Nuclear structure
(theory)
related to NUSTAR and FAIR

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University of Barcelona
Institute of Cosmos Sciences

FAIRness 2024, 8th FAIRness workshop

Donji Seget, 27th September 2024

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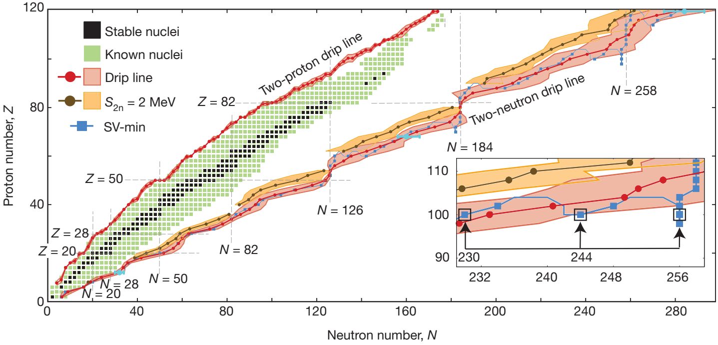
NextGenerationEU
Plan de Recuperación, Transformación y Resiliencia
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
AGENCIA ESTATAL DE INVESTIGACIÓN

Nuclear landscape

The goal of nuclear theory is a unified description of nuclear structure, across the nuclear chart and based on nuclear forces



~ 3000 isotopes measured

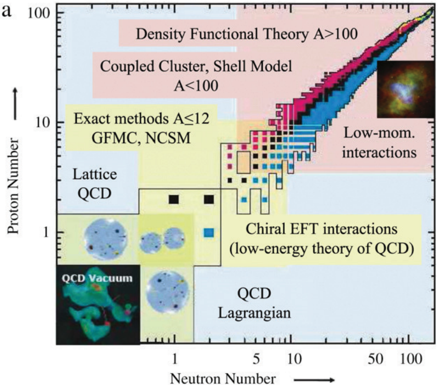
~ 7000 predicted

Erler et al.
Nature 486 509 (2012)

Limits of existence, ground-state properties, shell evolution, excitation spectra, spectroscopy, shape coexistence, β decays, fission...

Nuclear Structure from First Principles

All nuclear structure calculations are, to some extent, phenomenological



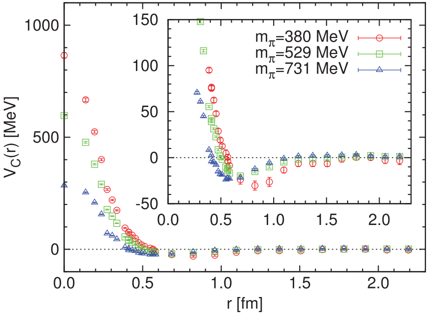
Relevant degrees of freedom:
protons and neutrons
Many-body problem
too hard in general,
approximations are needed

Nuclear force at low
(nuclear structure) energies:
adjustments to reproduce
finite nuclei needed

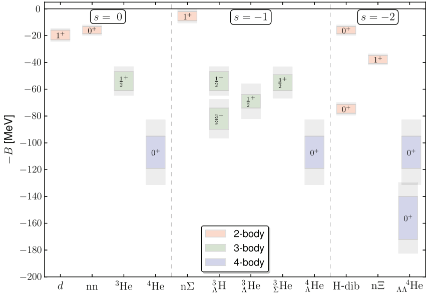
Can we connect nuclear structure calculations to quantum chromodynamics (QCD)?

Lattice QCD

QCD non-perturbative at low energies relevant for nuclear structure
Lattice QCD solves the QCD Lagrangian in discretized space-time lattice



HALQCD Collaboration



NPLQCD Collaboration

Nuclear potentials, and lightest nuclei and hypernuclei solved
at non-physical pion mass $m_\pi \sim 400 - 800$ MeV, ongoing improvements

Theory for nuclear forces

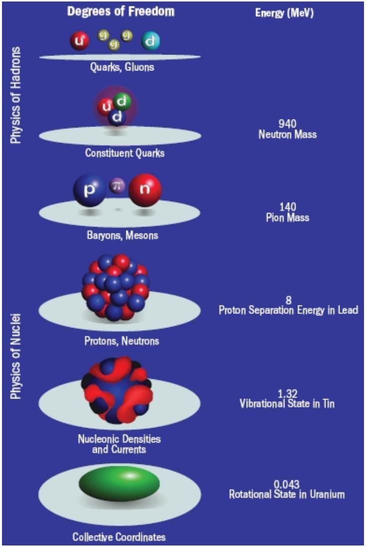
Difficult to find NN potential with consistent NNN forces and connected to QCD...

