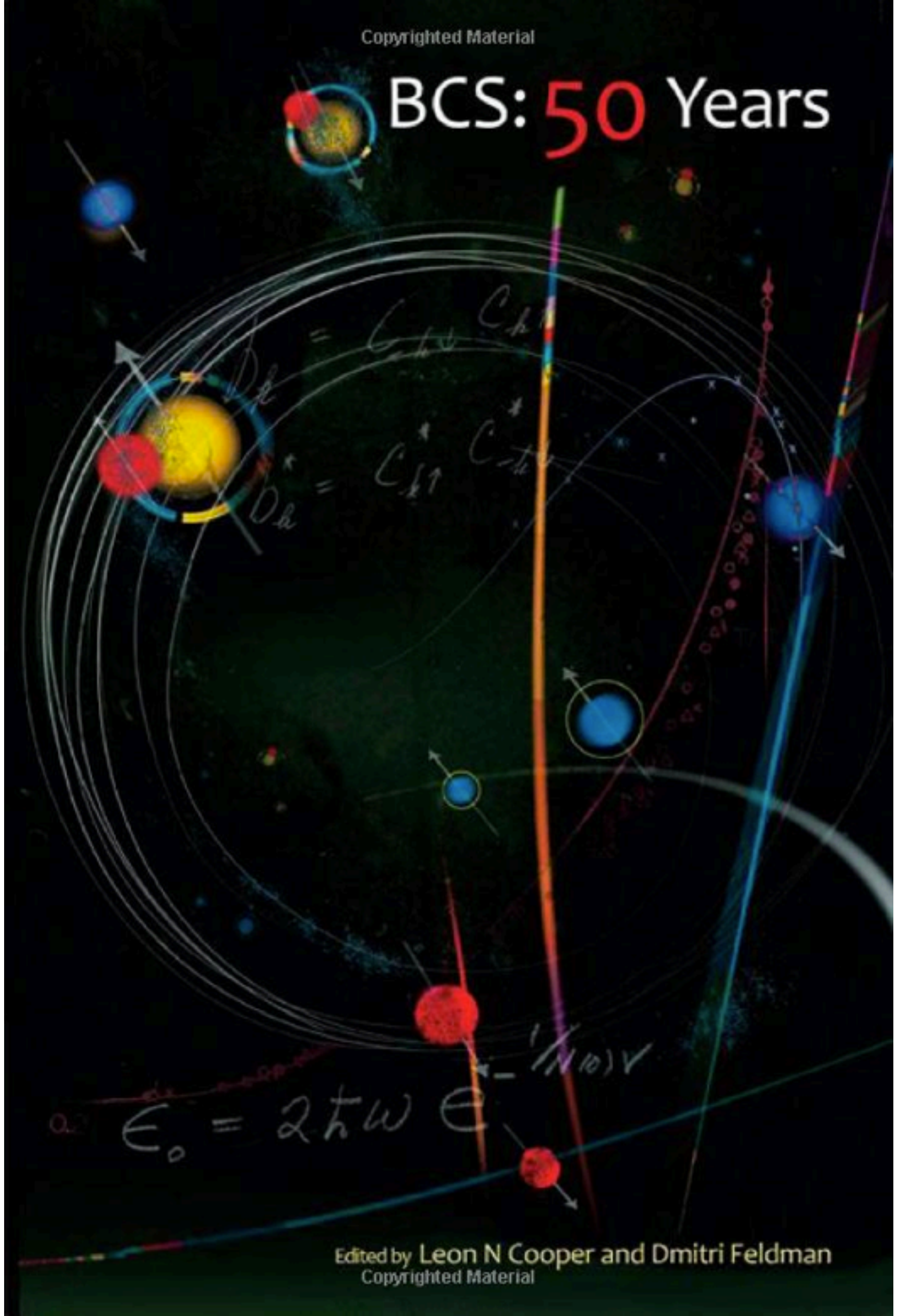
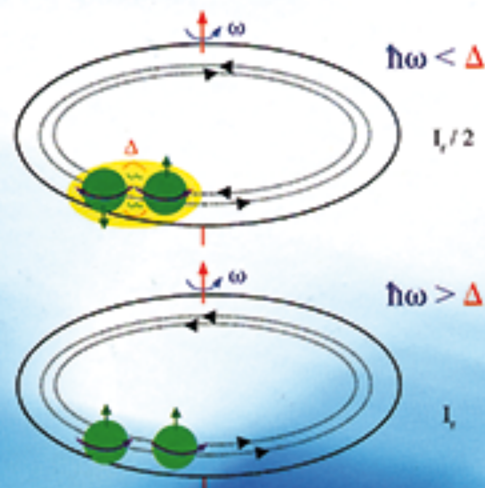
BCS: 50 Years



Edited by Leon N Cooper and Dmitri Feldman

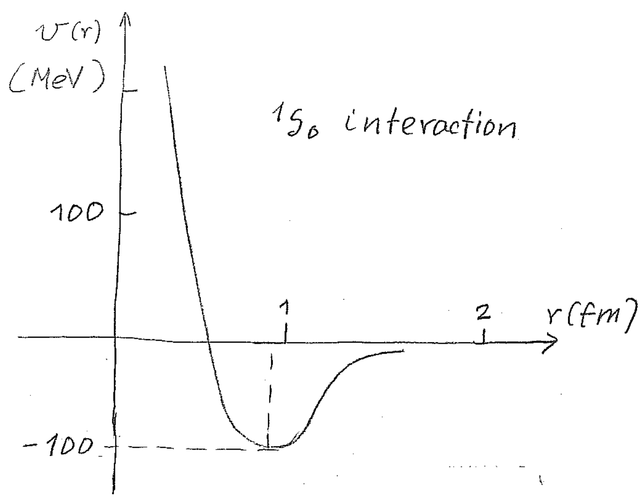
Fifty Years of Nuclear BCS

Pairing in Finite Systems



Ricardo A Broglia
Vladimir Zelevinsky
editors

World Scientific



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

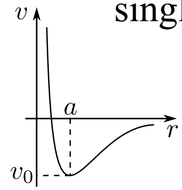
Classical localization and quantal ZPF

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

structure

Independent motion of

single nucleons



$a \approx 1$ fm

$v_0 = -100$ MeV

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

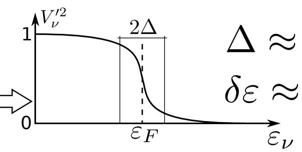
$\delta x \delta k = \frac{a|v_0|}{\hbar v_F} \geq 1$

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

$$H = T + v = \underline{T + U + V_p} + (v - U - V_p)$$

MEAN FIELD

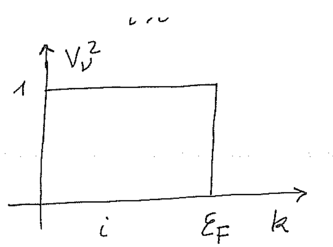
Diagon. $\alpha_\nu^\dagger = U_\nu a_\nu^\dagger - V_\nu a_{\bar{\nu}}$

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

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

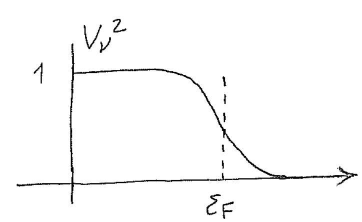
Ansatz 1 : sharp occupation distribution

