Why is matter stable?

Morten Hjorth-Jensen

National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, U.S.A.

Department of Physics, University of Oslo, Oslo, Norway

National Nuclear Physics Summer School, June 15-26 2015, Lake Tahoe, California

Outline

People

Michigan State University

Scott Bogner, Alex B. Brown and Witek Nazarewicz

University of Oslo

Gustav Bårdsen, Jørgen Høgberget, and Sarah Reimann

Oak Ridge National Laboratory and University of Tennessee, Knoxville

David J. Dean, Andreas Ekström, Gaute Hagen, Gustav Jansen, Thomas Papenbrock and Kyle Wendt

University of Idaho

Ruprecht Machleidt

Argonne National Laboratory

Stefan Wild and Jason Sarich

Chalmers, Gothenburg

Christian Forssen and Boris Karlsson

Questions and take away messages for understanding physics towards driplines

How can we define correlations in many-particle systems? And why are these important? Here I will define correlations to be contributions beyond Hartree-Fock.

- In nuclear systems three-body and more complicated forces are expected to play an important role and should be included in first principle calculations.
- Continuum (resonances and non-resonant contributions) needs to be included in theory analyses.
- Correlations are strong towards the dripline, mean field is not a useful picture.

Big Questions in nuclear physics today (NAS report)

- How did matter come into being and how does it evolve?
- How does subatomic matter organize itself and what phenomena emerge?
- Are the fundamental interactions that are basic to the structure of matter fully understood?
- How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?

- Fundamental aspects
  - Nature of building blocks (nuclear degrees of freedom)
  - Nature of nuclear interactions
- Self-organization of building blocks
  - Nature of composite structures and phases
  - Origin of simple patterns in complex systems

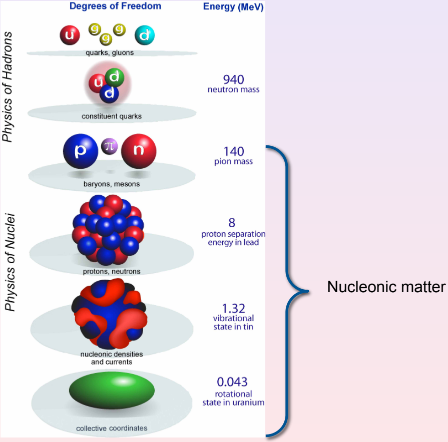
The Nuclear Landscape

- QCD transition (color singlets formed): 10 μs after Big Bang (13.8 billion years ago)
- D, 3,4He, 7Be/7Li formed 3-50 min after Big Bang
- Other nuclei born later in heavy stars and supernovae

Important questions from QCD to the nuclear many-body problem

- How to derive the in medium nucleon-nucleon interaction from basic principles?
- How does the nuclear force depend on the proton-to-neutron ratio?
- What are the limits for the existence of nuclei?
- How can collective phenomena be explained from individual motion?
- Shape transitions in nuclei?

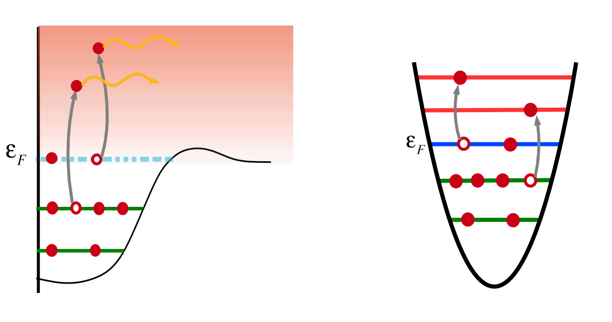
The many scales pose a severe challenge to *ab initio* descriptions of nuclear systems.



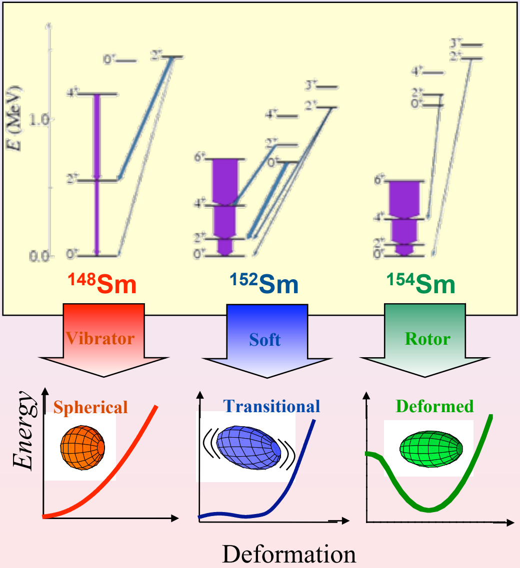
Halo nuclei and moving towards the limits of nuclear stability

Open Quantum System.
Coupling with continuum needs to be taken into account.

Closed Quantum System.
No coupling with external continuum.



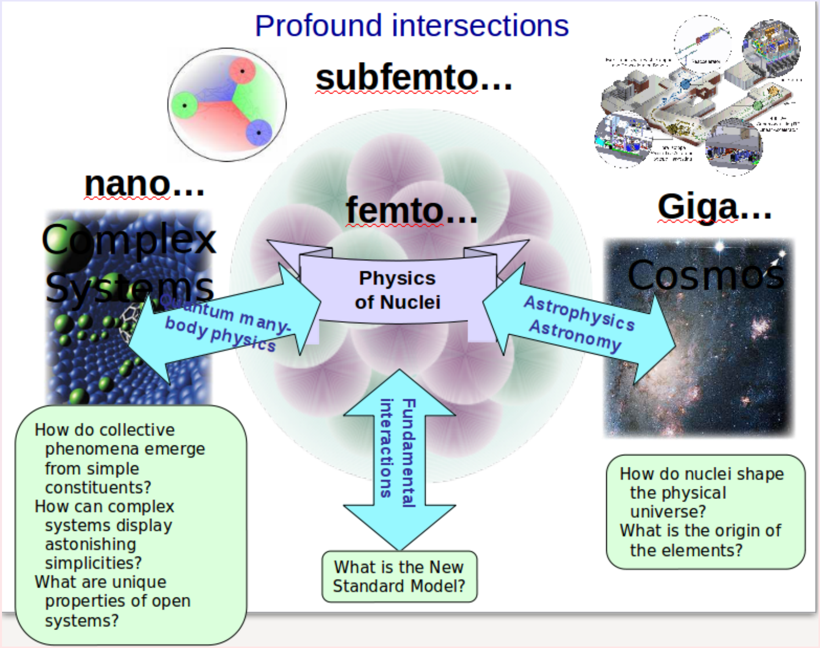
Shape coexistence and transitions, a multiscale challenge