Use concept of separation of scales!

The energy scale relevant determines the degrees of freedom

For nuclear structure,
typical energies of interest
point to nucleons and pions
(pions are particularly light mesons!)

Effective theory with nucleons and pions as degrees of freedom, with connection to QCD



Effective theories

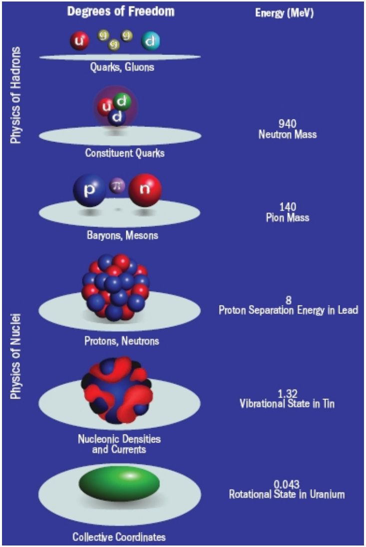
Effective theory:
approximation of the full theory
valid at relevant scales

Expansion in terms of small parameter: typical scale / breakdown scale

In an effective theory
the physics resolved
at relevant energies is explicit

Terms at different orders given by symmetries of the full theory

Unresolved physics
encoded in Low Energy Couplings

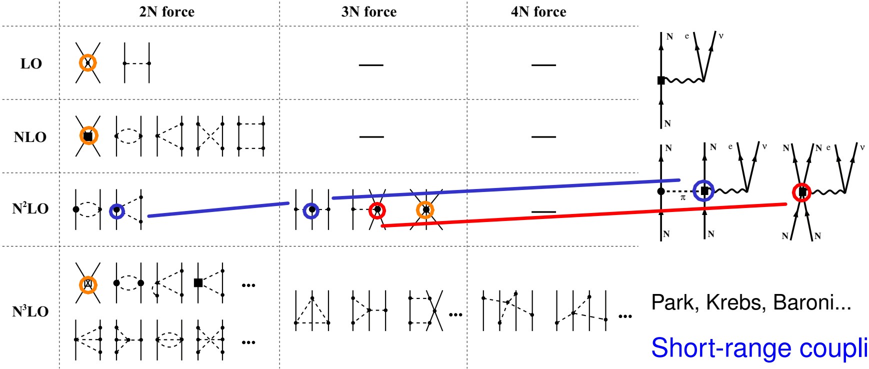


Chiral Effective Field Theory (EFT)

Chiral EFT: low energy approach to QCD, nuclear structure energies

Approximate chiral symmetry: pion exchanges, contact interactions

Systematic expansion: nuclear forces and electroweak currents



Park, Krebs, Baroni...

Short-range couplings fitted to experiment once

Weinberg, van Kolck, Kaplan, Savage, Wise, Meißner, Epelbaum...

Ab initio many-body methods

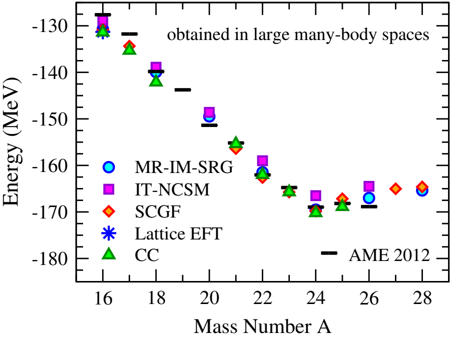
Oxygen dripline using chiral NN+3N forces correctly reproduced
ab-initio calculations treating explicitly all nucleons
excellent agreement between different approaches