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



Ansatz 2 : sigmoidal occupation distribution

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



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

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

$$x > 1$$

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

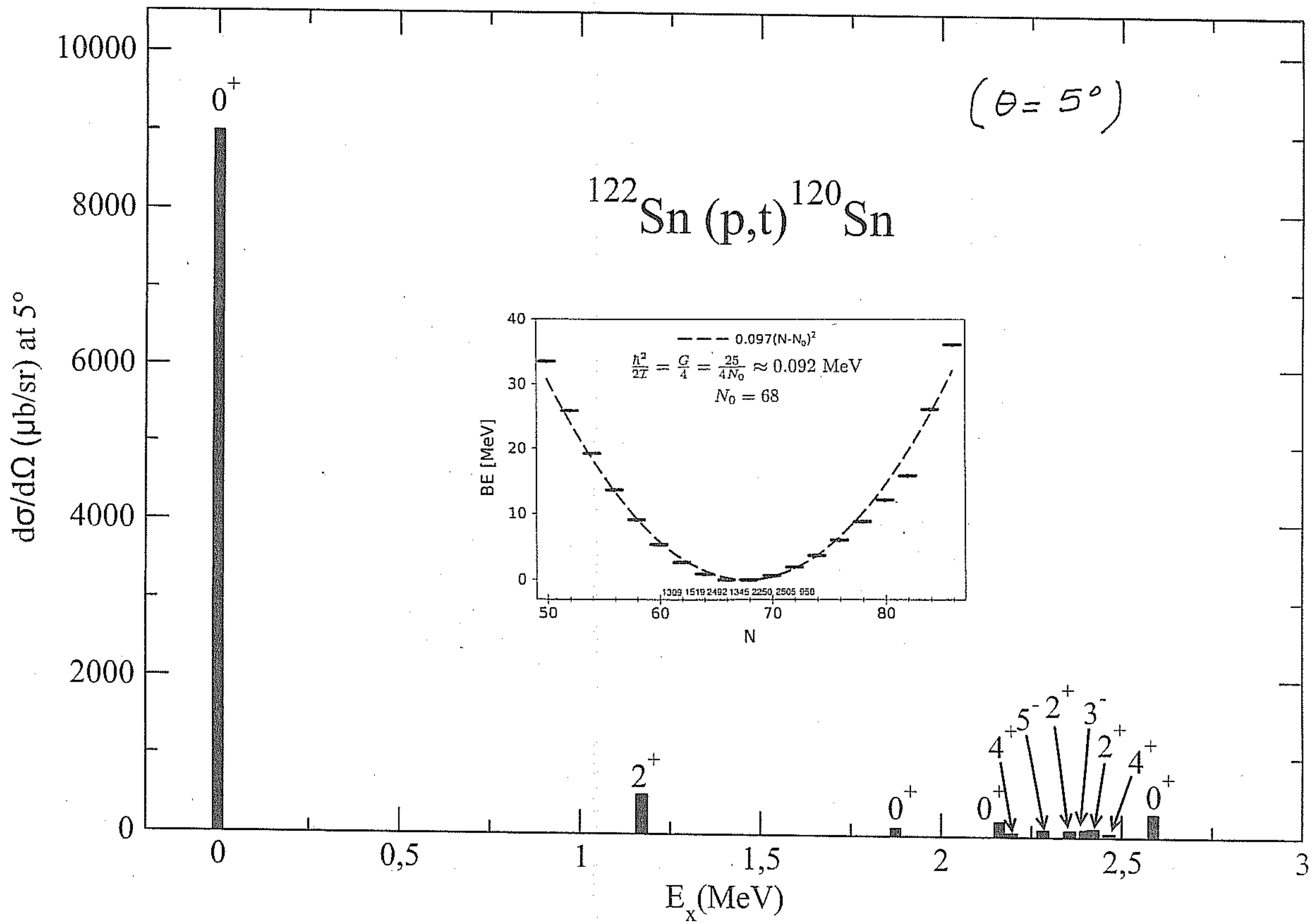
$$x < 1$$

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

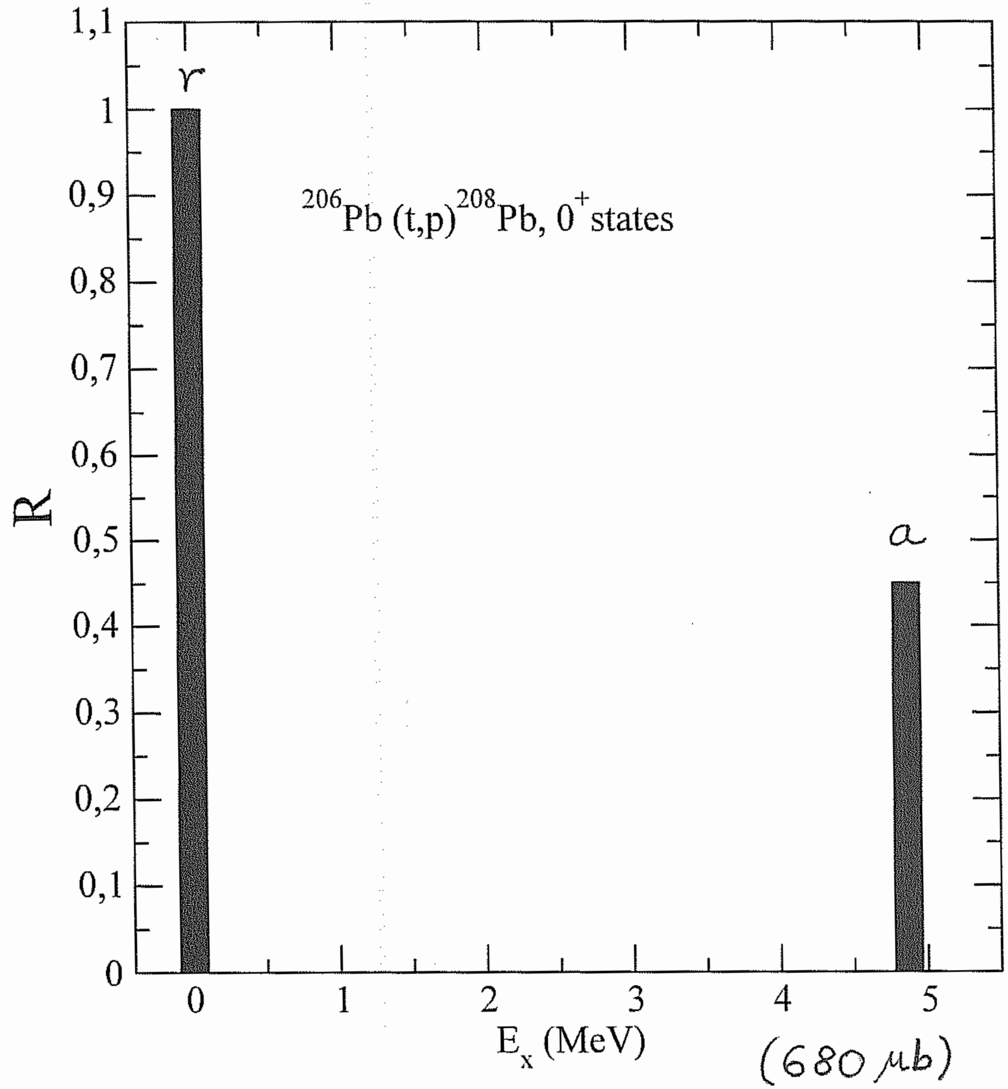
$$\approx \quad \frac{1}{2}\left(\frac{E_{corr}(A+2)}{G} + \frac{E_{corr}(A-2)}{G}\right) \approx 10$$

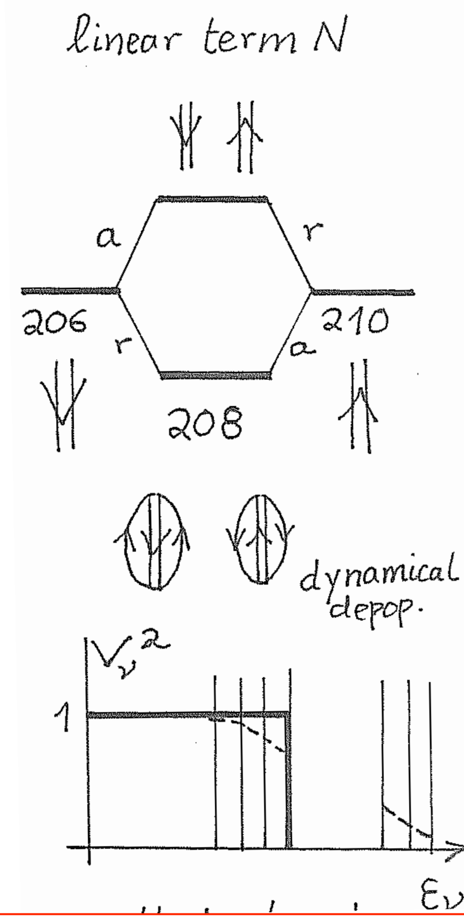
$$\frac{\alpha_0}{\alpha_{dyn}} \approx 0.7$$

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



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





Well developed vibr. bands
(very anaharmonic at the edge of
phase transition, thus very collective
cf. Clark et al. PRL 96 (2006)032501)

<u>Spectroscopic amplitudes</u>

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

U_ν V_ν (BCS)

<u>Pairing vibrations</u> $^{208}Pb(p,t)^{206}Pb(gs)$

X_r Y_r (RPA)

<u>Coherent states: essentially exact</u>

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

$$\xi = \frac{\hbar v_F}{E_{corr}}$$ ≈ 30-35 *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,

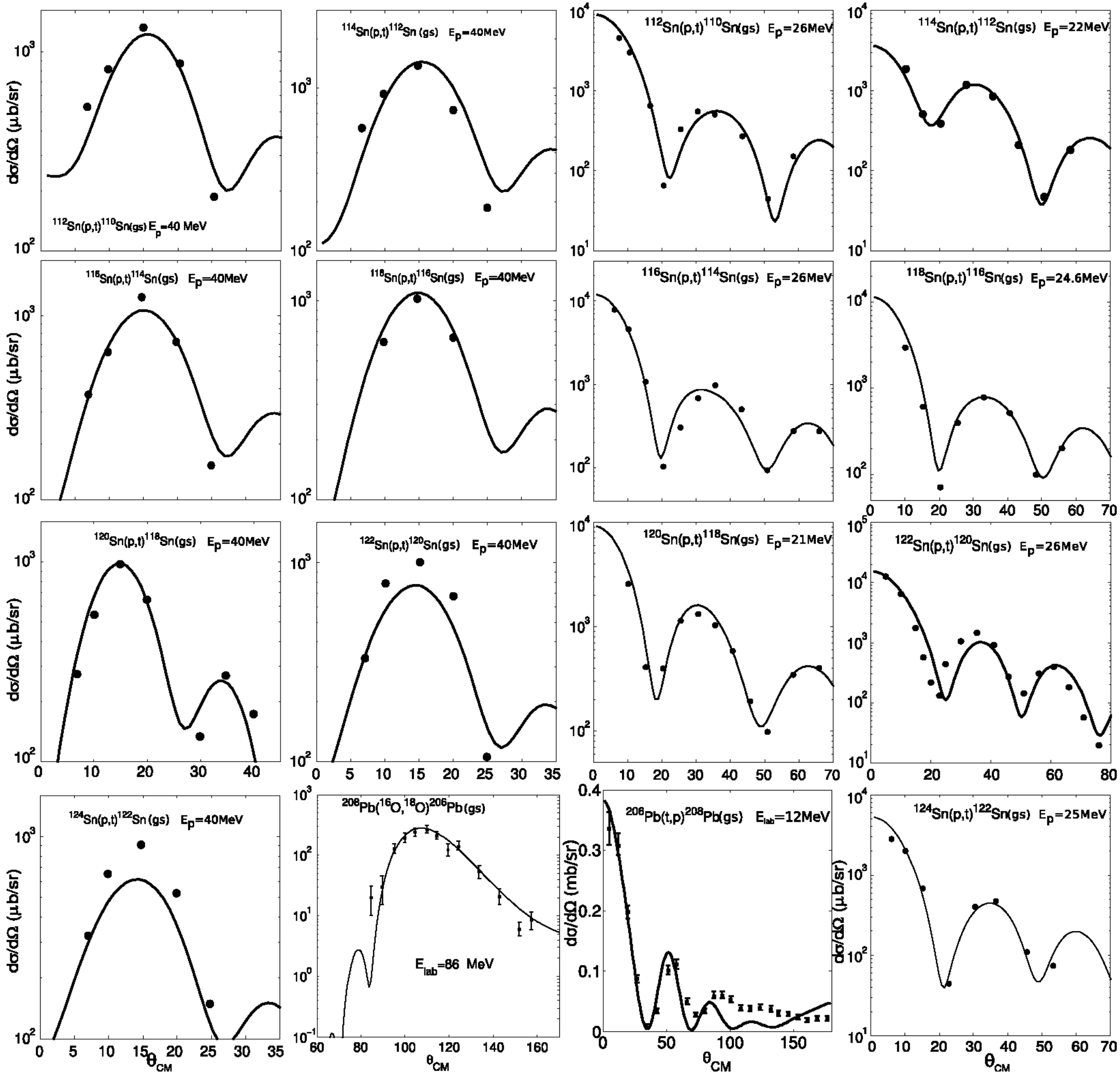
$$T^{(2)}_{\rm succ} = 2\sum_{l_i,j_i}\sum_{l_f,j_f,m_f}\sum_{\substack{\sigma_1\sigma_2\\ \sigma_1'\sigma_2'}}\int d\mathbf{r}_{dF}d\mathbf{r}_{p1}d\mathbf{r}_{A2}\big[\phi^{A+2}_{l_i,j_i}(\mathbf{r}_{A1},\sigma_1,\mathbf{r}_{A2},\sigma_2)\big]^{0*}_0 \chi^{(-)*}_{pB}(\mathbf{r}_{pB})v(r_{p1})\phi_d(r_{p1},\sigma_1)\varphi^{A+1}_{l_f,j_f,m_f}(\mathbf{r_{A2}},\sigma_2)$$

$$\times\int d\mathbf{r}'_{dF}d\mathbf{r}'_{p1}d\mathbf{r}'_{A2}G(\mathbf{r}_{dF},\mathbf{r}'_{dF})\phi_d(r'_{p1},\sigma_1')^*\varphi^{A+1*}_{l_f,j_f,m_f}(\mathbf{r}'_{\mathbf{A2}},\sigma_2')\frac{2\mu_{dF}}{\hbar^2}v(r'_{p2})\phi_d(r'_{p1},\sigma_1')\phi_d(r'_{p2},\sigma_2')\chi^{(+)}_{tA}(\mathbf{r}'_{tA}), \tag{38b}$$

and nonorthogonal,

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

$$\times\int d\mathbf{r}'_{p1}d\mathbf{r}'_{A2}d\mathbf{r}'_{dF}\phi_d(r'_{p1},\sigma_1')^*\varphi^{A+1*}_{l_f,j_f,m_f}(\mathbf{r}'_{\mathbf{A2}},\sigma_2')\phi_d(r'_{p1},\sigma_1')\phi_d(r'_{p2},\sigma_2')\chi^{(+)}_{tA}(\mathbf{r}'_{tA}), \tag{38c}$$



