Pairing and symmetry energy effects in low density nuclear matter: nuclear structure and neutron stars

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³ Department of Physics, Bucharest - Magurele

Superfluidity in neutron stars and giant resonances in nuclei Dynamics in many-body systems: the BNV model

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Collective patterns and effective interaction terms

• Collective phenomena and correlations in nuclear many-body systems

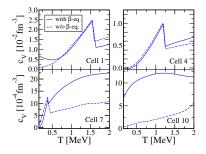
- Superfluidity in neutron stars: pairing effect on heat capacity (cooling)
 Collaboration with theoretical group of LPC of Caen, France
- Dipole excitations in nuclei: Giant/Pygmy Dipole Resonances (GDR/PDR) Collaboration with theoretical group of IPN of Orsay, France
- Isovector term of effective interaction: symmetry energy in EoS

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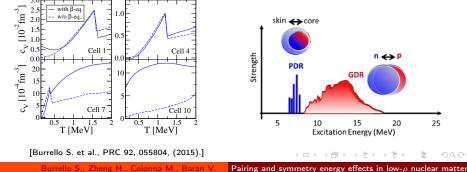
[Burrello S. et al., PRC 92, 055804, (2015).]

Collective phenomena in nuclear physics

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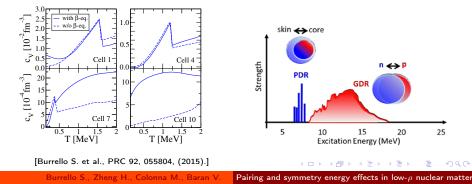


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Dynamics in many-body systems: the BNV model

• Small amplitude dynamics of nuclei

- Quantal approaches: HF+RPA, TDHF, ...
- Semi-classical approaches: BNV model [see V. Baran et al., PRC88, (2013)]
- **Transport equation** for the 1-body distributions f_q (r, p, t) \Rightarrow Vlasov equations:

$$\frac{\partial f_q}{\partial t} + \frac{\partial \epsilon_q}{\partial \mathbf{p}} \frac{\partial f_q}{\partial \mathbf{r}} - \frac{\partial \epsilon_q}{\partial \mathbf{r}} \frac{\partial f_q}{\partial \mathbf{p}} = 0 \qquad \text{added} \qquad \frac{\partial \sigma}{\partial \mathbf{r}} \frac{\partial \sigma}{\partial \mathbf{p}} = 0 \qquad \text{added} \qquad \frac{\partial \sigma}{\partial \mathbf{r}} \frac{\partial \sigma}{\partial \mathbf{p}} = 0$$

Mean-field with Skyrme interactions: SAMi-J [X. Roca-Maza et al., PRC87, (2013)]

$$\mathcal{E} = \frac{\hbar^2}{2m}\tau + C_0\rho^2 + D_0\rho_3^2 + C_3\rho^{\sigma+2} + D_3\rho^{\sigma}\rho_3^2 + C_{eff}\rho\tau + D_{eff}\rho_3\tau_3 + C_{\nabla}(\nabla\rho)^2 + D_{\nabla}(\nabla\rho_3)^2$$

 $\tau = \tau_n + \tau_p \qquad \tau_3 = \tau_n - \tau_p$ • Test-particle method (finite width wave packets

⇒ no **explicitly** surface terms ($C_{\nabla} = D_{\nabla} = 0$) to reproduce **experimental** values ($\sqrt{\langle r_p^2 \rangle}$, B/A)

Semi-classical model ⇒ no shell effects

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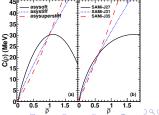
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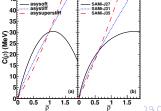
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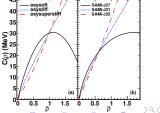
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Coupling of IS-IV modes and influence of interaction terms Comparison with TDHF and future perspectives

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Dipole oscillations and response functions

Instantaneous ground-state perturbation:

$$\hat{V}_{K}^{ext}(\mathbf{r},t) = \eta_{K}\delta(t-t_{0})\hat{D}_{K}(\mathbf{r}) \qquad K = S, V$$

