Equazione di Stato ed energia di simmetria

Xavier Roca-Maza
Università degli Studi di Milano e INFN, sezione di Milano
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INTRODUCTION

The Nuclear Many-Body Problem:

- **Nucleus:** from few to more than 200 strongly interacting and **self-bound fermions**.
- **Underlying interaction** is **not perturbative** at the (low)energies of interest for the study of masses, radii, deformation, giant resonances,...
- **Complex systems**: **spin, isospin, pairing, deformation,** ...
- **Many-body** calculations based on **NN scattering data** in the vacuum are **not conclusive** yet:
  - **different nuclear interactions in the medium** are found **depending** on the **approach**
  - EoS and (recently) **few groups** in the world are able to perform extensive calculations for **light and medum mass nuclei**
- Based on effective interactions, **Nuclear Energy Density Functionals** are **successful** in the description of **masses, nuclear sizes, deformations, Giant Resonances,...**

Nuclear Energy Density Functionals:

Main types of successful EDFs for the description of masses, deformations, nuclear distributions, Giant Resonances, ...

Relativistic mean-field models, based on Lagrangians where effective mesons carry the interaction:

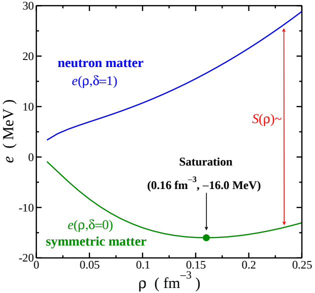
$$\begin{aligned}\mathcal{L}_{int} \quad &= \bar{\Psi}\Gamma_\sigma(\bar{\Psi},\Psi)\Psi\Phi_\sigma \quad + \bar{\Psi}\Gamma_\delta(\bar{\Psi},\Psi)\boldsymbol{\tau}\Psi\Phi_\delta \\ &- \bar{\Psi}\Gamma_\omega(\bar{\Psi},\Psi)\gamma_\mu\Psi A^{(\omega)\mu} \quad - \bar{\Psi}\Gamma_\rho(\bar{\Psi},\Psi)\gamma_\mu\tau\Psi A^{(\rho)\mu} \\ &- e\bar{\Psi}\hat{Q}\gamma_\mu\Psi A^{(\gamma)\mu}\end{aligned}$$

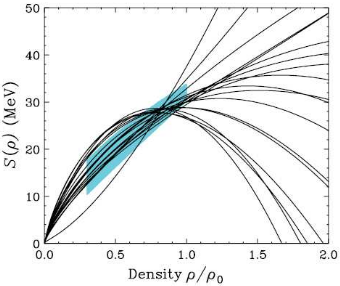
Non-relativistic mean-field models, based on Hamiltonians where effective interactions are proposed and tested:

$$V^{\rm eff}_{\rm Nucl} = V^{\rm long-range}_{\rm attractive} + V^{\rm short-range}_{\rm repulsive} + V_{\rm SO} + V_{\rm pair}$$

- Fitted **parameters contain** (important) **correlations beyond the mean-field**
- Nuclear energy functionals are **phenomenological** → **not directly connected to any NN** (or NNN) **interaction**

The Nuclear Equation of State: Infinite System



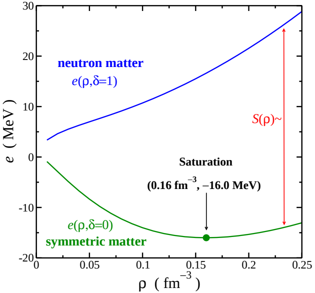


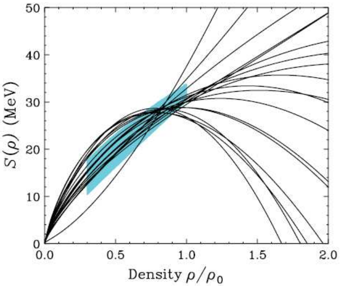
$$\frac{E}{A}(\rho, \beta) = \frac{E}{A}(\rho, \beta = 0) + S(\rho)\beta^2 + \mathcal{O}(\beta^4)$$

- Nuclear Matter

$$\left[\beta = \frac{\rho_n - \rho_p}{\rho}\right]$$

The Nuclear Equation of State: Infinite System



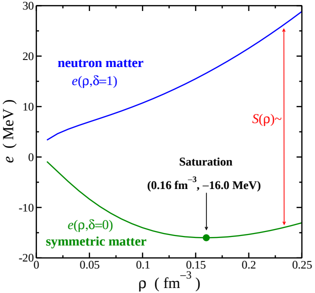


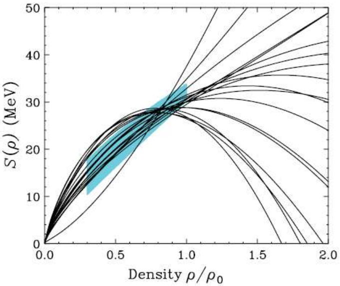
$$\boxed{\frac{E}{A}(\rho,\beta)} = \boxed{\frac{E}{A}(\rho,\beta=0)} + \boxed{S(\rho)\beta^2} + \mathcal{O}(\beta^4)$$

- Nuclear Matter
- Symmetric Matter

$$\left[\beta = \frac{\rho_n - \rho_p}{\rho}\right]$$

The Nuclear Equation of State: Infinite System



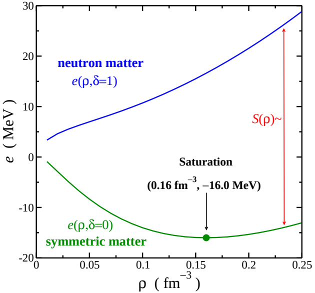


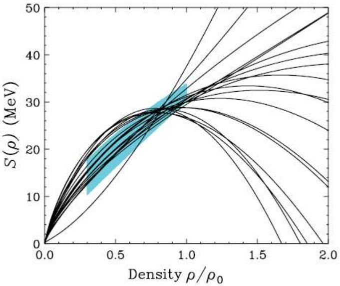
$$\frac{E}{A}(\rho, \beta) = \frac{E}{A}(\rho, \beta = 0) + S(\rho)\beta^2 + \mathcal{O}(\beta^4)$$

