Medium-mass nuclei from chiral EFT interactions

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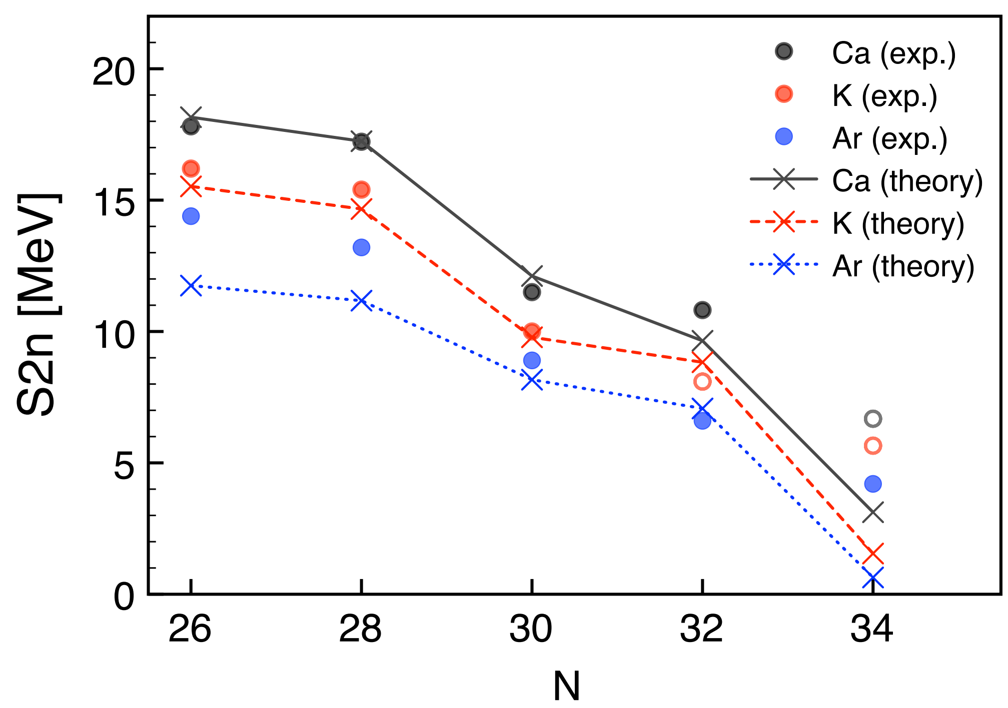
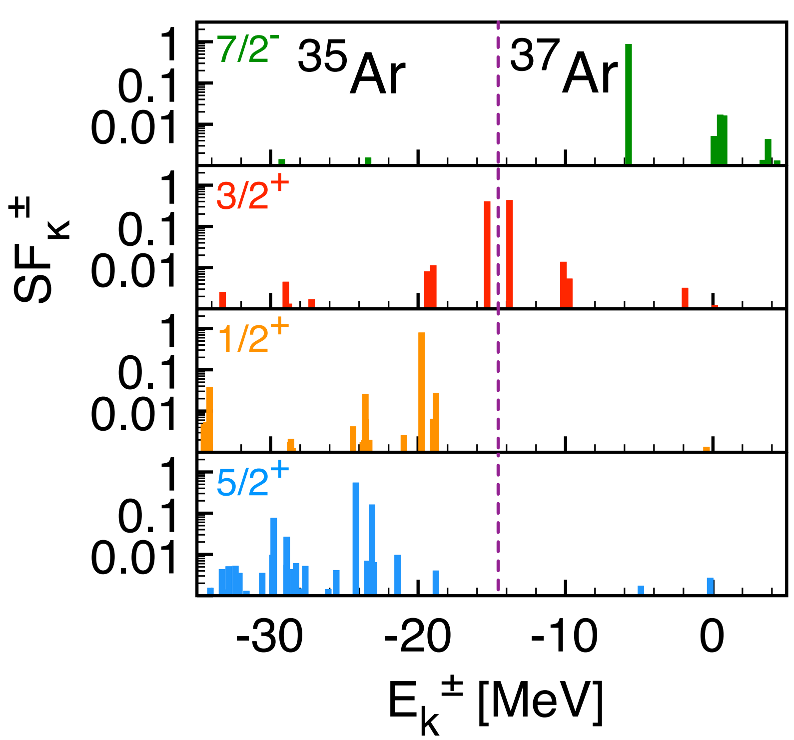
EMMI

Vittorio Somà (TU Darmstadt & EMMI)





Nuclear Structure Physics with Advanced Gamma-Detector Arrays

Padova, 10 June 2013

Towards a first-principle description of nuclei

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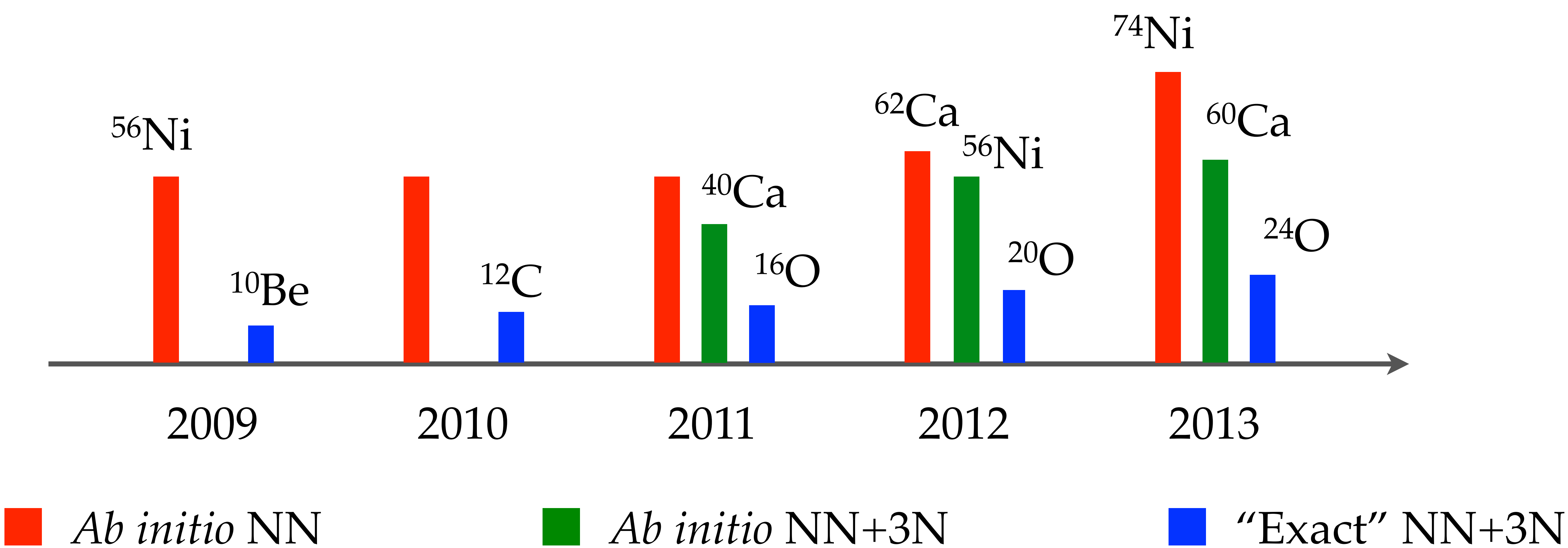
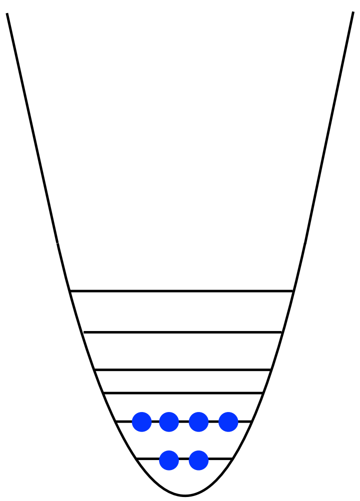
- *Ab initio* methods
  - ➟ Light systems with good precision
  - ➟ First *ab initio* calculations of reactions
  - ➟ *Ab initio* frontier: medium-mass isotopic chains

- Great progress in the last few years



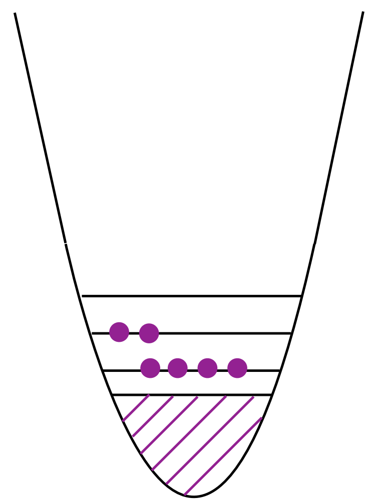
Towards a first-principle description of nuclei

Light nuclei



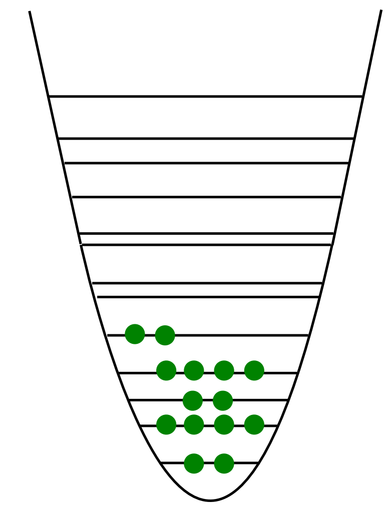
NCSM, GFMC, ...

