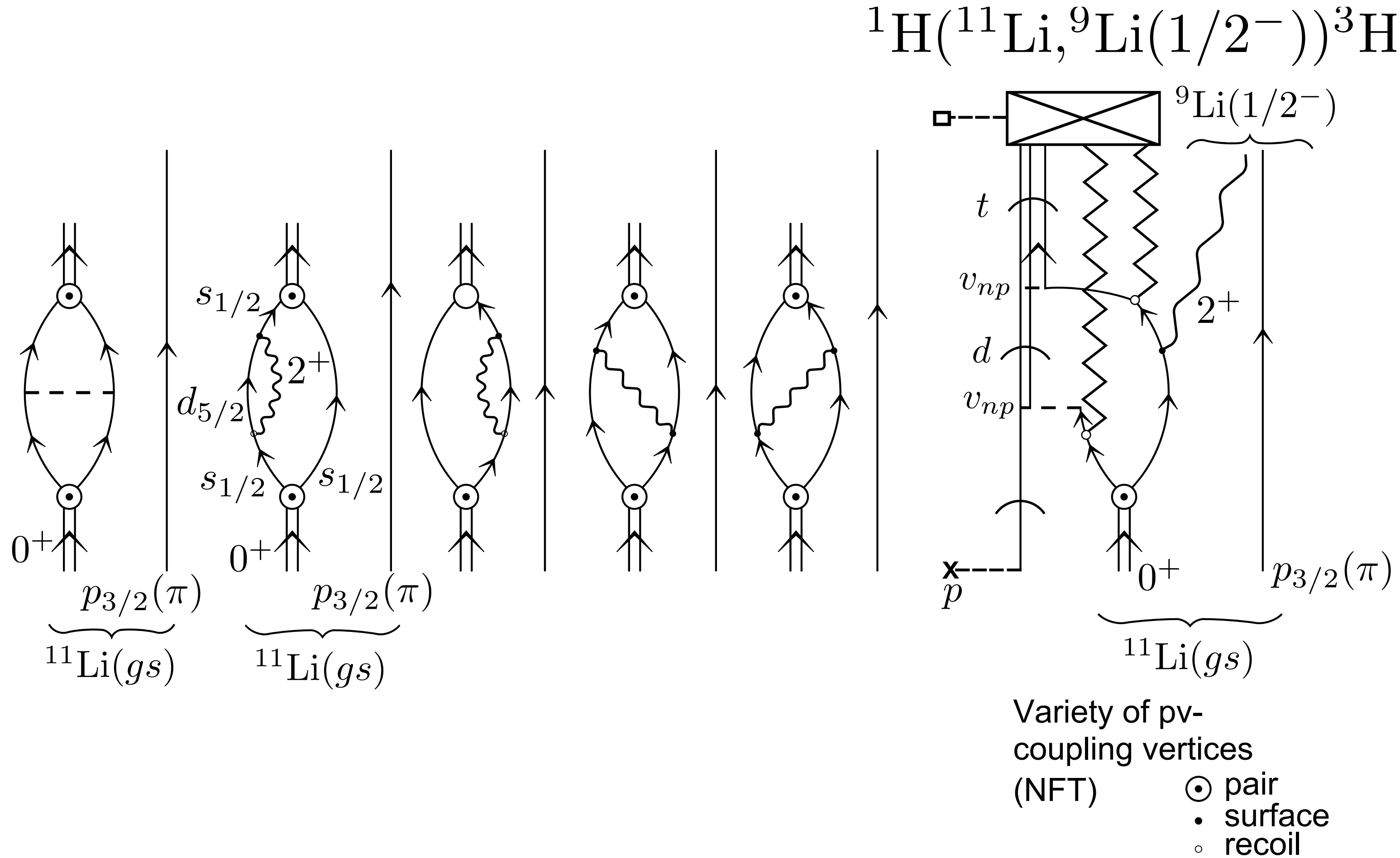
$s^2_{1/2}(0)$, $r_1 = 5$ fm
$p^2_{1/2}(0)$, $r_1 = 5$ fm
Barranco et al
EPJ, A11 (2001) 305
Tanihata et al
PRL, 100 (2008) 192502
Potel et al
PRL, 105 (2010) 172502
^{1}H(^{11}Li,^{9}Li(1/2$^-$;2.69 MeV)) ^{3}H
E$_{lab}$=33MeV
d /dΩ (mb/sr)
CM
NFT. Renorm.
r_1 = 5 fm
r_1 = 7,5 fm
$|\tilde{0}\rangle_\nu = |0\rangle + 0.7|(p_{1/2}, s_{1/2})_{1^-} \otimes 1^-;0\rangle + 0.1|(s_{1/2}, d_{5/2})_{2^+} \otimes 2^+;0\rangle$
$|0\rangle = 0.45|s^2_{1/2}(0)\rangle + 0.55|p^2_{1/2}(0)\rangle + 0.04|d^2_{5/2}(0)\rangle$
N=0.5
Barranco et al
EPJ, A11 (2001) 305
$|\tilde{0}\rangle_\nu = |0\rangle$
$|0\rangle = 0.63|s^2_{1/2}(0)\rangle + 0.77|p^2_{1/2}(0)\rangle + 0.06|d^2_{5/2}(0)\rangle$
N=1

$^1\mathrm{H}(^{11}\mathrm{Li},{}^9\mathrm{Li}(gs))^3\mathrm{H}$

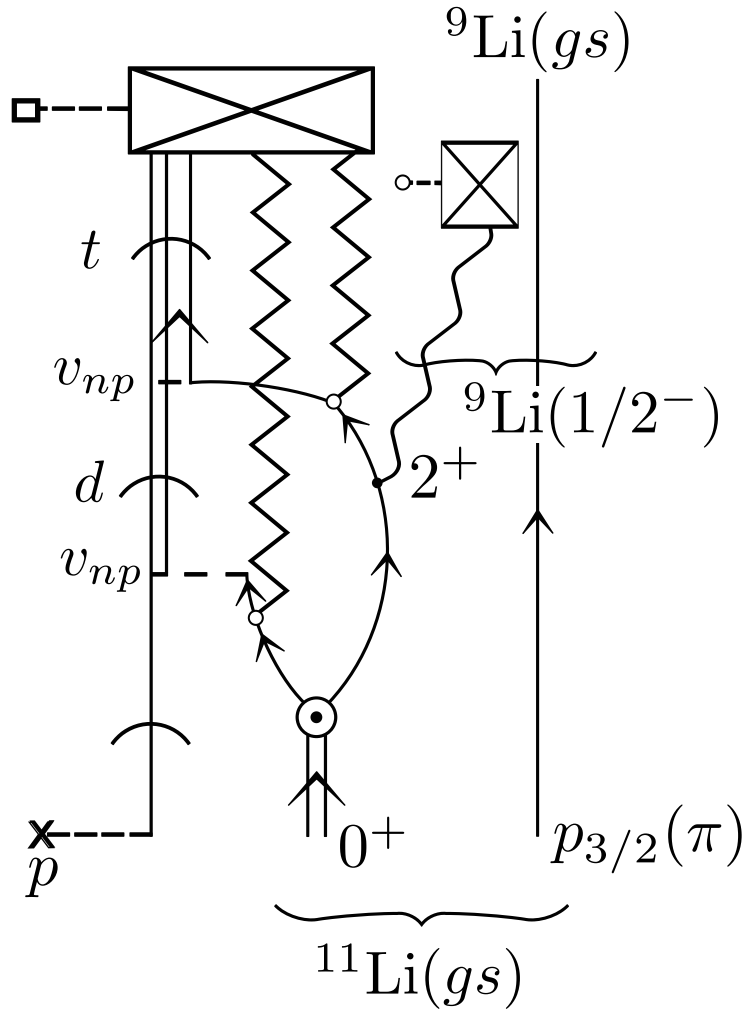


Variety of pv-
coupling vertices
(NFT)