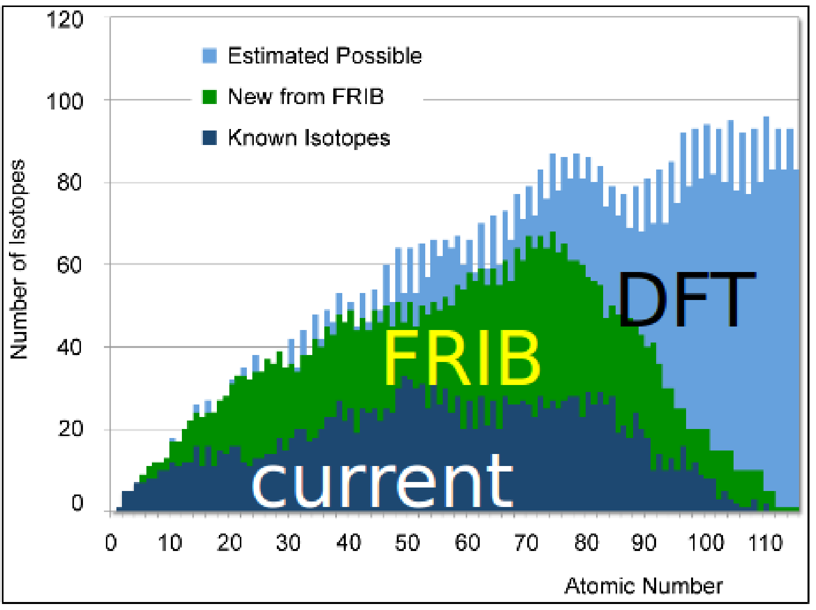
Challenges for theory

- Possible shape transitions, huge spaces needed to describe properly.
- Theory: need to marry *ab initio* methods with density functional theories in order to describe such systems
- Need a large wealth of experimental data to constrain theory

The many interesting intersections

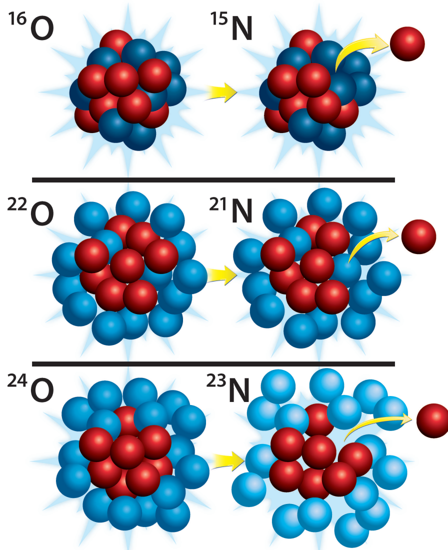


Known nuclei and predictions



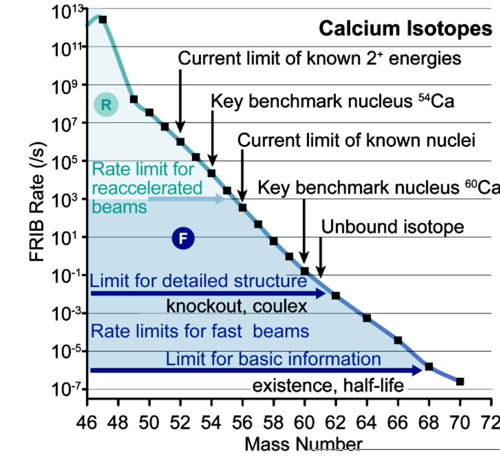
Do we understand the physics of dripline systems?

- The oxygen isotopes are the heaviest isotopes for which the drip line is well established.
- Two out of four stable even-even isotopes exhibit a doubly magic nature, namely ^{22}O ($Z = 8$, $N = 14$) and ^{24}O ($Z = 8$, $N = 16$).
- The structure of ^{22}O and ^{24}O is assumed to be governed by the evolution of the $1s_{1/2}$ and $0d_{5/2}$ one-quasiparticle states.
- The isotopes ^{25}O ^{26}O, ^{27}O and ^{28}O are outside the drip line, since the $0d_{3/2}$ orbit is not bound.



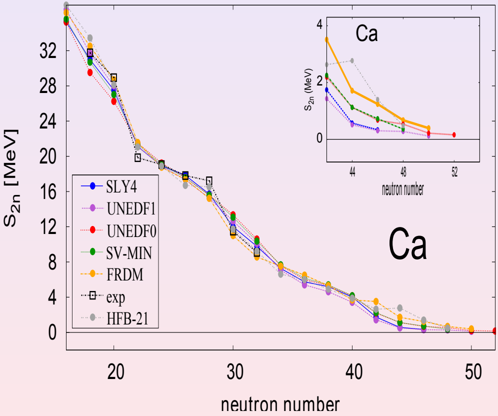
Calcium isotopes and FRIB plans and capabilities

- The Ca isotope exhibit several possible closed-shell nuclei ^{40}Ca, ^{48}Ca, ^{52}Ca, ^{54}Ca, and ^{60}Ca.
- Magic neutron numbers are then $N = 20, 28, 32, 34, 40$.
- Masses available up to ^{54}Ca, Gallant *et al.*,Phys. Rev. Lett. **109**, 032506 (2012) and K. Baum *et al*, Nature **498**, 346 (2013).
- Heaviest observed ^{57,58}Ca. NSCL experiment, O. B. Tarasov *et al.*, Phys. Rev. Lett. **102**, 142501 (2009). Cross sections for ^{59,60}Ca assumed small ($< 10^{-12}$mb).
- Which degrees of freedom prevail close to ^{60}Ca?