Medium-mass nuclei



Miscroscopic SM, ...

Medium-mass nuclei



GF, CC, IM-SRG, ...

Configuration interaction limited to small valence/model spaces

Expansion schemes allow to reach heavier systems

Ab initio Green's function approach

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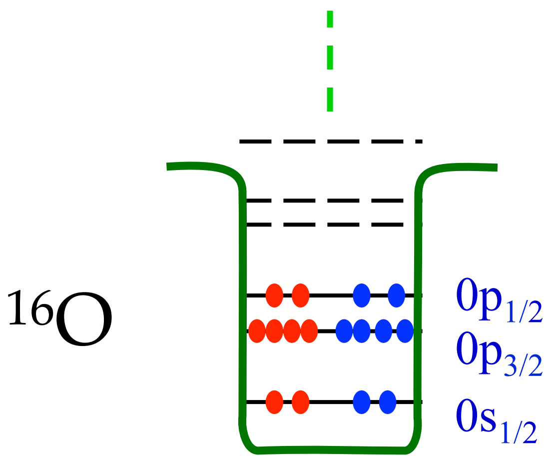
- ✪ Only input: NN+3N interactions
- ✪ Aim: parameter-free predictions of nuclear properties
  - ➟ Essential for exotic nuclei
  - ➟ Theoretical error estimates possible (and mandatory)
- ✪ Diagrammatic expansion of the solution
  - ➟ Beyond perturbation theory, controlled and improvable
  - ➟ Current scheme: ADC(3)

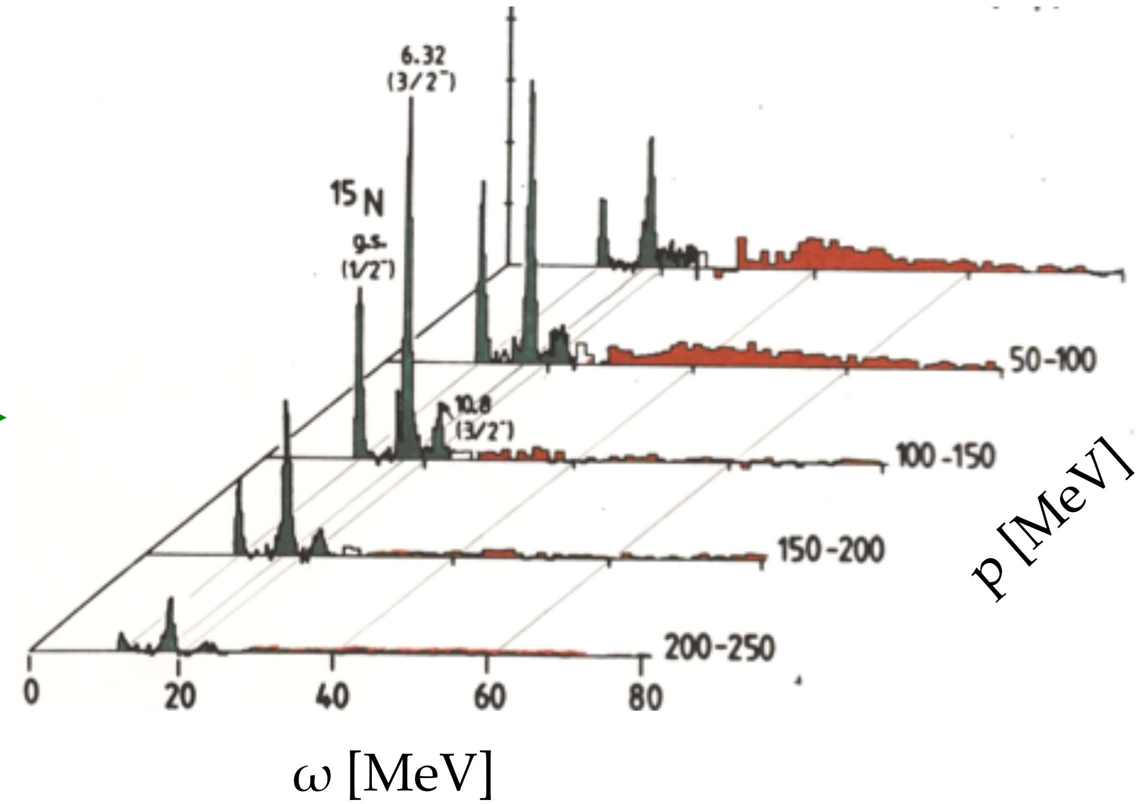
- ✪ NN potential: chiral N^3LO (500 MeV) SRG-evolved to 2.0 fm^{-1} [Entem & Machleidt 2003]
- ✪ 3N potential: chiral N^2LO (400 MeV) SRG-evolved to 2.0 fm^{-1} [Navrátil 2007]
  - ➟ Fit to three- and four-body systems only
  - ➟ Modified cutoff to reduce induced 4N contributions [Roth *et al*. 2012]

One-nucleon spectral function

✪ Independent-particle picture



Correlations →



Saclay data for ^{16}O(e,e'p) [Mougey *et al.* 1980]

✪ Spectral function

$$S_p^{-}(\omega) \equiv \sum_k \left| \langle \psi_k^{A-1} | a_p | \psi_0^A \rangle \right|^2 \delta(\omega - (E_0^A - E_k^{A-1}))$$

➠ Distribution of momenta and energies

Inside the Green's function

✪ Separation energy spectrum

$$G^{11}_{ab}(\omega) = \sum_k \left\{ \frac{\mathcal{U}^k_a \, \mathcal{U}^{k*}_b}{\omega - \omega_k + i\eta} + \frac{\bar{\mathcal{V}}^{k*}_a \, \bar{\mathcal{V}}^k_b}{\omega + \omega_k - i\eta} \right\}$$

Lehmann representation

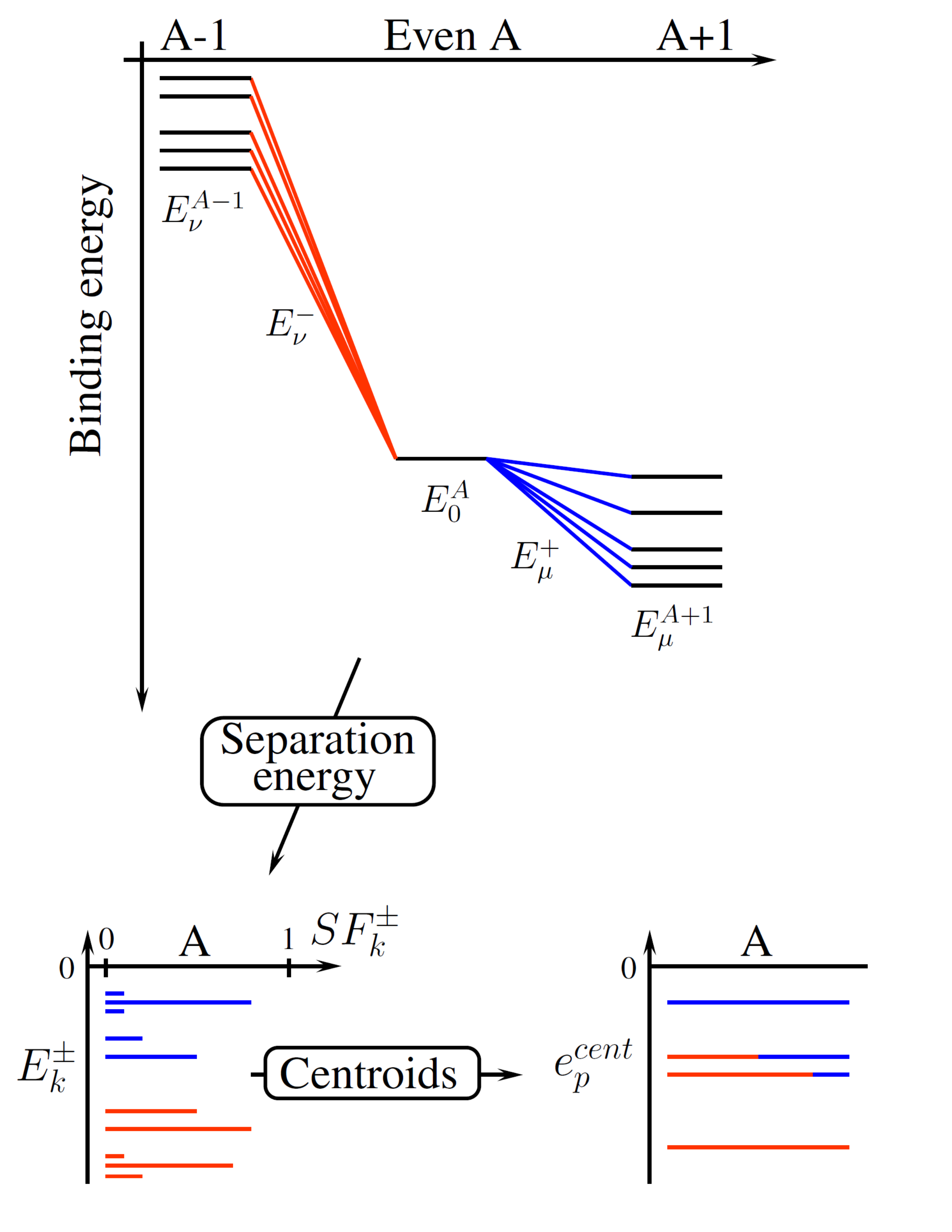
where
$$\begin{cases} \mathcal{U}^{k*}_a \equiv \langle \Psi_k | a^\dagger_a | \Psi_0 \rangle \\ \mathcal{V}^{k*}_a \equiv \langle \Psi_k | \bar{a}_a | \Psi_0 \rangle \end{cases}$$

and
$$\begin{cases} E^{+\,(A)}_k \equiv E^{A+1}_k - E^A_0 \equiv \mu + \omega_k \\ E^{-\,(A)}_k \equiv E^A_0 - E^{A-1}_k \equiv \mu - \omega_k \end{cases}$$