⊙ pair
• surface
∘ recoil



$^{1}\mathrm{H}(^{11}\mathrm{Li},^{9}\mathrm{Li}(1/2^-))^3\mathrm{H}$
$^{9}\mathrm{Li}(1/2^-)$
t
v_{np}
d
v_{np}
2^+
p
0^+
$p_{3/2}(\pi)$
$^{11}\mathrm{Li}(gs)$
$s_{1/2}$
$d_{5/2}$
$s_{1/2}$
$s_{1/2}$
0^+
$p_{3/2}(\pi)$
$^{11}\mathrm{Li}(gs)$
Variety of pv-coupling vertices (NFT)
pair
surface
recoil



Variety of pv-coupling vertices (NFT)

- ⊙ pair
- • surface
- ∘ recoil

$$V(r_{12}) = -4\pi V_0 \delta(|\vec{r}_1 - \vec{r}_2|)$$

$$\mathcal{R}_j = \sqrt{\frac{3}{R_0^3}}\Theta(r - R_0)$$

$$I(j) = \int_0^\infty dr \mathcal{R}_j^4 \, r^2 = \frac{3}{R_0^3}$$

$$M_j = < (j)^2_0 |V| (j)^2_0 > = -\frac{2j+1}{2} V_o I(j)$$

$$r = \frac{(M_j)_{halo}}{(M_j)_{syst}} = \left(\frac{R_0}{R}\right)^3$$

Halo anti-pairing effect
(cf. Bennaceur, Dobaczewski,
Hamamoto, Mottelson, Ploszajczak)

R_0 = 1.2 $A^{1/3}$ fm
(systematics)

R: halo radius

$$\Theta(r - R) = \begin{cases} 1 & r \leq R \\ 0 & r > R \end{cases}$$

core radius (systematics)

$$R_0 = 1.2 \times 9^{1/3} \approx 2.5 \text{ fm}$$

$$\mathcal{R} = \sqrt{\tfrac{3}{R_0^3}}\Theta(r - R_0)$$

$$\int_0^\infty dr\; r^2 \mathcal{R}^2 \; = \frac{3}{R_0^3}\int_0^\infty \frac{dr^3}{3} = 1$$

Halo radius

$$R \approx \sqrt{\tfrac{5}{3}}\;(3.55\;\pm 0.1)\text{ fm} \approx 4.6 \pm 1.3 \text{ fm}$$

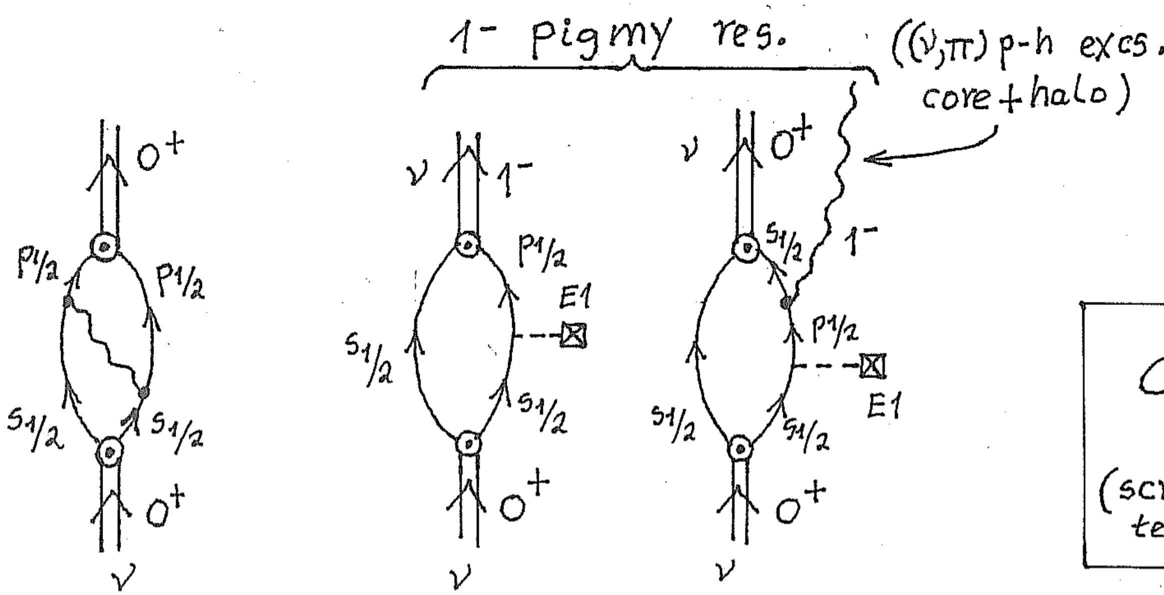
$$\mathcal{R}_{halo} = \sqrt{\tfrac{3}{R^3}}\Theta(r - R)$$

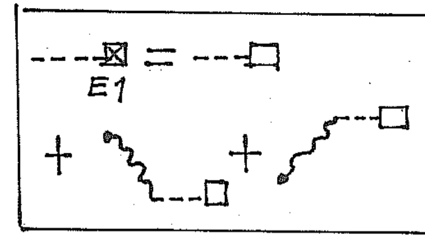
Two-nucleon overlap probability

$$o = |<\mathcal{R}_{halo}|\mathcal{R}>|^2$$

$$o = \left(\int_0^\infty \; dr\; r^2 \mathcal{R}_{halo}\mathcal{R}\right)^2 \; = \; \left(\sqrt{\tfrac{3}{R^3}}\sqrt{\tfrac{3}{R_0^3}}\int_0^\infty \tfrac{dr^3}{3}\right)^2 = \left(\tfrac{R_0}{R}\right)^3 \approx 0.16$$

$$\Theta(r - R) = \begin{cases} 1 & r \leq R \\ 0 & r > R \end{cases}$$





$$\sigma \approx \left(\frac{R_0}{R}\right)^3 \approx 0.16$$

(screening of symmetry term)