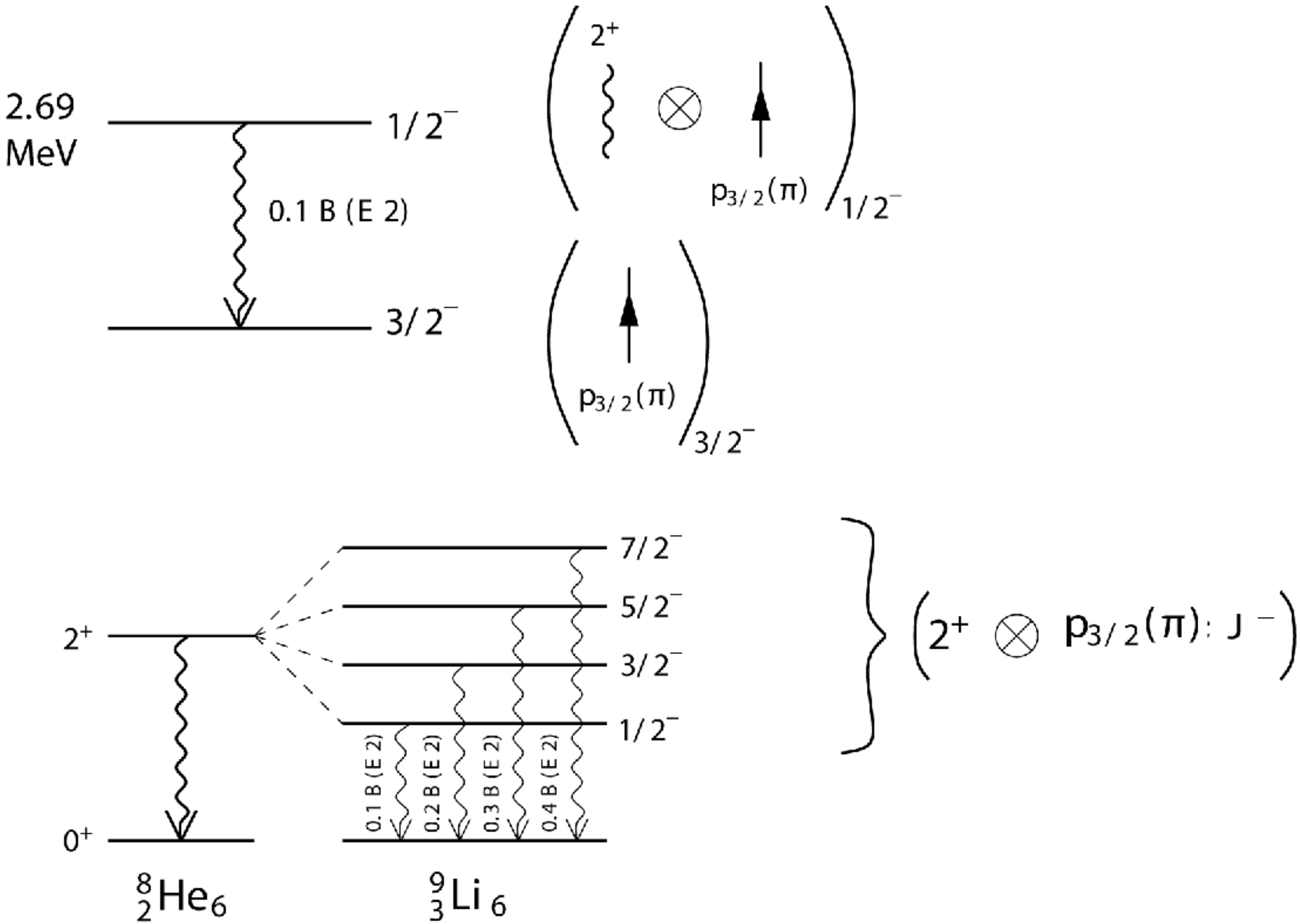
^{112}Sn(p,t)^{110}Sn(gs) E$_p$=40 MeV
^{114}Sn(p,t)^{112}Sn (gs) E$_p$=40MeV
^{112}Sn(p,t)^{110}Sn(gs) E$_p$=26MeV
^{114}Sn(p,t)^{112}Sn(gs) E$_p$=22MeV
^{116}Sn(p,t)^{114}Sn(gs) E$_p$=40MeV
^{118}Sn(p,t)^{116}Sn(gs) E$_p$=40MeV
^{116}Sn(p,t)^{114}Sn(gs) E$_p$=26MeV
^{118}Sn(p,t)^{116}Sn(gs) E$_p$=24.6MeV
^{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$_{CM}$

New Technical Achievement

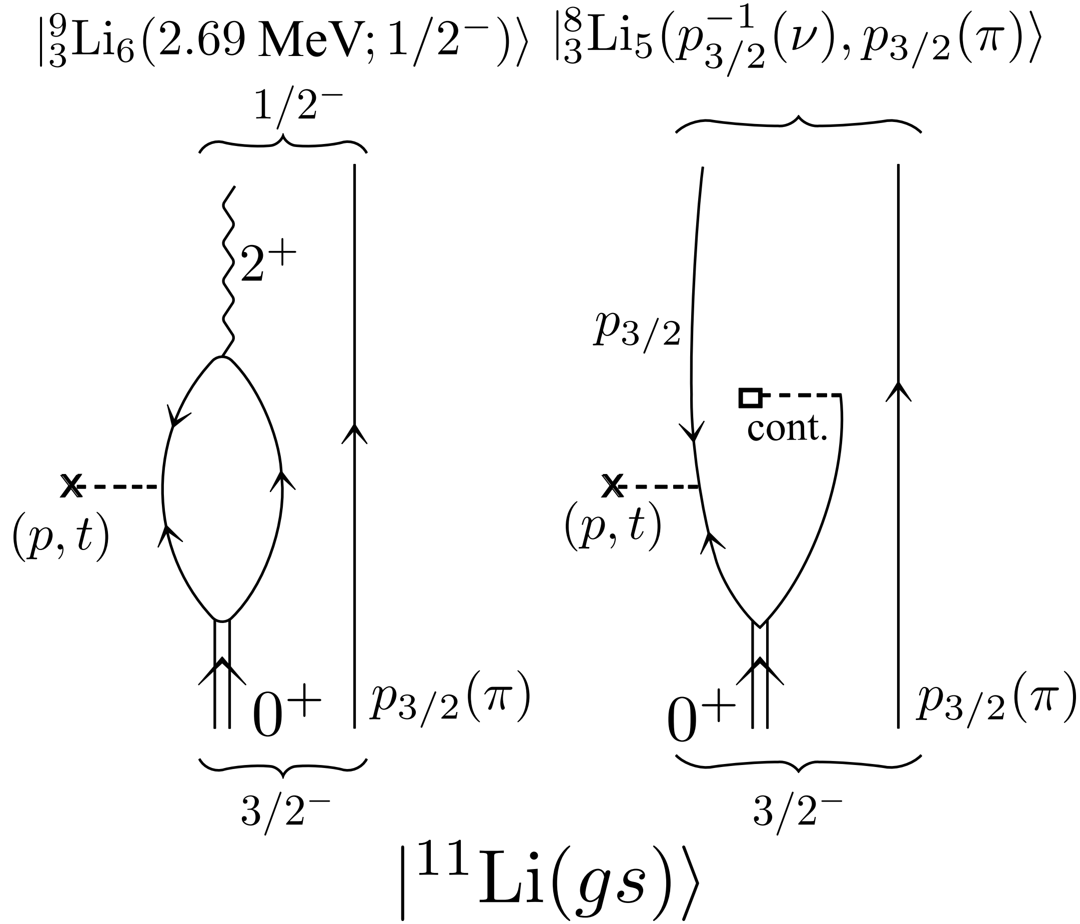
		σ(gs$\to$f)	
	f	Theory $^{a)\ b)\ f)}$	Experiment$^{f-m)}$
^{7}Li$(t,p)^{9}$Li	gs	14.3 $^{c)}$	14.7 ± 4.4 $^{c,i)}$ $[9.4° < \theta < 108.7°]$
^{1}H(^{11}Li,^{9}Li)^{3}H	gs	6.1 $^{c)}$	5.7 ± 0.9 $^{c,b)}$ $[20° < \theta < 154.5°]$
	$1/2^{-}$	0.7 $^{c)}$	1.0 ± 0.36 $^{c,b)}$ $[30° < \theta < 100°]$
^{10}Be$(t,p)^{12}$Be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