- Nuclear Matter
- Symmetric Matter
- Symmetry energy

$$\left[\beta = \frac{\rho_n - \rho_p}{\rho}\right]$$

The Nuclear Equation of State: Infinite System



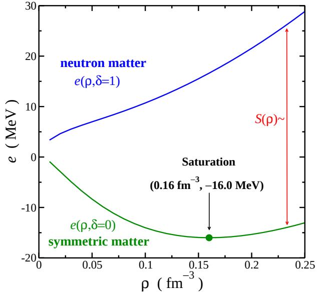


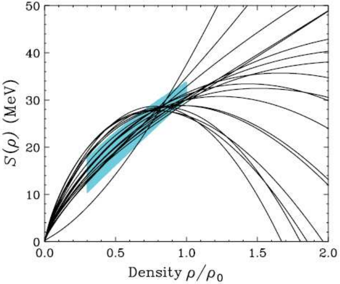
$$\frac{E}{A}(\rho,\beta) = \frac{E}{A}(\rho,\beta=0) + S(\rho)\beta^2 + \mathcal{O}(\beta^4)$$

$$= \frac{E}{A}(\rho,\beta=0) + \beta^2\left(J + Lx + \frac{1}{2}K_{sym}x^2 + \mathcal{O}(x^3)\right)$$

$$\left[\beta = \frac{\rho_n - \rho_p}{\rho}; \quad x = \frac{\rho-\rho_0}{3\rho_0}\right]$$

The Nuclear Equation of State: Infinite System



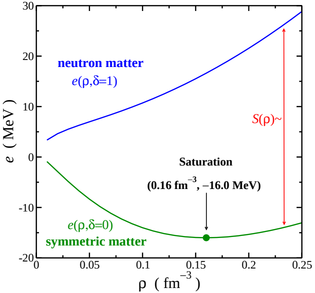


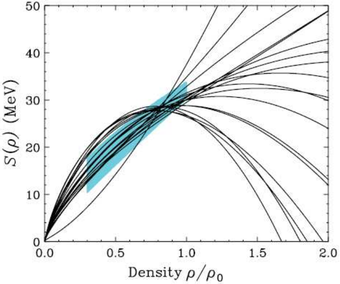
$$\frac{E}{A}(\rho,\beta) = \frac{E}{A}(\rho,\beta=0) + \beta^2\left(\boxed{J} + \boxed{L}\,x + \frac{1}{2}\boxed{K_{sym}}\,x^2 + \mathcal{O}(x^3)\right)$$

- $S(\rho_0) = J$
- $\left.\frac{d}{d\rho}S(\rho)\right|_{\rho_0} = \frac{L}{3\rho_0} = \frac{P_0}{\rho_0^2}$
- $\left.\frac{d^2}{d\rho^2}S(\rho)\right|_{\rho_0} = \frac{K_{sym}}{9\rho_0^2}$

$$\left[\beta = \frac{\rho_n - \rho_p}{\rho};\quad x = \frac{\rho - \rho_0}{3\rho_0}\right]$$

The Nuclear Equation of State: Infinite System





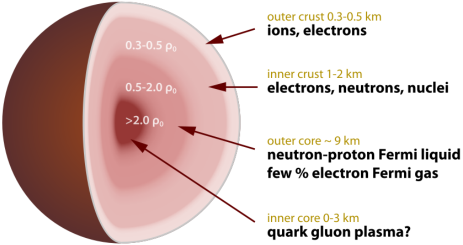
The uncertainties on $S(\rho)$ **impacts** on many nuclear physics and astrophysics **observables**.

▸ sym ρ_0^2

$$\left[\beta = \frac{\rho_n - \rho_p}{\quad}; \quad x = \frac{\rho - \rho_0}{\quad}\right]$$

The impact of the symmetry energy on nuclear and astrophyiscs observables

Relevance of the neutron star crust on the star evolution and dynamics (brief motivation)



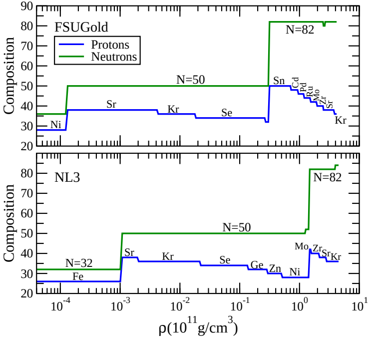
- The crust separates neutron star interior from the photosphere (X-ray radiation).
- The thermal conductivity of the crust is relevant for determining the relation between observed X-ray flux and the temperature of the core.
- Electrical resistivity of the crust might be important for the evolution of neutron star magnetic field.
- Conductivity and resistivity depend on the structure and composition of the crust

- Neutrino emission from the crust may significantly contribute to total neutrino losses from stellar interior (in some cooling stages).
- A crystal lattice (solid crust) is needed for modelling pulsar glitches, enables the excitation of toroidal modes of oscillations, can suffer elastic stresses...
- Mergers (binary systems that merge) may enrich the interstellar medium with heavy elements, created by a rapid neutron-capture process.
- In accreting neutron stars, instabilities in the fusion light elements might be responsible for the phenomenon of X-ray bursts

Source: Pawel Haensel 2001

The symmetry energy and the structure and composition of a neutron star outer crust

