Progress in Ab-Initio Techniques in Nuclear Physics TRIUMF -- 17-20 February 2015



### Evolution of correlations and shell model charges from SCGF

Carlo Barbieri — University of Surrey

**Collaborators:** 

A. Cipollone, CB, P. Navrátil:

Phys. Rev. Lett. **111**, 062501 (2013) arXiv:1412.0491 [nucl-th] (2014)

V. Somà, A. Cipollone, CB, P. Navrátil, T. Duguet:

Phys. Rev. C 89, 061301R (2014)

CB, J. Phys.: Conf. Ser. 529, 012005 (2014)



### Nuclear forces in exotic nuclei



#### Carlo Barbieri – 5/11

### Example of spectral function <sup>56</sup>Ni

One-body Green's function (or propagator) describes the motion of quasiparticles and holes:

$$g_{\alpha\beta}(E) = \sum_{n} \frac{\langle \Psi_{0}^{A} | c_{\alpha} | \Psi_{n}^{A+1} \rangle \langle \Psi_{n}^{A+1} | c_{\beta}^{\dagger} | \Psi_{0}^{A} \rangle}{E - (E_{n}^{A+1} - E_{0}^{A}) + i\eta} + \sum_{k} \frac{\langle \Psi_{0}^{A} | c_{\beta}^{\dagger} | \Psi_{k}^{A-1} \rangle \langle \Psi_{k}^{A-1} | c_{\alpha} | \Psi_{0}^{A} \rangle}{E - (E_{0}^{A} - E_{k}^{A-1}) - i\eta}$$

...this contains all the structure information probed by nucleon transfer (spectral function):



### Concept of correlations



[CB and W. H. Dickhoff, Prog. Part. Nucl. Phys 52, 377 (2004)]

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### Concept of correlations



[CB and W. H. Dickhoff, Prog. Part. Nucl. Phys 52, 377 (2004)]

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Truncation scheme:	Dyson formulation (closed shells)	Gorkov formulation (semi-magic)		
1 <sup>st</sup> order:	Hartree-Fock	HF-Bogolioubov		
2 <sup>nd</sup> order:	2 <sup>nd</sup> order	2 <sup>nd</sup> order (w/ pairing)		
 3 <sup>rd</sup> and all-orders sums, P-V coupling:	ADC(3) FRPA etc	G-ADC(3) work in progress		







### Gorkov self-energy up to 2<sup>nd</sup> order

an name of M

 $= \delta_{J_{ux}j_x} \delta_{M_{ux}-m_x} \sum_{\kappa,n,\kappa} \eta_\alpha \pi_{k_1} f_{\alpha\kappa_1\kappa_1\kappa_2}^{n_\alpha n,n,n_1} \frac{\sqrt{2J}}{\sqrt{2J}}$ 

 $= -\delta_{I_{\alpha}i_{\alpha}}\delta_{M_{\alpha}-m_{\alpha}}\eta_{\alpha}\mathcal{N}_{n,[m_{\alpha}n_{\alpha}]I_{\alpha}}^{n_{i_{1}}n_{i_{2}}n_{i_{3}}}$ 

which recovers relation (72a). The remaining quan

{k1, k2, k3} indices and can be obtained from Eqs. (C

 $\mathcal{P}_{a(J_{c}J_{at})}^{k_{1}k_{2}k_{3}} = \sum_{J_{c}} (-1)^{J_{c}+J_{d}+j_{k_{2}}+j_{k_{3}}} \sqrt{2J_{c}}$ 

 $= -\delta_{J_{ik}j_k}\delta_{M_{ik}m_k}\sum_{i}\sum_{j}\pi_k$ 

 $= \delta_{J_{uv}, j_u} \delta_{M_{uv}, m_u} \sum \sum \pi_{k_2}$ 

 $\mathcal{R}_{a(J_cJ_{us})}^{k_1k_2k_3} = \sum (-1)^{2j_1+2J_d} \sqrt{2J_c+1}$ 

×  $\bar{V}_{n_{4}n_{5}n_{5}n_{6}}^{J_{d}[\alpha\kappa_{1}\kappa_{1}]} \mathcal{V}_{n_{5}[\kappa_{1}]}^{n_{k_{1}}} \mathcal{V}_{n_{5}[\kappa_{1}]}^{n_{k_{3}}}$  with  $\equiv \delta_{J_{uv} i_i} \delta_{M_{uv} m_i} Q_{n_e [a \kappa_1 \kappa_1 \kappa_2] J_e}^{n_{i_1} n_{i_2} n_{i_3}}$ 