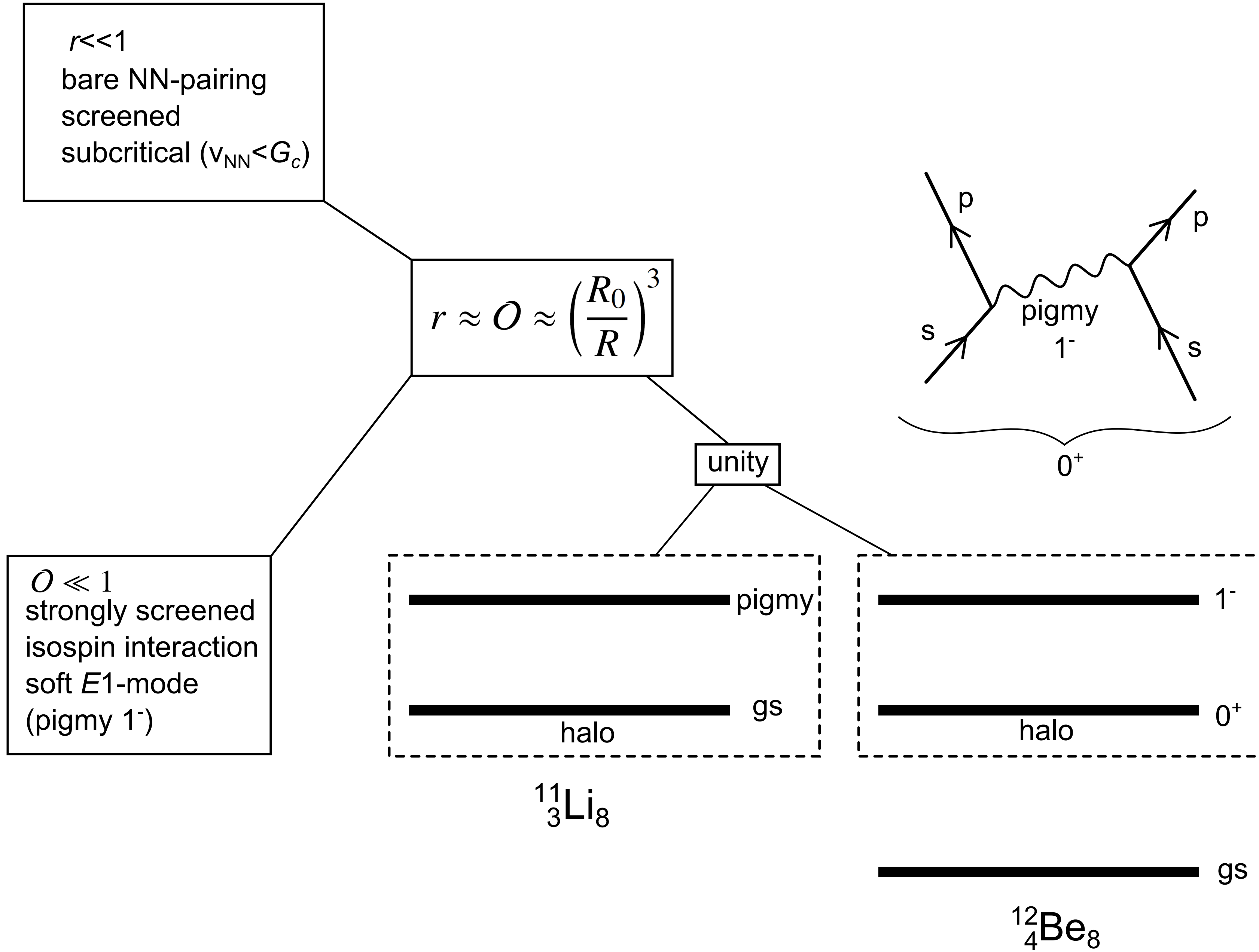
The ^{11}Li pigmy resonance can hardly be viewed but in symbiosis with the ^{9}Li halo neutron pair addition mode

anti – (halo-anti-pairing effect)

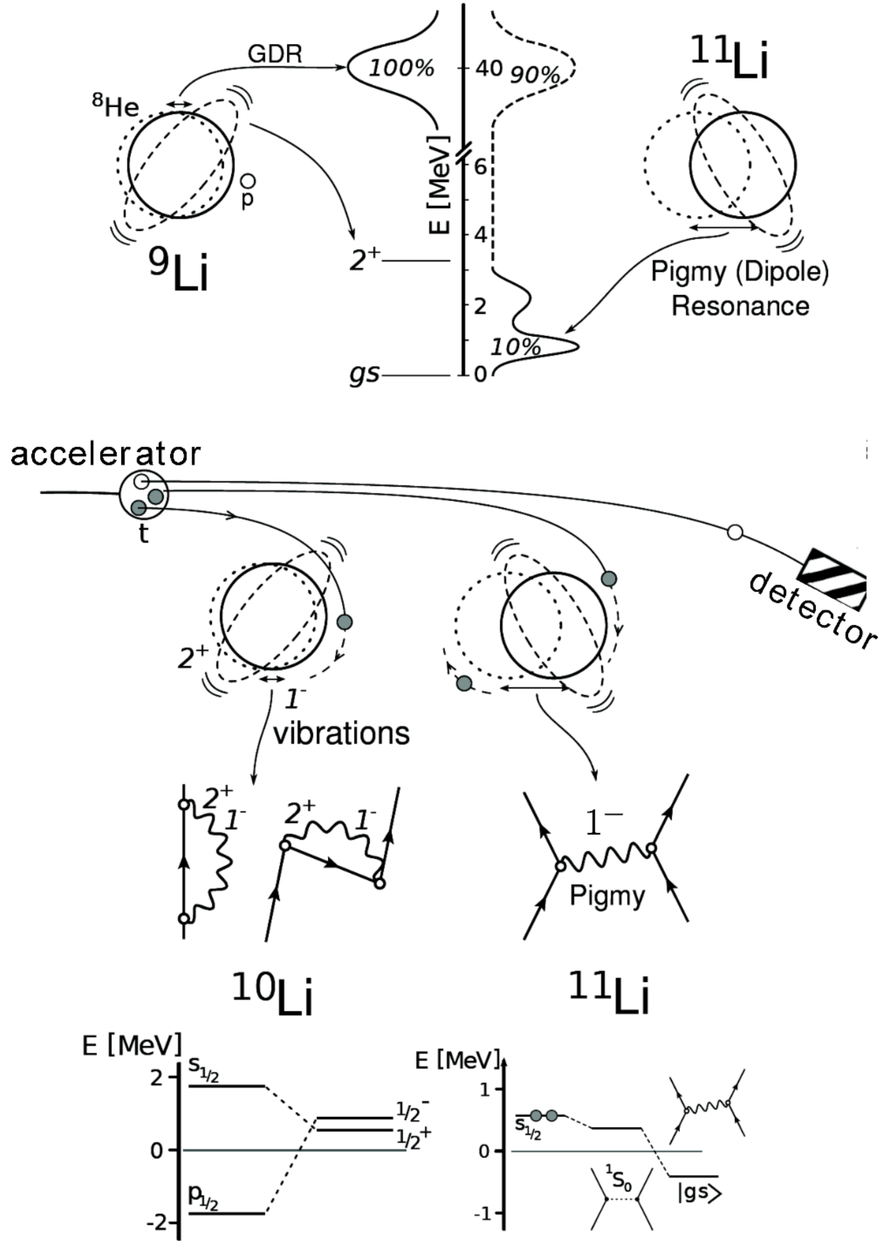
The pigmy resonance is built on a ground state with little overlap with the gs on which the GDR is built. It is thus a different (new) elementary mode of nuclear excitation

Extreme example of inhomogeneous damping (radial degree of freedom instead of quadrupole deformation)