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

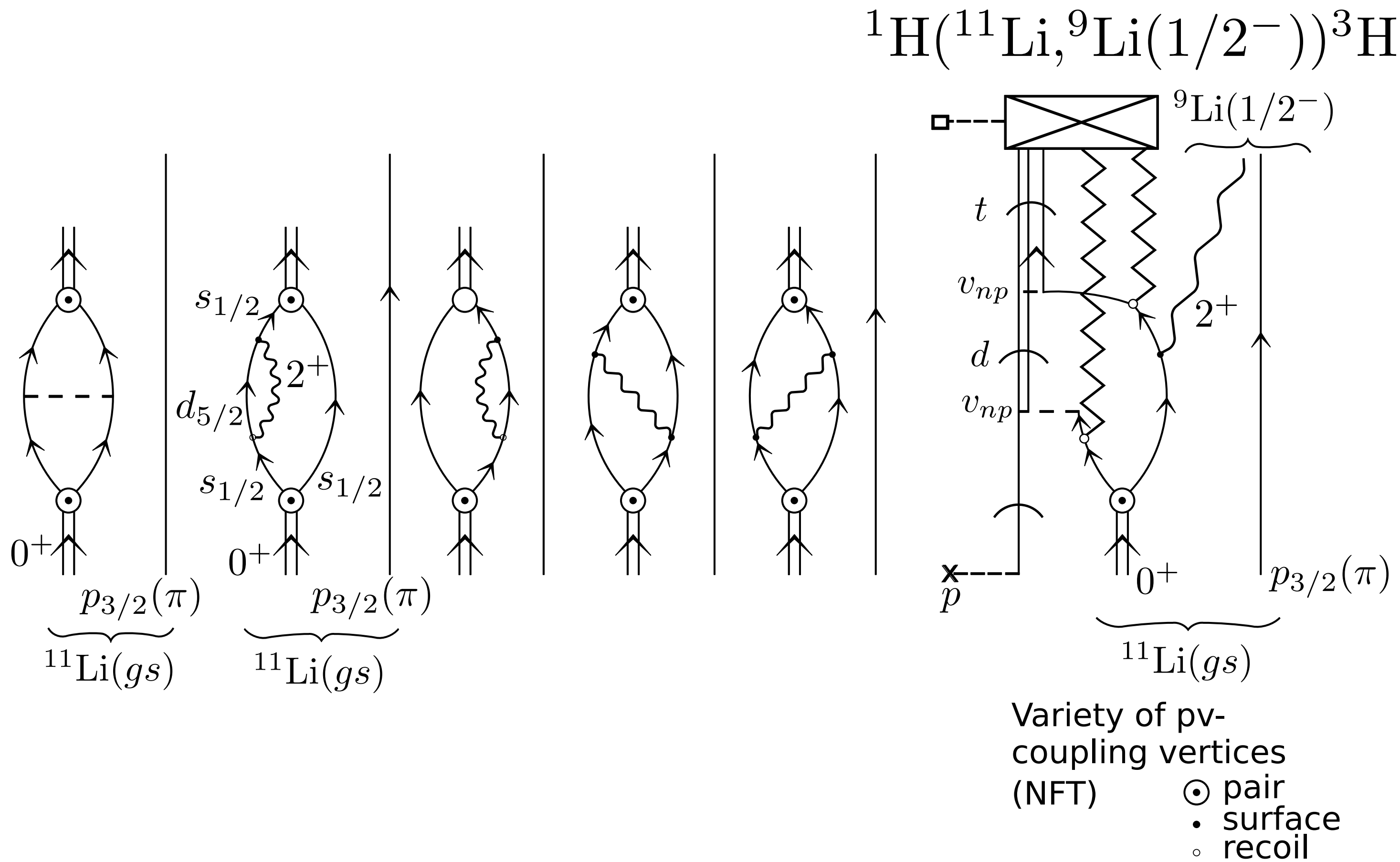
$^{a)}$ G. Potel et al., Phys. Rev. Lett. **107**, (2011) 092501.
$^{b)}$ G. Potel et al., Phys. Rev. Lett. **105**, (2010) 172502.
$^{c)}$ mb
$^{d)}$ μb
$^{e)}$ μb/sr ($\sum_{i=1}^{N}(d\sigma/d\Omega)$; differential cross section summed over the few, $N = 3 - 7$ experimental points).
$^{f)}$ B. Bayman 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.



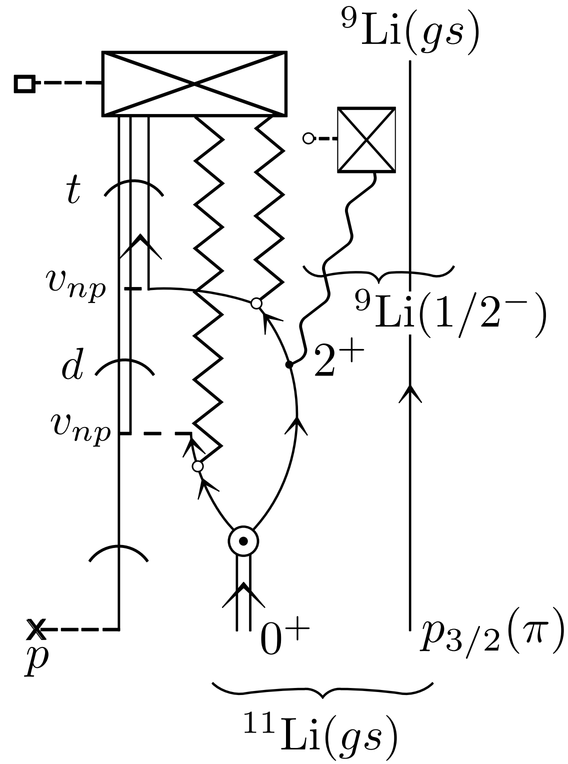
2.69
MeV
1/2⁻
0.1 B (E 2)
3/2⁻
2⁺
$p_{3/2}(\pi)$
1/2⁻
$p_{3/2}(\pi)$
3/2⁻
7/2⁻
5/2⁻
3/2⁻
1/2⁻
2⁺
0⁺
0.1 B (E 2)
0.2 B (E 2)
0.3 B (E 2)
0.4 B (E 2)
$\left(2^+ \otimes p_{3/2}(\pi): J^-\right)$
$^8_2\mathrm{He}_6$
$^9_3\mathrm{Li}_6$



$|{}^{9}_{3}\mathrm{Li}_{6}(2.69\,\mathrm{MeV}; 1/2^{-})\rangle$
$|{}^{8}_{3}\mathrm{Li}_{5}(p^{-1}_{3/2}(\nu), p_{3/2}(\pi)\rangle$
$1/2^{-}$
2^{+}
(p,t)
0^{+}
$p_{3/2}(\pi)$
$3/2^{-}$
$p_{3/2}$
cont.
(p,t)
0^{+}
$p_{3/2}(\pi)$
$3/2^{-}$
$|{}^{11}\mathrm{Li}(gs)\rangle$

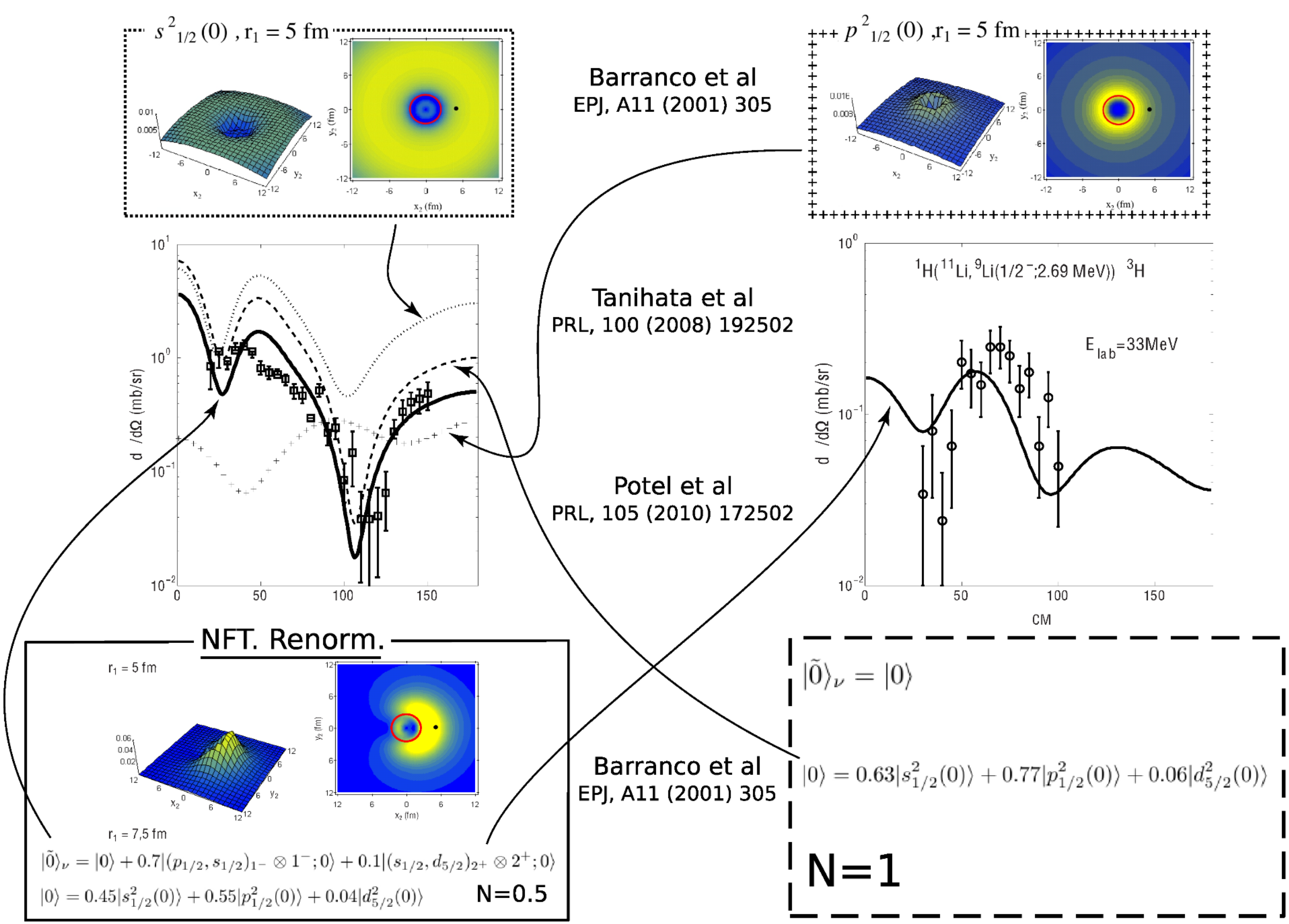


$^1\mathrm{H}(^{11}\mathrm{Li},^9\mathrm{Li}(1/2^-))^3\mathrm{H}$
$^9\mathrm{Li}(1/2^-)$
t
v_{np}
d
v_{np}
2^+
p
0^+
$p_{3/2}(\pi)$
$^{11}\mathrm{Li}(gs)$
$s_{1/2}$
$d_{5/2}$
2^+
$s_{1/2}$
$s_{1/2}$
0^+
$p_{3/2}(\pi)$
$^{11}\mathrm{Li}(gs)$
0^+
$p_{3/2}(\pi)$
$^{11}\mathrm{Li}(gs)$
Variety of pv-coupling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



Variety of pv-coupling vertices (NFT)

- ⊙ pair
- • surface
- ∘ recoil



$s^2_{1/2}(0)$, $r_1 = 5$ 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

core radius (systematics)