 $\times \bar{V}_{n,n,n,n}^{J_d[a\kappa_1\kappa_3\kappa_2]} U_{n,n+1}^{n_{k_3}} U_{n,n+1}^{n_{k_2}}$  $\equiv \delta_{J_{uv}, j_u} \delta_{M_{uv}m_u} \mathcal{R}_{n_u}^{n_{k_1}n_{k_2}n_{k_3}} \mathcal{R}_{n_u}^{n_{k_1}n_{k_2}n_{k_3}} \mathcal{I}_{\mathcal{I}}$  $S_{a(J_cJ_{ud})}^{k_1k_2k_3} = \sum (-1)^{2j_1+2J_d} \sqrt{2J_c+1}$ 

 $= \delta_{J_{uv}, j_u} \delta_{M_{uv} m_u} \sum_{n_v n_v n_v} \sum_{J_d} \pi_{k_1}$ 

 $\times \bar{V}_{n,n,n,n}^{J_d[\alpha\kappa_1\kappa_2\kappa_2]} \mathcal{V}_{n,n,n}^{\kappa_{k_1}} \mathcal{V}_{n,n,n}^{\kappa_{k_2}}$ 

These terms are finally put together to form the different contributions to second-order self-energies. Let us consider  $\Sigma_{ab}$  as

an example [see Eq. (75)]. By inserting Eqs. (C35) and (C36) and summing over all possible total and intermediate angular

 $\equiv \delta_{J_{uv} j_{u}} \delta_{M_{uv} m_{u}} S^{n_{k_{1}} n_{k_{2}} n_{k_{3}}}_{n_{u} (m_{v} n_{v} n_{v}) J_{v}}$ 

 $j_{k_1}$  to  $J_{10t}$  and  $J_c$  as follows:



Ab INITIO SELF-CONSISTENT GORKOV-GREEN's ...

#### 5. Block-diagonal structu

a. First or The goal of this subsection is to discuss how the block-diagona reflects in the various self-energy contributions, starting with the fir and (C19) into Eq. (B7), and introducing the factor

$$f_{\alpha\beta\nu\delta}^{n_sn_bn_cn_d} \equiv \sqrt{1 + \delta_{\alpha\beta} \delta_{n_sn_s}}$$

one obtains

$$\begin{split} \Sigma_{ab}^{11(1)} &= \sum_{cd,k} \widehat{V}_{acdd} \widehat{V}_{d}^{k*} \widehat{V}_{c}^{k} & \text{angular momentum couplings of the three} \\ &= \sum_{cd,k} \sum_{\gamma} \sum_{m_{c}} \sum_{JM} \int_{a\gamma\beta\gamma}^{m_{c}n_{c}n_{c}n_{c}} C_{j,m_{c}}^{JM} & \text{give } J_{kk}. \text{ The recoupled } \mathcal{M} \text{ term is coupling} \\ &= \delta_{agb} \delta_{m_{c}m_{b}} \sum_{n_{c}n_{c}} \sum_{J} \int_{a\gamma\beta\gamma}^{J} f_{a\gamma\alpha\gamma}^{n_{c}n_{c}n_{c}} \frac{2}{2} & \mathcal{M}_{a(J,J_{m})}^{k,k} = \sum_{m_{c}m_{c}m_{c}} C_{j,m_{c}}^{J,M_{c}} C_{J,M_{c}}^{Jm} \\ &= \delta_{agb} \delta_{m_{c}m_{b}} \sum_{n_{c}n_{c}} \sum_{J} \int_{a\gamma\alpha\gamma}^{J} f_{a\gamma\alpha\gamma\gamma}^{n_{c}n_{c}n_{c}} \frac{2}{2} & \mathcal{M}_{a(J,J_{m})}^{k,k} = \sum_{m_{c}m_{c}m_{c}m_{c}M_{c}} C_{j,m_{c}}^{J,M_{c}} C_{J,M_{c}}^{Jm} \\ &= \delta_{agb} \delta_{m_{c}m_{c}} \sum_{n_{c}n_{c}n_{c}} \sum_{m_{c}n_{c}n_{c}} \sum_{m_{c}n_{c}n_{c}} \sum_{m_{c}n_{c}n_{c}} \sum_{m_{c}n_{c}n_{c}} \sum_{m_{c}} \sum_{m$$

where the block-diagonal normal density matrix is introduced throu  $\rho_{n_s n_b}^{[\alpha]} = \sum \mathcal{V}_{n_b [\alpha]}^{n_b}$ 