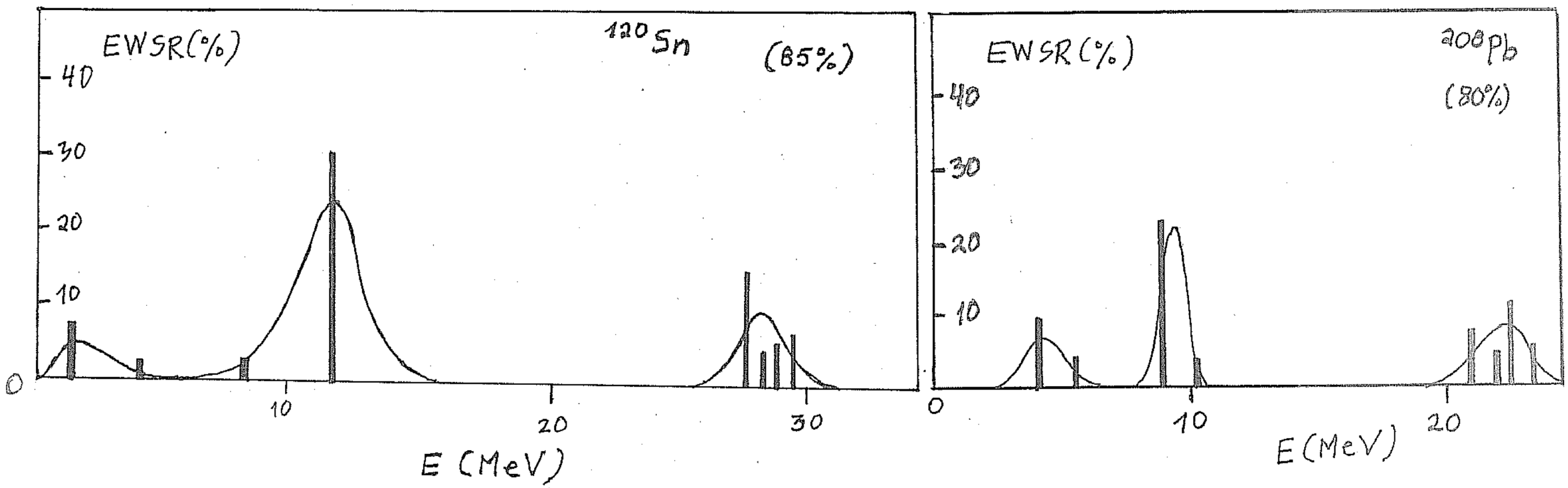
New physics



pair addition
halo mode



Bootstrap pairing correlations



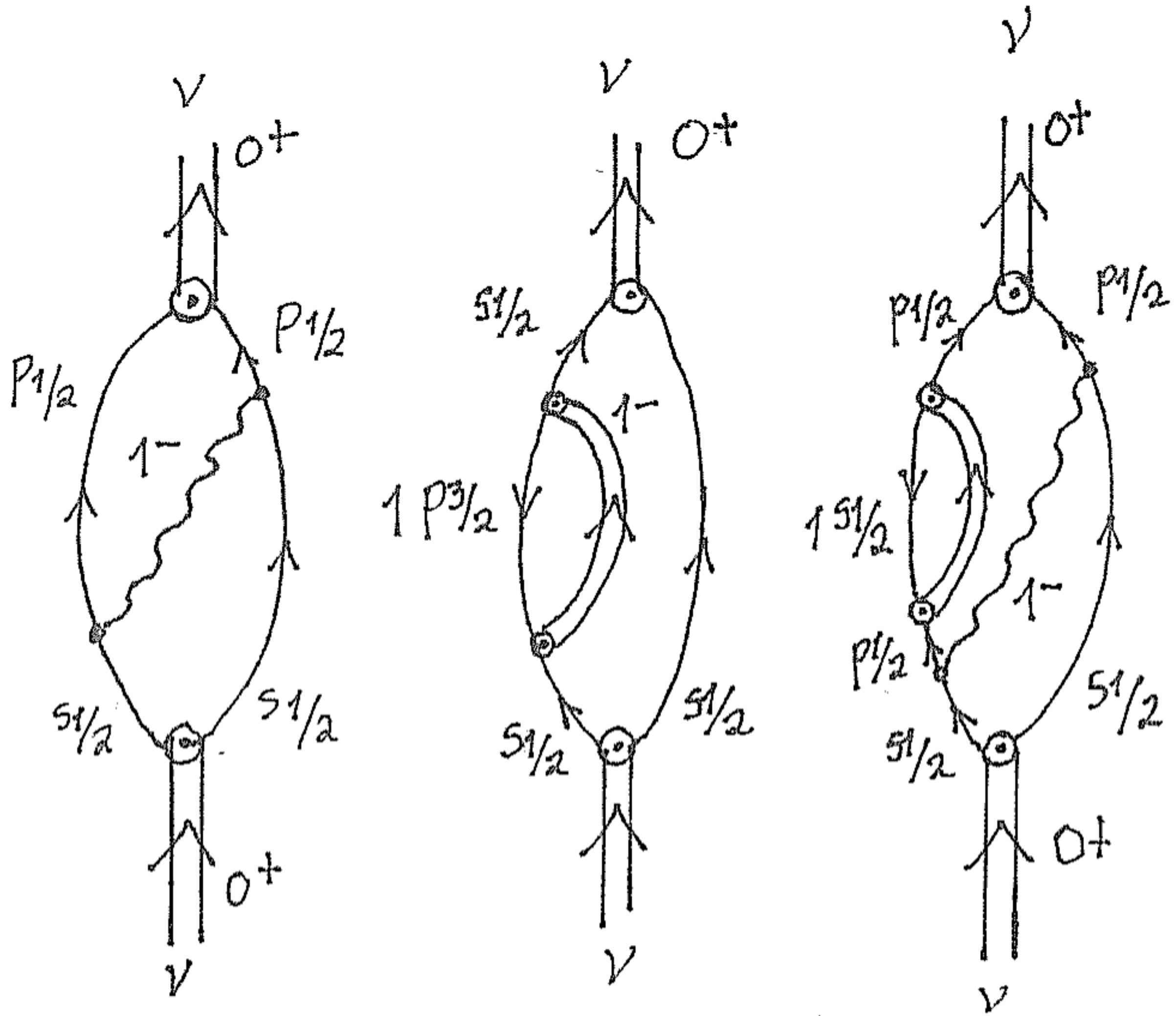
D.R. Bès, R.A. Broglia and B.S. Nilsson,
Microscopic description of isoscalar and isovector giant quadrupole resonances,
Phys. Rep. 16 (1975) 1–56.