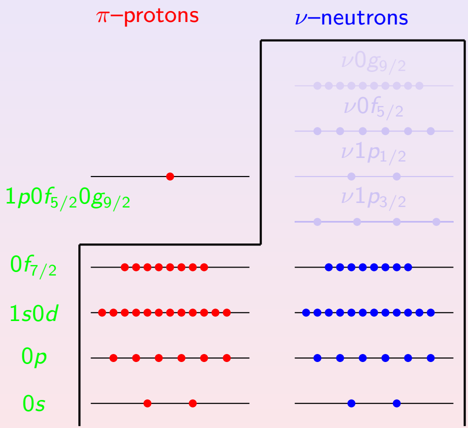
More on Calcium Isotopes

- **Mass models and mean field models predict the dripline at $A \sim 70$!** Important consequences for modeling of nucleosynthesis related processes.
- Can we predict reliably which is the last stable calcium isotope?
- And how does this compare with popular mass models on the market? See Nature 486, 509 (2012).
- And which parts of the underlying forces are driving the physics towards the dripline?



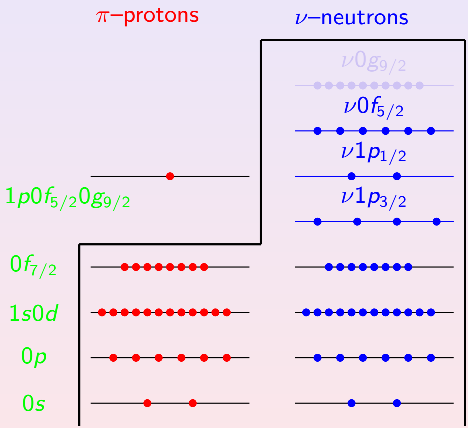
Other chains of isotopes of crucial interest for FRIB like physics: nickel isotopes

- This chain of isotopes exhibits four possible closed-shell nuclei ^{48}Ni, ^{56}Ni, ^{68}Ni and ^{78}Ni. **FRIB plans systematic studies from ^{48}Ni to ^{88}Ni.**
- Neutron skin possible for ^{84}Ni at FRIB.
- Which is the best closed-shell nucleus? And again, which part of the nuclear forces drives it? Is it the strong spin-orbit force, the tensor force, or ..?



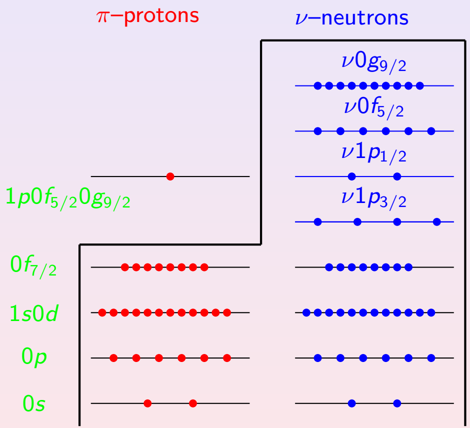
Other chains of isotopes of crucial interest for FRIB like physics: nickel isotopes

- This chain of isotopes exhibits four possible closed-shell nuclei ^{48}Ni, ^{56}Ni, ^{68}Ni and ^{78}Ni. **FRIB plans systematic studies from ^{48}Ni to ^{88}Ni.**
- Neutron skin possible for ^{84}Ni at FRIB.
- Which is the best closed-shell nucleus? And again, which part of the nuclear forces drives it? Is it the strong spin-orbit force, the tensor force, or ..?



Other chains of isotopes of crucial interest for FRIB like physics: nickel isotopes

- This chain of isotopes exhibits four possible closed-shell nuclei ^{48}Ni, ^{56}Ni, ^{68}Ni and ^{78}Ni. **FRIB plans systematic studies from ^{48}Ni to ^{88}Ni.**
- Neutron skin possible for ^{84}Ni at FRIB.
- Which is the best closed-shell nucleus? And again, which part of the nuclear forces drives it? Is it the strong spin-orbit force, the tensor force, or ..?

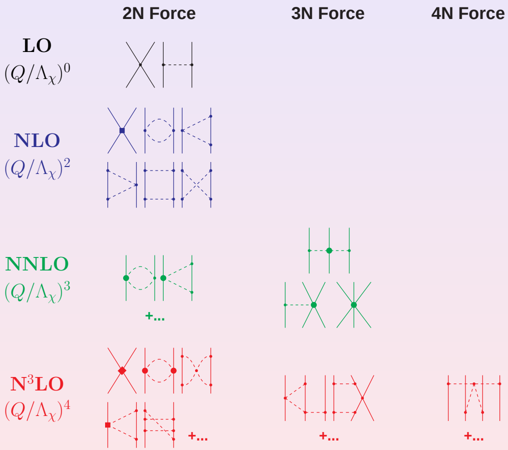


Tin isotopes

From ^{100}Sn to nuclei beyond ^{132}Sn

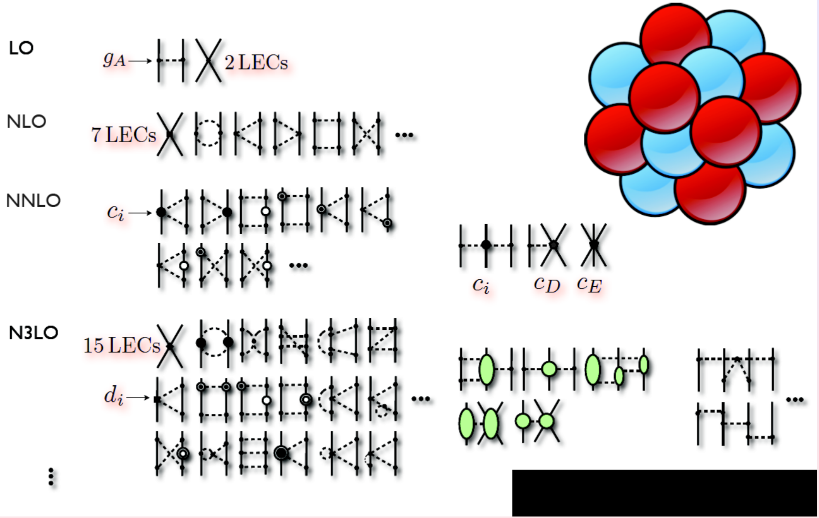
1. We will most likely be able to run coupled-cluster calculations for nuclei like ^{100}Sn, ^{114}Sn, ^{116}Sn, ^{132}Sn, ^{140}Sn and $A \pm 1$ and $A \pm 2$ nuclei within the next one to two years. FRIB can reach to ^{140}Sn. Interest also for EOS studies.
2. Can then test the development of many-body forces for an even larger chain of isotopes.
3. ^{137}Sn is the last reported neutron-rich isotope (with half-life).
4. To understand which parts of the nuclear Hamiltonian that drives the properties of such nuclei will be crucial for our understanding of the stability of matter.
5. Zr isotopes form also long chains of neutron-rich isotopes. **FRIB plans from ^{80}Zr to ^{120}Zr.**
6. And why neutron rich isotopes? **Here the possibility to constrain nuclear forces from in-medium results.**

Nuclear interactions from Effective Field Theory (Δ-less)



- Nucleons and Pions as effective degrees of freedom only. Most general Lagrangian consistent with all symmetries of low-energy QCD.
- Chiral perturbation theory for different orders (ν) of the expansion in terms of $(Q/\Lambda_\chi)^\nu$.
- At order $\nu = 4$ one should include four-body forces in many-body calculations! Not including these will result in what we call missing many-body correlations.