and properties of Clebsch-Gordan coefficients has been used. The  $\delta_{\pi_a \pi_b}$  and  $\delta_{q_a q_b}$ , leading to  $\delta_{\alpha \beta} = \delta_{j_a j_b} \delta_{\pi_a \pi_b} \delta_{q_a q_b}$ . Similarly, for  $\Sigma^{22(1)}$ 

$$\begin{split} \Sigma_{ab}^{22(1)} &= -\sum_{cd,k} \tilde{V}_{bcdd} \tilde{V}_{c}^{k} \tilde{V}_{d}^{k*} \\ &= -\delta_{ad,k} \delta_{m_{a}m_{b}} \sum_{\substack{\kappa,n_{i}, \gamma \\ \sigma \neq \sigma}} \sum_{j} \int_{\sigma j} \int_{\sigma j} f_{\sigma j}^{n_{i}} \\ &= -\delta_{jd} \delta_{m_{a}m_{b}} \sum_{\substack{\kappa,n_{i}, \gamma \\ \sigma \neq \sigma}} \sum_{j} \int_{\sigma j} f_{\sigma j}^{n_{i}} \\ &= -\delta_{jd} \delta_{m_{a}m_{b}} \sum_{\substack{\kappa,n_{i}, \gamma \\ \sigma \neq \sigma}} \sum_{j} \int_{\sigma j} f_{\sigma j}^{n_{i}} \\ &= -\delta_{ad} \delta_{m_{a}m_{b}} \left[ \Lambda_{\alpha j}^{n_{a}} \right]^{*} \\ &= -\delta_{ad} \delta_{m_{a}m_{b}} \left[ \Lambda_{\alpha j}^{n_{a}} \right]^{*} \\ &= \delta_{ad} \delta_{$$

where general properties of Clebsch-Gord

Let us consider the anomalous contributions to the first-order self-er derives  $\Sigma_{ab}^{12\,(1)} = \frac{1}{2} \sum \overline{V}_{abcd} \overline{V}_c^{k*} \overline{U}_d^k$ 

$$\mathcal{N}_{a(J_c J_{un})}^{-(-)} = \delta_{J_{un} J_a} \delta_{M_{un} m_a} \sum_{n,n}^{-}$$
  
 $\equiv \delta_{J_{un} J_a} \delta_{M_{un} m_a} \mathcal{N}_c$ 

- Arderlander

 $\equiv \delta_{\alpha\beta} \delta_{m_c m_b} \Sigma^{21}_{n_c}$ =  $\delta_{\alpha\beta} \delta_{m_c m_b} \tilde{h}^{(\alpha)}_{n_c s}$ 

Block-diagonal forms of second-order s

 $\times C_{j_1,m_1,j_2,m_3}^{J_{cd}M_c} C_{J_{cd}M_{cd},m_1}^{J_{cd}M_{cd}} C_{J_{cd}M_{cd},m_1}^{J_{cd}M_{cd}}} C_{J_{cd}M_{cd},m_1}^{J_{cd}M_{cd}}} C_{J_{cd}M_{cd},m_1}^{J_{cd}M_{cd}}} C_{J_{cd}M_{cd},m_1}^{J_{cd}M_{cd}}} C_{J_{cd}M_{cd},m_2}^{J_{cd}M_{cd}}} C_{J_{cd}M_{cd},m_2}^{J_{cd}M_{cd}}} C_{J_{cd}M_{cd}}} C_{J_{cd}M_{cd}}^{J_{cd}M_{cd}}} C_{J_{cd}M_{cd}}} C_{J_{cd}M_{cd}}^{J_{cd}M_{cd}}} C_{J_{cd}M_{cd}}} C_{J_{cd}M_{$  $= \sum_{m_1m_2m_3}\sum_{M_r}\sum_{n_rn_rn_r}\sum_{J_rM_r}\eta_{k_3} f_{\alpha\kappa_3}^{n_rr}$ 

$$= -\frac{1}{2} \sum_{n,n,q_1} \sum_{\gamma} \sum_{m_i} \sum_{JM} f_{\alpha\beta\gamma\gamma}^{n_i n_i n_i n_i} \eta_b \eta_c C_j$$
 One can show that the same result is obtain

$$= -\frac{1}{2} \sum_{n,k,l} \sum_{p} \sum_{m_{c}} \sum_{j} \int_{a,k_{c}}^{a_{p},a_{p},a_{m_{c}}} f_{ab} \gamma_{p} \gamma_{c}}^{a_{p},a_{p},a_{m_{c}}} \eta_{b} \pi_{c} C_{j,n}^{J,M_{c}} = \sum_{m_{l}m_{2}m_{3}} C_{j,m_{c}}^{J,M_{c}} \sum_{j} C_{j,m_{c}}^{J,M_{c}$$