Dual origin of pairing in nuclei

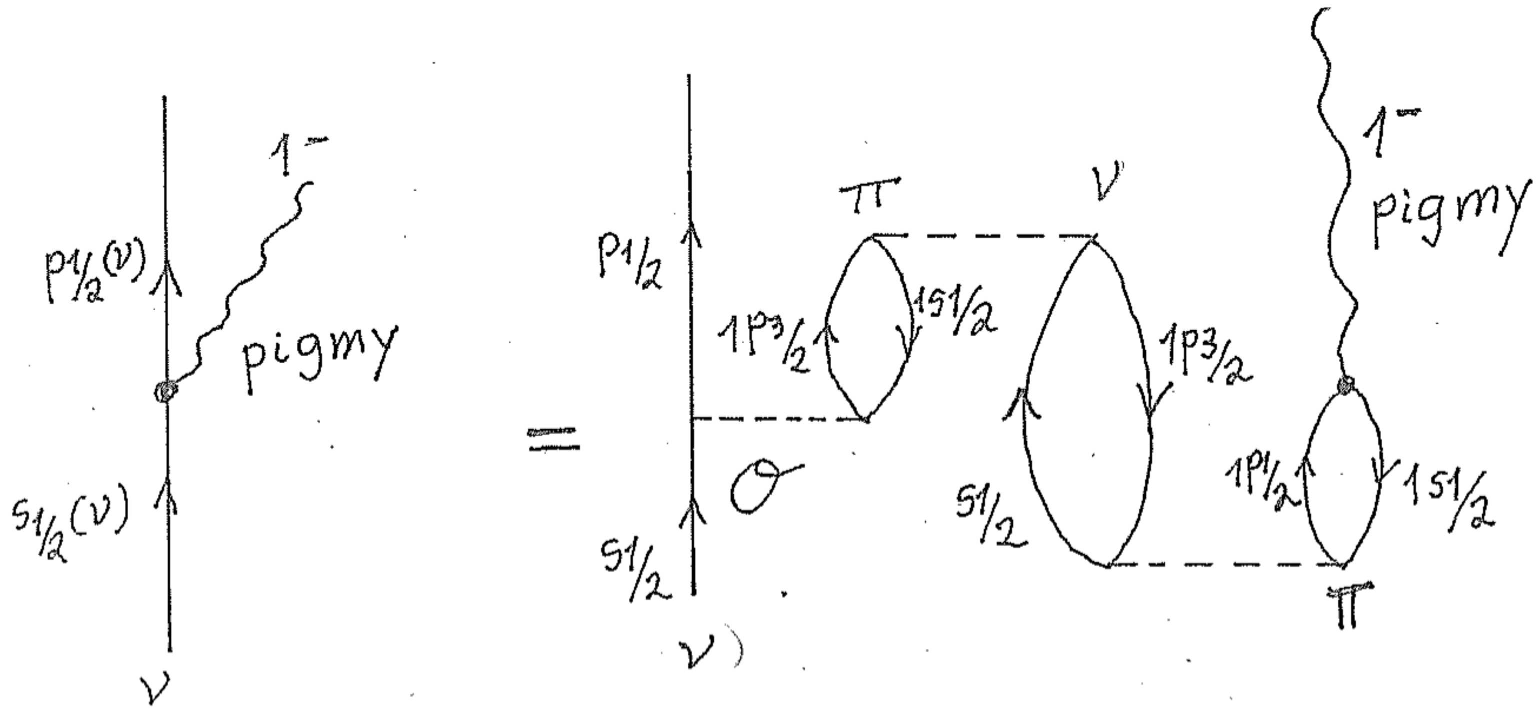
$v_{pair} = v_{bare}$ (N-N + 3N) $+ v_{ind}$

Direct and circumstantial evidence for v_{ind} in ^{11}Li

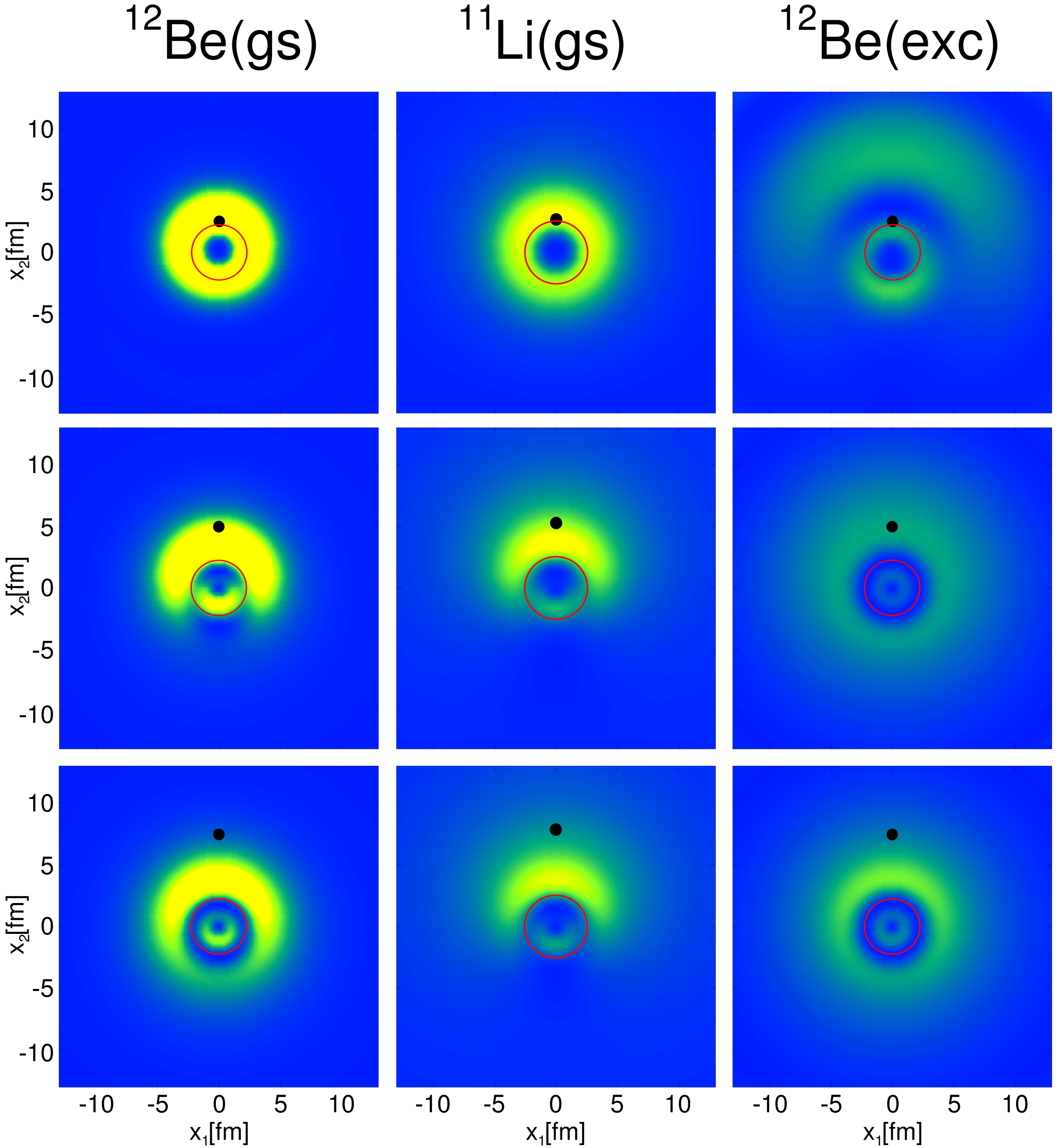
In nuclei along the stability valley, calculations estimate similar contributions from v_{pair} and v_{ind}
Open problem
(cf. A. Idini et al., nucl-th/1404.7365)



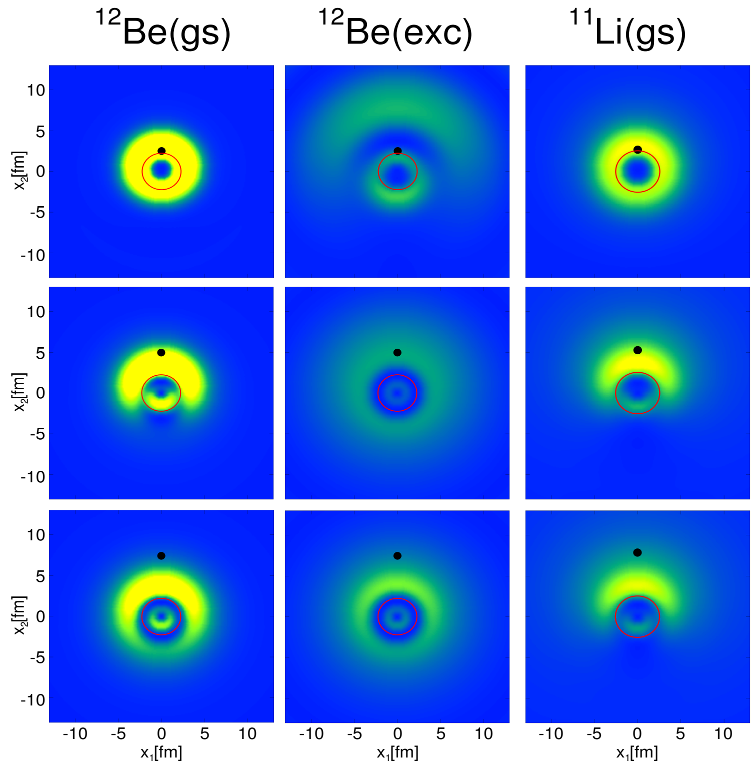
ν
0+
P1/2
P1/2
1⁻
s1/2
s1/2
0+
ν
ν
0+
s1/2
1⁻
1 p3/2
s1/2
s1/2
0+
ν
ν
0+
p1/2
p1/2
1 s1/2
1⁻
p1/2
s1/2
s1/2
0+
ν