 $\Rightarrow |\Phi_{0}\rangle \rightarrow |\Phi_{K}(t_{0})\rangle = e^{i\eta_{K}\hat{D}_{K}} |\Phi_{0}\rangle$

Isoscalar (IS) or isovector (IV) dipole operator:

$$\hat{D}_{S} = \sum_{i} \left(r_{i}^{2} - \frac{5}{3} < r^{2} > \right) z_{i}, \qquad \hat{D}_{V} = \sum_{i} \tau_{i} \frac{N}{A} z_{i} - (1 - \tau_{i}) \frac{Z}{A} z_{i}, \quad \tau_{i} = 0 (1) \quad \text{for n (p)}$$

• Dynamical evolution of the excitation: $D_{\mathcal{K}}(t) = \langle \Phi_{\mathcal{K}}(t) | \hat{D}_{\mathcal{K}} | \Phi_{\mathcal{K}}(t) \rangle$ • Strength function: $S_{\mathcal{K}}(E) = \sum_{n} |\langle n | \hat{D}_{\mathcal{K}} | 0 \rangle |^2 \, \delta \left(E - (E_n - E_0) \right)$

$$S_{\mathcal{K}}(\omega) = rac{\operatorname{Im} D_k(\omega)}{\pi \eta_k}$$
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Results (1) : coupling between IS and IV modes

• Symmetric nuclear matter: IS and IV modes are decoupled

• Neutron-rich systems: n and p oscillate with different amplitudes \Rightarrow coupling

Coupling of IS-IV modes and influence of interaction terms Comparison with TDHF and future perspectives

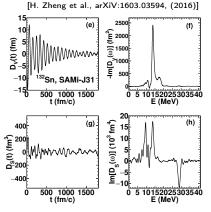
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- Neutron-rich systems: n and p oscillate with different amplitudes ⇒ coupling

Coupling of IS-IV modes and influence of interaction terms Comparison with TDHF and future perspectives

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IV perturbation \rightarrow IV + IS response

• IV response:

- main IV GDR peak
- smaller IV peak at higher E
- some strength at lower E (PDR)

IS response:

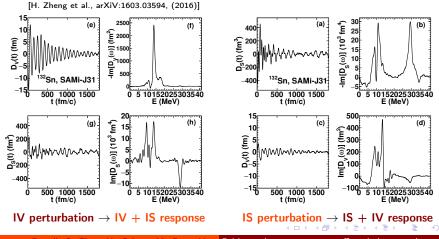
• larger PDR strength \Rightarrow isoscalar-like

peak at higher E (IS GDR)

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Coupling of IS-IV modes and influence of interaction terms Comparison with TDHF and future perspectives

Results (2): influence of IV term of the interaction

• Three regions of A: 68 Ni (N/Z = 1.43), 132 Sn (N/Z = 1.64), 208 Pb (N/Z = 1.54)

[H. Zheng et al., arXiV:1603.03594, (2016)] 25r ¹³²Sn (a) ----- SAMi-J31 20 SAMi-J35 $S_{s}(E)$ (10³ fm⁶/MeV) 15 10 ዔ 10 15 20 25 30 35 40 45 5 E (MeV)

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- Two peaks in PDR region [see M. Urban, PRC85, (2012)]
- Semi-classical treatment for surface
 - \Rightarrow discrepancy with RPA

[X. Roca-Maza et al., PRC85, (2012)] 12 5300 sGII 5813 sK13 7500 sK137500 sK13

- Larger L ⇒ higher IV PDR peak (mixing)
- Larger $L \Rightarrow$ larger neutron-skin

Burrello S., Zheng H., Colonna M., Baran V.

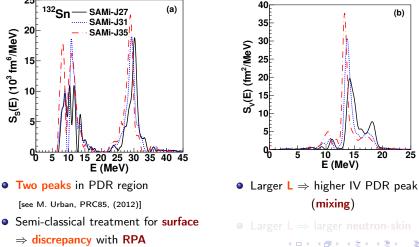
・ロト・オヨト・オヨト・ヨー シーマー Pairing and symmetry energy effects in low-p nuclear matter Dipole oscillations and response functions

Coupling of IS-IV modes and influence of interaction terms Comparison with TDHF and future perspectives

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Burrello S., Zheng H., Colonna M., Baran V.