Forces in Nuclear Physics (without isobars)



[redacted]

Effective Manybody Hamiltonian: assume that a three-body Hamiltonian is something we can accept

Case of Normal-ordered three-body Hamiltonian

Introducing a reference state $|\Phi_0\rangle$ as our new vacuum state leads to the redefinition of the Hamiltonian in terms of a constant reference energy E_0 defined as

$$E_0 = \sum_{i \le \alpha_F} \langle i|\hat{h}_0|i\rangle + \frac{1}{2}\sum_{ij \le \alpha_F} \langle ij|\hat{v}|ij\rangle + \frac{1}{6}\sum_{ijk \le \alpha_F} \langle ijk|\hat{w}|ijk\rangle,$$

and a normal-ordered Hamiltonian

$$\hat{H}_N = \sum_{pq} \langle p|\tilde{f}|q\rangle a_p^\dagger a_q + \frac{1}{4}\sum_{pqrs} \langle pq|\tilde{v}|rs\rangle a_p^\dagger a_q^\dagger a_s a_r +$$

$$\frac{1}{36}\sum_{\substack{pqr\\stu}} \langle pqr|\hat{w}|stu\rangle a_p^\dagger a_q^\dagger a_r^\dagger a_u a_t a_s$$

Effective Manybody Hamiltonian: assume that a three-body Hamiltonian is something we can accept

Case of Normal-ordered three-body Hamiltonian

We have defined a one-body term as

$$\langle p|\tilde{f}|q\rangle = \langle p|\hat{h}_0|q\rangle + \sum_{i\le\alpha_F}\langle pi|\hat{v}|qi\rangle + \frac{1}{2}\sum_{ij\le\alpha_F}\langle pij|\hat{w}|qij\rangle.$$

It represents a correction to the single-particle operator $\hat{h}_0$ due to contributions from the nucleons below the Fermi level. The two-body matrix elements are now modified in order to account for medium-modified contributions from the three-body interaction, resulting in

$$\langle pq|\tilde{v}|rs\rangle = \langle pq|\hat{v}|rs\rangle + \sum_{i\le\alpha_F}\langle pqi|\hat{w}|rsi\rangle.$$

The Monopole Part of an Interaction

An important ingredient in studies of effective interactions and their applications to nuclear structure, is the so-called monopole interaction, normally defined in terms of a nucleon-nucleon interaction $\hat{v}$

$$\bar{V}_{j_pj_q} = \frac{\sum_J (2J+1)\langle (j_pj_q)J|\hat{v}|(j_pj_q)J\rangle}{\sum_J (2J+1)},$$

where the total angular momentum of a two-body state J runs over all possible values. The monopole Hamiltonian can be interpreted as an angle-averaged matrix element. This equation can also be expressed in terms of the medium-modified two-body interaction

$$\tilde{V}_{j_pj_q} = \frac{\sum_J (2J+1)\langle (j_pj_q)J|\tilde{v}|(j_pj_q)J\rangle}{\sum_J (2J+1)}.$$

The Monopole Part of an Interaction

The single-particle energy ϵ_p resulting from for example a self-consistent Hartree-Fock field, or from first order in many-body perturbation theory, is given by

$$\epsilon_{j_p} = \langle j_p|\hat{h}_0|j_p\rangle + \frac{1}{2j_p+1}\sum_{j_i\leq F}\sum_J (2J+1)\langle (j_p j_i)J|\hat{v}|(j_p j_i)J\rangle,$$

or

$$\epsilon_{j_p} = \langle j_p|\hat{h}_0|j_p\rangle + \frac{1}{2j_p+1}\sum_{j_i\leq F}\sum_J (2J+1)\langle (j_p j_i)J|\tilde{v}|(j_p j_i)J\rangle,$$

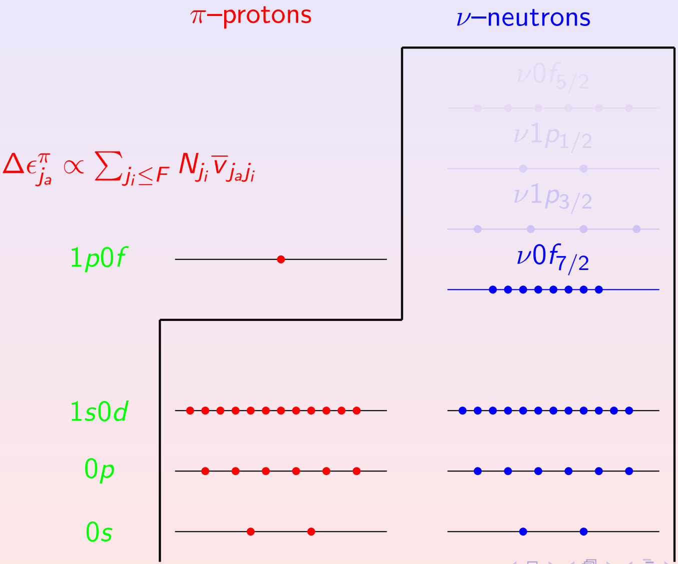
where the first equation contains a two-body force only while the second includes the medium-modified contribution from the three-body interaction as well. These equations can be rewritten in terms of the monopole contribution as

$$\epsilon_{j_p} = \langle j_p|\hat{h}_0|j_p\rangle + \sum_{j_i\leq F} N_{j_i}\bar{V}_{j_p j_i},$$