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

Halo radius

$$R \approx 3.5 \text{ fm}$$

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

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

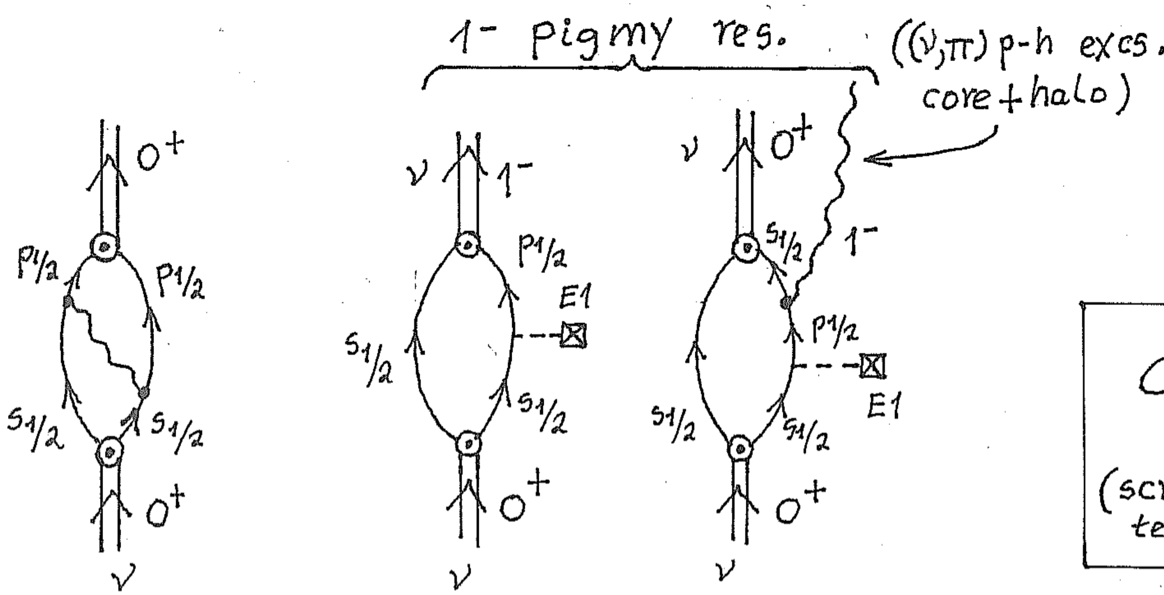
$$\int_0^{R_0} dr\ r^2\mathcal{R}^2 = \frac{3}{R_0^3}\int_0^{R_0} \frac{dr^3}{3} = 1$$

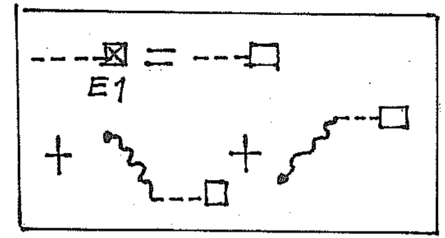
$\boxed{\text{Two-nucleon overlap}}$

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

$$o = \left(\int_0^{R_0} drr^2\mathcal{R}_{halo}\,\mathcal{R}\right)^2 = \left(\sqrt{\frac{3}{R^3}}\sqrt{\frac{3}{{R_0}^3}}\int_0^{R_0}\frac{dr^3}{3}\right)^2 = \left(\frac{R_0}{R}\right)^3$$

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





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

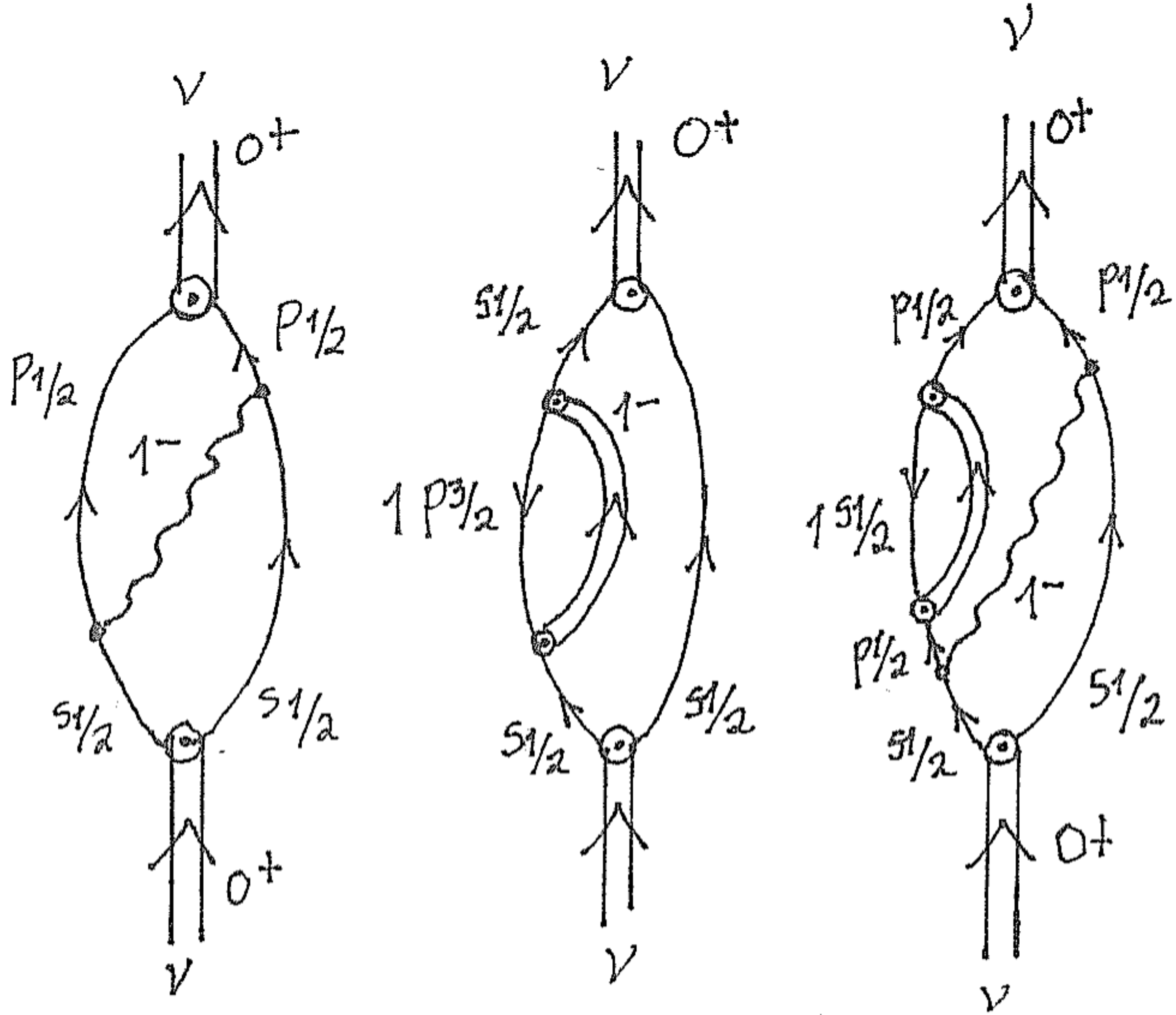
(screening of symmetry term)

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

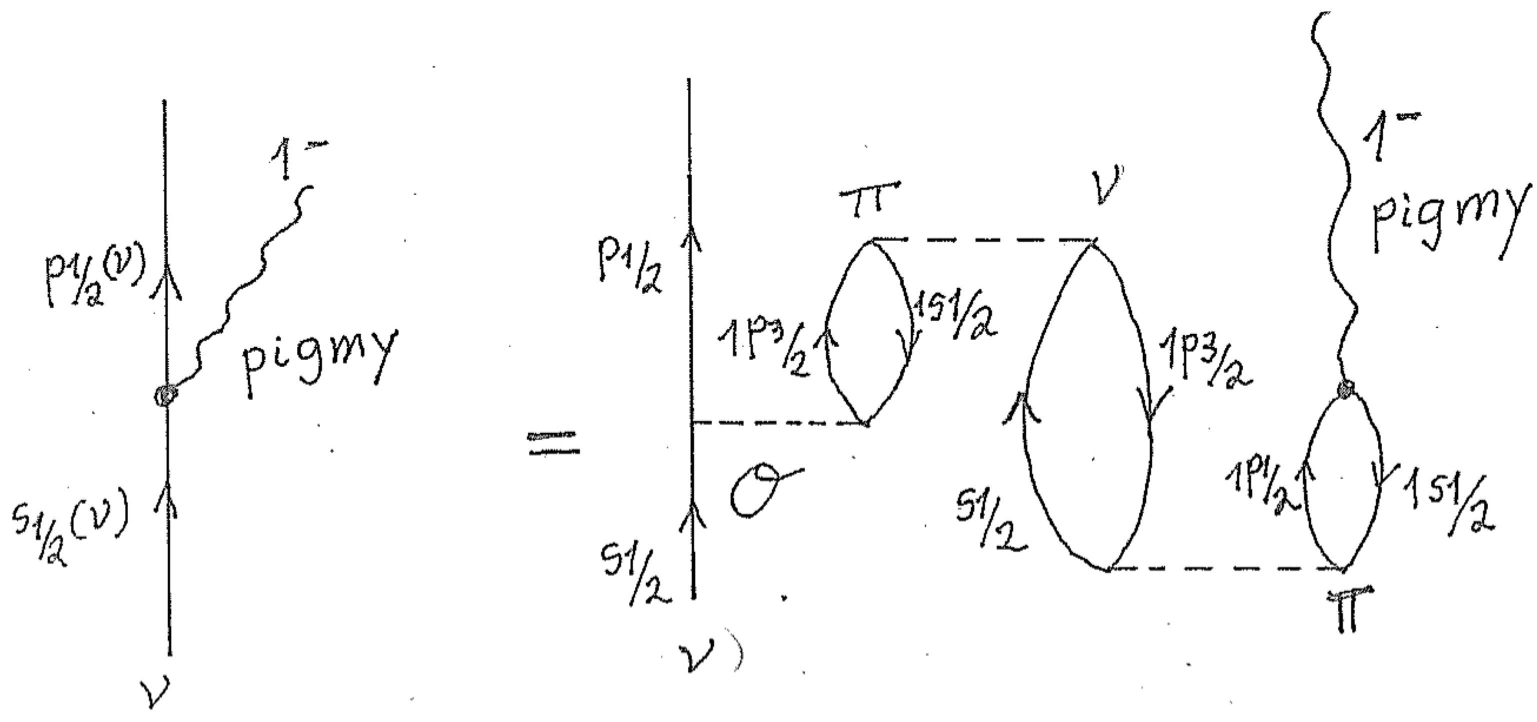
anti – (halo-anti-pairing effect)