.

where the block-diagonal anomalous density matrix is introduced th

$$\tilde{\rho}_{n_{k}\bar{n}_{b}}^{[\alpha]} = \sum_{n_{k}} U_{n_{k}[\alpha]}^{n_{k}} V_{n_{k}[\alpha]}^{n_{k}}.$$

momenta, one has

$$= \sum_{n,M,n,n,n} \sum_{j,k} \eta_{\alpha} \eta_{kj} f_{\alpha \alpha \beta n \alpha n}^{j,n,n} C_{j,n}^{j,k}$$

$$= \sum_{n,M,n,n,n} \sum_{j,k} \eta_{\alpha} \eta_{kj} f_{\alpha \alpha \beta n \alpha n}^{j,n,n} C_{j,n}^{j,n}$$

$$= \sum_{n,M,n,n,n} \eta_{\alpha} \pi_{kj} f_{\alpha \alpha \beta n \alpha \beta n}^{j,n,n,n,n} \frac{\sqrt{2J_c + 1}}{\sqrt{2J_a + 1}} (- \sum_{n,M,n,n,n} \sum_{j,k} \sum_{n,M,n,n,n} \sum_{j,k} \sum_{n,M,n,n,n} \frac{\sqrt{2J_c + 1}}{\sqrt{2J_a + 1}} (- \sum_{n,M,n,n,n} \sum_{j,k} \sum_{n,M,n,n,n} \sum_{j,k} \sum_{n,M,n,n,n} \frac{\sqrt{2J_c + 1}}{\sqrt{2J_a + 1}} (- \sum_{n,M,n,n,n} \sum_{j,k} \sum_{j,k} \sum_{n,M,n,n,n} \sum_{j,k} \sum_{n,M,n,n,n} \sum_{j,k} \sum_{j,k} \sum_{n,M,n,n,n} \sum_{j,k} \sum_{j,k$$

$$\Sigma_{n_{c}n_{b}}^{11(a)(2)} = \sum_{n_{i_{1}}n_{i_{2}}} \sum_{l_{c}} \sum_{e_{i_{1}}\in S_{i_{2}}} \sum_{l_{c}} \sum_{e_{i_{1}}\in S_{i_{1}}} \sum_{l_{c}} \sum_{e_{i_{1}}\in S_{i_{1}}$$

 $C_{n_{a}[ax)\kappa_{1}\kappa_{2}]J_{c}}^{n_{b_{1}}n_{b_{2}}n_{b_{3}}} = \frac{1}{\sqrt{c}} \left[ \mathcal{M}_{n_{a}[ax)\kappa_{1}\kappa_{2}]J_{c}}^{n_{b_{1}}n_{b_{2}}n_{b_{3}}} - \mathcal{P}_{n_{a}[ax)\kappa_{1}\kappa_{2}]J_{c}}^{n_{b_{1}}n_{b_{2}}n_{b_{3}}} - \mathcal{R}_{n_{a}[ax)\kappa_{1}\kappa_{2}]J_{c}}^{n_{b_{1}}n_{b_{2}}n_{b_{3}}} \right]$ 

$$= \sum_{n_1, n_2, n_3} \sum_{L_{\ell}} \sum_{e_1 \in e_2, e_3} \left[ \omega - (\omega_{k_1} + \omega_{k_2} + \omega_{k_3}) + i\eta + \omega + (\omega_{k_1} + \omega_{k_1} + \omega_{k_2}) - i\eta \right], \quad (Cover)$$

$$\Sigma_{n_{0}n_{0}}^{22(a)(2)} = \sum_{n_{11}n_{12},n_{13}} \sum_{J_{c}} \sum_{e_{1},e_{2},e_{3}} \left\{ \frac{\nu_{n_{c}}(ae_{1}e_{1}e_{2})J_{c}}{\omega - (\omega_{k_{1}} + \omega_{k_{2}} + \omega_{k_{3}}) + i\eta} + \frac{\nu_{n_{c}}(ae_{1}e_{1}e_{2})J_{c}}{\omega + (\omega_{k_{1}} + \omega_{k_{2}}) - i\eta} \right\}.$$
(C44d

