Linear response theory for D-wave terms

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AGENCE NATIONALE DE LA RECHERCHE ANR

Outline

Skyrme functionals

We can write the total energy of the system for a general Skyrme functional

$$\mathcal{E} = \mathcal{E}_{kin} + \mathcal{E}_{Skyrme} + \mathcal{E}_{pairing} + \mathcal{E}_{Coulomb} + \mathcal{E}_{corr.}$$

Skyrme functional

$$\begin{aligned}\mathcal{E}_{Skyrme} \quad = \quad & \sum_{t=0,1} \int d^3\mathbf{r} \left\{ C_t^{\rho}\left[\rho_0\right]\rho_t^2 + C_t^{\Delta\rho}\rho_t\Delta\rho_t + C_t^{\tau}\rho_t\tau_t + C_t^{j}\mathbf{j}_t^2 + C_t^{s}\left[\rho_0\right]s_t^2 \right. \\ & + C_t^{\nabla s}(\nabla\cdot s_t)^2 + C_t^{\Delta s}s_t\cdot\Delta s_t + C_t^{T}s_t\cdot\mathbf{T}_t + C_t^{F}s_t\cdot\mathbf{F}_t + C_t^{\nabla J}\rho_t\nabla\cdot\mathbf{J}_t \\ & \left. + C_t^{\nabla j}s_t\cdot(\nabla\times\mathbf{j}_t) + C_t^{J^{(0)}}(J_t^{(0)})^2 + C_t^{J^{(1)}}(\mathbf{J}_t^{(1)})^2 + C_t^{J^{(2)}}\sum_{\mu\nu=x}^{z} J_{t\mu\nu}^{(2)}J_{t\mu\nu}^{(2)} \right\}\end{aligned}$$

[E . Perlinska et al. Phys. Rev C 69, 014316 (2004))]

The coupling constants are fitted on data.

How to determine the coupling constants?

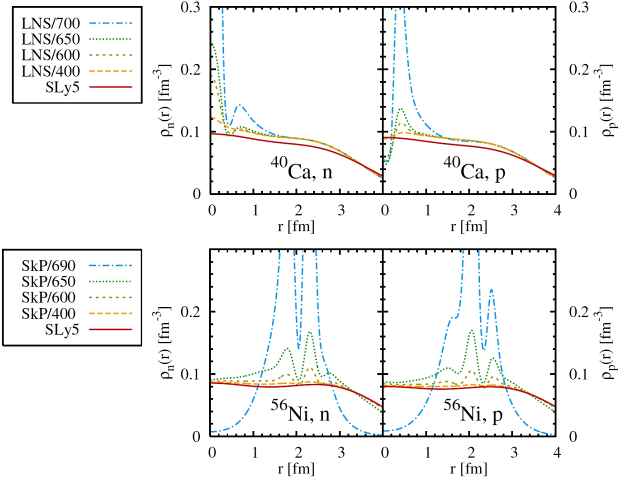
We impose a fitting protocol (observables and pseudo-observables)

- IM properties ($i.e.\ E/A, K_\infty, m^*, ...$)
- Ground state of some nuclei ($i.e.$ ^{40}Ca, ^{48}Ca,^{208}Pb, ...)
- Charge radii
- Spin orbit splitting
- ...

[M . Kortelainen et al. Phys. Rev C 85 (2012)024304]

An example

Good description of masses $\sigma_{rms} = 0.582$ MeV. [S . Goriely et al. Phys. Rev Lett. 112 (2009), 152503]



[T. Lesinski et al. Phys. Rev. C 76, 014312 (2007)]

Outline

RPA formalism

The RPA correlated Green function is the solution of Bethe-Salpeter equation

$$
\begin{aligned}
G^{(\mathsf{S,M,I})}_{RPA}(q,\omega,\mathbf{k}_1) &= G_{HF}(q,\omega,\mathbf{k}_1) \\
&+ G_{HF}(q,\omega,\mathbf{k}_1)\sum_{\mathsf{S',M',I'}}\int\frac{d^3k_2}{(2\pi)^3}V_{ph}^{\mathsf{S,M,I;S',M',I'}}(q,\mathbf{k}_1,\mathbf{k}_2)G^{\mathsf{S',M',I'}}_{RPA}(q,\omega,\mathbf{k}_2)
\end{aligned}
$$

The response function is now defined as

$$
\chi^{\alpha}_{RPA}(q,\omega) = g\int\frac{d^3k_1}{(2\pi)^3}G^{\alpha}_{RPA}(q,\omega,\mathbf{k}_1)
$$

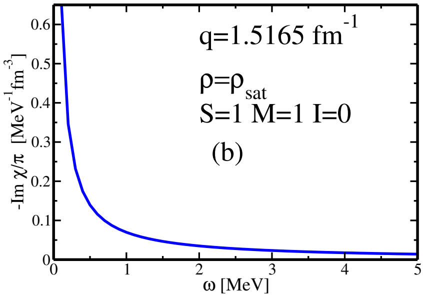
$g=4$ is the degeneracy of SNM.