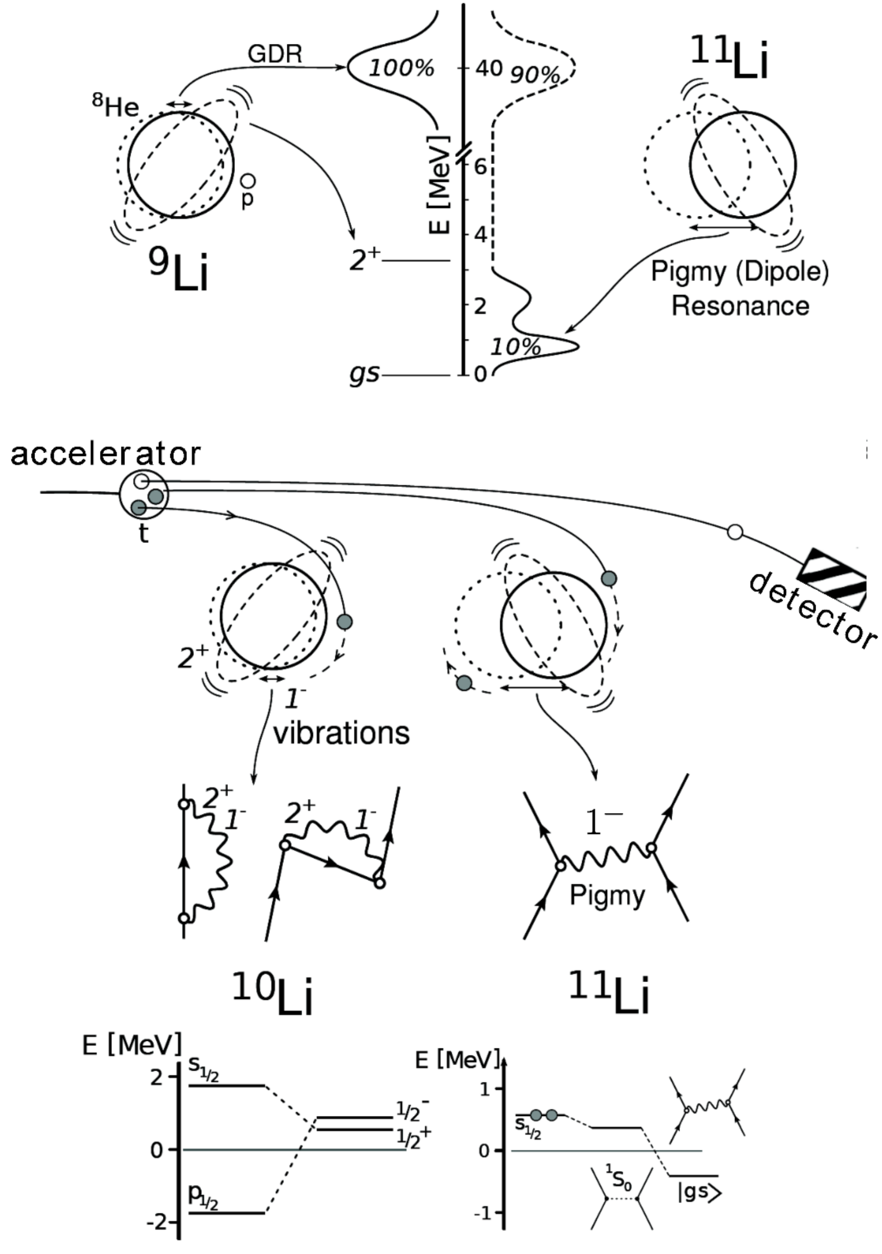
The pigmy resonance is built on a ground state with little overlap with the gs on which the GDR is built. It is thus a different (new) elementary mode of nuclear excitation

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



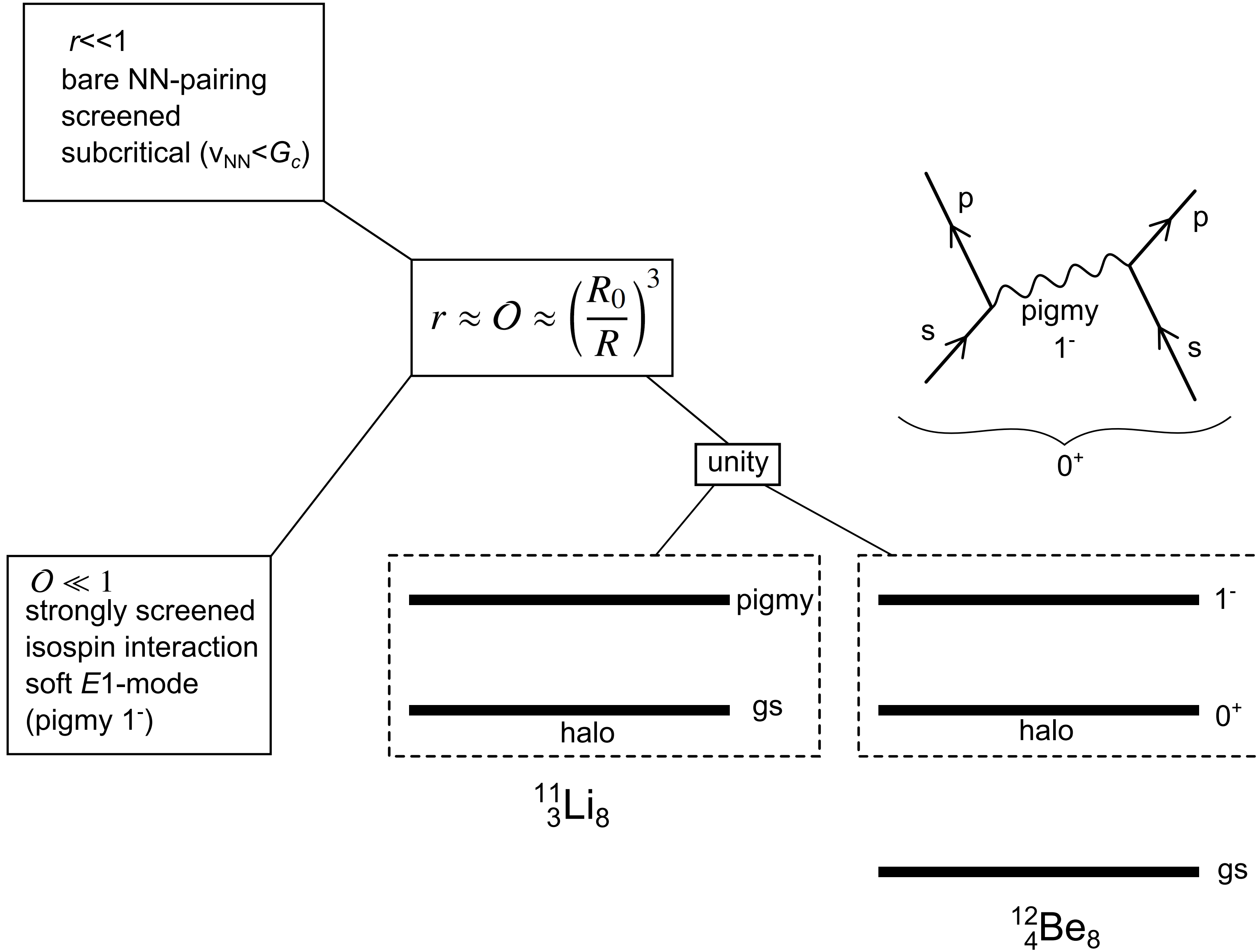
ν
0+
P1/2
P1/2
1⁻
s1/2
s1/2
0+
ν
ν
0+
s1/2
1⁻
1 p3/2
s1/2
s1/2
0+
ν
ν
0+
p1/2
p1/2
1 s1/2
1⁻
p1/2
s1/2
s1/2
0+
ν


1⁻
pigmy
p1/2(ν)
s1/2(ν)
ν
=
p1/2
s1/2
ν
π
1p3/2
1s1/2
ν
1p3/2
s1/2
1⁻
pigmy
1p1/2
1s1/2
π



Bootstrap pairing correlations

New physics



pair addition
halo mode

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

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

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

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

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

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

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

R: halo radius

Dual origin of pairing in nuclei

$v_{pair} = v_{bare} \quad (\text{N-N} + 3\text{N}) \; + v_{ind}$

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)

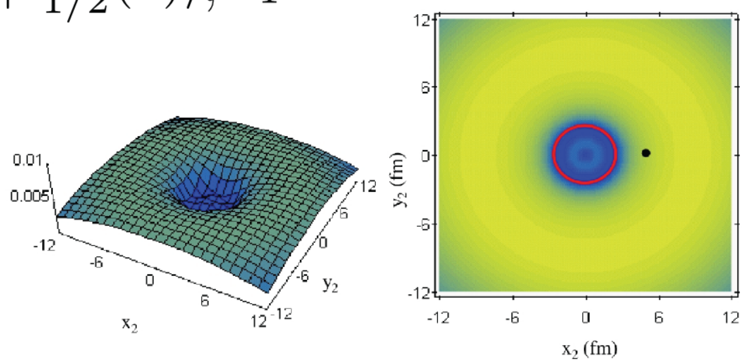
G. Potel (Livermore)