#### 6. Block-diagonal structure of Gorkov's equations

 $\times \bar{V}^{J_d[a\kappa_1\kappa_1\kappa_3]}_{\kappa_a\kappa_1\kappa_s\kappa_s}\mathcal{U}^{n_{k_1}}_{n_s[\kappa_1]}\mathcal{U}^{n_{k_3}}_{n_s[\kappa_1]}\mathcal{U}^{n_{k_3}}_{n_s[\kappa_3]}$ In the previous subsections it has been proven that all single-particle Green's functions and all self-energy contributions entering  $\equiv \delta_{J_{uv}, j_u} \delta_{M_{uv}, m_u} \mathcal{P}_{\pi_u}^{n_{k_1} n_{k_2} \pi_{k_3}} \int_{J_u}$ Gorkov's equations display the same block-diagonal structure if the systems is in a 0+ state. Defining

$$T_{ab} - \mu \delta_{ab} \equiv \delta_{\alpha\beta} \delta_{m_am_b} \left[ T_{n,n_b}^{(a)} - \mu^{(q_a)} \delta_{n_an_b} \right],$$
 (C45)

 $Q_{a(J_cJ_{ust})}^{k_1k_2k_3} = \sum_{i} (-1)^{J_c+J_d+j_{k_2}+j_{k_3}} \sqrt{2J_c}$ introducing block-diagonal forms for amplitudes W and Z through

$$\mathcal{W}_{k,[i_{r},j_{sc}]}^{k,[i_{r},j_{sc}]} \equiv \delta_{J_{sc}j_{s}}\delta_{M_{sc}m_{k}} \mathcal{W}_{n_{k}[v_{r}(n_{i_{r}})n_{i_{r}}],r}^{i_{l}(i_{r}(n_{i_{r}})n_{i_{r}})}$$
(C46a)  
$$\sigma_{k}^{i_{k},i_{r}(n_{i_{r}})} = \delta_{j_{sc}j_{s}}\delta_{m_{sc}m_{k}} \mathcal{U}_{n_{sc}}^{i_{l}(i_{r}(n_{i_{r}})n_{i_{r}})}$$
(C46a)

$$Z_{k(J_{c}J_{bs})}^{*} \equiv -\delta_{J_{bs}j_{k}}\delta_{M_{bs}-m_{k}} \eta_{k} Z_{n_{k}[\kappa_{3}\kappa_{1}\kappa_{2}]J_{c}}, \qquad (C46b)$$

$$(\omega_k - E_{k_1 k_2 k_3}) \mathcal{M}_{n_k}^{n_k, n_{k_3}, n_{k_3}}_{n_k (k_1 \times n_{k_3}) I_i} \equiv \sum_{n_k, a} [ (\mathcal{G}_{n_k}^{n_k, n_k, n_{k_3}}_{n_k (a \times n_k) I_i})^* \mathcal{U}_{n_k}^{n_k} (a) + (\mathcal{D}_{n_k}^{n_k, n_k, n_{k_3}}_{n_k (a \times n_k) I_i})^* \mathcal{V}_{n_k}^{n_k} (a) ],$$
(C47a)

$$\left(\omega_{k} + E_{k_{1}k_{2}}\right) \mathcal{Z}_{n_{k}\{k_{3},n_{4}\},I}^{n_{k_{1}}n_{k_{3}}n_{4}} \equiv \sum_{n_{d} \neq 0} \left[ \mathcal{D}_{n_{a}\{n_{3},n_{4}\},I}^{n_{a},n_{4}} \mathcal{U}_{A_{a}\{a\}}^{n_{a}} + \mathcal{C}_{n_{a}\{ax,y,n_{2}\},I}^{n_{a}} \mathcal{U}_{A_{a}\{a\}}^{n_{a}} \right], \quad (C47b)$$

$$128$$

#### and using Eqs. (C29), (C31), (C32), (C34), and (C44), one finally writes Eqs. (81) as $= -\delta_{J_{ac}j_c}\delta_{M_{ac}m_s}\sum_{n.n,n_c}\sum_{J_c}\pi_i$