Instabilities in SNM I

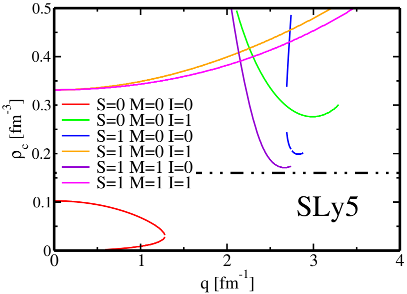
Poles

We look for the poles of the response function at zero energy.

$$1/\chi^{SMI}(\omega = 0, q) = 0$$



Instabilities in SNM II



Features

- Instabilities appear in different (S,I) channels
- Instabilities can appear for finite values of the transfer momentum q
- $\approx$ 1 second CPU time
- Analytic formulas simple to code

Outline

Relations with finite nuclei

Can we relate a pole in SNM with an instability in a finite nucleus?

Protocol

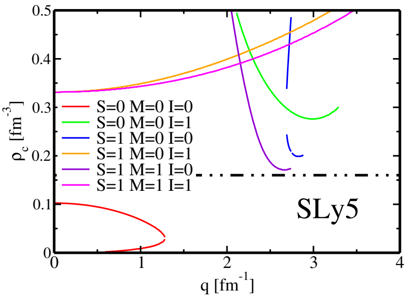
- Extensive calculations using different HF codes
  1. Lenteur (spherical r-space code)
  2. HOSPHE (spherical HO code)
  3. cr8 (3D cartesian code)
- Calculation of instabilities in IM

Result

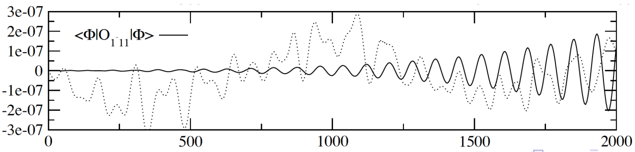
A pole in SNM at $\rho_{pole} < 1.4\rho_{sat} \rightarrow$ nucleus unstable!

Good News! ...

According to our prescription SLy5 is unstable in the spin channel ($\rho_{crit}^{110} = 1.07\rho_0$)



SLy5 unstable in TDHFB calculations! S. Fracasso, E. B. Suckling, and P. D. Stevenson, arXiv:1206.0056



... Bad news

We analyze 236 standard Skyrme functionals

Channel	Number of EDF ($\rho_{crit} < 1.4\rho_{sat}$)
S=0,I=1	15
S=1 I=0	191
S=1 I=1	28

A catastrophe!

86% of analyzed EDF have at least one pole in SNM at $\rho_{crit} < 1.4\rho_{sat}$

And now?

It is mandatory to abandon such functionals!

Outline

D wave

Example: we introduce a new term on top of a standard Skyrme functional

$$v^D(\mathbf{R},\mathbf{r}) = t_D(1 + x_D\hat{P}_\sigma)\left[\mathbf{k}'^2\delta(\mathbf{r})\mathbf{k}^2 - (\mathbf{k}'\delta(\mathbf{r})\mathbf{k})^2\right]$$

[K.Bennaceur et al., *in preparation*]

Not so easy to fit!!!

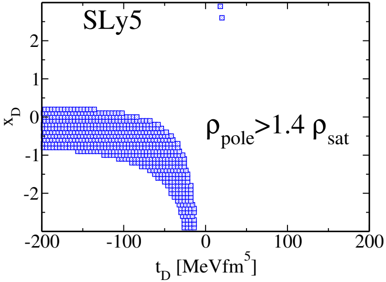
- Highly unstable and difficult to fit
- Naturalness analysis: 4th order c.c. smaller then 2 order

  [M. Kortelainen et al., Phys.Rev C **82**, 011403, (2010)]
- Density Matrix Expansion can be a starting point
- New couplings among spin channels ($i.e.$ spin-orbit, tensor, ...)