✪ Spectroscopic factors

$$SF^+_k \equiv \sum_{a \in \mathcal{H}_1} \left| \langle \psi_k | a^\dagger_a | \psi_0 \rangle \right|^2 = \sum_{a \in \mathcal{H}_1} \left| \mathcal{U}^k_a \right|^2$$

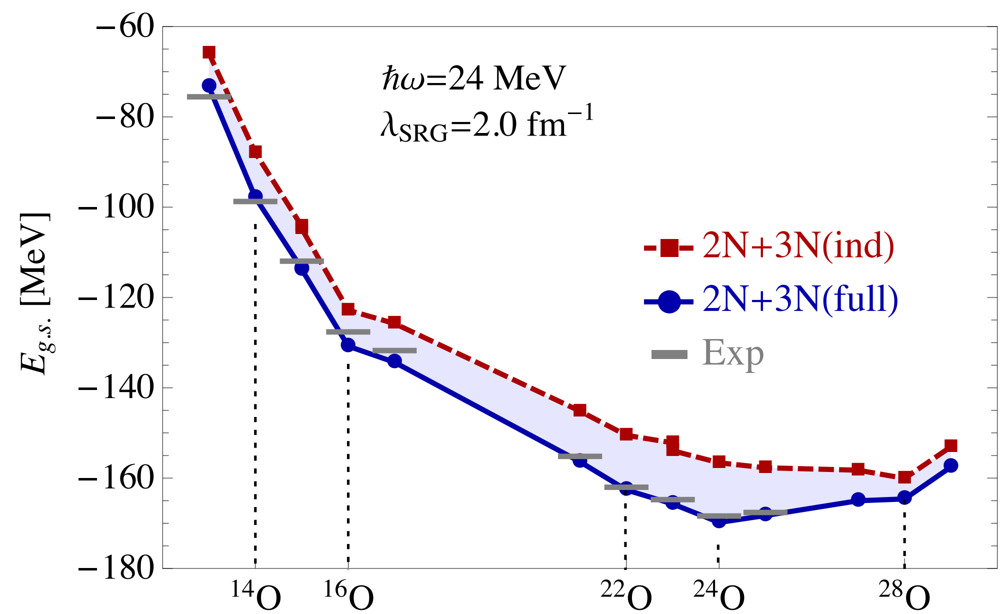
$$SF^-_k \equiv \sum_{a \in \mathcal{H}_1} \left| \langle \psi_k | a_a | \psi_0 \rangle \right|^2 = \sum_{a \in \mathcal{H}_1} \left| \mathcal{V}^k_a \right|^2$$

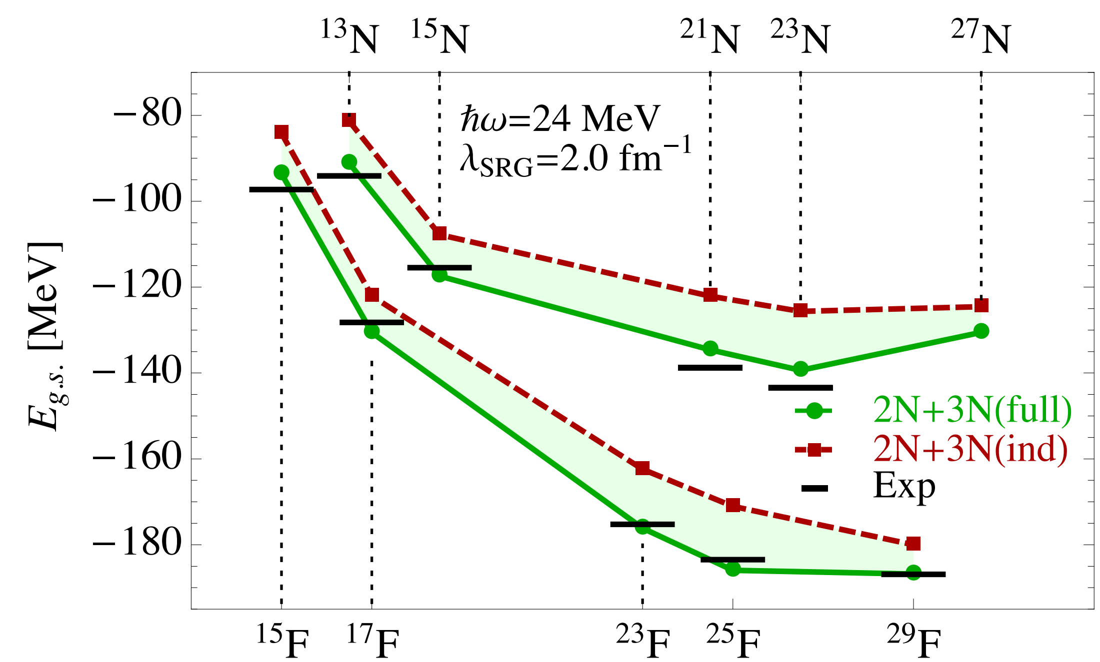


[figure from J. Sadoudi]

Around oxygen

✪ Consistent description of Z = 7, 8, 9 isotopic chains



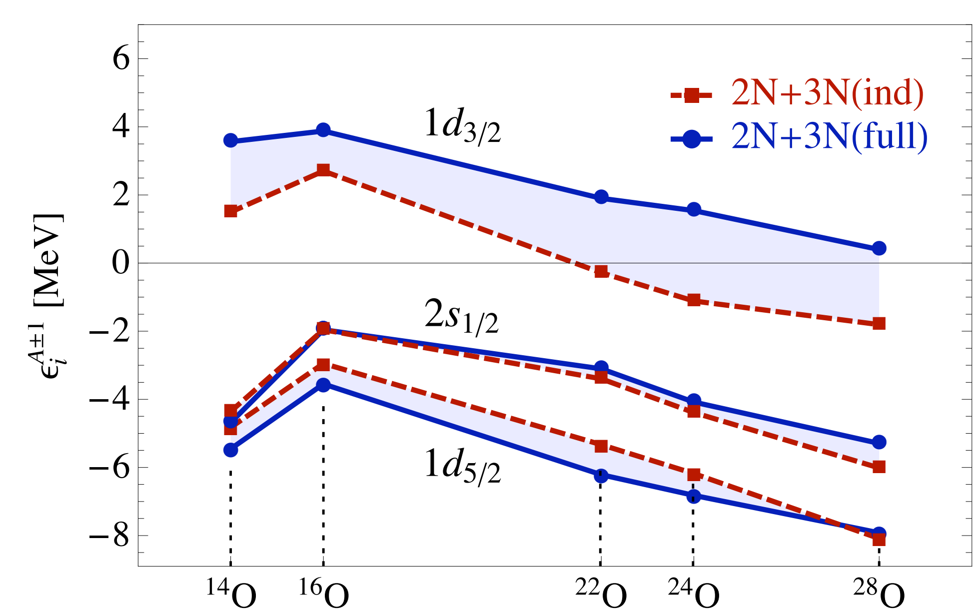


[Cipollone *et al.* arXiv:1303.4900]