$$\omega_{k} \mathcal{U}_{n_{k}}^{a_{k}}[\mu] = \sum_{n_{0}} \left[ \left( \mathcal{I}_{n_{k}}^{a_{k}} - \mu^{(q_{k})} \delta_{n_{k},n_{k}} + \Lambda_{n_{k}}^{a_{k}} \right) \mathcal{U}_{n_{k}}^{a_{k}}[\mu] + \tilde{h}_{n_{k}}^{a_{k}} \mathcal{V}_{n_{k}}^{a_{k}} \right] \right] \\ + \sum_{n_{k}, n_{0}} \sum_{n_{k}, n_{0}} \sum_{n_{k}, n_{0}} \sum_{n_{k}, n_{0}} \sum_{n_{k}, n_{0}} \left[ \mathcal{L}_{n_{k}, (n_{0}, n_{0}, n_{0})}^{a_{k}} \mathcal{L}_{n_{k}, (n_{0}, n_{0}, n_{0},$$

$$\begin{split} \gamma_{n_{c}}^{e_{1}}(\mu) &= \sum_{n_{0}} \left[ - \left( T_{n_{0}n_{0}}^{e_{1}} - \mu^{(q_{c})} \, \delta_{n_{0}n_{0}} + \Lambda_{n_{c}n_{0}}^{(\mu)} \right) \mathcal{V}_{n_{0}}^{e_{1}}(\mu) + \mathcal{K}_{n_{0}n_{0}}^{(\mu)} \, \mathcal{U}_{n_{0}}^{e_{1}}(\mu) \right] \\ &+ \sum_{n_{1},n_{2},n_{3}} \sum_{\kappa_{1}c_{1}\kappa_{1}} \sum_{J_{c}} \left[ \mathcal{D}_{n_{0}}^{n_{1},n_{2},n_{3}} \mathcal{W}_{n_{0}}^{n_{1},n_{2},n_{3}}(\mu) + \left( \mathcal{C}_{n_{0}}^{e_{1},n_{2},n_{1}} \mathcal{U}_{n_{0}}^{e_{1}}(\mu) \right)^{*} \mathcal{Z}_{n_{0}}^{e_{1},n_{2},n_{3}}(\mu) \right]. \end{split}$$
(C48b)

064317-30

cdefek

(B31)

330)

(C43a)

011)

326)

327)

 $^{11}_{ab}(\omega') G^{12}_{ab}(\omega'') G^{21}_{ab}(\omega' + \omega'' - \omega)$ 

$$-\frac{1}{2}\sum_{\substack{cide_{f}k,k_{1}k_{2}k_{3}}} \bar{V}_{cfar} \bar{V}_{k} \bar{\omega}_{k} \delta_{k}} \left\{ \frac{V_{k}^{k_{1}} U_{k}^{k_{2}*} U_{k}^{k_{3}*} U_{k}^{k_{3}*} \bar{U}_{k}^{k_{3}*} \bar{V}_{f}^{k_{3}}}{\omega - (\omega_{k_{1}} + \omega_{k_{2}} + \omega_{k_{3}}) + i\eta} + \frac{\bar{U}_{k}^{k_{1}} \bar{V}_{k}^{k_{3}} \bar{U}_{k}^{k_{3}*} U_{k}^{k_{3}} U_{k}^{k_{3}*}}{\omega + (\omega_{k_{1}} + \omega_{k_{1}} + \omega_{k_{3}}) - i\eta} \right\}.$$
(B32)

064317-23

### Gorkov self-energy up to 2<sup>nd</sup> order

1<sup>st</sup> order → energy-independent self-energy V. Somà, CB, T. Duguet, , Phys. Rev. C 89, 024323 (2014)
V. Somà, CB, T. Duguet, Phys. Rev. C 87, 011303R (2013)
V. Somà, T. Duguet, CB, Phys. Rev. C 84, 064317 (2011)



2<sup>nd</sup> order and energy-dependent self-energy



### The FRPA Method in Two Words

Particle vibration coupling is the main cause driving the distribution of particle strength—on both sides of the Fermi surface...

(ph)

(ph)

**O**<sup>II</sup>(pp/hh)

= hole

R<sup>(2p1h</sup>

= particle

*CB et al., Phys. Rev. C***63**, 034313 (2001) *Phys. Rev. A***76**, 052503 (2007) *Phys. Rev. C***79**, 064313 (2009)

•A complete expansion requires <u>all</u> <u>types</u> of particle-vibration coupling

"Extended" Hartree Fock

...these modes are all resummed exactly and to all orders in a *ab-initio* many-body expansion.

•The Self-energy  $\Sigma^*(\omega)$  yields both single-particle states and scattering

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### Ab-initio Nuclear Computation & BcDor code



### Quenching of absolute spectroscopic factors



### Reaching medium mass and neutron rich isotopes

Degenerate system (open shells, deformations...)