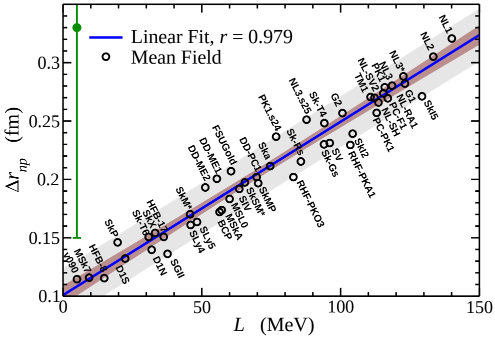
- span **7** orders of magnitude in **denisty** (from **ionization** $\sim 10^4$ g/cm to the **neutron drip** $\sim 10^{11}$ g/cm)
- it is organized into a **Coulomb lattice** of neutron-rich nuclei (ions) embedded in a relativistic **uniform electron gas**
- $T \sim 10^6$ K ~ 0.1 keV $\rightarrow$ one can treat **nuclei and electrons at $T = 0$ K**
- At the **lowest densities**, the electronic contribution is negligible so the Coulomb lattice is populated by ^{56}**Fe** nuclei.
- As the **density increases**, the electronic contribution becomes important, it is energetically advantageous to lower its electron fraction by $e^- + (N, Z) \rightarrow (N+1, Z-1) + \nu_e$ and therefore $Z \downarrow$ with constant (approx) number of N
- As the **density continues to increase, penalty energy from the symmetry energy** due to the neutron excess changes the composition to a different $N-$*plateau*
  $\frac{Z}{A} \approx \frac{Z_0}{A_0} - \frac{p_{F_e}}{8 a_{sym}}$ where $(A_0, Z_0) = {}^{56}Fe_{26}$
- The Coulomb lattice is made of more and more neutron-rich nuclei until the critical **neutron-drip density is reached ($\mu_{drip} = m_n$)**.
  $[M(N, Z) + m_n < M(N+1, Z)]$



Physical Review C **78**, *025807 (2008)*

The faster the symmetry energy increases with density **(L ↑)**, the more exotic the composition of the outer crust.

The symmetry energy and the neutron skin in nuclei



Physical Review Letters **106**, *252501 (2011)*

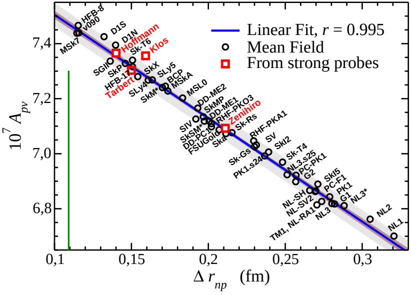
The faster the symmetry energy increases with density, the largest the size of the neutron skin in (heavy) nuclei.

$$\Delta r_{np} \sim \frac{1}{12}\frac{IR}{J} L$$

[Exp. from strongly interacting probes: 0.18 ± 0.03 **fm (***Physical Review C* **86** *015803 (2012)***)].**

The symmetry energy and parity violating electron scattering

(A_{pv}: relative difference between the elastic cross sections of right- and left-handed electrons)



Physical Review Letters **106**, *252501 (2011)*

(Calculation at a fixed q equal to PREx)

- Electrons interact by exchanging a γ **(couples to** p**)** or a Z_0 **boson (couples to** n**)**
- Ultra-relativistic electrons, **depending on their helicity** ($\pm$), will interact with the nucleus **seeing a slightly different potential**: **Coulomb** $\pm$ **Weak**
- $A_{pv} \equiv \frac{d\sigma_+/d\Omega - d\sigma_-/d\Omega}{d\sigma_+/d\Omega + d\sigma_-/d\Omega} \sim \frac{\text{Weak}}{\text{Coulomb}}$
- Input for the calculation are the ρ_p and ρ_n **(main uncertainty)** and nucleon form factors for the e-m and the weak neutral current.
- In PWBA for small momentum transfer:
  $$A_{pv} \approx \frac{G_F q^2}{4\sqrt{2}\pi\alpha}\left(1 - \frac{q^2 \langle r_p^2 \rangle^{1/2}}{3F_p(q)} \Delta r_{np}\right)$$

The largest the size of the neutron distribution in nuclei, the smaller the elastic electron parity violating asymmetry.
[Exp. from ew probes: 0.302 ± 0.175 **fm (***Physical Review C* **85**, *032501 (2012)***)].**

Isovector Giant Resonances

- In **isovector** giant resonances **neutrons and protons "oscillate" out of phase**
- **Isovector** resonances will depend on oscillations of the density $\rho_{iv} \equiv \rho_n - \rho_p \Rightarrow S(\rho)$ will drive such "oscillations"
- The **excitation energy (E_x)** within a **Harmonic Oscillator** approach is expected to depend on the symmetry energy:

$$\omega = \sqrt{\frac{1}{m}\frac{d^2U}{dx^2}} \propto \sqrt{k} \to E_x \sim \sqrt{\frac{\delta^2 e}{\delta\beta^2}} \propto \sqrt{\mathbf{S}(\boldsymbol{\rho})}$$

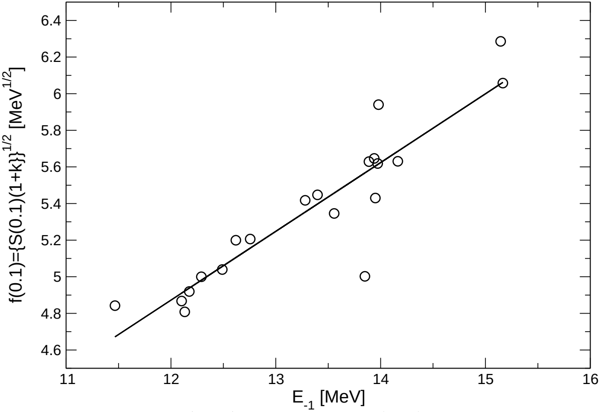
where $\beta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$

- The **dipole polarizability** ($\alpha \sim \int \frac{\sigma_{\gamma-abs}}{\text{Energy}^2} \sim$ **IEWSR**) measures the tendency of the nuclear charge distribution to be distorted, that is, from a **macroscopic** point of view

$$\alpha \sim \frac{\text{electric dipole moment}}{\text{external electric field}}$$

The symmetry energy and the Giant Dipole Resonance

($E_x \approx f(0.1) \propto \sqrt{S(0.1\text{fm}^{-3})}$)

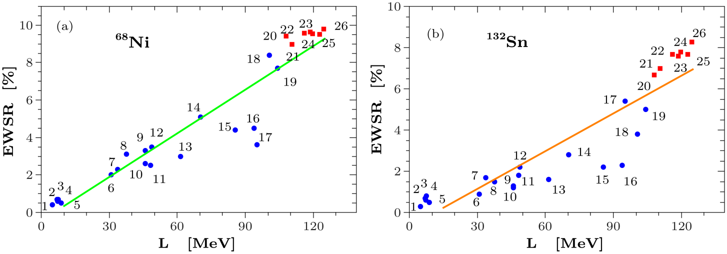


Physical Review C **77***, 061304 (2008)*

The larger the symmetry energy at an average density of a finite heavy nucleus, the larger the excitation energy of the Giant Dipole Resonance (GDR).