No-core shell model
(Importance-truncated)

In-medium SRG
Hergert et al. PRL110 242501(2013)

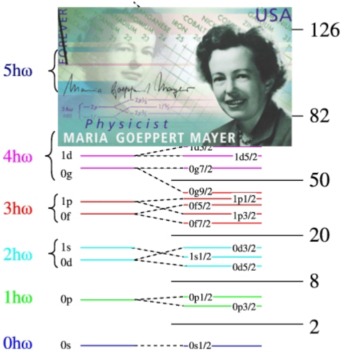
Self-consistent Green's function
Cipollone et al. PRL111 062501(2013)

Coupled-clusters
Jansen et al. PRL113 142502(2014)



Recent application to ^{208}Pb
Hu, Jiang, Miyagi et al. Nature Phys. 18, 1196 (2022)

Nuclear shell model



Nuclear shell model configuration space only keep essential degrees of freedom

- High-energy orbitals: always empty
- Valence space:
  where many-body problem is solved
- Inert core: always filled

$$H|\Psi\rangle = E|\Psi\rangle \;\rightarrow H_{eff}|\Psi\rangle_{eff} = E|\Psi\rangle_{eff}$$

$$|\Psi\rangle_{eff} = \sum_{\alpha} c_\alpha |\phi_\alpha\rangle\,, \quad |\phi_\alpha\rangle = a^+_{i1}a^+_{i2}...a^+_{iA}|0\rangle$$

Shell model diagonalization:

$\sim 10^{10}$ Slater dets. Caurier et al. RMP77 (2005)

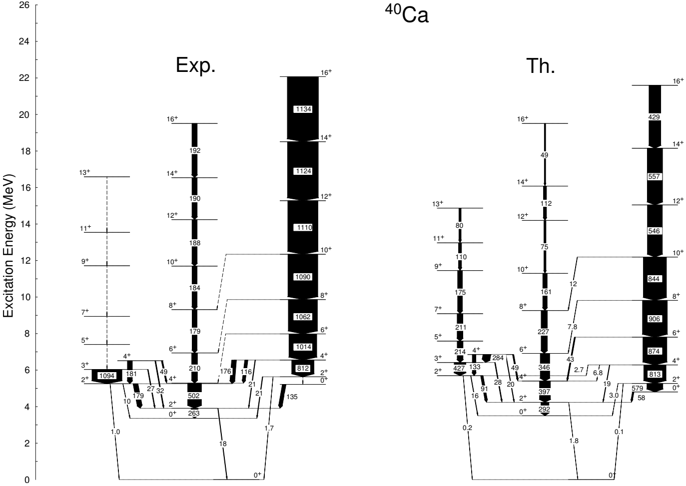
$\gtrsim 10^{24}$ Slater dets. with Monte Carlo SM

Otsuka, Shimizu, Y.Tsunoda

H_{eff} includes effects of

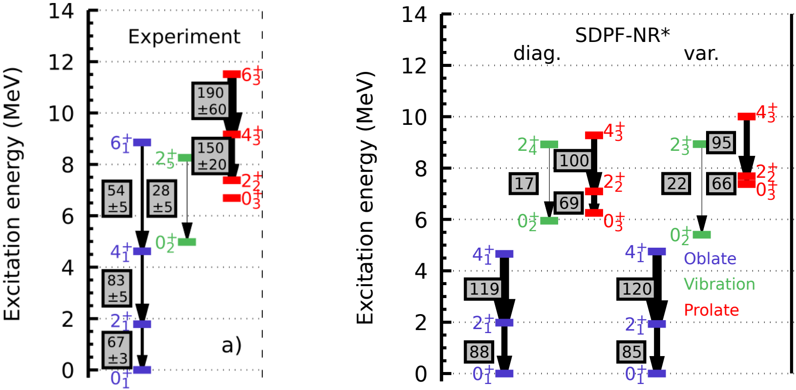
- inert core
- high-energy orbitals

Test of shell-model calculations, ^{40}Ca



Caurier, JM, Nowacki, Poves, PRC 75, 054317 (2007)