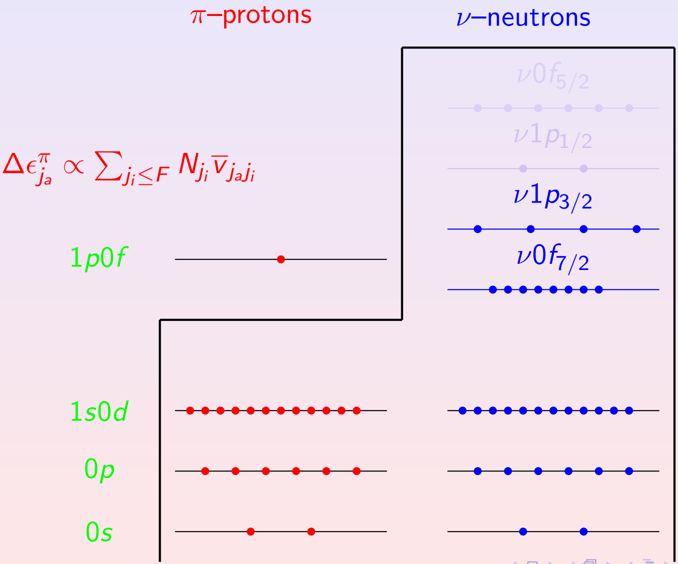
with $N_{j_i} = 2j_i + 1$, and

$$\epsilon_{j_p} = \langle j_p|\hat{h}_0|j_p\rangle + \sum_{j_i\leq F} N_{j_i}\tilde{V}_{j_p j_i}.$$

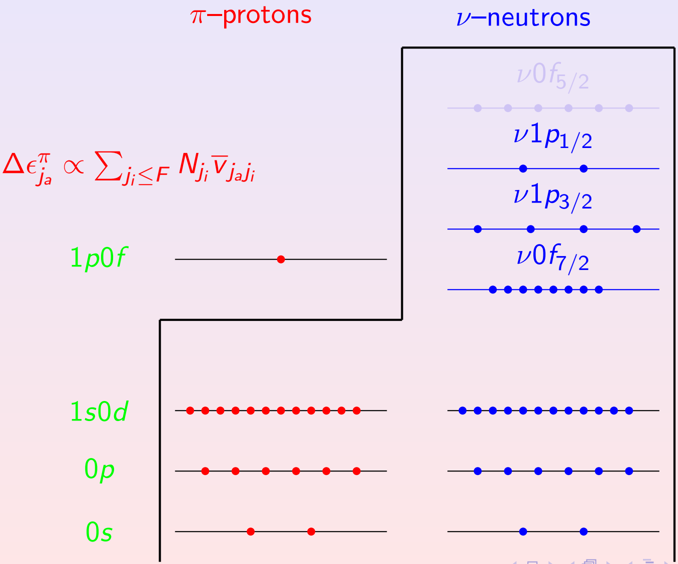
Evolution of quasiparticle states in terms of the monopole part: ^{48,52,54,60}Ca



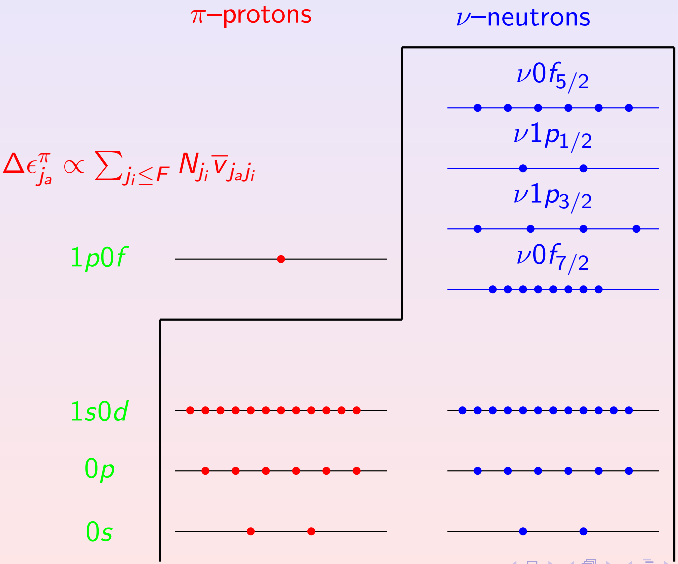
Evolution of quasiparticle states in terms of the monopole part: ^{48,52,54,60}Ca



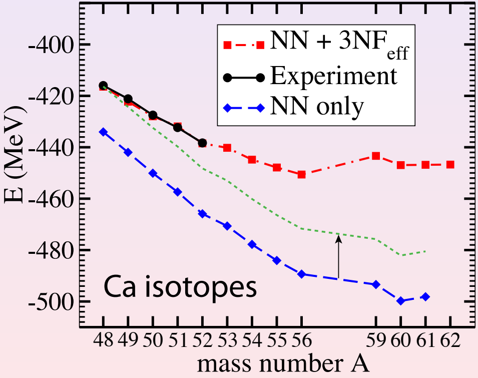
Evolution of quasiparticle states in terms of the monopole part: ^{48,52,54,60}Ca



Evolution of quasiparticle states in terms of the monopole part: ^{48,52,54,60}Ca

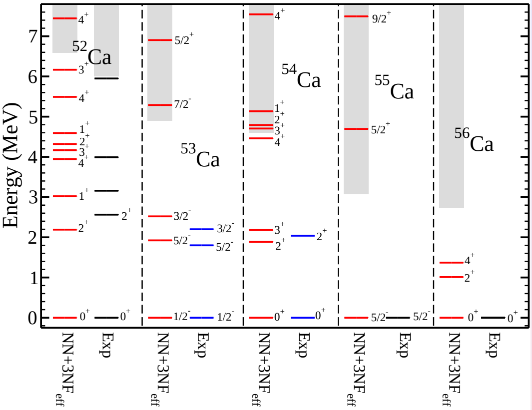


Calcium isotopes with three-body forces, Hagen *et al*, Phys. Rev. Lett. **109**, 032502 (2012)



- Three-body force is taken as a density dependent contribution to a two-body interaction
- Three-body force based on a nuclear matter calculation with $k_F = 1.0$ fm^{-1}.
- Dashed line: two-body results normalized at $A = 48$.
- Most mass models predict dripline at $A = 70$
- We predict it at $A \sim 60$?