The symmetry energy and the Pygmy Dipole Resonance

(Pygmy: low-energy excited state appearing in the dipole response of N ≠ Z nuclei)

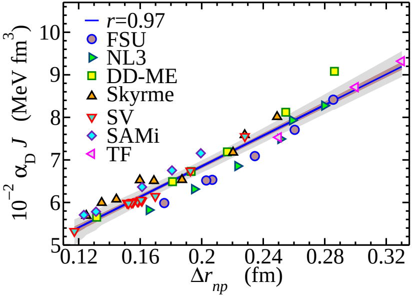


Physical Review C **81**, *041301 (2010)*

The faster the symmetry energy increases with density, the larger is the energy (E) times the probability (P) of exciting the Pygmy state ⇒ larger the Energy Weighted Sum Rule (EWSR) $\propto E \times P$.

WARNING: we lack of a clear understanding of the physical reason for this correlation

Dipole polarizability and the symmetry energy



Physical Review C **88** *024316 (2013)*

Macroscopic model:

- Using the **dielectric theorem:** m_{-1} moment can be computed from the expectation value of the Hamiltonian in the constrained (D dipole operator) ground state $\mathcal{H}' = \mathcal{H} + \lambda D$
- Assuming the **Droplet Model** (heavy nucleus):
  $\alpha_D \approx \alpha_D^{\text{bulk}} \left[1 + \frac{1}{5}\frac{L}{J}\right]$ where
  $\alpha_D^{\text{bulk}} \equiv \frac{\pi e^2}{54}\frac{A\langle r^2\rangle}{J}$ (Migdal first derived)
- $L \approx \frac{\alpha_D^{\text{exp}} - \alpha_D^{\text{bulk}}}{\alpha_D^{\text{bulk}}} 5J$

By using the Droplet Model one can also find:

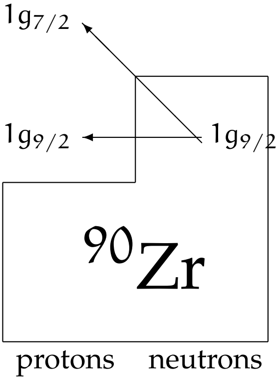
$$\alpha_D J \approx \frac{\pi e^2}{54} A\langle r^2\rangle \left[1 + \frac{5}{2}\frac{\Delta r_{np} - \Delta r_{np}^{\text{coul}} - \Delta r_{np}^{\text{surf}}}{\langle r^2\rangle^{1/2}(I - I_C)}\right]$$

For a fixed value of the symmetry energy at saturation, the faster the symmetry energy increases with density, the larger the dipole polarizability.

The symmetry energy and the Gamow-Teller Resonance

(GT transitions change spin and isospin of the initial quantum state and favors $\Delta n \to 0$)

- Spin orbit splittings around the Fermi surface
- Proton and neutron single particle potentials $\Rightarrow V_{sym}$



Gamow-Teller transitions determine:

- weak interaction rates essential in core-collapse dynamics of massive stars
- in neutron-rich environment, neutrino-induced nucleosynthesis
- studies of double-β decay
- useful in the calibration of detectors used to measure neutrinos

Physical Review C **86** 031306 (2012)

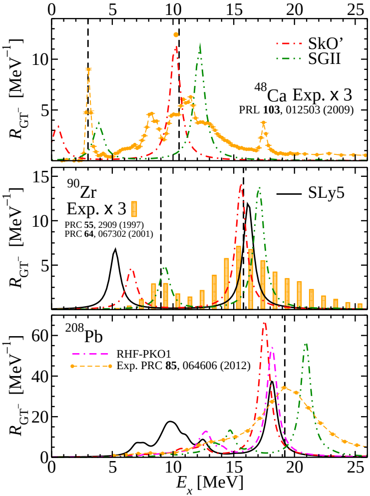
New EDF for a better description of spin-isospin properties: SAMi

Motivation:

Gamow Teller Resonance I

Neither the strength nor the E_x properly described in HF+RPA

- SGII[a] ⇒ earliest attempt to give a quantitative description of the GTR
- SkO′[b] ⇒ accurate in ground state finite nuclear properties and improves the GTR
- Relativistic MF and Relativistic HF (PKO1[c]) calculations are also available



[a] N. Giai and H. Sagawa, Phys. Lett. B **106**, 379 (1981), [b] P.-G. Reinhard et al., Phys. Rev. C **60**, 014316 (1999), [c] H. Liang, N. Van Giai, and J. Meng, Phys. Rev. Lett. **101**, 122502 (2008), SLy5 – E. Chabanat et al., Nucl. Phys. A **635**, 231 (1998); E. Chabanat *et al.*, ibid. **643**, 441 (1998)

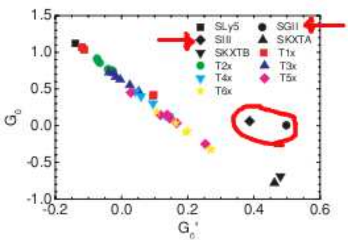
Motivation:

Which gs properties are important for describing the E_x^{GTR}?