1^-
$p_{1/2}(\nu)$
pigmy
$s_{1/2}(\nu)$
ν
=
π
ν
1^-
pigmy
$p_{1/2}$
$1p_{3/2}$
$1s_{1/2}$
$1p_{3/2}$
σ
$s_{1/2}$
$1p_{1/2}$
$1s_{1/2}$
$s_{1/2}$
ν
π



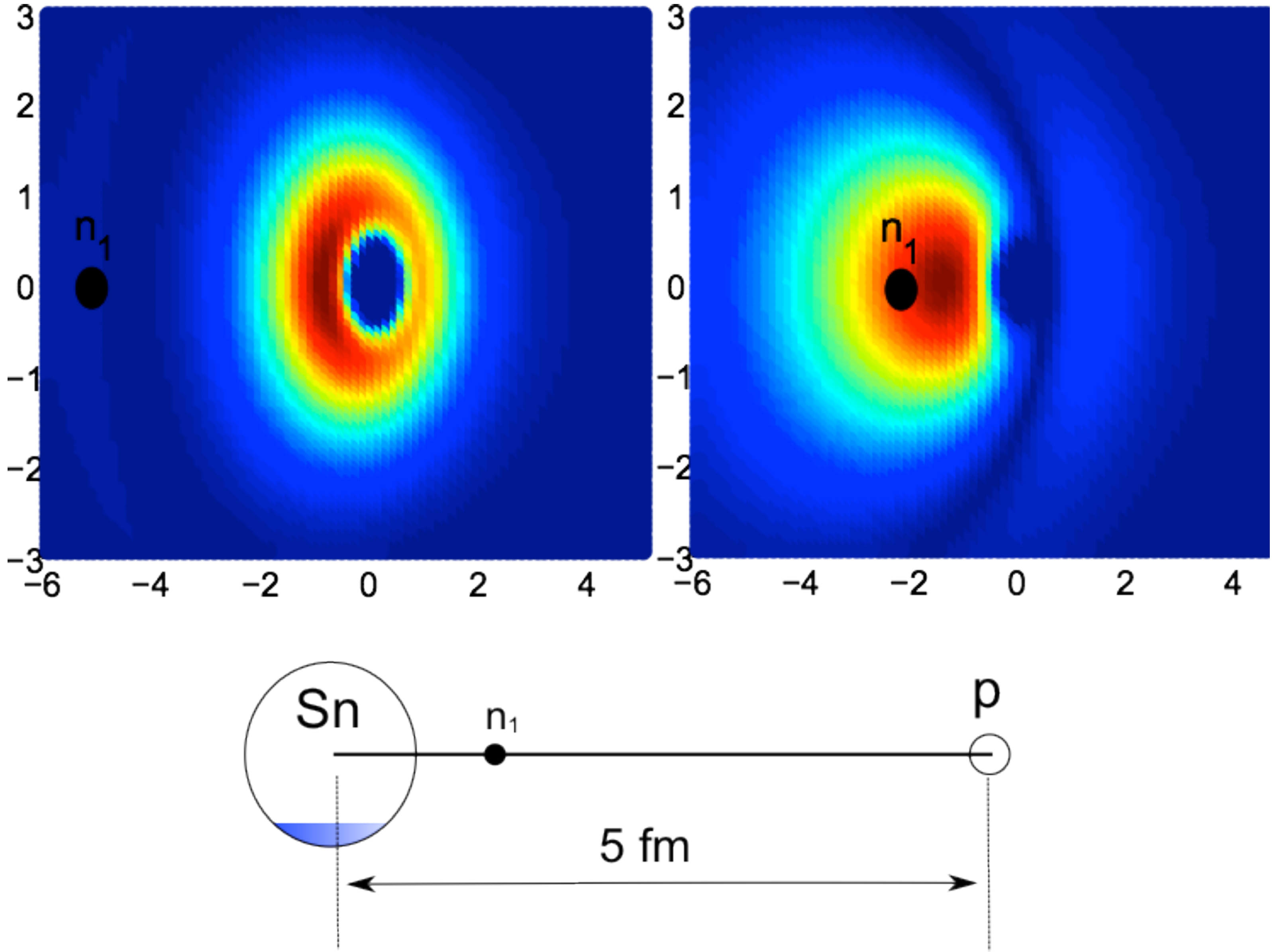
12Be(gs)
11Li(gs)
12Be(exc)
10
5
0
-5
-10
x2[fm]
-10
-5
0
5
10
x1[fm]



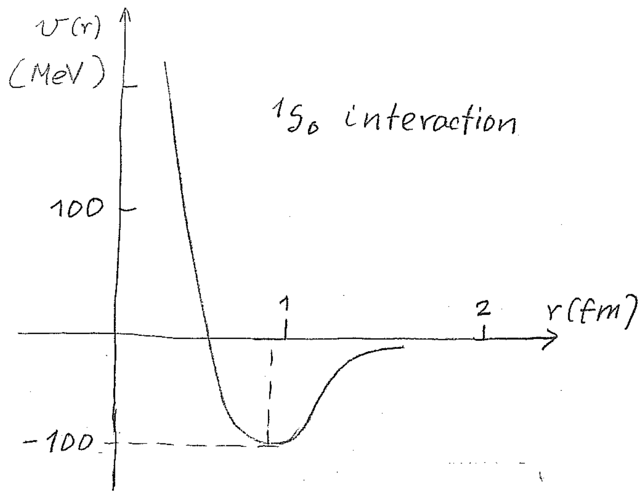
$$|0\rangle_\nu = |0\rangle + \alpha|(p,s)_{1^-} \otimes 1^-;0\rangle + \beta|(s,d)_{2^+} \otimes 2^+;0\rangle + \gamma|(p,d)_{3^-} \otimes 3^-;0\rangle$$

$$|0\rangle_\nu = a|s^2(0)\rangle + b|p^2(0)\rangle + c|d^2(0)\rangle$$

	^{11}Li(gs)	^{12}Be(gs)	^{12}Be(exc)
α	0.7	0.10	0.08
β	0.1	0.30	-0.39
γ	–	0.37	-0.1
a	0.45	0.37	0.89
b	0.55	0.50	0.17
c	0.04	0.60	0.19



n1
n1
Sn
n1
p
5 fm



Quantality parameter

$$q = \left(\frac{\hbar^2}{Ma^2}\right)\frac{1}{|v_0|}$$

$q << 1$ Crystalline structure (T=0)

$q \approx 1$ Quantum fluid (T=0)