Hamiltoninan, including three nucleon forces



### Convergence of s.p. spectra w.r.t. SRG

Cutoff dependence is reduces, indicating good convergence of many-body truncation and many-body forces



### Results for the N-O-F chains

A. Cipollone, CB, P. Navrátil, Phys. Rev. Lett. **111**, 062501 (2013) *and* arXiv:1412.0491 [nucl-th] (2014)



> cf. microscopic shell model [O<sup>·</sup> et al, PRL**105**, 032501 (2010).]



### Results for the N-O-F chains

A. Cipollone, CB, P. Navrátil, Phys. Rev. Lett. **111**, 062501 (2013) and arXiv:1412.0491 [nucl-th] (2014)



 $\rightarrow$  3NF crucial for reproducing binding energies and driplines around oxygen

→ cf. microscopic shell model [Otsuka et al, PRL105, 032501 (2010).]

UNIVERSITY OF  $\frac{N3LO (\Lambda = 500 \text{Mev/c}) \text{ chiral NN interaction evolved to 2N + 3N forces (2.0 \text{fm}^{-1})}{N2LO (\Lambda = 400 \text{Mev/c}) \text{ chiral 3N interaction evolved (2.0 \text{fm}^{-1})}$ 

### Results for the oxygen chain

A. Cipollone, CB, P. Navrátil, arXiv:1412.0491 [nucl-th] (2014)



 $\rightarrow$  Single particle spectra slightly diluted and

 $\rightarrow$  systematic underestimation of radii



## The sd-pf shell gap

Neutron spectral distributions for <sup>48</sup>Ca and <sup>56</sup>Ni:



#### - sd-pf separation is overestimated <u>even</u> with leading order N2LO 3NF

- Correct increase of *p*<sub>3/2</sub>-*f*<sub>7/2</sub> splitting (see Zuker 2003)

		2NF only	2+3NF(ind.)	2+3NF(full)	Experiment
	<sup>16</sup> O:	2.10	2.41	2.38	2.718±0.210 [19]
CB <i>et al.</i> , arXiv:1211.3315 [nucl-th]	<sup>44</sup> Ca:	2.48	2.93	2.94	3.520±0.005 [20]

# Neutron spectral function of Oxygens



### Z/N asymmetry dependence of SFs - Theory

Ab-initio calculations explain the Z/N dependence but the effect is much lower than suggested by direct knockout

Effects of continuum become important at the driplines





### Z/N asymmetry dependence of SFs - Theory

Ab-initio calculations explain the Z/N dependence but the effect is much lower than suggested by direct knockout

Effects of continuum become important at the driplines





### Single nucleon transfer in the oxygen chain

[F. Flavigny et al, PRL110, 122503 (2013)]

### $\rightarrow$ Analysis of <sup>14</sup>O(d,t)<sup>13</sup>O and <sup>14</sup>O(d,<sup>3</sup>He)<sup>13</sup>N transfer reactions @ SPIRAL

Reaction	<i>E</i> * (MeV)	$J^{\pi}$	R <sup>HFB</sup> (fm)	<i>r</i> <sub>0</sub> (fm)	$C^2 S_{exp}$ (WS)	$\frac{C^2 S_{\rm th}}{0p + 2\hbar\omega}$	R <sub>s</sub> (WS)	$C^2 S_{exp}$ (SCGF)	$C^2 S_{\rm th}$ (SCGF)	R <sub>s</sub> (SCGF)
$^{14}O(d, t)$ $^{13}O$	0.00	3/2-	2.69	1.40	1.69 (17)(20)	3.15	0.54(5)(6)	1.89(19)(22)	3.17	0.60(6)(7)
$^{14}$ O ( <i>d</i> , $^{3}$ He) $^{13}$ N	0.00	$1/2^{-}$	3.03	1.23	1.14(16)(15)	1.55	0.73(10)(10)	1.58(22)(2)	1.58	1.00(14)(1)
	3.50	$3/2^{-}$	2.77	1.12	0.94(19)(7)	1.90	0.49(10)(4)	1.00(20)(1)	1.90	0.53(10)(1)
$^{16}$ O ( <i>d</i> , <i>t</i> ) $^{15}$ O	0.00	$1/2^{-}$	2.91	1.46	0.91(9)(8)	1.54	0.59(6)(5)	0.96(10)(7)	1.73	0.55(6)(4)
$^{16}$ O ( <i>d</i> , $^{3}$ He) $^{15}$ N [19,20]	0.00	$1/2^{-}$	2.95	1.46	0.93(9)(9)	1.54	0.60(6)(6)	1.25(12)(5)	1.74	0.72(7)(3)
	6.32	$3/2^{-}$	2.80	1.31	1.83(18)(24)	3.07	0.60(6)(8)	2.24(22)(10)	3.45	0.65(6)(3)
$^{18}$ O ( <i>d</i> , $^{3}$ He) $^{17}$ N [21]	0.00	$1/2^{-}$	2.91	1.46	0.92(9)(12)	1.58	0.58(6)(10)			