A recent study[a] on the GTR and the spin-isospin Landau-Migdal parameter G_0' using several Skyrme sets,

- concluded that G_0' **is not the only important quantity** in determining the **excitation energy of the GTR** in nuclei
- **spin-orbit splittings** also influences the GTR

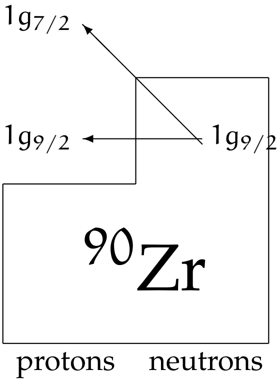
- Empirical indications[b] suggest that $G_0' > G_0 > 0$
- **Not a very common feature** within available Skyrme forces[c]



[a] M. Bender, J. Dobaczewski, J. Engel, and W. Nazarewicz, Phys. Rev. C **65**, 054322 (2002); [b] T. Wakasa, M. Ichimura, and H. Sakai, Phys. Rev. C **72**, 067303 (2005); T. Suzuki and H. Sakai, Phys. Lett. B **455**, 25 (1999), [c] Li-Gang Cao, G. Colo, and H. Sagawa, Phys. Rev. C **81**, 044302 (2010)

Why spin-orbit splittings are important?

$$E_x^1 \approx \epsilon_{\pi 1 g_{7/2}} - \epsilon_{\nu 1 g_{9/2}} + \epsilon_{ph}^1$$
$$E_x^2 \approx \epsilon_{\pi 1 g_{9/2}} - \epsilon_{\nu 1 g_{9/2}} + \epsilon_{ph}^2$$
$$\Delta E_x \approx \Delta\epsilon_{\pi 1 g} + \Delta\epsilon_{ph}$$



Schematic picture of single-particle transitions involved in the Gamow Teller Resonance of ^{90}Zr. Transitions excited by $\sigma\tau_-$ operator.

Skyrme Model

Hamiltonian[a]

Includes **central tensor terms (J^2 terms)** due to the coupling of tensor and spin and gradients terms and **two spin-orbit parameters** (same as SkO and some SkI forces)

$$\mathcal{H} = \mathcal{K} + \mathcal{H}_0 + \mathcal{H}_3 + \mathcal{H}_{\text{eff}} + \mathcal{H}_{\text{fin}} + \mathcal{H}_{\text{SO}} + \mathcal{H}_{\text{sg}} + \mathcal{H}_{\text{Coul}}$$

$$\begin{aligned}
\mathcal{K} &= \hbar^2\tau/2m \\
\mathcal{H}_0 &= (1/4)t_0[(2+x_0)\rho^2 - (2x_0+1)(\rho_n^2+\rho_p^2)] \\
\mathcal{H}_3 &= (1/24)t_3\rho^\alpha[(2+x_3)\rho^2 - (2x_3+1)(\rho_n^2+\rho_p^2)] \\
\mathcal{H}_{\text{eff}} &= (1/8)[t_1(2+x_1)+t_2(2+x_2)]\tau\rho \\
&\quad + (1/8)[t_2(2x_2+1)-t_1(2x_1+1)](\tau_n\rho_n+\tau_p\rho_p) \\
\mathcal{H}_{\text{fin}} &= (1/32)[3t_1(2+x_1)-t_2(2+x_2)](\nabla\rho)^2 \\
&\quad - (1/32)[3t_1(2x_1+1)+t_2(2x_2+1)][(\nabla\rho_n)^2+(\nabla\rho_p)^2] \\
\mathcal{H}_{\text{SO}} &= (1/2)W_0\mathbf{J}\cdot\nabla\rho + (1/2)W_0'(\mathbf{J}\cdot_{\mathbf{n}}\nabla\rho_n + \mathbf{J_p}\cdot\nabla\rho_p) \\
\mathcal{H}_{\text{sg}} &= -(1/16)(t_1x_1+t_2x_2)\mathbf{J}^2 + (1/16)(t_1-t_2)(\mathbf{J_n}^2+\mathbf{J_p}^2)
\end{aligned}$$

[a] E. Chabanat et al., Nucl. Phys. A **635**, 231 (1998); E. Chabanat *et al.*, ibid. **643**, 441 (1998)

Fitting Protocol

χ^2 definition:

$$\chi^2 = \frac{1}{N_{data}} \sum_{i}^{N_{data}} \frac{(\mathcal{O}_i^{theo.} - \mathcal{O}_i^{data})^2}{(\Delta\mathcal{O}_i^{data})^2}$$

Landau-Migdal parameters in infinite nuclear matter G_0 and G_0' fixed to **0.15** and **0.35**, respectively, at ρ_0.

Table: Data and *pseudo*-data $\mathcal{O}_i$, adopted errors for the fit $\Delta\mathcal{O}_i$ and selected finite nuclei and EoS.

$\mathcal{O}_i$	$\Delta\mathcal{O}_i$	
B	1.00 MeV	^{40,48}Ca, ^{90}Zr, ^{132}Sn and ^{208}Pb
r_c	0.01 fm	^{40,48}Ca, ^{90}Zr and ^{208}Pb
ΔE_{SO}	$0.04\times\mathcal{O}_i$	$\pi 1g$ in ^{90}Zr and $\pi 2f$ in ^{208}Pb
$e_n(\rho)$	$0.20\times\mathcal{O}_i$	R. B. Wiringa *et al.*, PRC **38**, 1010 (1988)

Skyrme Aizu Milano interaction: SAMi

Parameter set and nuclear matter properties:

Table: SAMi parameter set and saturation properties with the estimated standard deviations inside parenthesis

	value(σ)			value(σ)	
t_0	−1877.75(75)	MeV fm^3	ρ_∞	0.159(1)	fm^{-3}
t_1	475.6(1.4)	MeV fm^5	e_∞	−15.93(9)	MeV
t_2	−85.2(1.0)	MeV fm^5	m^*_{IS}	0.6752(3)	
t_3	10219.6(7.6)	MeV fm$^{3+3\alpha}$	m^*_{IV}	0.664(13)	
x_0	0.320(16)		J	28(1)	MeV
x_1	−0.532(70)		L	44(7)	MeV
x_2	−0.014(15)		K_∞	245(1)	MeV
x_3	0.688(30)		G_0	0.15	(fixed)
W_0	137(11)		G'_0	0.35	(fixed)
W'_0	42(22)				
α	0.25614(37)				