Test of shell-model calculations, ^{28}Si

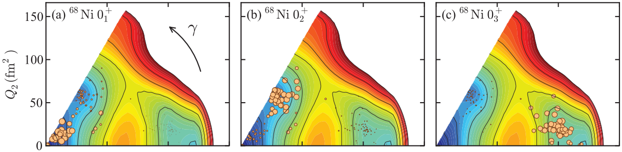


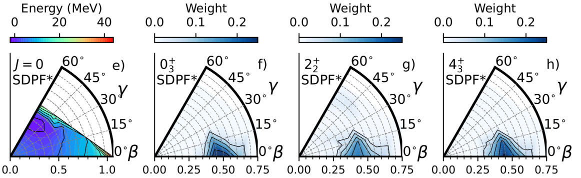
Frycz et al. arXiv:2404.14506

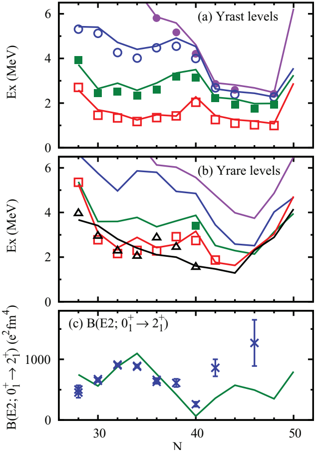
Good description of both oblate and prolate bands simultaneously!

Nuclear shell model: energy surfaces

The Shell Model is the method of choice for shell model nuclei: energies, deformation, electromagnetic and beta transition rates...







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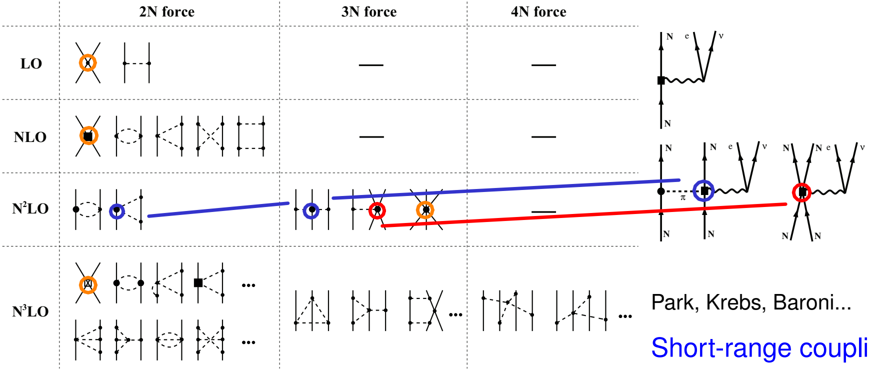

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Short-range couplings fitted to experiment once

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Effective shell-model interactions

Coupled Cluster:

Solve coupled-cluster equations for core (reference state $|\Phi\rangle$), $A+1$ and $A+2$ systems

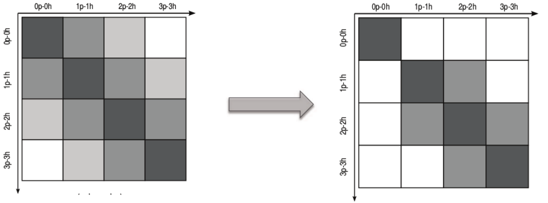
Project the coupled-cluster solution into valence space (Okubo-Lee-Suzuki transformation)

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

In-medium similarity renormalization group

decouple core from excitations

decouple A particles in valence space from rest



$\langle i|H|j\rangle$

$\langle \mathrm{npn}h|H(\infty)|\Phi_{\mathrm{core}}\rangle =$

Stroberg et al.