A. Idini (Darmstadt)

F. Barranco (Sevilla)

E. Vigezzi (Milano)

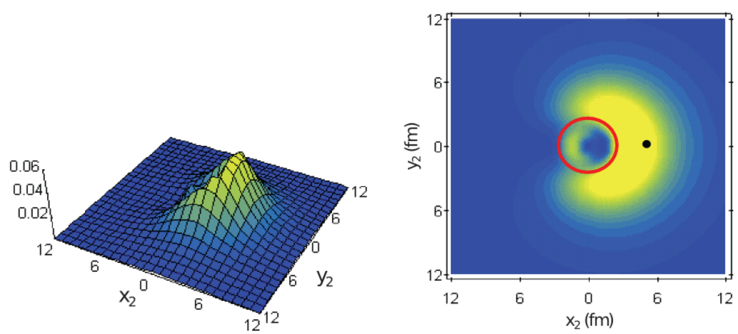
a) $|s^2_{1/2}(0)\rangle,\ r_1 = 5$ fm

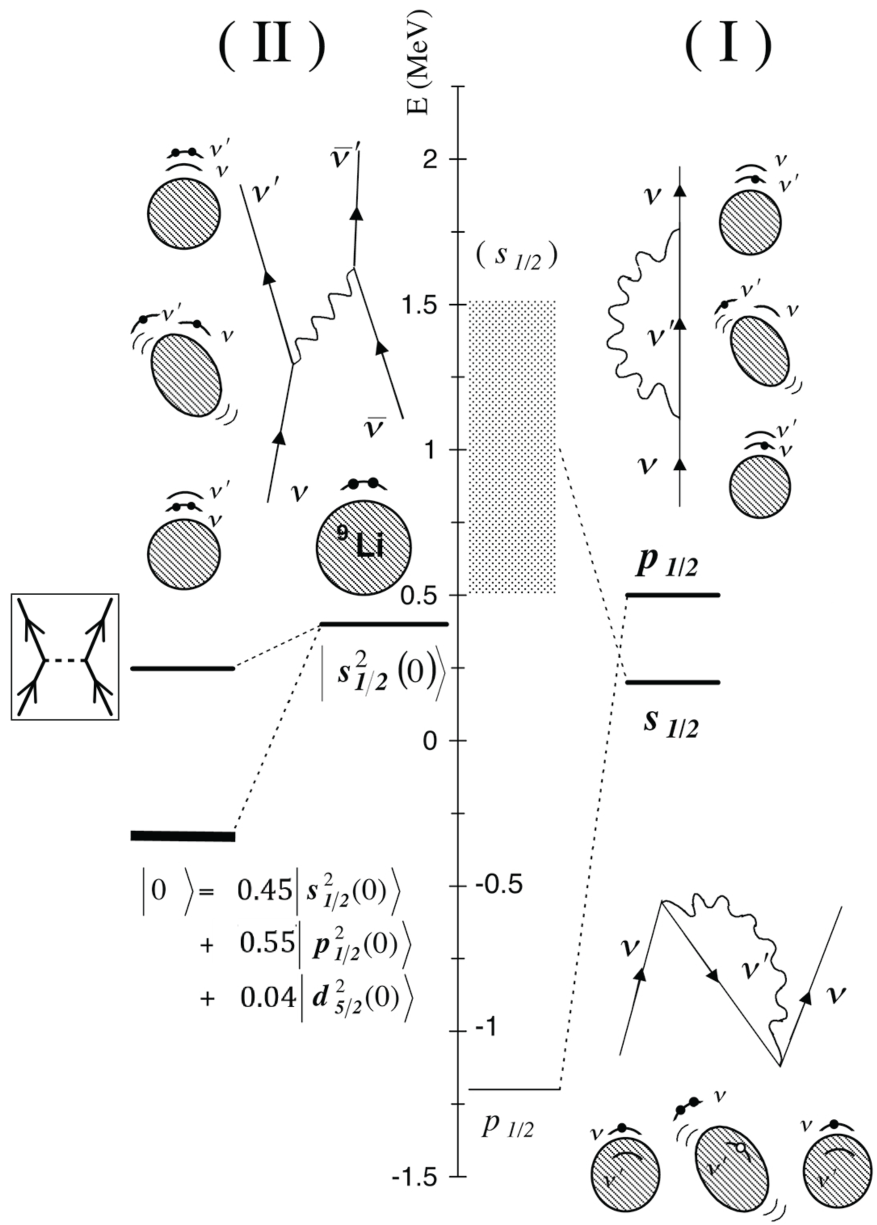


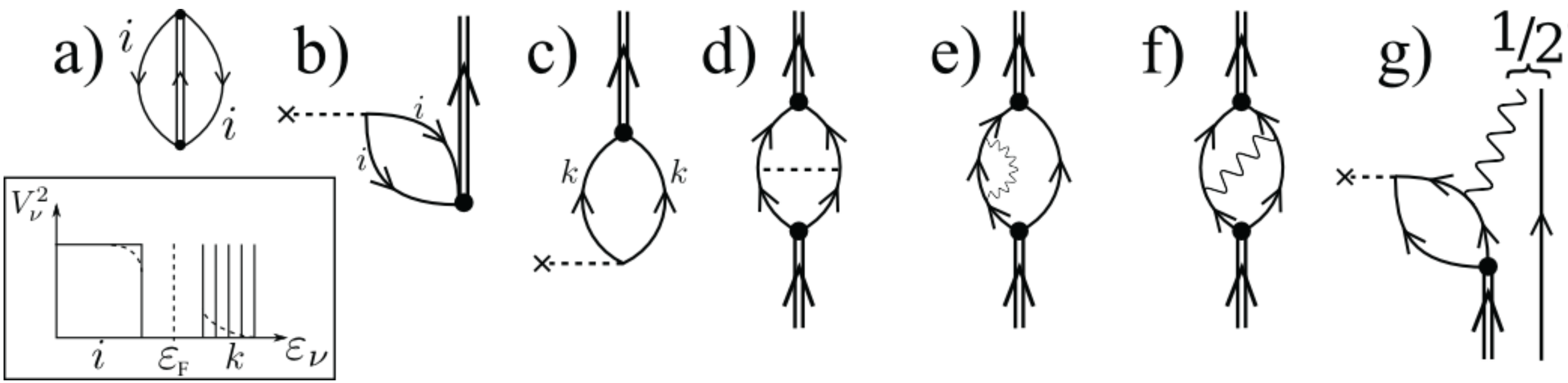
b) $|\tilde{0}\rangle = |0\rangle + 0.7\left|(p_{1/2}, s_{1/2})_{1^-} \otimes 1^-; 0\right\rangle$