Results

Equation of State: SAMi vs *ab*–initio calculations

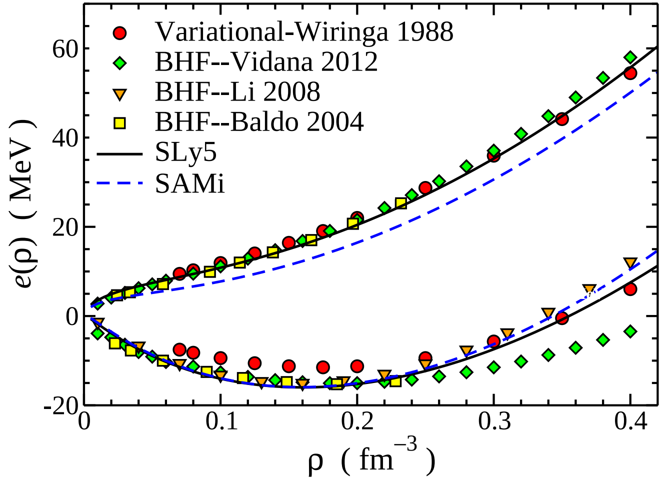


Figure: Neutron and symmetric matter EoS as predicted by the HF SAMi (dashed line) and SLy5 (solid line) interactions and by the benchmark microscopic calculations of R. B. Wiringa *et al.*, PRC **38**, 1010 (1988) (circles). State-of-the-art BHF calculations are shown by diamonds I. Vidaña, private communication, triangles Z. H. Li *et al.*, Phys. Rev. C **77**, 034316 (2008) and squares M. Baldo *et al.*, Nucl. Phys. A **736**, 241 (2004).

Results

Finite Nulcei: spherical double-magic nuclei

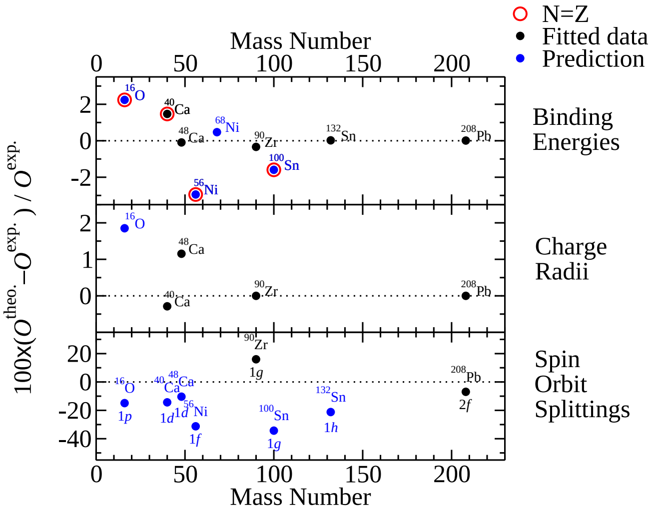


Figure: Finite nuclei properties as predicted by the HF SAMi (black circles) and some predictions (blue circles) for spherical double-magic nuclei. Experimental data taken from Refs. G. Audi *et al.*, NPA **729**, 337 (2003), I. Angeli, ADNDT **87**, 185 (2004), M. Zalewski *et al.*, PRC **77**, 024316 (2008)

Results

Giant Monopole and Dipole Resonances in ^{208}Pb

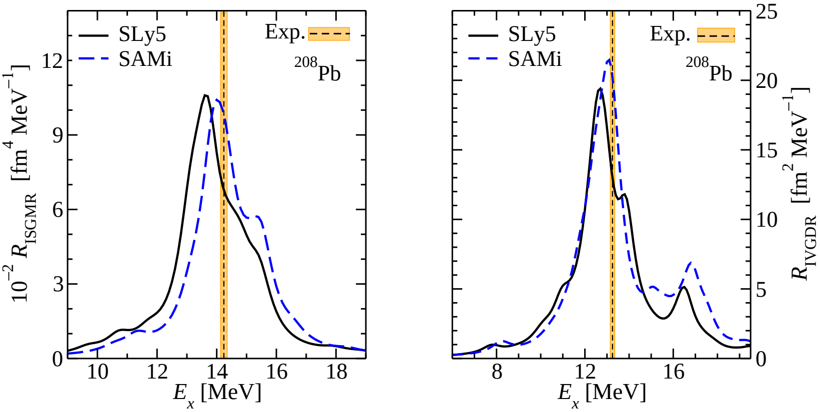


Figure: Strength function at the relevant excitation energies in ^{208}Pb as predicted by SLy5 and the SAMi interaction for GMR and GDR. A Lorentzian smearing parameter equal to 1 MeV is used. Experimental data for the centroid energies are also shown: $E_c(GMR) = 14.24 \pm 0.11$ MeV [D. H. Youngblood, et al., Phys. Rev. Lett. **82**, 691 (1999)] and $E_c(GDR) = 13.25 \pm 0.10$ MeV [N. Ryezayeva et al., Phys. Rev. Lett. **89**, 272502 (2002)].

Results

Gamow Teller Resonance in ^{48}Ca, ^{90}Zr and ^{208}Pb

Operator:

$$\sum_{i=1}^{A} \sigma(i)\tau_{\pm}(i)$$

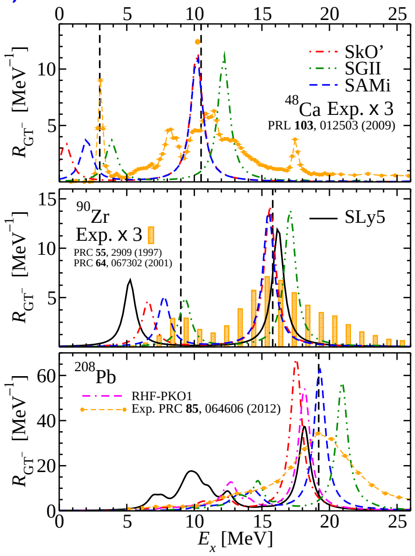


Figure: Gamow Teller strength distributions in ^{48}Ca (upper panel), ^{90}Zr (middle panel) and ^{208}Pb (lower panel) as measured in the experiment [T. Wakasa *et al.*, Phys. Rev. C **55**, 2909 (1997), K. Yako *et al.*, Phys. Rev. Lett. **103**, 012503 (2009), A. Krasznaborkay *et al.*, Phys. Rev. C **64**, 067302 (2001), H. Akimune *et al.*, Phys. Rev. C **52**, 604 (1995) and T. Wakasa et al., Phys. Rev. C **85**, 064606 (2012)] and predicted by SLy5, SkO', SGII and SAMi forces.