- Overlap functions and strengths from GF

- Rs independent of asymmetry

# Mapping Ab-Initio calculation into the shell model approach

Recent works through CCM and IMRSG:

Bogner et al Phys. Rev. Lett. 113, 142501 (2014) Jansen et al Phys. Rev. Lett. 113, 142502 (2014)

✓ works well for spectra

Calculation of observables: <u>need many-body corrections, to evolve operators,</u> <u>add electroweak currents, ect...</u>

See Menendez , Stroberg, Pastore and other talks today...

To have a look at the many-body and effects:

Extract vibration coupling form microscopic calculations...

CB, T. Otsuka, in preparation



## "traditional" MBPT approach

#### PT expansion of effective interactions:



### Effective charges (estimate form many-body effects):







Dressed (self consistent) propagator:



PT expansion of effective interactions:



but NO self-en insertions

Effective charges (many-body contributions):









### Some results - <sup>A</sup>Ni chain in pfg<sub>9/2</sub> shell

Interaction: NNLO-opt, AV18 (+Gmatrix)

### Single particle basis: HF



CB, T. Otsuka, in preparation

### Some results - <sup>A</sup>Ni chain in pfg<sub>9/2</sub> shell

Interaction: NNLO-opt, AV18 (+Gmatrix)

Single particle basis: HF

### Averaged charges



Preliminary

→ "predicted" charges are smaller than usual phenomenological ones

→ NO higher order currents here -- just the many-body correction...

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# Some results - O and C chains Preliminary

Interaction: N3LO(500) (+Gmatrix)

### Single particle basis: HF or HFB

	C10	C22	O14	O16	O20
$ u_{s1/2} $ - $ u_{d3/2}$ :	0.142	0.094	-0.751	0.160	0.128
$ u_{s1/2} $ - $ u_{d5/2}$ :	0.226	0.125	0.261	0.214	0.181
$ u_{d3/2} $ - $ u_{d3/2}$ :	0.278	0.121	0.198	0.082	0.155
$ u_{d3/2} $ - $ u_{d5/2}$ :	0.320	0.137	0.249	0.274	0.214
$ u_{d5/2} $ - $ u_{d5/2}$ :	0.278	0.151	0.294	0.250	0.232
, ,					
$\pi_{s1/2}$ - $\pi_{d3/2}$ :	1.131	1.051	0.594	1.105	1.078
$\pi_{s1/2}$ - $\pi_{d5/2}$ :	1.155	1.094	1.161	1.142	1.134
$\pi_{d3/2}$ - $\pi_{d3/2}$ :	1.061	1.054	1.441	0.976	1.070
$\pi_{d3/2}$ - $\pi_{d5/2}$ :	1.141	1.107	1.042	1.091	1.170
$\pi_{d5/2}$ - $\pi_{d5/2}$ :	1.161	1.077	1.139	1.107	1.099
$ u_{p1/2} $ - $ u_{p3/2}$ :	0.359	0.319	0.344	0.401	0.404
$ u_{p3/2} $ - $ u_{p3/2}$ :	0.315	0.247	0.367	0.316	0.307
,					
$\pi_{p1/2}$ - $\pi_{p3/2}$ :	1.102	1.134	1.183	1.179	1.198
$\pi_{p3/2}$ - $\pi_{p3/2}$ :	1.128	1.103	1.075	1.056	1.082

**BE(2)** charges

→ "predicted" charges are smaller than usual phenomenological ones

→ NO higher order currents here -- just the many-body correction...



### Conclusions

- What to did we learn about realistic chiral forces from ab-initio calculations?
  - → Leading order 3NF are crucial to predict many important features that are observed experimentally (drip lines, saturation, orbit evolution, etc...)
  - → Experimental binding is predicted accurately up to the lower sd shell (A≈30) but deteriorates for medium mass isotopes (Ca and above) with roughly 1 MeV/A over binding.
  - → more short-range repulsion or fitting to mid masses will help [see NNLOsat talk, atc...].

Thank you for your attention!!!











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