Annu. Rev. Nucl. Part. Sci. 69, 307 (2019)

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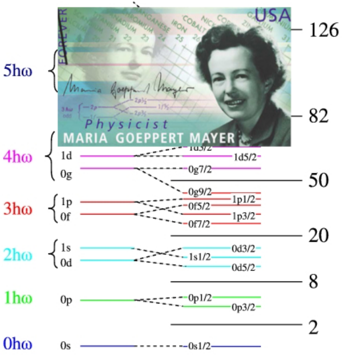
Nuclear shell model



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Otsuka, Shimizu, Y.Tsunoda

H_{eff} includes effects of

- inert core
- high-energy orbitals

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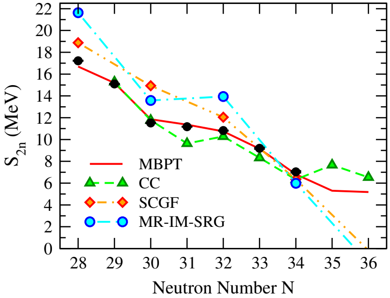
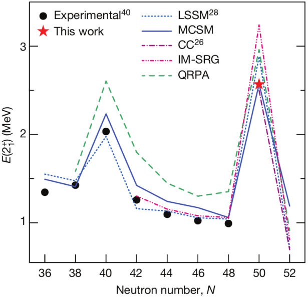
Shell evolution in medium-mass nuclei

Calculations with NN+3N forces predict doubly-magic ^{52}Ca, ^{54}Ca, ^{78}Ni
groundbreaking mass / 2^+ measurements at ISOLDE / RIBF





LETTER

doi:10.1038/nature12226

Masses of exotic calcium isotopes pin down nuclear forces

F. Wienholtz[1], D. Beck[2], K. Blaum[3], Ch. Borgmann[3], M. Breitenfeldt[4], R. B. Cakirli[3,5], S. George[1], F. Herfurth[2], J. D. Holt[6,7], M. Kowalska[8], S. Kreim[3,8], D. Lunney[9], V. Manea[9], J. Menéndez[6,7], D. Neidherr[2], M. Rosenbusch[1], L. Schweikhard[1], A. Schwenk[7,6], J. Simonis[6,7], J. Stanja[10], R. N. Wolf[1] & K. Zuber[10]

ARTICLE

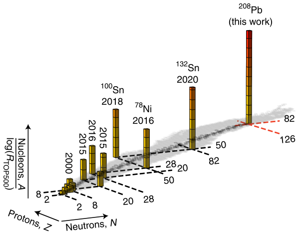
https://doi.org/10.1038/s41586-019-1155-x

^{78}Ni revealed as a doubly magic stronghold against nuclear deformation

R. Taniuchi[1,2], C. Santamaria[2,3], P. Doornenbal[2*], A. Obertelli[2,3,4], K. Yoneda[2], G. Authelet[3], H. Baba[2], D. Calvet[3], F. Château[3], A. Corsi[3], A. Delbart[3], J.-M. Gheller[3], A. Gillibert[3], J. D. Holt[5], T. Isobe[2], V. Lapoux[3], M. Matsushita[6], J. Menéndez[6], S. Momiyama[1,2], T. Motobayashi[2], M. Niikura[1], F. Nowacki[7], K. Ogata[8,9], H. Otsu[2], T. Otsuka[1,2,6], C. Péron[3], S. Péru[10], A. Peyaud[3], E. C. Pollacco[3], A. Poves[11], J.-Y. Roussé[3], H. Sakurai[1,2], A. Schwenk[4,12,13], Y. Shiga[2,14], J. Simonis[4,12,15], S. R. Stroberg[5,16], S. Takeuchi[2], Y. Tsunoda[6], T. Uesaka[2], H. Wang[2], F. Browne[17], L. X. Chung[18], Z. Dombradi[19], S. Franchoo[20], F. Giacoppo[21], A. Gottardo[20], K. Hadyńska-Klęk[21], Z. Korkulu[19], S. Koyama[1,2], Y. Kubota[2,6], J. Lee[22], M. Lettmann[4], C. Louchart[4], R. Lozeva[7,23], K. Matsui[1,2], T. Miyazaki[1,2], S. Nishimura[2], L. Olivier[20], S. Ota[6], Z. Patel[24], E. Şahin[21], C. Shand[24], P.-A. Söderström[2], I. Stefan[20], D. Steppenbeck[6], T. Sumikama[25], D. Suzuki[20], Z. Vajta[19], V. Werner[4], J. Wu[2,26] & Z. Y. Xu[22]