Results

Spin Dipole Resonance: $\sum_{M} \tau_{\pm} r^{L} [Y_L(\hat{r}) \otimes \sigma]_{JM}$

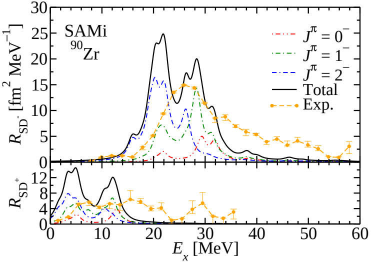


Figure: Spin Dipole strength distributions in ^{90}Zr as a function of the excitation energy E_x in the τ_- channel (upper panel) and τ_+ channel (lower panel) measured in the experiment [K. Yako *et al.*, Phys. Rev. C **74**, 051303(R) (2006)] and predicted by SAMi. Multipole decomposition is also shown. A Lorentzian smearing parameter equal to 2 MeV is used.

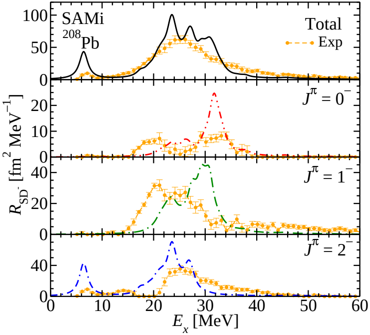


Figure: SDR strength distributions for ^{208}Pb in the τ_- channel from experiment [T. Wakasa *et al.*, Phys. Rev. C **85**, 064606 (2012)] and SAMi calculations. Total and multipole decomposition of the SDR strength are shown: total (upper panel), $J^\pi = 0^-$ (middle-upper panel), $J^\pi = 1^-$ (middle-lower panel) and $J^\pi = 2^-$ (lower panel). A Lorentzian smearing parameter equal to 2 MeV is used.

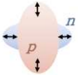
SAMi family of systematically varied interactions

SAMi family of systematically varied interactions

After an optimal model is found. The **systematic variation** of a quantity, fixing it to a non-optimal value (but close) and re-fitting the model for preserving its accuracy, is a **technique to isolate** (or better understand) the **correlations** predicted by the choosen **model**.

- We have produced three **SAMi** families using the fitting protocol previously described ...
- **SAMi-J**: we fix the values of the K, $m*$ to the SAMi values, change J in steps of 1 MeV around the optimal SAMi value refitting at each step.
- **SAMi-m**: we fix the values of the K, J and L to the SAMi values, change $m*$ in steps of $0.05m$ around the optimal SAMi value refitting at each step.
- **SAMi-K**: we fix the values of the $m*$, J and L to the SAMi values, change K in steps of 5 MeV around the optimal SAMi value refitting at each step.

Results: IVGQR



Within the Quantum Harmonic Oscillator approach

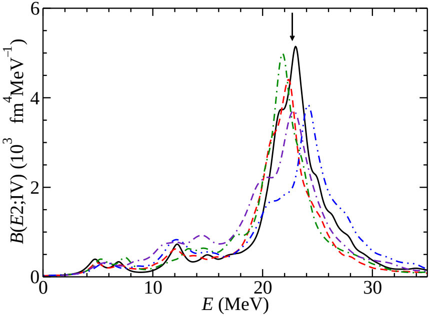
$$E_x^{IV} = 2\hbar\omega_0 \sqrt{1 + \frac{5}{4}\frac{\hbar^2}{2m}\frac{V_{sym}\langle r^2\rangle}{(\hbar\omega_0)^2\langle r^4\rangle}}$$

and EDF calculations, one can deduce

$$V_{sym} \approx 8(S(\rho_A) - S^{kin}(\rho_0))$$

$$S^{kin}(\rho_0) \approx \varepsilon_{F_0}/3$$

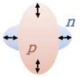
and the expression one finds depend on well known quantities from the theory and observable GQR energies.

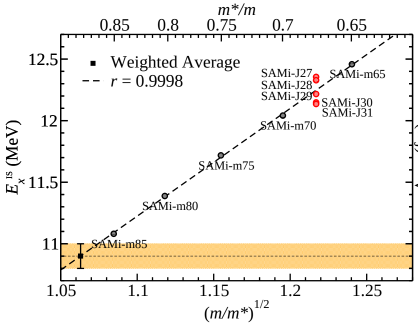


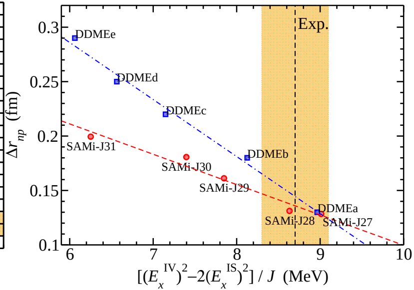
$$S(\rho_A) = \frac{\varepsilon_{F_0}}{3}\left\{\frac{A^{2/3}}{8\varepsilon_{F_0}^2}\left[\left(E_x^{IV}\right)^2 - 2\left(E_x^{IS}\right)^2\right] + 1\right\}$$

$$S(\rho = 0.1\ \mathbf{fm}^{-3}\ \mathbf{for}\ ^{208}\mathbf{Pb}) = 23.3 \pm 0.6\ \mathbf{MeV}$$

Results: IGQR



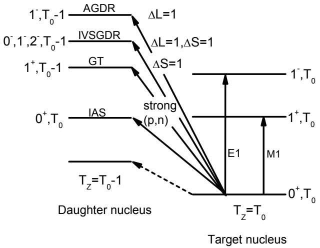


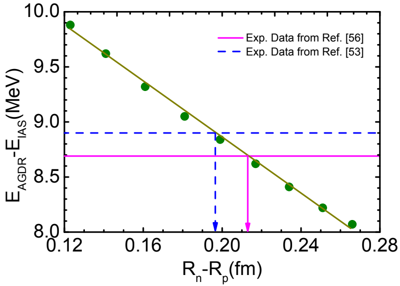


$$\frac{\Delta r_{np} - \Delta r_{np}^{surf}}{\langle r^2 \rangle^{1/2}} = \frac{2}{3}(I - I_C)\left\{1 - \frac{\varepsilon_{F_\infty}}{3J} - \frac{3}{7}\frac{I_C}{I - I_C} - \frac{A^{2/3}}{24\varepsilon_{F_\infty}}\left[\frac{\left(E_x^{IV}\right)^2 - 2\left(E_x^{IS}\right)^2}{J}\right]\right\}$$

$$\Delta r_{np} \approx 0.14 \pm 0.03 \ \mathbf{fm}$$

Results: AGDR





AGDR ($\Delta J^{\pi} = 1^{-}$ with $\Delta L = 1$ and $\Delta S = 0$) is the $T_0 - 1$ component of the charge-exchange of the GDR.