➟ 3NF crucial for reproducing driplines

➟ $d_{3/2}$ raised by genuine 3NF

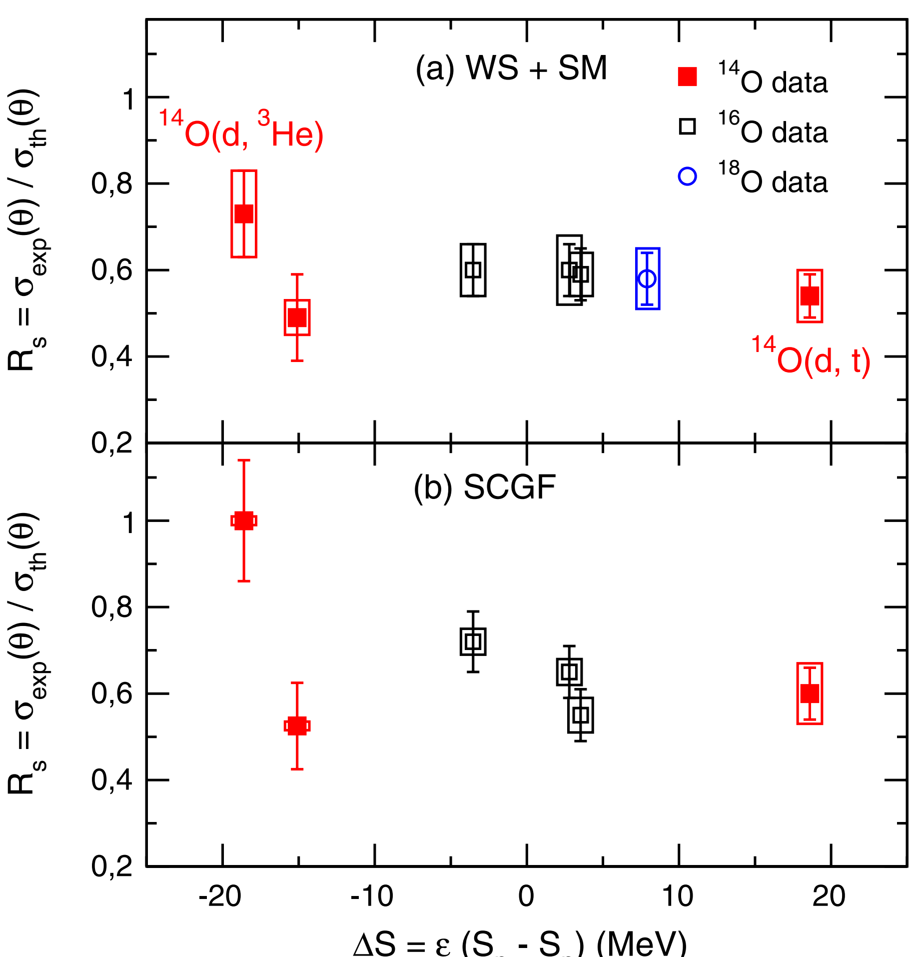
➟ cf. microscopic shell model [Otsuka *et al.* (2010)]

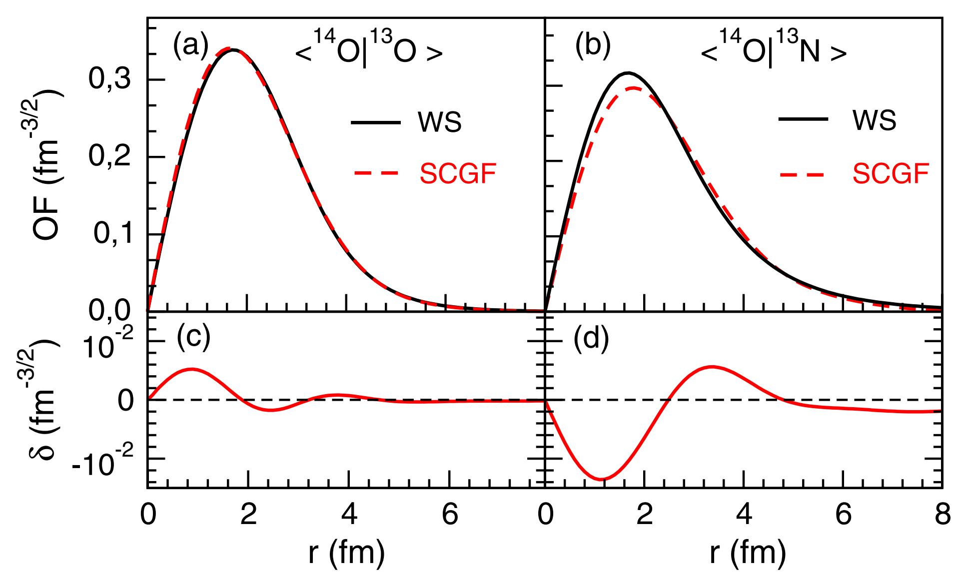


Single-nucleon transfer in the oxygen chain

✪ Analysis of ^{14}O(d, t) ^{13}O and ^{14}O(d, ^{3}He) ^{13}N transfer reactions @ SPIRAL

Reaction	E^* (MeV)	J^π	$R_{\rm rms}^{\rm HFB}$ (fm)	r_0 (fm)	$C^2S_{\rm exp}$ (WS)	$C^2S_{\rm th}$ $0p + 2\hbar\omega$	R_s (WS)	$C^2S_{\rm exp}$ (SCGF)	$C^2S_{\rm th}$ (SCGF)	R_s (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 (d, ^{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 (d, t) ^{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 (d, ^{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 (d, ^{3}He) ^{17}N [21]	0.00	$1/2^-$	2.91	1.46	0.92(9)(12)	1.58	0.58(6)(10)			





➟ Overlaps functions and cross sections from GF

➟ R_s independent of asymmetry

[Flavigny *et al.* PRL **110** (2013)]