Ab initio predictions for nuclear neutron radius

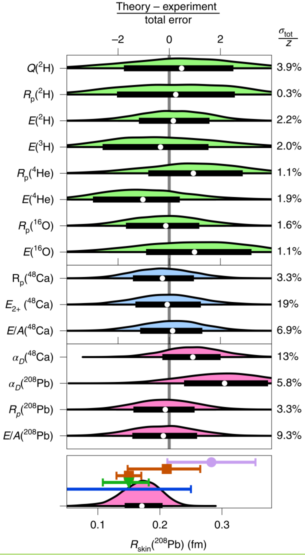
Remarkable progress ab initio calculations of (relatively uncorrelated) heavy nuclei, ^{208}Pb



Determine ^{208}Pb neutron skin using Bayesian approach sampling of 10^9 (parameters of) nuclear Hamiltonians

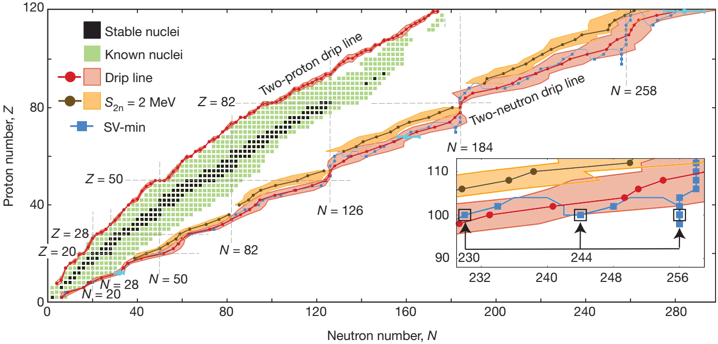
Hu, Jiang, Miyagi et al.

Nature Phys. 18 1196 (2022)



Nuclear landscape

The goal of nuclear theory is a unified description of nuclear structure, across the nuclear chart and based on nuclear forces



∼ 3000 isotopes measured

∼ 7000 predicted

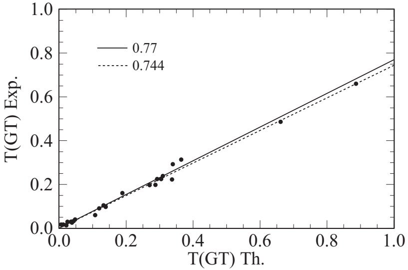
Erler et al.

Nature 486 509 (2012)

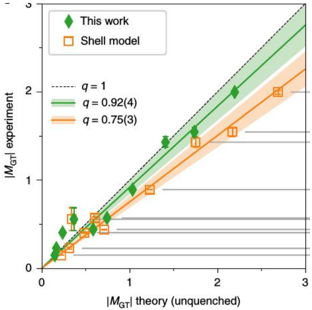
Limits of existence, ground-state properties, shell evolution, excitation spectra, spectroscopy, shape coexistence, β decays, fission...

β–decay Gamow-Teller transitions: “quenching”

β decays (e^- capture): nuclear shell model vs ab initio



Martinez-Pinedo et al. PRC53 2602(1996)



Gysbers et al. Nature Phys. 15 428 (2019)

$$\langle F|\sum_i [g_A\, \boldsymbol{\sigma}_i \tau_i^-]^{\rm eff}\, |I\rangle\,, \quad [\boldsymbol{\sigma}_i \tau]^{\rm eff} \approx 0.7 \boldsymbol{\sigma}_i \tau$$

Shell model: $\boldsymbol{\sigma}_i \tau$ “quenching”

quenching: effects not in model

Ab initio calculations including
meson-exchange currents
and additional nuclear correlations