Calcium isotopes with three-body forces and continuum, Hagen *et al*, Phys. Rev. Lett. **109**, 032502 (2012)



	^{53}Ca		^{55}Ca		^{61}Ca	
J^π	Re$[E]$	Γ	Re$[E]$	Γ	Re$[E]$	Γ
$5/2^+$	1.99	1.97	1.63	1.33	1.14	0.62
$9/2^+$	4.75	0.28	4.43	0.23	2.19	0.02

What about refitting the force? Ekström *et al*, Phys. Rev. Lett. **110**, 192502 (2013) and arXiv:1502.04682.

Our dataset of fit-observables includes the binding energies and charge radii of ^{3}H, ^{3,4}He, ^{14}C, and ^{16}O, as well as binding energies of ^{22,24,25}O.
From the *NN* sector we includes proton-proton and neutron-proton scattering observables up to 35 MeV scattering energy in the laboratory system as well as effective range parameters, and deuteron properties. The maximum scattering energy was chosen such that an acceptable fit to both *NN* scattering data and many-body observables could be achieved.

What about refitting the force? Ekström *et al*, Phys. Rev. Lett. **110**, 192502 (2013) and arXiv:1502.04682.

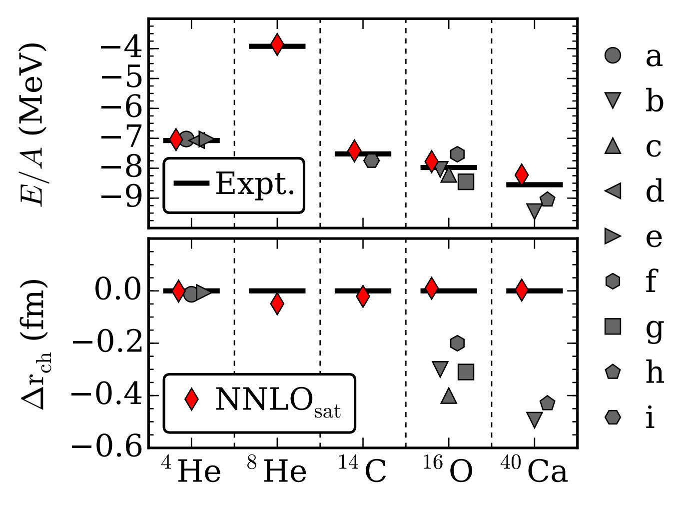
	E_{gs}	Exp.	r_{ch}	Exp.
^{3}H	8.52	8.482	1.78	1.7591(363)
^{3}He	7.76	7.718	1.99	1.9661(30)
^{4}He	28.43	28.296	1.70	1.6755(28)
^{14}C	103.6	105.285	2.48	2.5025(87)
^{16}O	124.4	127.619	2.71	2.6991(52)
^{22}O	160.8	162.028(57)		
^{24}O	168.1	168.96(12)		
^{25}O	167.4	168.18(10)		

What about refitting the force? Ekström *et al*, Phys. Rev. Lett. **110**, 192502 (2013) and arXiv:1502.04682.

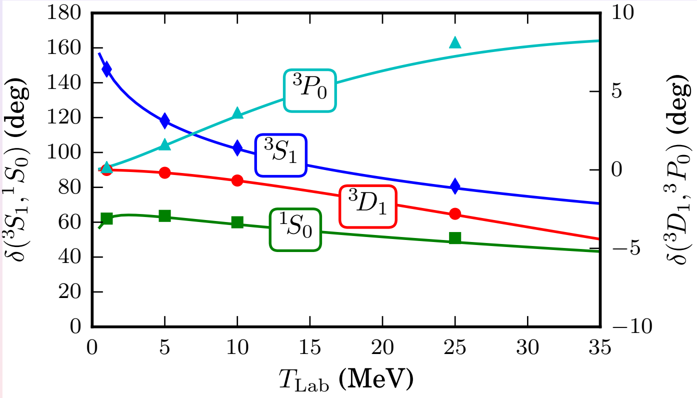
LEC	Value	LEC	Value	LEC	Value
c_1	-1.12	c_3	-3.93	c_4	3.77
$\tilde{C}^{pp}_{^1S_0}$	-0.16	$\tilde{C}^{np}_{^1S_0}$	-0.16	$\tilde{C}^{nn}_{^1S_0}$	-0.16
$C_{^1S_0}$	2.54	$C_{^3S_1}$	1.00	$\tilde{C}_{^3S_1}$	-0.18
$C_{^1P_1}$	0.56	$C_{^3P_0}$	1.40	$C_{^3P_1}$	-1.14
$C_{^3S_1-^3D_1}$	0.60	$C_{^3P_2}$	-0.80	c_D	0.82
c_E	-0.04				

The values of the LECs. The c_i, $\tilde{C}_i$, and C_i are in units of GeV^{-1}, 10^4 GeV^{-2}, and 10^4 GeV^{-4}, respectively.

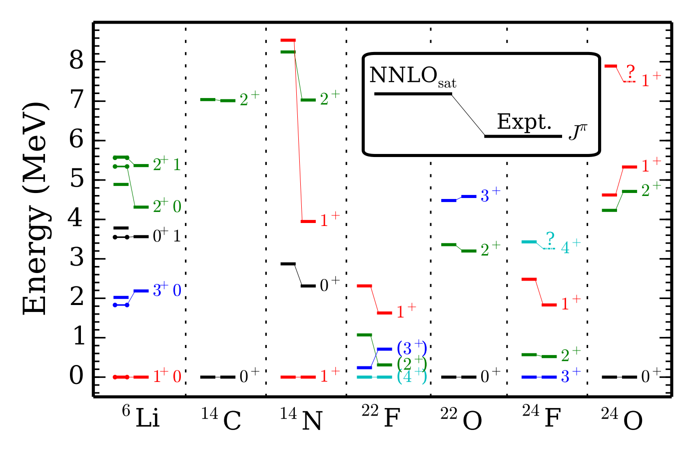
Ground state properties. Ekström *et al*, arXiv:1502.04682.