$q \approx 0.4$ Nuclei

$$H = T + v = \underbrace{T + U + V_p}_{\text{MEAN FIELD}} + (v - U - V_p)$$

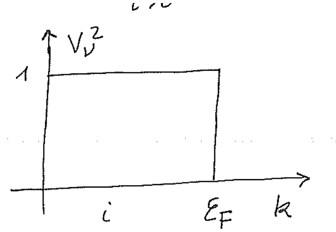
Diagon. $\alpha_\nu^\dagger = U_\nu a_\nu^\dagger - V_\nu a_{\bar{\nu}}$

g.s. $\alpha_\nu |\tilde{0}>= 0$

$$|\tilde{0}>= \Pi_{\nu>0}\, \alpha_\nu \alpha_{\bar{\nu}} |0> \sim \Pi_{\nu>0}(U_\nu + V_\nu a_\nu^\dagger a_{\bar{\nu}}^\dagger)|0>$$

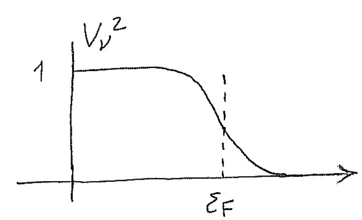
Ansatz 1 : sharp occupation distribution

$|\tilde{0}>=$ $|HF>= \Pi_{i>0}\, a_i^\dagger a_{\tilde{i}}^\dagger |0>= \Pi_i a_i^\dagger |0>$



Ansatz 2 : sigmoidal occupation distribution

$|\tilde{0}>$ = $|BCS>= \Pi_{\nu>0}\, (U_\nu + V_\nu a_\nu^\dagger a_{\bar{\nu}}^\dagger)|0>$



$$\xi = \frac{\hbar v_F}{E_{corr}} \approx 30\text{-}35\,fm$$

$$v_{np} \approx 0.4 fm$$

$$T^{(1)} = 2\sum_{l_i,j_i}\sum_{\sigma_1\sigma_2}\int d\mathbf{r}_{tA}d\mathbf{r}_{p1}d\mathbf{r}_{A2}\big[\phi^{A+2}_{l_i,j_i}(\mathbf{r}_{A1},\sigma_1,\mathbf{r}_{A2},\sigma_2)\big]^{0*}_0\chi^{(-)*}_{pB}(\mathbf{r}_{pB})v(r_{p1})\phi_t(r_{p1},\sigma_1,r_{p2},\sigma_2)\chi^{(+)}_{tA}(\mathbf{r}_{tA}), \tag{38a}$$

successive,

$$T^{(2)}_{\text{succ}} = 2\sum_{l_i,j_i}\sum_{l_f,j_f,m_f}\sum_{\substack{\sigma_1\sigma_2\\ \sigma_1'\sigma_2'}}\int d\mathbf{r}_{dF}d\mathbf{r}_{p1}d\mathbf{r}_{A2}\big[\phi^{A+2}_{l_i,j_i}(\mathbf{r}_{A1},\sigma_1,\mathbf{r}_{A2},\sigma_2)\big]^{0*}_0\chi^{(-)*}_{pB}(\mathbf{r}_{pB})v(r_{p1})\phi_d(r_{p1},\sigma_1)\varphi^{A+1}_{l_f,j_f,m_f}(\mathbf{r}_{\mathbf{A2}},\sigma_2)$$
$$\times\int d\mathbf{r}'_{dF}d\mathbf{r}'_{p1}d\mathbf{r}'_{A2}G(\mathbf{r}_{dF},\mathbf{r}'_{dF})\phi_d(r'_{p1},\sigma'_1)^*\varphi^{A+1*}_{l_f,j_f,m_f}(\mathbf{r}'_{\mathbf{A2}},\sigma'_2)\frac{2\mu_{dF}}{\hbar^2}v(r'_{p2})\phi_d(r'_{p1},\sigma'_1)\phi_d(r'_{p2},\sigma'_2)\chi^{(+)}_{tA}(\mathbf{r}'_{tA}), \tag{38b}$$

and nonorthogonal,

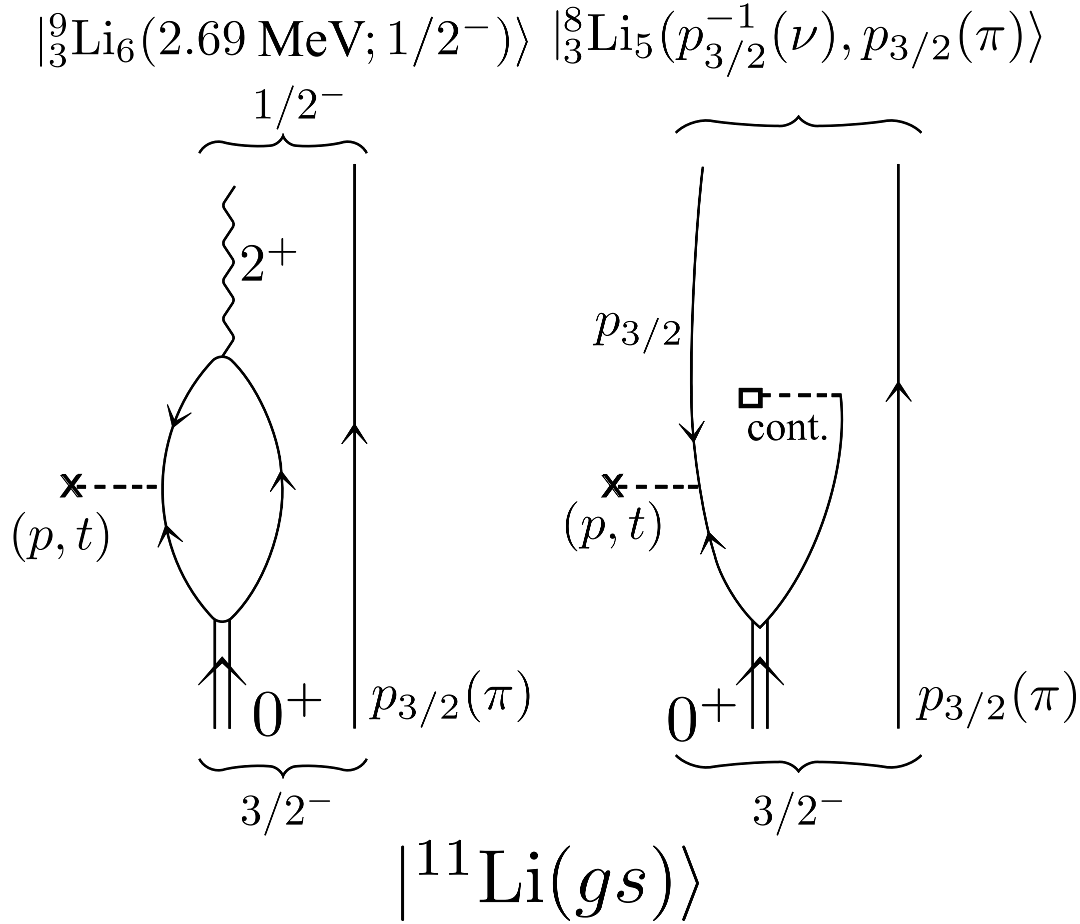
$$T^{(2)}_{\text{NO}} = 2\sum_{l_i,j_i}\sum_{l_f,j_f,m_f}\sum_{\substack{\sigma_1\sigma_2\\ \sigma_1'\sigma_2'}}\int d\mathbf{r}_{dF}d\mathbf{r}_{p1}d\mathbf{r}_{A2}\big[\phi^{A+2}_{l_i,j_i}(\mathbf{r}_{A1},\sigma_1,\mathbf{r}_{A2},\sigma_2)\big]^{0*}_0\chi^{(-)*}_{pB}(\mathbf{r}_{pB})v(r_{p1})\phi_d(r_{p1},\sigma_1)\varphi^{A+1}_{l_f,j_f,m_f}(r_{A2},\sigma_2)$$
$$\times\int d\mathbf{r}'_{p1}d\mathbf{r}'_{A2}d\mathbf{r}'_{dF}\phi_d(r'_{p1},\sigma'_1)^*\varphi^{A+1*}_{l_f,j_f,m_f}(\mathbf{r}'_{\mathbf{A2}},\sigma'_2)\phi_d(r'_{p1},\sigma'_1)\phi_d(r'_{p2},\sigma'_2)\chi^{(+)}_{tA}(\mathbf{r}'_{tA}), \tag{38c}$$