Going *open-shell:* Gorkov-Green's functions

✪ Standard expansion schemes fail to account for pairing correlations

➟ Limited to to doubly-closed-shell ± 1 and ± 2 nuclei

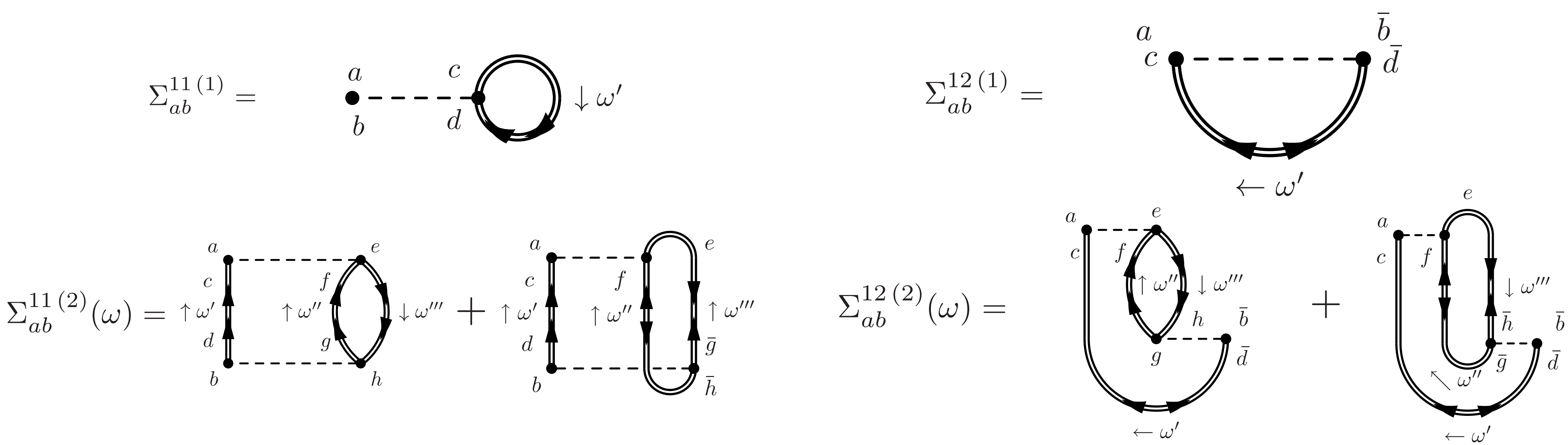
✪ Gorkov-Green's functions

➟ Address explicitly the non-perturbative physics of Cooper pairs

➟ Formulate the expansion scheme around a Bogoliubov vacuum

➟ From few tens to hundreds of medium-mass open-shell nuclei

✪ Anomalous diagrams in the self-energy expansion



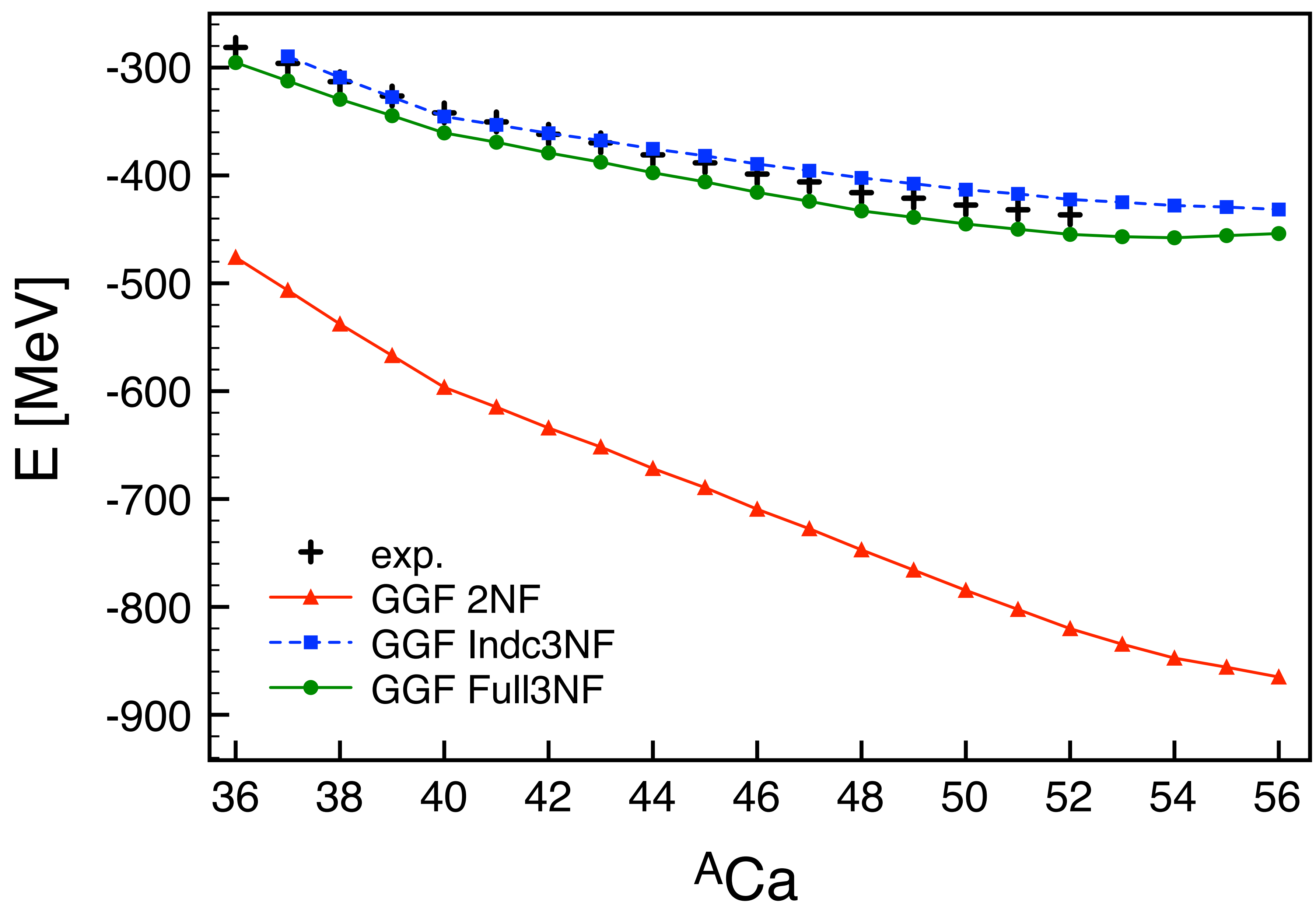
[Somà, Duguet & Barbieri PRC **84** (2011)]

Calcium isotopic chain

✪ First *ab initio* calculation of the whole Ca chain with NN + 3N forces

➠ 3NF bring energies close to experiment

➠ Induced 3NF and full 3NF investigated



Calcium isotopic chain

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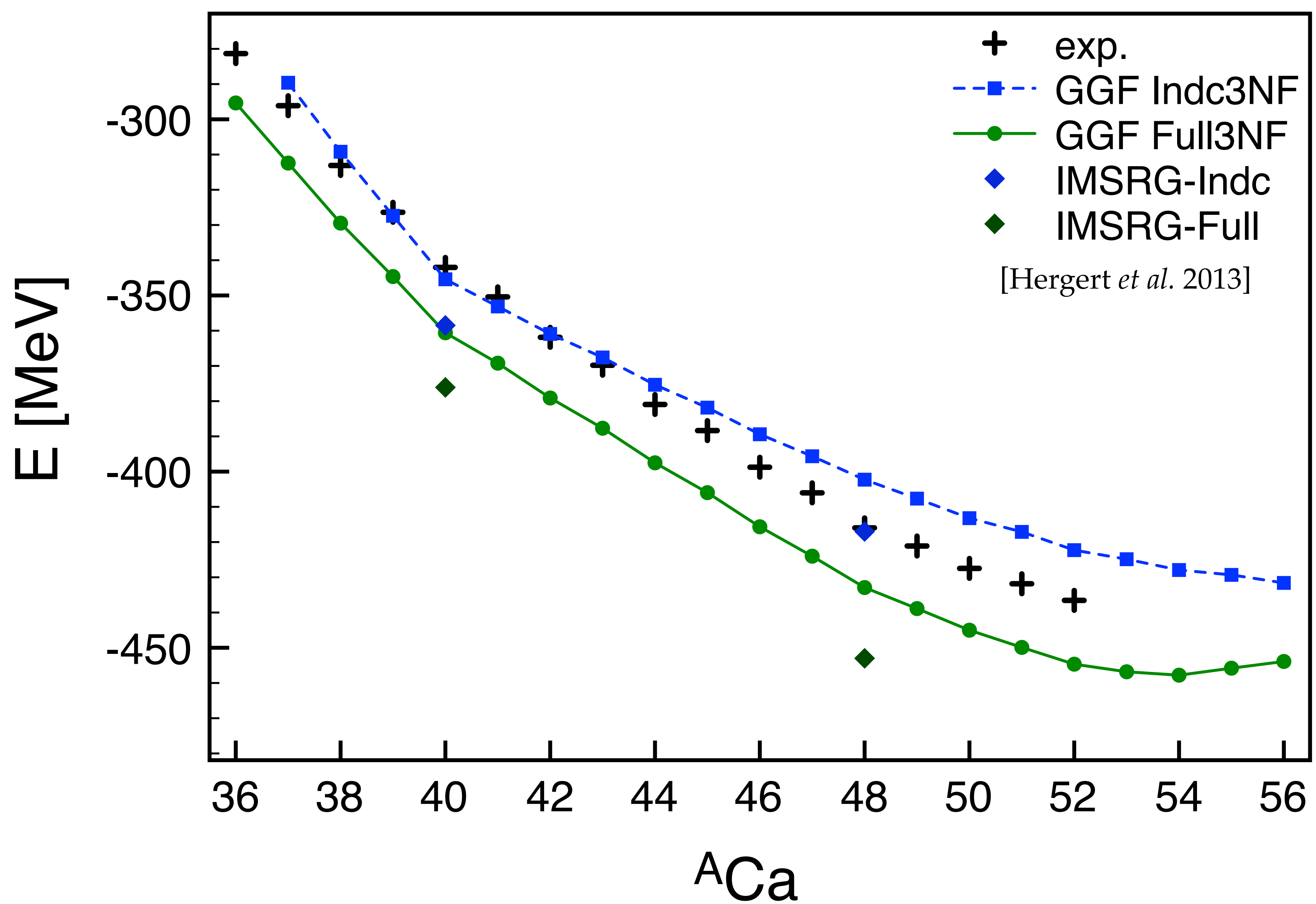
- ➟ Original 3NF correct the energy curvature
- ➟ Good agreement with IM-SRG (quantitative when 3rd order included)



Two-neutron separation energies

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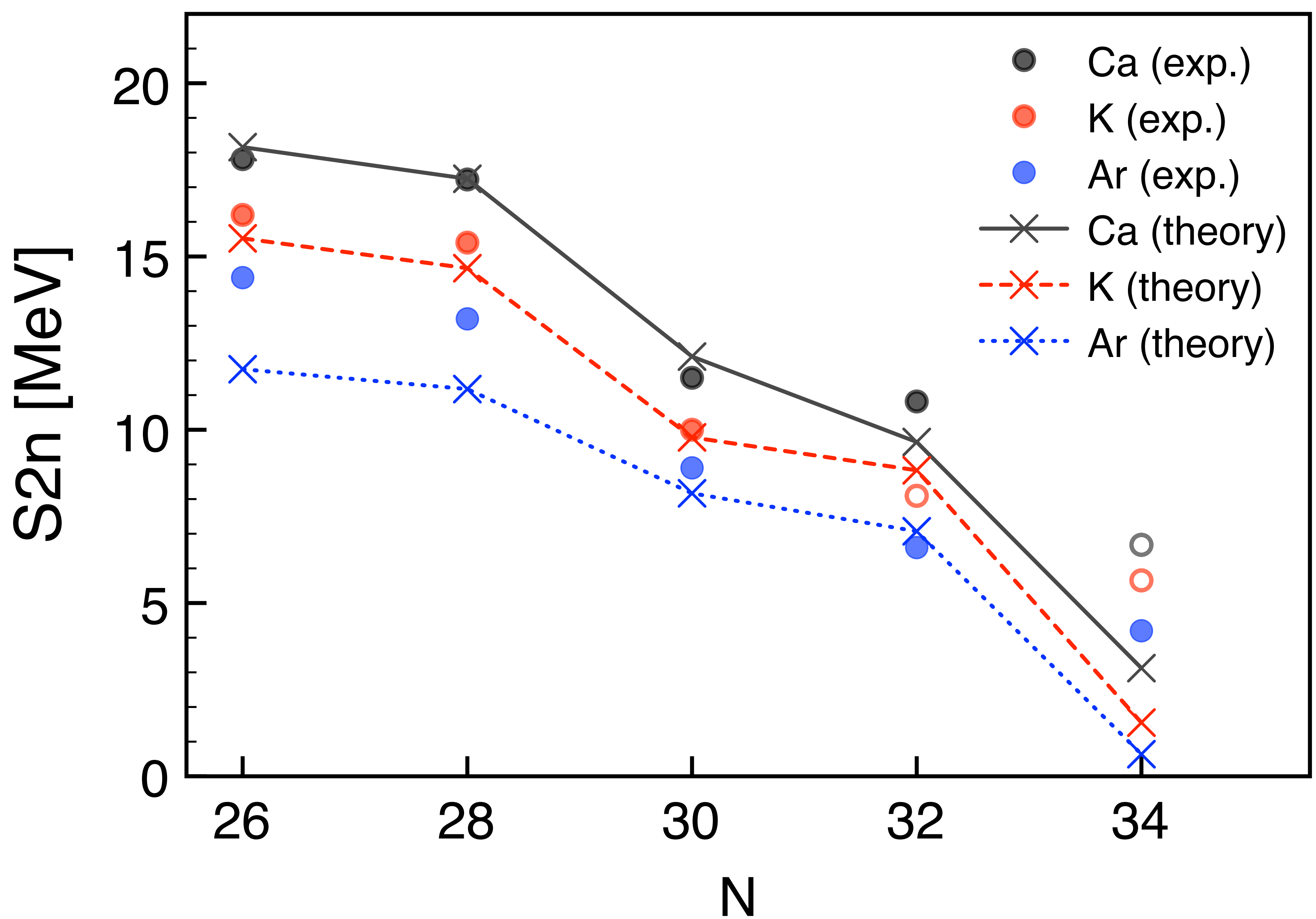
- ✪ Neutron-rich extremes of the nuclear chart
  - ➟ Good agreement with measured S2n
  - ➟ Towards a quantitative *ab initio* description of the medium-mass region