New fitting protocol

1 step

- Starting point SLy5 functional (perturbative).
- Identification of a stable region of parameters x_D, t_D

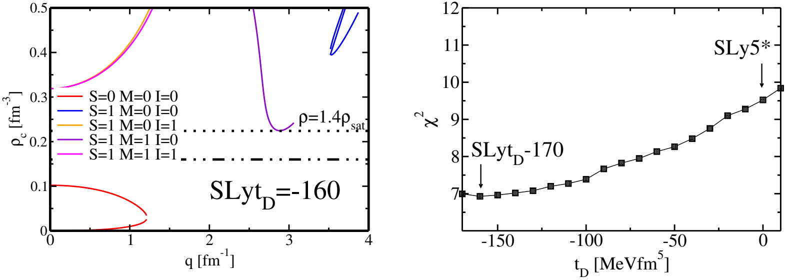


2 step

- Starting point: perturbative approach
- We re-fit all coupling constant
- LR criterium checked at every iteration

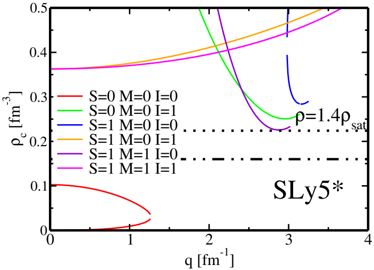
Preliminary results

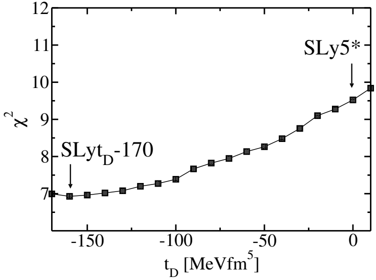
Exploratory analysis: we impose $x_D = 0$ and vary t_D.



The effect of the D-wave is small.

An interesting results: a stable version of SLy5!

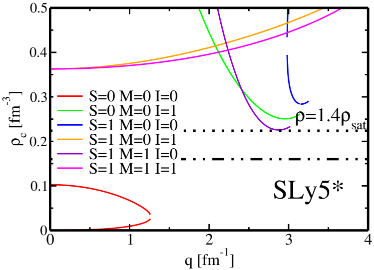


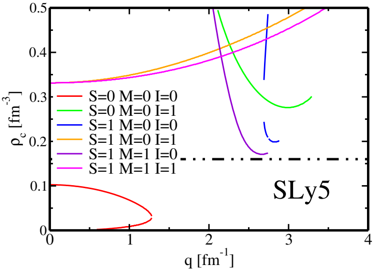


A *modern* Skyrme functional free from pathologies.

Preliminary results

An interesting results: a stable version of SLy5!





A *modern* Skyrme functional free from pathologies.

Conclusions

Some open questions:

- Why so many functionals close to instability?
- Is it the limit of the zero range force?
- It is possible to use LR to cure instabilities (no time consuming!)
- We can now explore a new generation of functionals

Status of LR calculations

- 3-body terms have been added [J. Sadoudi et al. , private communication]
- Pure Neutron Matter (Neutrino mean free path) [A. Pastore et al. , arXiv:1207.4006 (2012)]
- LR code now included in Saclay-Lyon fitting protocol
- Extension to asymmetric matter at finite temperature

Thank you!!!

I thank for collaboration and/or discussions

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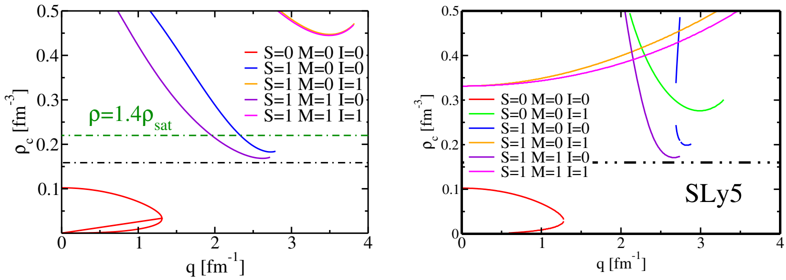
- M. Bender, J. Sadoudi, B. Avez, B. Bally (Bordeaux)

SLy5* vs SLy5

	SLy5*	Sly5
t_0	-2495.31	-2484.880
t_1	484.02	483.130
t_2	-469.48	-549.400
t_3	13867.43	13763.000
x_0	0.620	0.778
x_1	-0.086	-0.328
x_2	-0.9469	-1.000
x_3	0.9343	1.267
α	1/6	1/6
W	120.25	126
J^2	yes	yes



0.5
0.4
0.3
0.2
0.1
ρc [fm-3]
ρ=1.4ρsat
S=0 M=0 I=0
S=1 M=0 I=0
S=1 M=0 I=1
S=1 M=1 I=0
S=1 M=1 I=1
0
1
2
3
4
q [fm-1]
S=0 M=0 I=0
S=0 M=0 I=1
S=1 M=0 I=0
S=1 M=0 I=1
S=1 M=1 I=0
S=1 M=1 I=1
SLy5