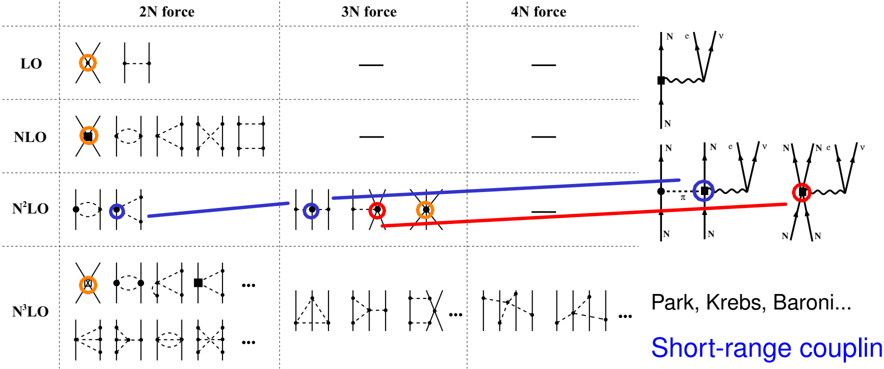
do not need “quenching”

Chiral effective field theory

Chiral EFT: low energy approach to QCD, nuclear structure energies

Approximate chiral symmetry: pion exchanges, contact interactions

Systematic expansion: nuclear forces and electroweak currents



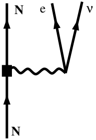
Park, Krebs, Baroni...

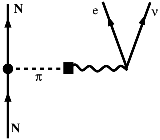
Short-range couplings fitted to experiment once

Weinberg, van Kolck, Kaplan, Savage, Wise, Meißner, Epelbaum...

Axial 1b and 2b currents

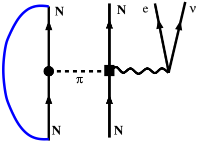
One-body currents receive contribution from two-body currents

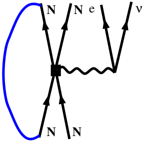




$$\mathbf{J}^3_{i,1\mathrm{b}} = \frac{1}{2}\,\tau^3_i \left(G^3_A(\mathbf{q}^2)\,\boldsymbol{\sigma}_i - \frac{G^3_P(\mathbf{q}^2)}{4m_N^2}\,(\mathbf{q}\cdot\boldsymbol{\sigma}_i)\,\mathbf{q} \right)$$

Approximate in medium-mass nuclei:
normal-ordered 1b part with respect to spin/isospin symmetric Fermi gas

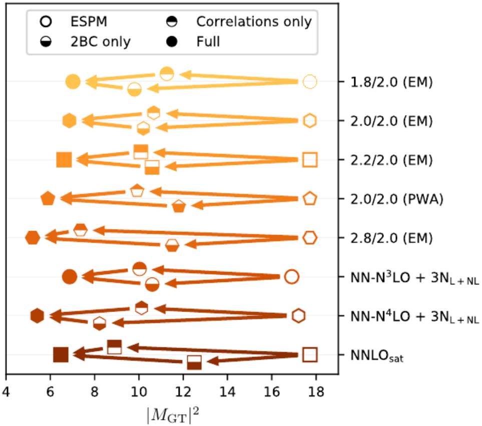




$$\mathbf{J}^{\mathrm{eff}}_{i,2\mathrm{b}}(\rho,\mathbf{q}) = g_A\,\frac{\tau^3_i}{2}\left[\delta a(\mathbf{q}^2)\,\boldsymbol{\sigma}_i + \frac{\delta a^P(\mathbf{q}^2)}{\mathbf{q}^2}(\mathbf{q}\cdot\boldsymbol{\sigma}_i)\mathbf{q}\right]$$

Origin of β decay “quenching”

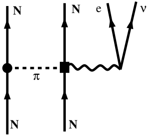
Which are main effects missing in conventional β-decay calculations?
Test case: GT decay of ^{100}Sn