Spectral strength distribution

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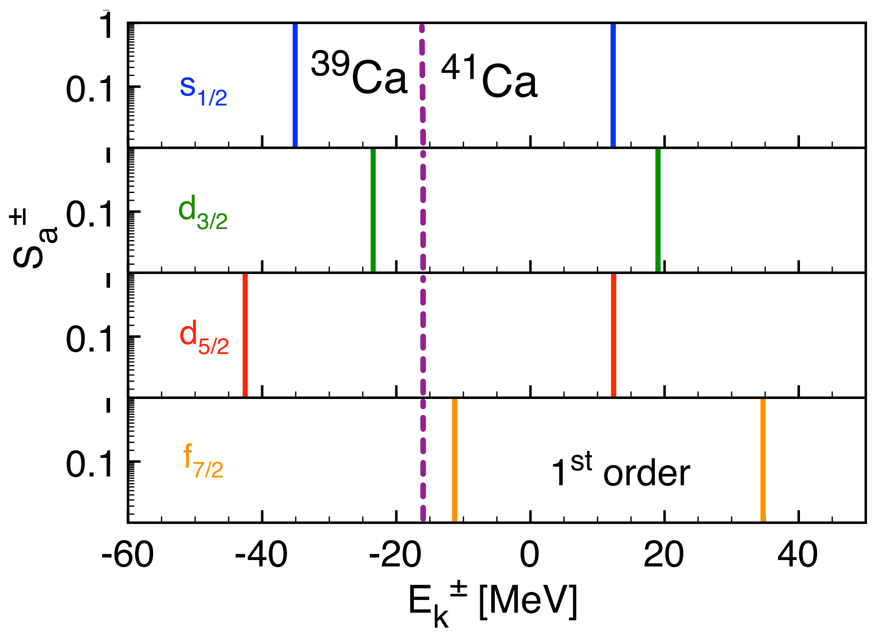
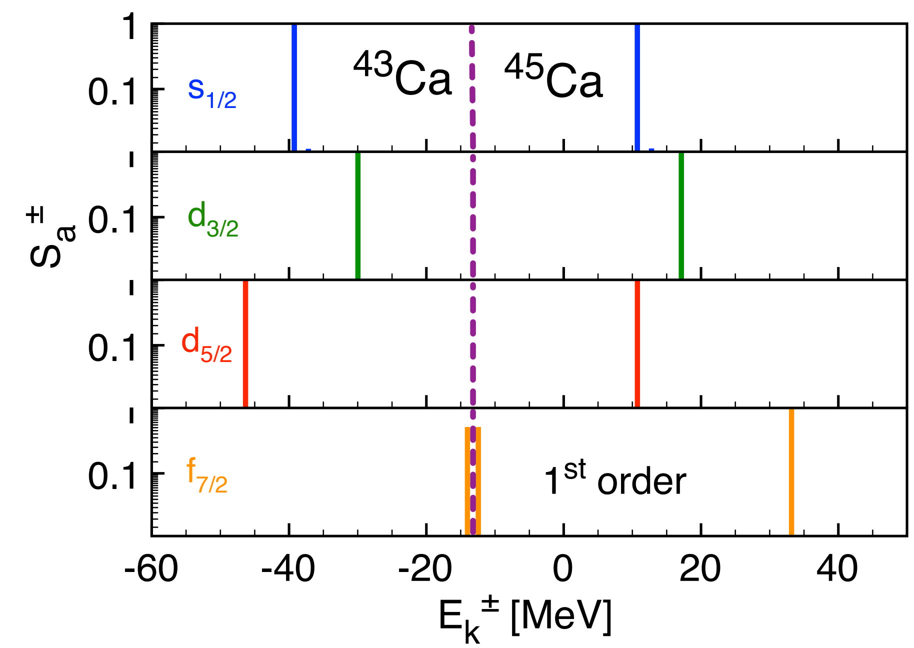
Dyson 1st order (HF)



Fragmentation

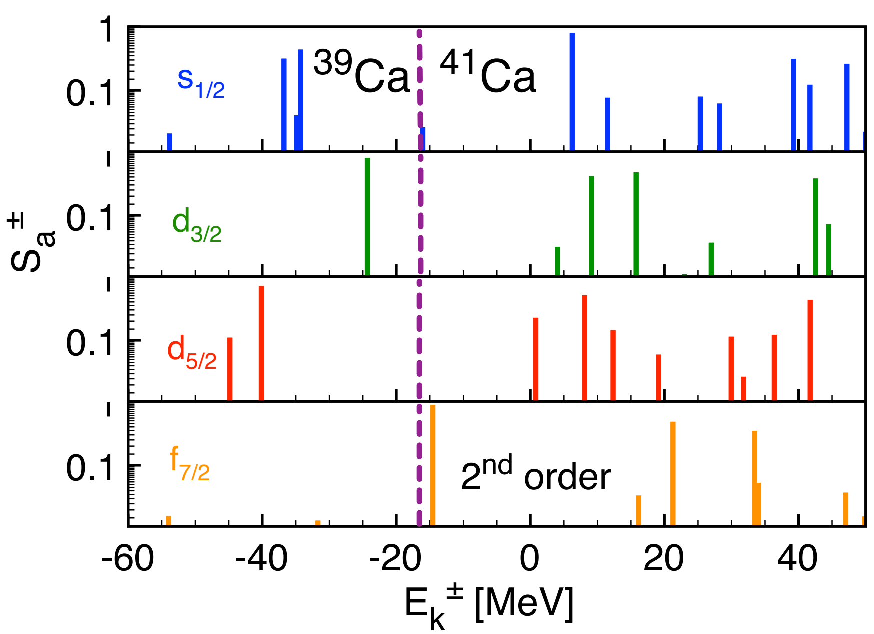
Static pairing

Gorkov 1st order (HFB)