$+\ 0.1\left|(s_{1/2}, d_{5/2})_{2^+} \otimes 2^+; 0\right\rangle$

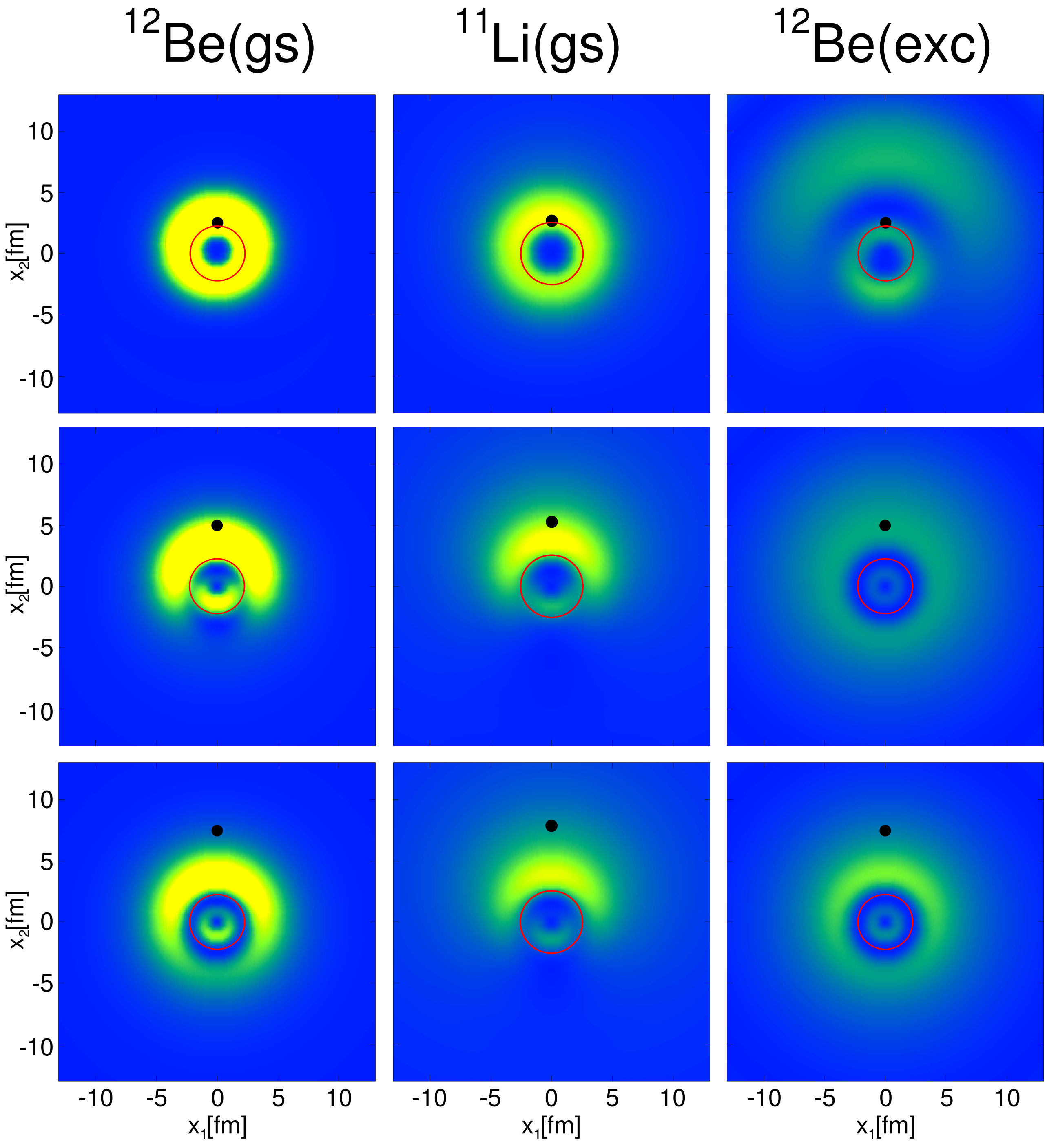
$r_1 = 5$ fm



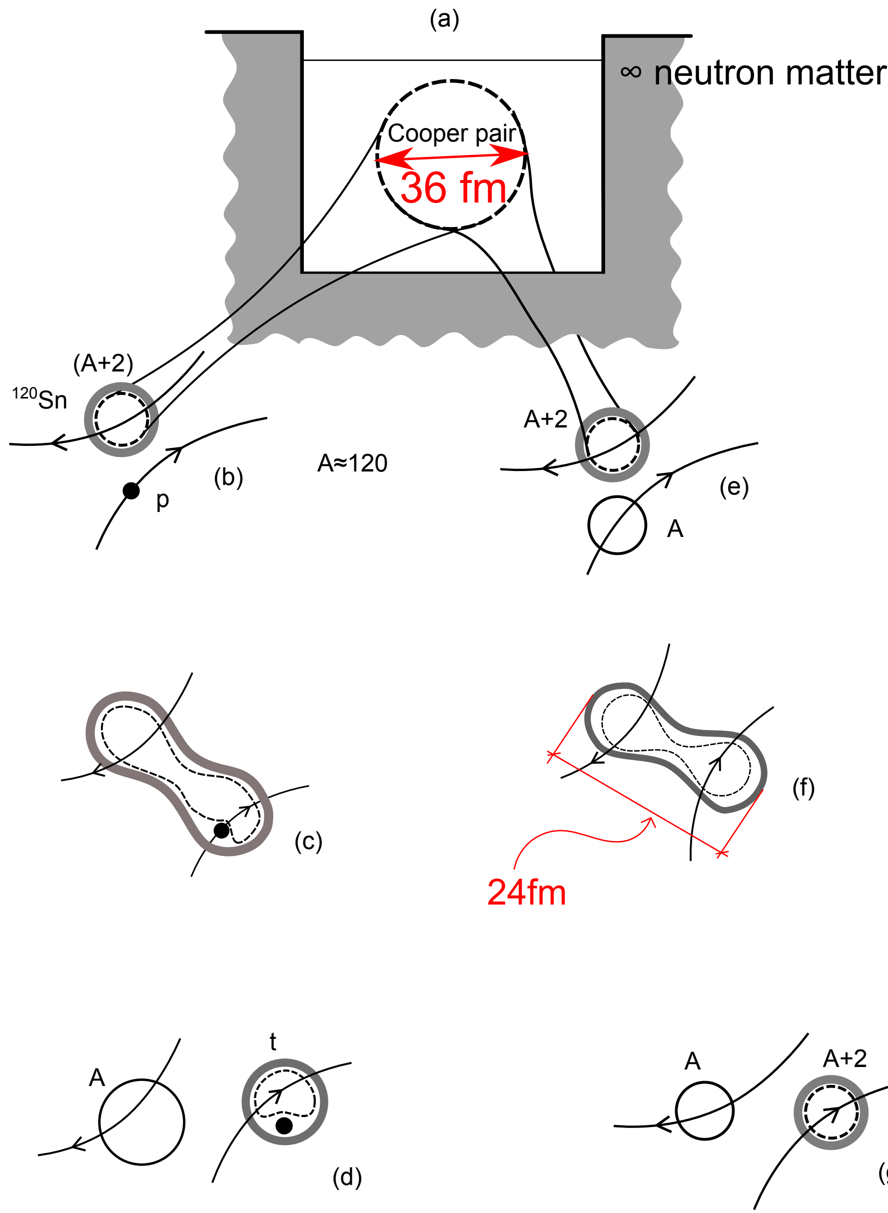




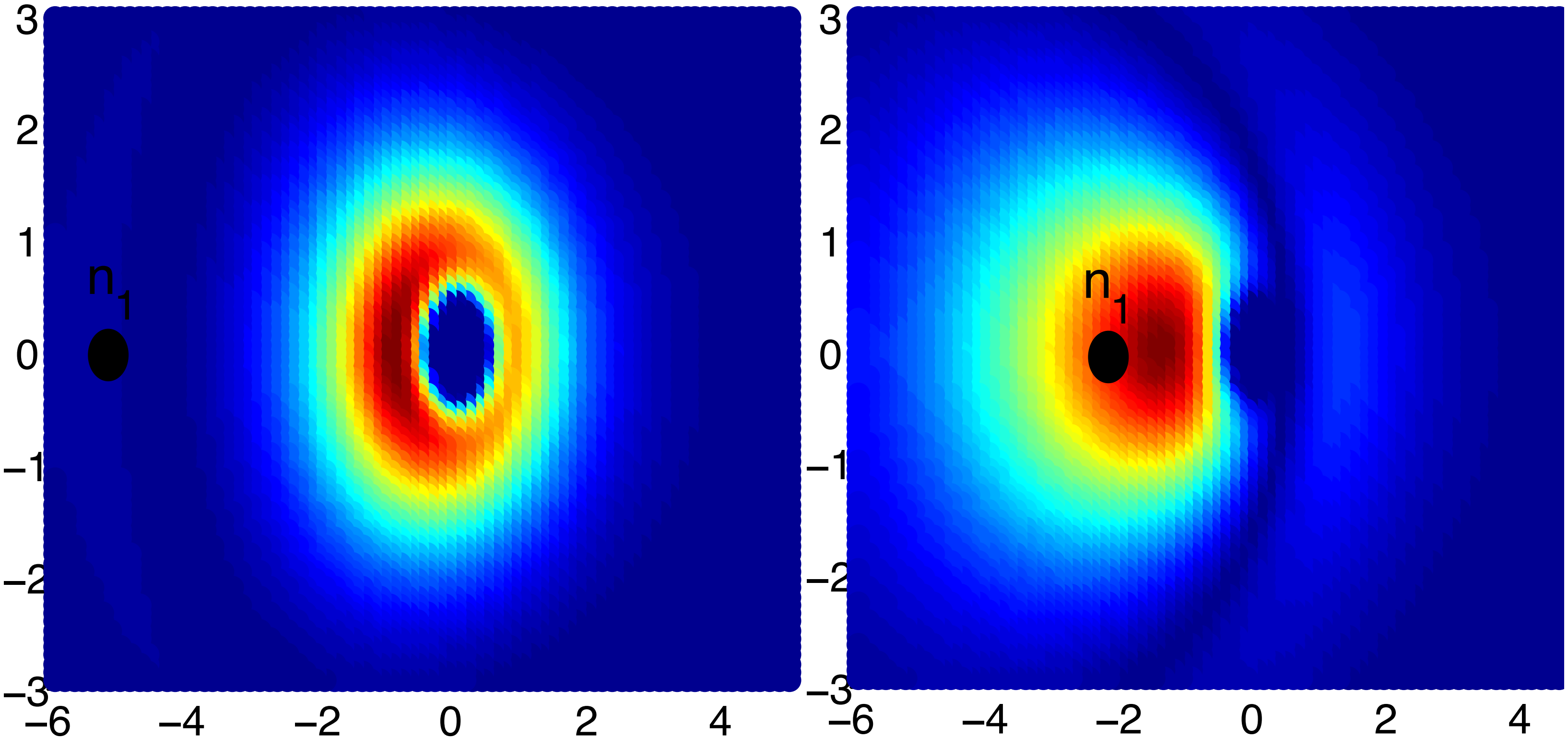
a)
i
i
b)
i
i
c)
k
k
d)
e)
f)
g)
1/2⁻
V_ν^2
i
ε_F
k
ε_ν

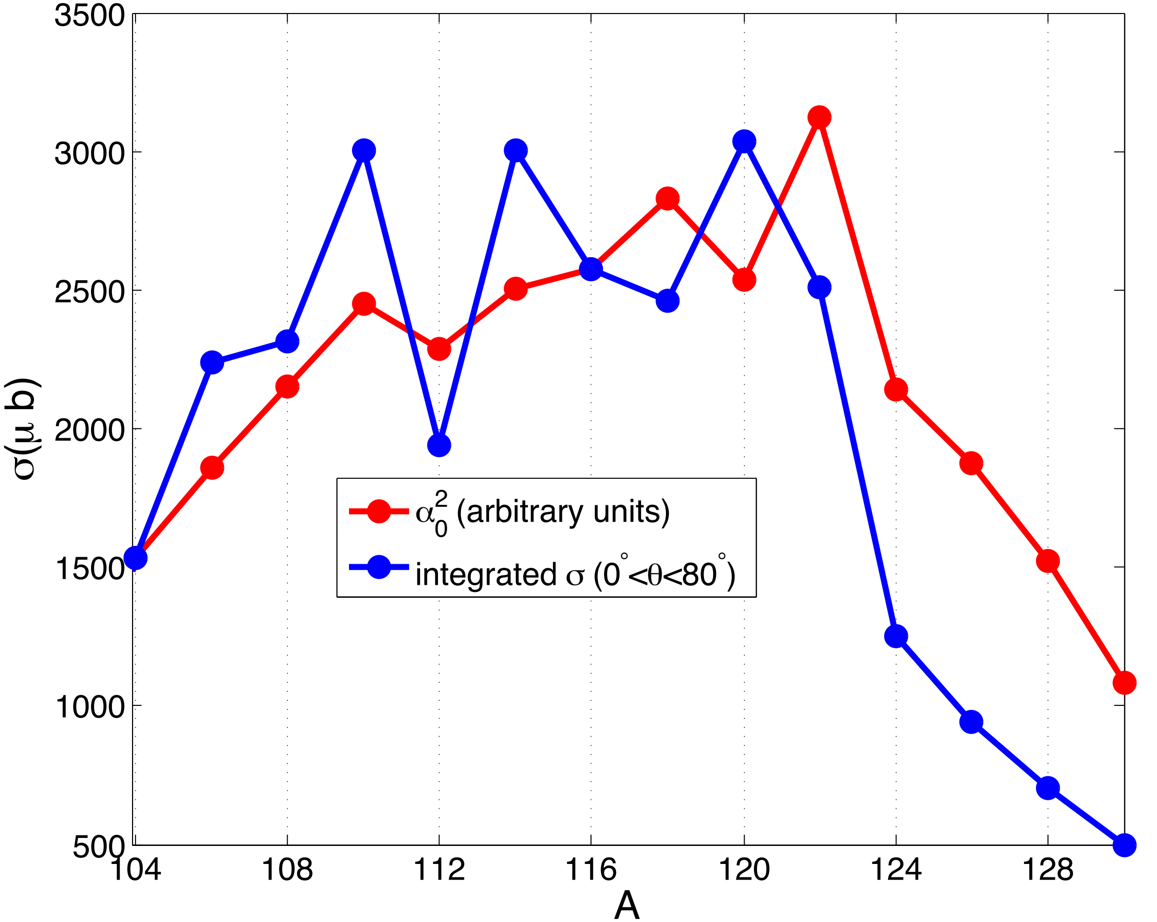


12Be(gs)
11Li(gs)
12Be(exc)
x2[fm]
x1[fm]
10
5
0
-5
-10

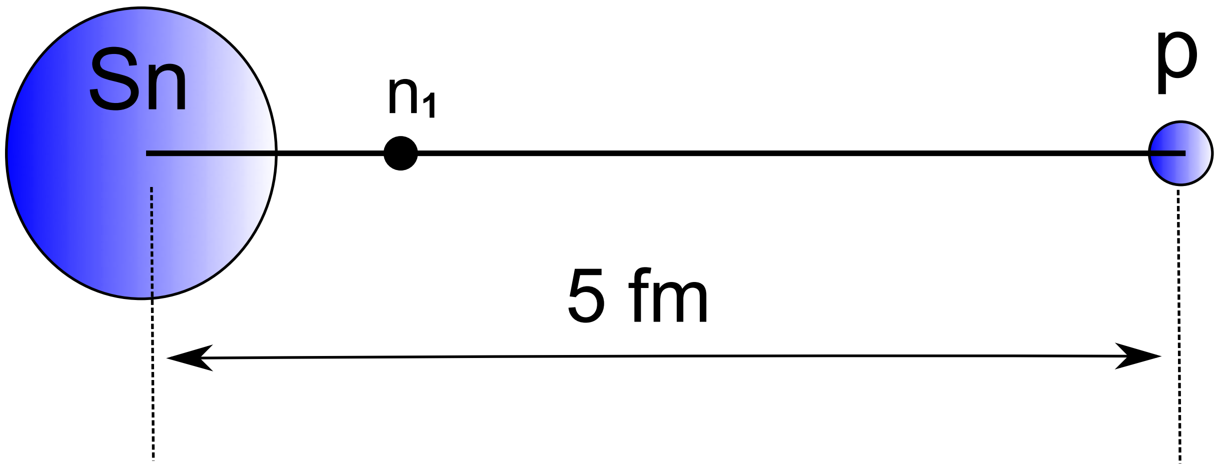


(a)
∞ neutron matter
Cooper pair
36 fm
(A+2)
120Sn
A≈120
(b)
p
A+2
(e)
A
(c)
(f)
24fm
A
t
(d)
A
A+2
(g)


3
2
1
0
−1
−2
−3
−6
−4
−2
0
2
4
n1
3
2
1
0
−1
−2
−3
−6
−4
−2
0
2
4
n1



3500
3000
2500
2000
1500
1000
500
$\sigma(\mu\,b)$
104
108
112
116
120
124
128
A
α_0^2 (arbitrary units)
integrated σ ($0^\circ<\theta<80^\circ$)


Sn
n1
p
5 fm