$$E_{AGDR} - E_{IAS} \approx 5\sqrt{\frac{5}{3}}\,\frac{J}{I}\,\frac{1+\gamma}{\alpha_H Z}\,\frac{\hbar c}{m\langle r^2\rangle^{1/2}}\left[\left(1-\frac{\varepsilon_{F\infty}}{3J}\right)I - \frac{3}{2}\left(\frac{\Delta R_{np} - \Delta R_{np}^{surf}}{\langle r^2\rangle^{1/2}}\right) - \frac{3}{7}I_C\right]$$

$$E_{AGDR} - E_{IAS} \approx \frac{\varepsilon}{\Delta E_C}\left(E_{IVGDR} - \varepsilon\right)\frac{m_0^{AGDR}}{m_0^{IVGDR}}$$

$$\Delta r_{np} \approx 0.21 \pm 0.01\ \textbf{fm}$$

CONCLUSIONS

Conclusions: EoS around saturation

- The **isovector channel** of the nuclear effective interaction is **not well constrained by current fits of modern EDFs.**
- Many **observables available in current laboratories** are sensitive to the symmetry energy. **Problems**: **accuracy and model dependent analysis**. **Systsematic experiments** may help.
- **Exotic nuclei more sensitive** to the isovector properties (due to larger neutron excess). **Problems**: more **difficult to measure, accuracy and model dependent analysis**. **Systematic experiments** may help.

Conclusions: SAMi

- we have **successfully determined a new Skyrme** energy density functional which **accounts** for the most relevant quantities in order to improve the description of **charge-exchange nuclear resonances**:
  - the **hierarchy** and **positive values** of the spin and spin-isospin Landau-Migdal parameters G_0 **and** G_0'
  - the **proton spin-orbit splittings** of different **high angular momenta** single-particle levels
- the **GTR** in ^{48}Ca and the **GTR**, **IAR**, and **SDR** in ^{90}**Zr** and ^{208}**Pb** are predicted with **good accuracy by SAMi**
- **SAMi** does **not deteriorate** the description of other **nuclear observables**
- **applicability in nuclear physics and astrophysics**
- **Varied interactions** may help in understanding **underlying correlations**. **Problem:** the fitting protocol may influence conclusions. **Macroscopic models** may **guide** and **systematics** on teoretical microscopic calculations **help**.

Co-workers:

G. Colò, P. F. Bortignon and M. Brenna (U. Milan, Italy)

M. Centelles and X. Viñas (U. Barcelona, Spain)

N. Paar and D. Vretenar (U. Zagreb, Croatia)

B. K. Agrawal (SINP, Kolkata, India)

W. Nazarewicz (U. Tennessee & ORNL, USA)

J. Piekarewicz (Florida State University, USA)

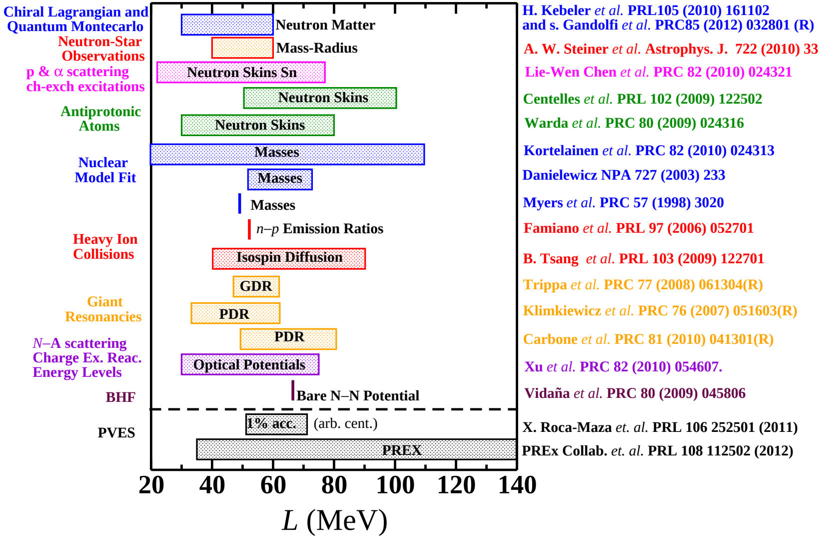
P.-G. Reinhard (Universität Erlangen-Nürnberg, Germany)

L. Cao (Electric Power U., ITP-CAS and NLHIA, China)

H. Sagawa (Aizu U. and RIKEN, Japan)

Thank you for your attention!

Available constraints on L



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Motivation:

Gamow Teller Resonance II: quenching of the strength

- **Experimentally**, the **GTR** exhausts **60–70%** of the **Ikeda sum rule**: $\int [R_{GT^-}(E) - R_{GT^+}(E)] dE = 3(N - Z)$
- To **explain** the problem, two possibilities that go beyond RPA correlations have been drawn:
  - the effects of the second-order configuration mixing: **2p-2h correlations**
  - within the quark model, a **n(p)** can become a **p(n)** or a $\Delta^+(\Delta^{++})$ under the action of the GT^- operator and since there is **no Pauli blocking for Δ−h excitations** ⇒ it may **contribute to the GTR**.
- The **experimental analysis of ^{90}Zr** ⇒ **quenching** (2/3) has to be **mainly attributed to 2p-2h** coupling and not to Δ−isobar effects much smaller [T. Wakasa *et. al.*, Phys. Rev. C **55**, 2909 (1997)].
- E_x **GTR in nuclei** mainly in the region of several **tens of MeV** and the Δ−h states are hundreds of MeV above the GT ⇒ **hard to excite the Δ** in the nuclear medium.