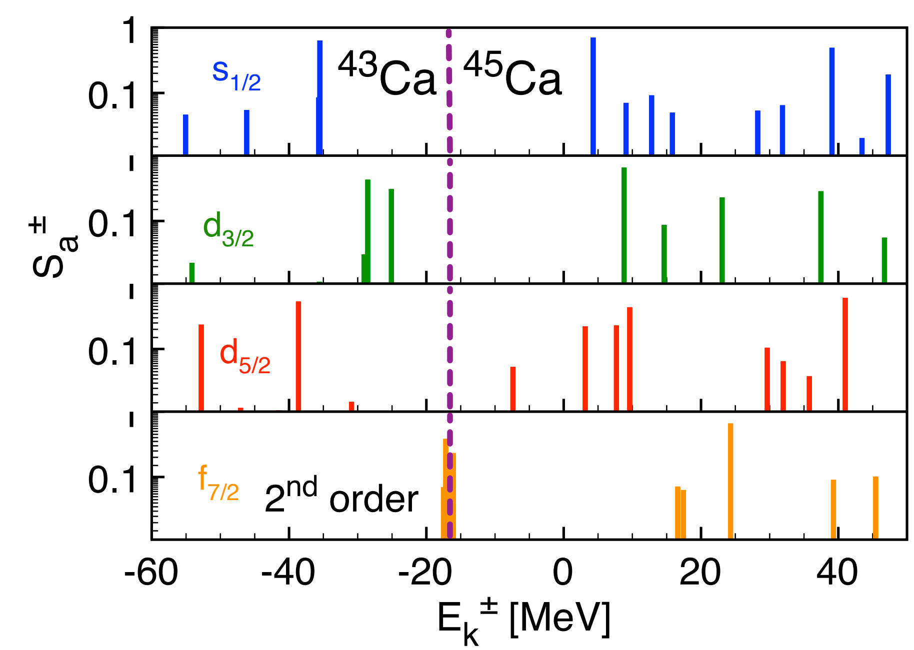


Dynamical fluctuations

Dyson 2nd order



Gorkov 2nd order



Shell structure evolution

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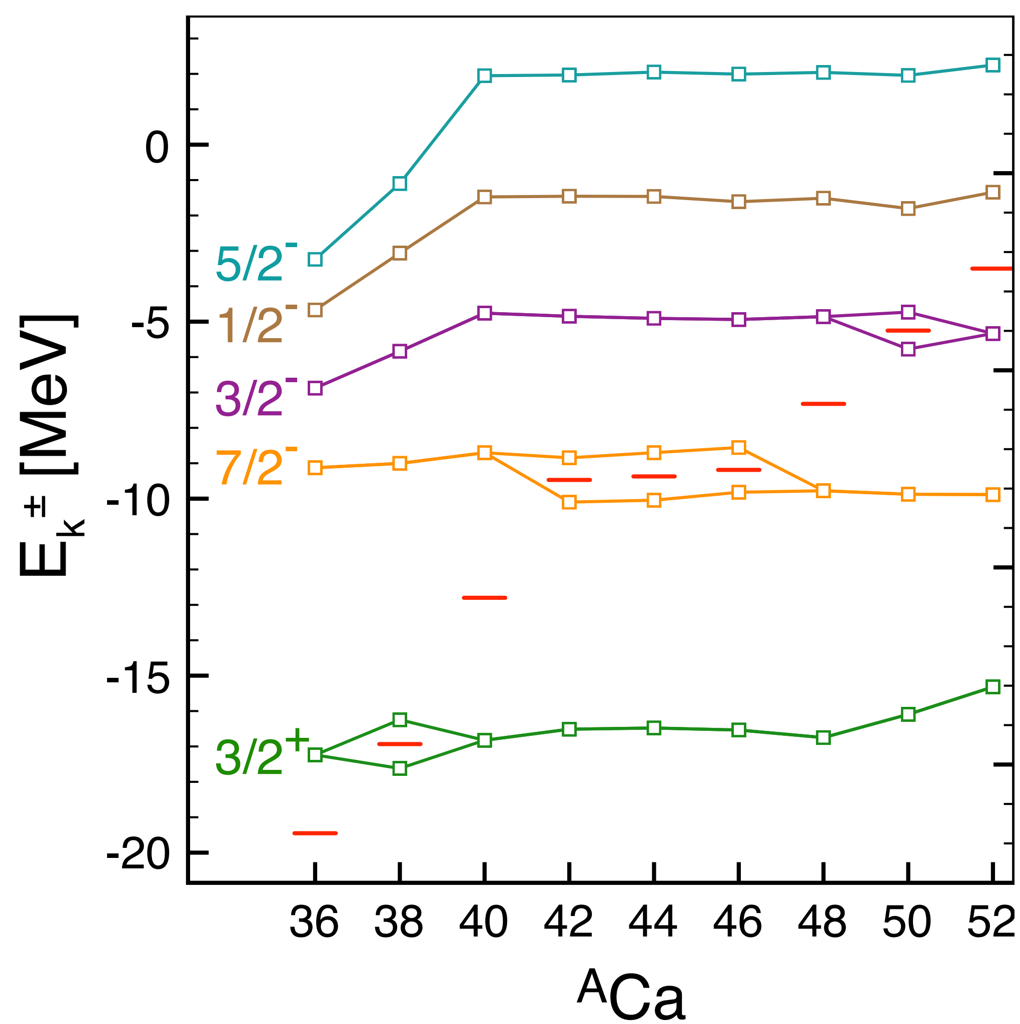
✪ ESPE collect fragmentation of "single-particle" strengths from both A±1

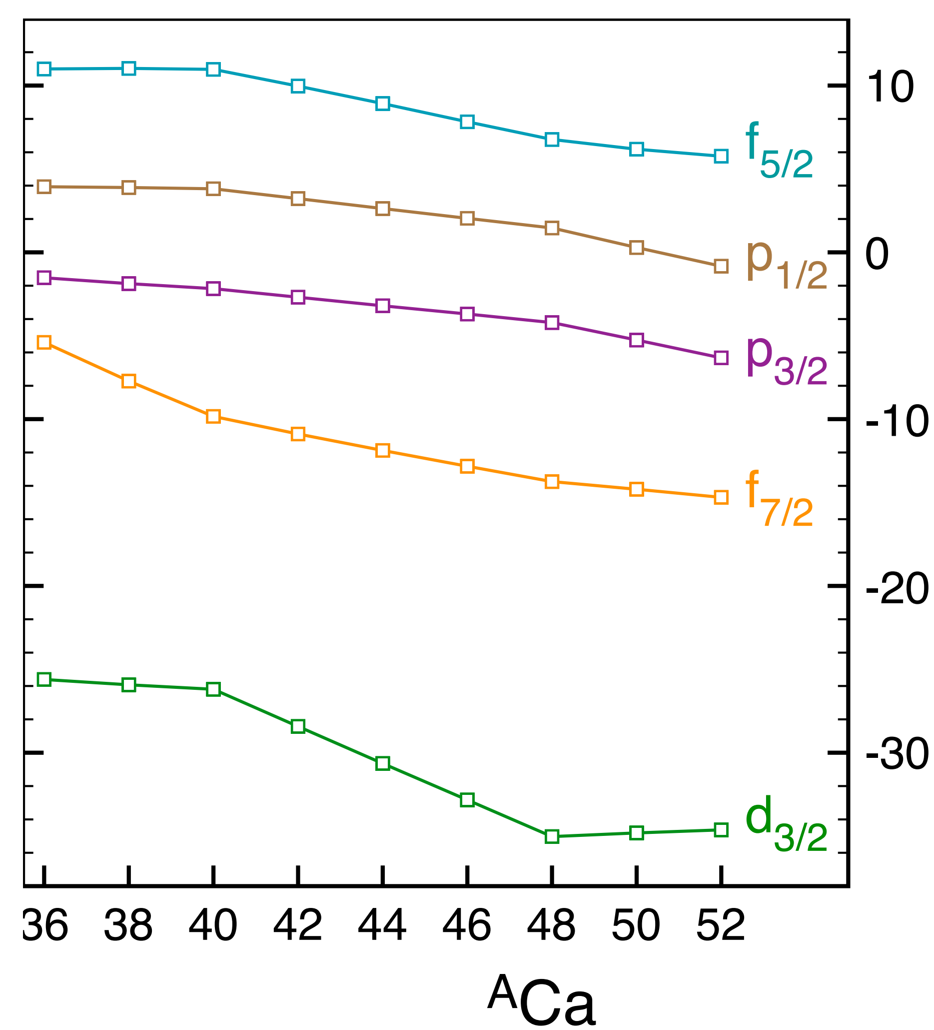
$$\epsilon_a^{cent} \equiv h_{ab}^{cent}\,\delta_{ab} = t_{aa} + \sum_{cd} \bar{V}_{acad}^{NN}\,\rho_{dc}^{[1]} + \sum_{cdef} \bar{V}_{acdaef}^{NNN}\,\rho_{efcd}^{[2]} \equiv \sum_{k} \mathcal{S}_k^{+a} E_k^{+} + \sum_{k} \mathcal{S}_k^{-a} E_k^{-}$$

[Baranger 1970, Duguet and Hagen 2011]

Separation energies



Centroids



Knockout & transfer experiments

✪ Neutron removal from proton- and neutron-rich Ar isotopes @ NSCL

Isotopes	lj^{π}	Sn(MeV)	ΔS (MeV)	(theo.) SF(LB-SM)	(expt.) SF(JLM + HF)	(expt.) Rs(JLM + HF)	(expt.) SF(CH89)	(expt.) Rs(CH89)
^{34}Ar	$s1/2^+$	17.07	12.41	1.31	0.85 ± 0.09	0.65 ± 0.07	1.10 ± 0.11	0.84 ± 0.08
^{36}Ar	$d3/2^+$	15.25	6.75	2.10	1.60 ± 0.16	0.76 ± 0.08	2.29 ± 0.23	1.09 ± 0.11
^{46}Ar	$f7/2^-$	8.07	−10.03	5.16	3.93 ± 0.39	0.76 ± 0.08	5.29 ± 0.53	1.02 ± 0.10

[Lee *et al.* 2010]