New Technical Achievement

	σ(gs$\to$f)		
	f	Theory [a) b) f)]	Experiment[f−m)]
^{7}Li$(t,p)^9$Li	gs	14.3 [c)]	14.7 ± 4.4 [c,i)] $[9.4^\circ < \theta < 108.7^\circ]$
^{1}H(^{11}Li,^{9}Li)^{3}H	gs	6.1 [c)]	5.7 ± 0.9 [c,b)] $[20^\circ < \theta < 154.5^\circ]$
	$1/2^-$	0.7 [c)]	1.0 ± 0.36 [c,b)] $[30^\circ < \theta < 100^\circ]$
^{10}Be$(t,p)^{12}$Be	gs	2.3 [c)]	1.9 ± 0.57 [c,j)] $[4.4^\circ < \theta < 57.4^\circ]$
^{48}Ca$(t,p)^{50}$Ca	gs	0.55 [c)]	0.56 ± 0.17 [c,m)] $[4.5^\circ < \theta < 174^\circ]$
^{112}Sn$(p,t)^{110}$Sn, $E_{CM} = 26$ MeV	gs	1301 [d)]	$1309 \pm 200(\pm 14)$ [d,g)] $[6^\circ < \theta < 62.2^\circ]$
^{114}Sn$(p,t)^{112}$Sn, $E_{CM} = 22$ MeV	gs	1508 [d)]	$1519 \pm 456(\pm 16.2)$ [d,g)] $[7.64^\circ < \theta < 62.24^\circ]$
^{116}Sn$(p,t)^{114}$Sn, $E_{CM} = 26$ MeV	gs	2078 [d)]	$2492 \pm 374(\pm 32)$ [d,g)] $[4^\circ < \theta < 70^\circ]$
^{118}Sn$(p,t)^{116}$Sn, $E_{CM} = 24.4$ MeV	gs	1304 [d)]	$1345 \pm 202(\pm 24)$ [d,g)] $[7.63^\circ < \theta < 59.6^\circ]$
^{120}Sn$(p,t)^{118}$Sn, $E_{CM} = 21$ MeV	gs	2190 [d)]	$2250 \pm 338(\pm 14)$ [d,g)] $[7.6^\circ < \theta < 69.7^\circ]$
^{122}Sn$(p,t)^{120}$Sn, $E_{CM} = 26$ MeV	gs	2466 [d)]	$2505 \pm 376(\pm 18)$ [d,g)] $[6^\circ < \theta < 62.2^\circ]$
^{124}Sn$(p,t)^{122}$Sn, $E_{CM} = 25$ MeV	gs	838 [d)]	$958 \pm 144(\pm 15)$ [d,g)] $[4^\circ < \theta < 57^\circ]$
^{112}Sn$(p,t)^{110}$Sn, $E_p = 40$ MeV	gs	3349 [e)]	3715 ± 1114 [e,h)]
^{114}Sn$(p,t)^{112}$Sn, $E_p = 40$ MeV	gs	3790 [e)]	3776 ± 1132 [e,h)]
^{116}Sn$(p,t)^{114}$Sn, $E_p = 40$ MeV	gs	3085 [e)]	3135 ± 940 [e,h)]
^{118}Sn$(p,t)^{116}$Sn, $E_p = 40$ MeV	gs	2563 [e)]	2294 ± 668 [e,h)]
^{120}Sn$(p,t)^{118}$Sn, $E_p = 40$ MeV	gs	3224 [e)]	3024 ± 907 [e,h)]
^{122}Sn$(p,t)^{120}$Sn, $E_p = 40$ MeV	gs	2339 [e)]	2907 ± 872 [e,h)]
^{124}Sn$(p,t)^{122}$Sn, $E_p = 40$ MeV	gs	1954 [e)]	2558 ± 767 [e,h)]
^{206}Pb$(t,p)^{208}$Pb	gs	0.52 [c)]	0.68 ± 0.21 [c,k)] $[4.5^\circ < \theta < 176.5^\circ]$
^{208}Pb(^{16}O,^{18}O)^{206}Pb	gs	0.80 [c)]	0.76 ± 0.18 [c,f)] $[84.6^\circ < \theta < 157.3^\circ]$

Table 4:
It is of notice that the number in parenthesis (last column) corresponds to the statistical errors.

[a)] G. Potel et al., Phys. Rev. Lett. **107**, (2011) 092501.
[b)] G. Potel et al., Phys. Rev. Lett. **105**, (2010) 172502.
[c)] mb
[d)] μb
[e)] μb/sr ($\sum_{i=1}^{N}(d\sigma/d\Omega)$; differential cross section summed over the few, $N = 3-7$ experimental points).
[f)] B. Bayman and J. Chen, Phys. Rev. **C 26** (1982) 1509 and refs. therein.
[g)] P. Guazzoni, L. Zetta, et al., Phys. Rev. **C 60**, 054603 (1999).
P. Guazzoni, L. Zetta, et al., Phys. Rev. **C 69**, 024619 (2004).
P. Guazzoni, L. Zetta, et al., Phys. Rev. **C 74**, 054605 (2006).
P. Guazzoni, L. Zetta, et al., Phys. Rev. **C 83**, 044614 (2011).
P. Guazzoni, L. Zetta, et al., Phys. Rev. **C 78**, 064608 (2008).
P. Guazzoni, L. Zetta, et al., Phys. Rev. **C 85**, 054609 (2012).
[h)] G. Bassani et al. Phys. Rev. **139**, (1965)B830.
[i)] P.G. Young and R.H. Stokes, Phys. Rev. **C 4**, (1971) 1597.
[j)] H.T. Fortune, G.B. Liu and D.E. Alburger, Phys. Rev. **C 50**, (1994) 1355.
[k)] J.H. Bjerregaard et al., Nucl. Phys. **89**, (1966) 337.
[l)] J.H. Bjerregaard et al., Nucl. Phys. **A 113**, (1968) 484.
[m)] J. H. Bjerregaard et al., Nucl. Phys. **A 103**, (1967) 33.



$|^9_3\mathrm{Li}_6(2.69\,\mathrm{MeV};1/2^-)\rangle$
$|^8_3\mathrm{Li}_5(p^{-1}_{3/2}(\nu),p_{3/2}(\pi)\rangle$
$1/2^-$
2^+
$p_{3/2}$
cont.
(p,t)
(p,t)
0^+
$p_{3/2}(\pi)$
0^+
$p_{3/2}(\pi)$
$3/2^-$
$3/2^-$
$|^{11}\mathrm{Li}(gs)\rangle$