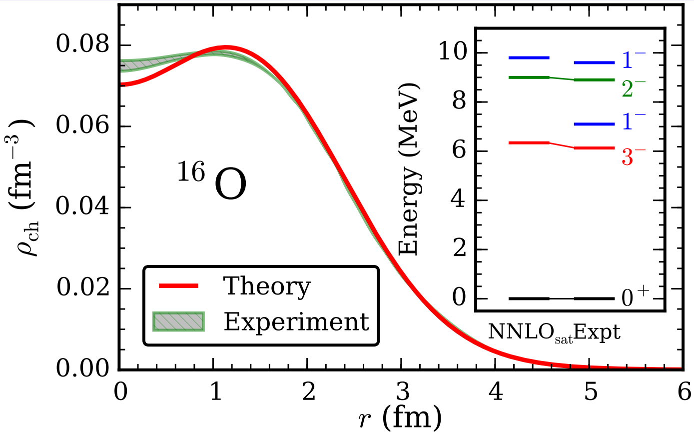
Neutron-proton scattering phase shifts. Ekström *et al*, arXiv:1502.04682.



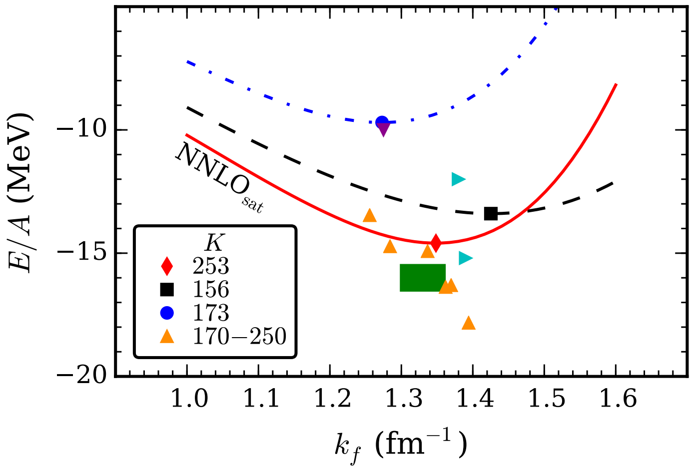
Selected spectra. Ekström *et al*, arXiv:1502.04682.



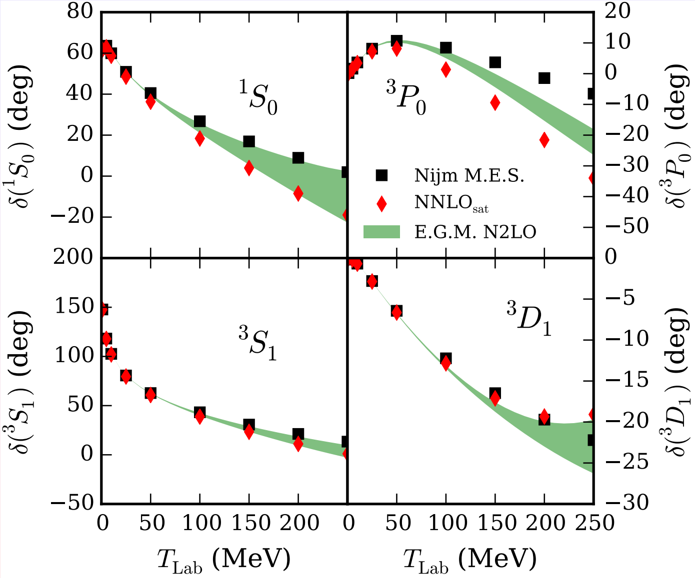
Charge density and states for ^{16}O. Ekström *et al*, arXiv:1502.04682.



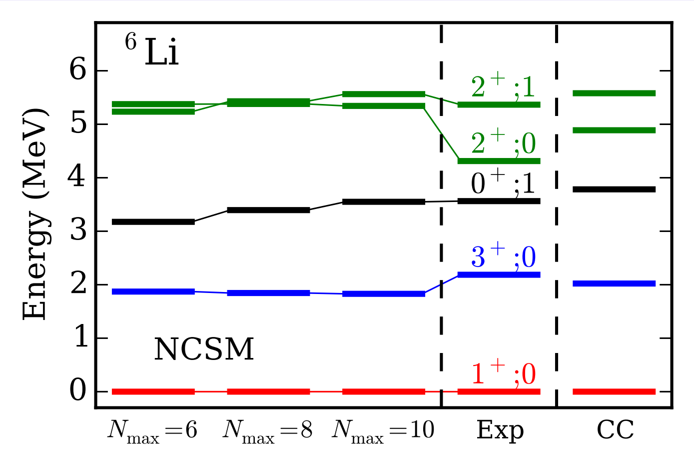
Equation of state for symmetric nuclear matter. Ekström *et al*, arXiv:1502.04682.



Predicted phase shifts. Ekström *et al*, arXiv:1502.04682.



Prediction for 6Li. Ekström *et al*, arXiv:1502.04682.



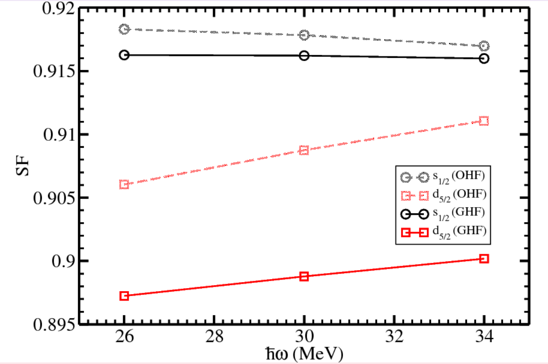
Spectroscopic factors for ^{24}O, Ø. Jensen *et al*, PRC **83**, 021305(R) (2011)

$$S_{A-1}^{A}(lj) = \left| O_{A-1}^{A}(lj;r) \right|^2 , \quad (1)$$

$$O_{A-1}^{A}(lj;r) = \sum_n \int \langle A-1||\tilde{a}_{nlj}||A\rangle \phi_{nlj}(r). \quad (2)$$

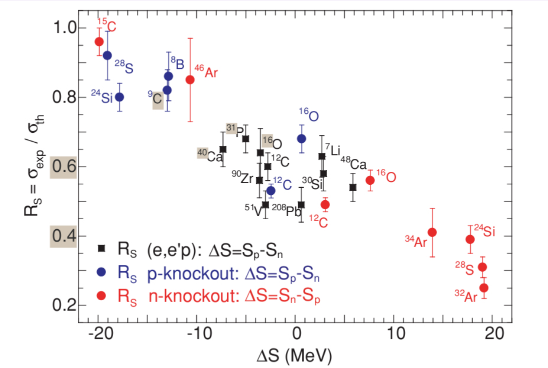
Here, $O_{A-1}^{A}(lj;r)$ is the radial overlap function of the many-body wavefunctions for the two independent systems with A and $A-1$ particles respectively. The double bar denotes a reduced matrix element, and the integral-sum over n represents both the sum over the discrete spectrum and an integral over the corresponding continuum part of the spectrum.