Relatively similar and complementary impact of

- nuclear correlations
- meson-exchange currents

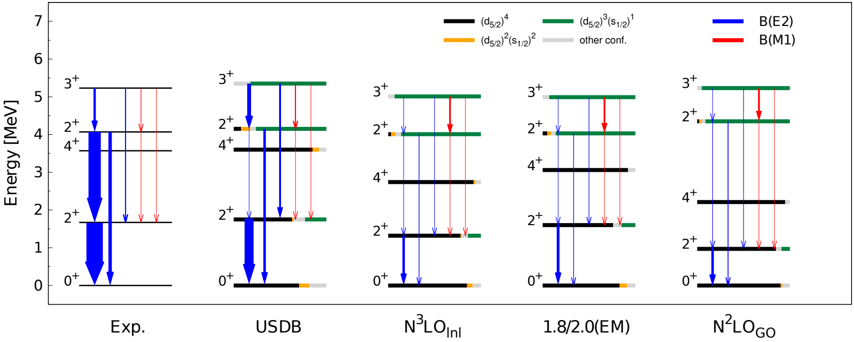
Gysbers et al.
Nature Phys. 15 428 (2019)



Electromagnetic transitions in neutron-rich nuclei

Study of B(E2) and B(M1) transitions in ^{20}O with nuclear shell model and ab initio VS-IMSRG

Zanon, Clément, Goasduff, JM, Miyagi et al. PRL 131 262501 (2023)



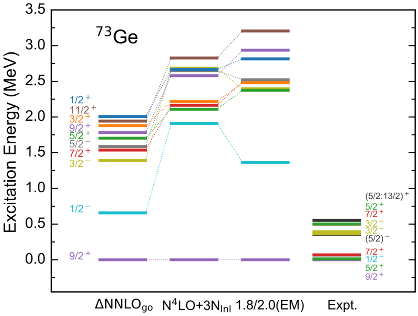
Systematic deficiency: B(E2)'s do not capture collectivity

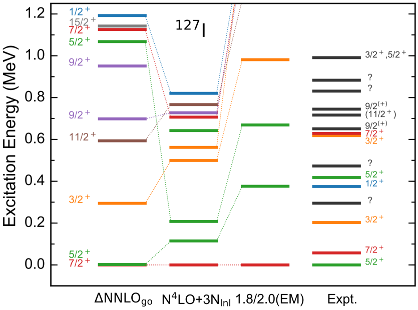
Nuclear structure details missing: $s-d$ mixing of 2_1^+ state

Ab initio spectra for heavy nuclei

While VS-IMSRG calculations high quality in light nuclei (eg Na) challenges remain in heavier systems, such as ^{73}Ge

Interesting sensitivity to the chiral nuclear Hamiltonian used for ^{127}I



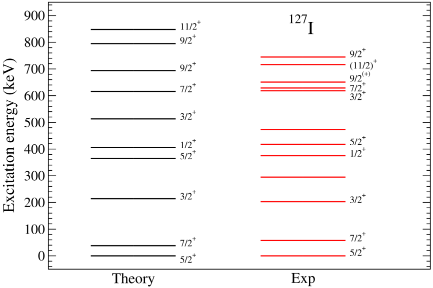


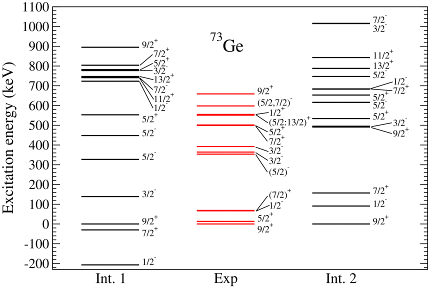
Hu et al. PRL 128, 072502 (2022)

Shell-model spectra for heavy nuclei

Very good general agreement
between the properties of low-energy nuclear states
and nuclear shell-model calculations

However, some nuclei present challenging features
such as ^{73}Ge ground and first-excited state, likely related to deformation





Klos, JM, Gazit, Schwenk, PRD 88, 083516 (2013)

Summary

Ab initio methods using chiral EFT forces such as the valence-space IMSRG access nuclei like nuclear shell model

Nuclear shell evolution, spectroscopy, β and γ decays with consistent operators

- Doubly-magic character of ^{78}Ni, ^{132}Sn...
- Quantified theoretical uncertainties (dominated by Hamiltonian)
- Reproduce β decay half-lives without adjustments (“quenching”)
- Challenge: electromagnetic decays even in light ^{20,21}O nuclei
- Challenge: complex heavy nuclei