$\Delta S = Sn - Sp$

Gorkov GF NN

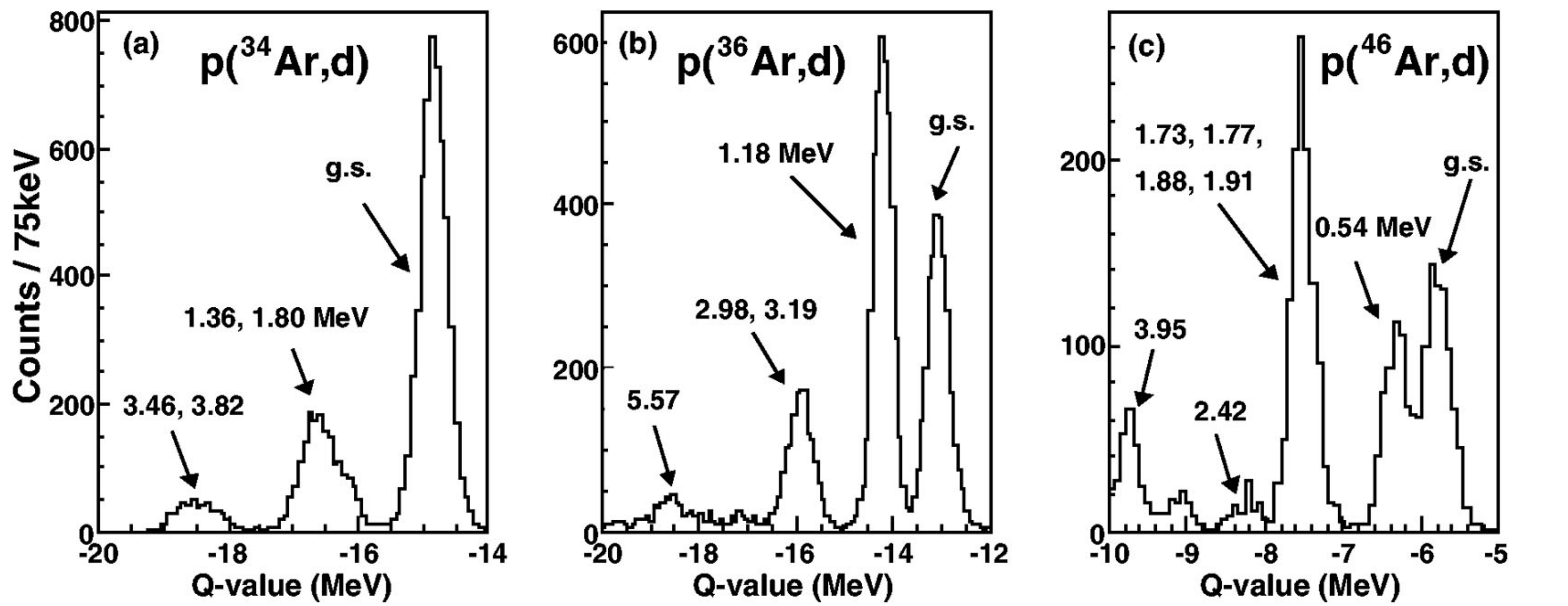
	Sn (MeV)	ΔS (MeV)	SF
^{34}Ar	33.0	18.6	1.46
^{36}Ar	27.7	7.5	1.46
^{46}Ar	16.0	-22.3	5.88

Gorkov GF NN + 3N

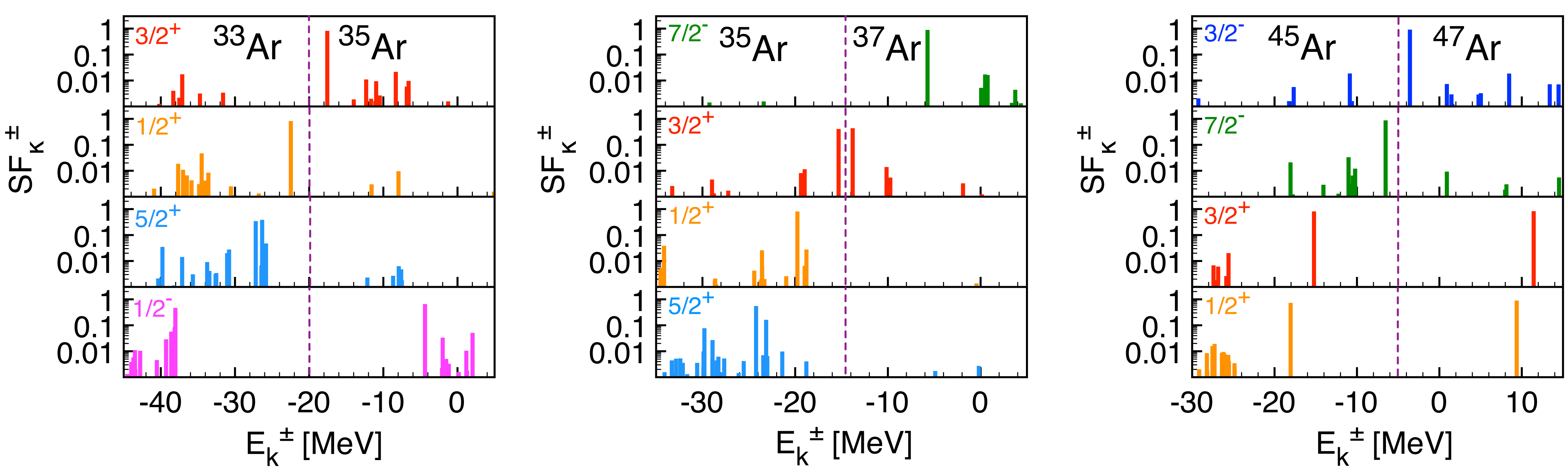
	Sn (MeV)	ΔS (MeV)	SF
^{34}Ar	22.4	15.5	1.56
^{36}Ar	15.3	7.2	1.54
^{46}Ar	6.5	-15.7	6.64

Knockout & transfer experiments

✪ Neutron removal from proton- and neutron-rich Ar isotopes @ NSCL



[Lee *et al.* 2010]



Conclusions and outlook

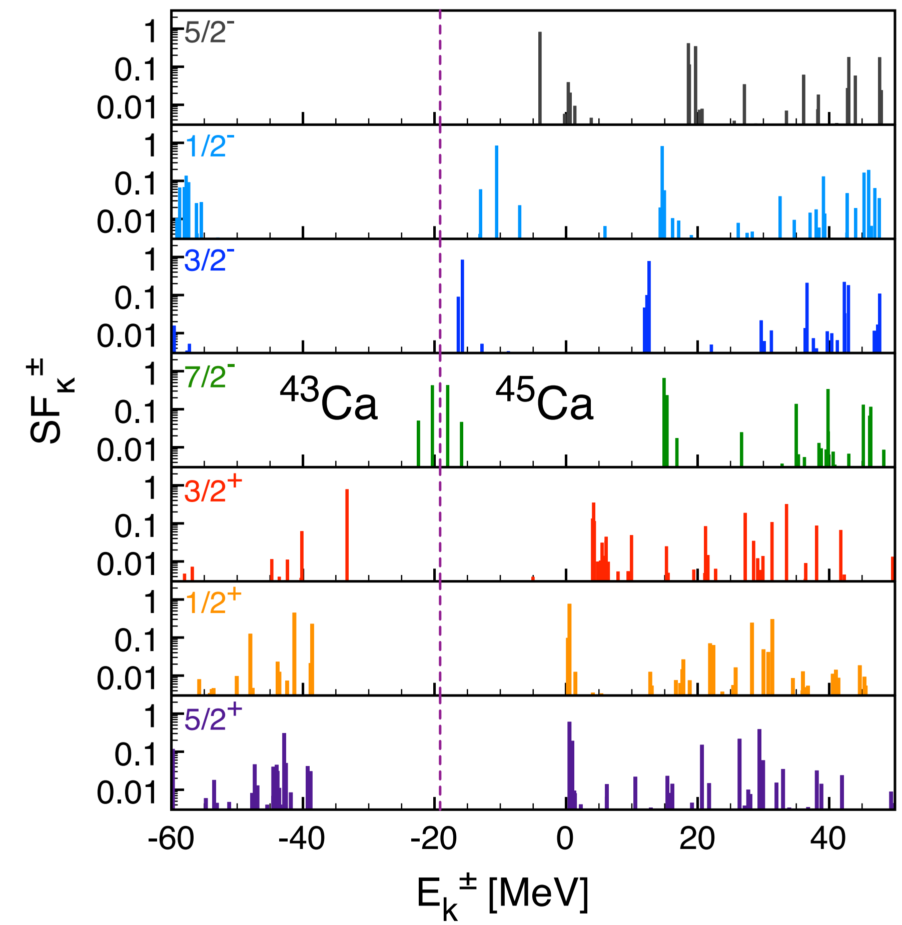
➟ *Ab initio* description of driplines around O

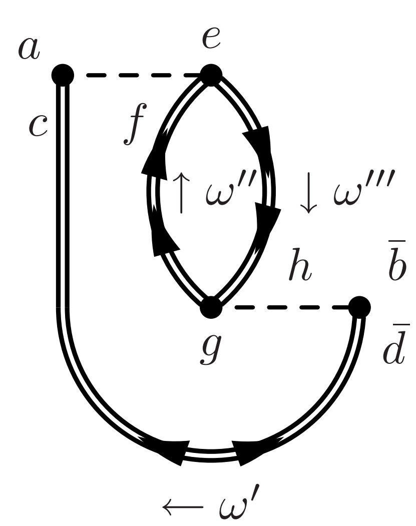
➟ One-nucleon transfer reactions

➟ GGF: Manageable route to degenerate systems

➟ Towards medium-mass isotopic chains

➟ 2NF + 3NF: towards predictive calculations





✪ Improvement of the self-energy expansion

✪ Proper coupling to the continuum

✪ Formulation of particle-number restored Gorkov theory

✪ Towards consistent description of structure and reactions

Acknowledgements

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