Spectroscopic factors for ^{24}O, Ø. Jensen *et al*, PRC **83**, 021305(R) (2011)



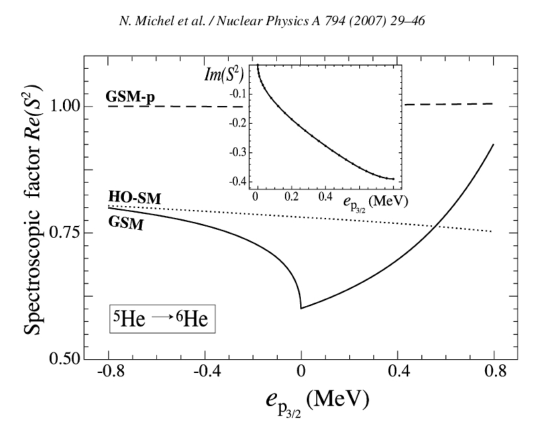
- N^{3}LO with $\Lambda = 500$ MeV interaction, CCSD calculation
- Bergren basis (GHF) and Harmonic oscillator basis (OHF)
- **Spectroscopic factors for neutron $d_{5/2}$ and $s_{1/2}$**
- 17 oscillator shells plus 30 Woods-Saxon Berggren states for each of the $s_{1/2}$, $d_{5/2}$, and $d_{3/2}$ states
- ^{24}O seemingly good closed shell nucleus.

Spectroscopic factors from Gade *et al*, PRC **77**, 044306 (2008). Can we understand these quenchings?



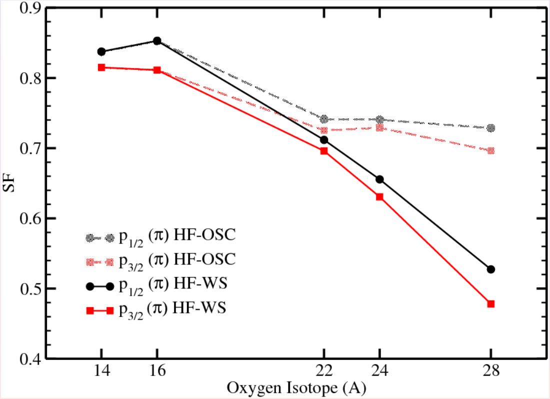
- Reduction of measured nucleon knock-out cross sections relative to theoretical
- Plotted as function of separation energies of the two nucleon species
- Results from heavy-ion induced one-π and one-ν knockout reactions and electron-induced proton removal from stable nuclei.
- Only expt uncertainties included

Wigner cusp due to continuum coupling, Michel, Nazarewicz, and Płoszajczak, Nucl. Phys. A **794**, 29 (2007).



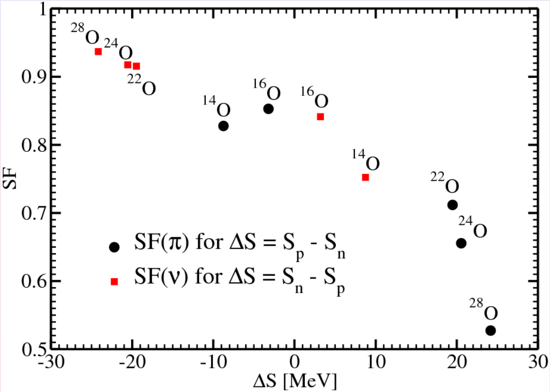
- Simple model for ^{5}He$+n \rightarrow {}^6$He
- Single-particle energies obtained using complex basis
- Vary the binding energy (and thereby separation energy) of $p_{3/2}$ state
- Cusp in SF due to coupling to scattering states

Spectroscopic factors for ^{14}O, ^{16}O, ^{22}O, ^{24}O and ^{28}O, Ø. Jensen *et al*, PRL **107**, 032501 (2011)



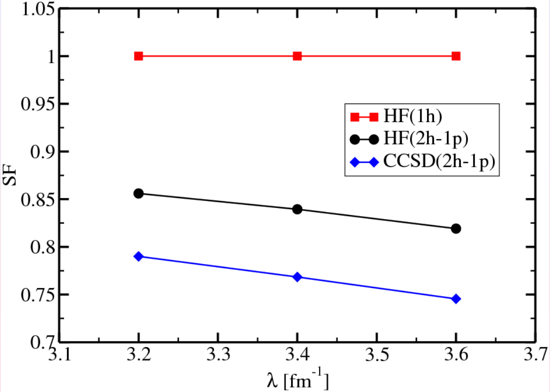
- N^{3}LO with $\Lambda = 500$ MeV interaction, CCSD calculation
- Spectroscopic factors for proton $p_{3/2}$ and $p_{1/2}$
- Quenching due to coupling to scattering states
- Different from standard scenario (long-range, short-range+tensor correlations)

SFs and separation energies ^{14}O, ^{16}O, ^{22}O, ^{24}O and ^{28}O, Ø. Jensen *et al*, in PRL **107**, 032501 (2011)



- SFs for $p_{1/2}$ as function of separation energies
- When large differences in separation energies, large quenchings for protons
- Neutrons are weakly bound and less quenched.

Many-body correlations Ø. Jensen *et al*, PRL **107**, 032501 (2011). SF for $p_{1/2}$ as function of various cutoffs for ^{24}O



- N^3LO interaction evolved to a lower momentum cutoff λ
- Case 1: SFs using a mean-field HF solution for the A and $A-1$ nuclei
- Case 2: HF for A nucleus and 2p1h for $A-1$ nucleus
- Case 3: full calculation

Conclusions and perspectives

- Three-body forces important in nuclear physics (we see this for all nuclear systems we have studied)
- Correlations due to two, three and more complicated interactions important, also towards the limits of stability
- Continuum important
- Departure from expected mean field picture (Hartree-Fock or harmonic oscillator) towards the nuclear driplines.
- Coming: better analysis of two- and three-body forces that are fitted to reproduce light and medium mass nuclei. Analysis of cutoffs and regulators in effective field theory in a nuclear many-body medium on several nuclear observables. This will allows us to extract $\langle T \rangle$ and $\langle V \rangle$ as function of the number of nucleons.