Pairing and symmetry energy effects in low- ρ nuclear matter

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0.09 ¹³²Sn 0.08 neutrons 0.07 protons 0.06 ິຍັ<mark>0.05</mark> ຍັງ 0.03 0.02 ΔMi-.127 SAMi-J31 0.01 SAMi-.135 2 6 8 10 r (fm)

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Results (3): transition densities analysis

• Transition densities: information on spatial structure of excitation dynamics

$$\delta
ho_q(r, E) \propto \int_{t_0}^{\infty} dt \, \delta
ho_q(r, t) \sin \frac{Et}{\hbar} \qquad E \equiv {
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m with a peak in the strength}$$

- Oscillations: in phase ⇒ isoscalar-like vs. out of phase ⇒ isovector-like
- Simultaneous agitation of all modes ⇒ interference

Coupling of IS-IV modes and influence of interaction terms Comparison with TDHF and future perspectives

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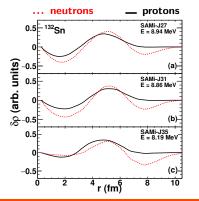
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PDR peak in IS response

- Larger oscillation for neutrons
- Amplitude in the surface increases while increasing L
 - Thicker neutron-skin
 - More symmetric central region

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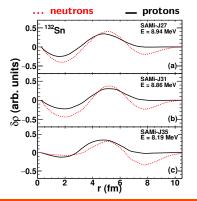
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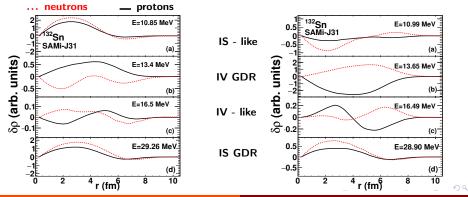
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Coupling of IS-IV modes and influence of interaction terms Comparison with TDHF and future perspectives

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Further developments: comparison with TDHF

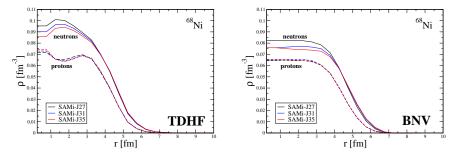
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- Difference in the initial density profile: sharper in TDHF case
- Overestimation of PDR energy and merging of IS-L peak with GDR
- TDHF + BCS: negligible pairing effects for ⁶⁸Ni (closed-shell) \Rightarrow CHECK!

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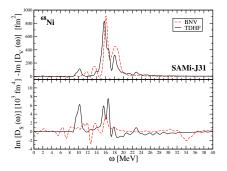
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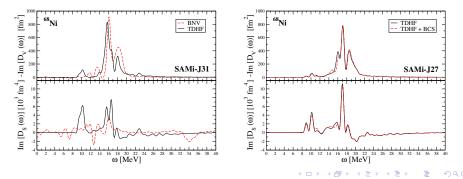
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Coupling of IS-IV modes and influence of interaction terms Comparison with TDHF and future perspectives

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Final remarks and conclusions

Summary

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- Examination of **both IS and IV** nuclear E1 response in neutron-rich systems

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Final remarks and conclusions

Summary

- Small amplitude dynamics in nuclei: semi-classical BNV transport model
- Examination of both IS and IV nuclear E1 response in neutron-rich systems

Main results

- Isoscalar/isovector mixing of dipole excitations
- Characterization of the nature of low-lying energy IV response (PDR)
- Essential role of L in shaping neutron-skin and E1 response in PDR region
- General good agreement with previous semi-classical and RPA studies

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Further developments and outlooks

- Tuning of finite size terms to improve the treatment of surface effects
- Comparison with TDHF calculations (coll. with D. Lacroix group, Orsay)
- Study some isotopes chains to understand isovector and pairing terms role

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French collaborations of our group

Nuclear structure (TDHF)

- D. Lacroix (IPN, IN2P3-CNRS, Orsay, France),
- G. Scamps (Department of Physics, Tohoku University, Japan)

Neutron stars modelization

- F. Gulminelli, F. Aymard (LPC, CNRS and ENSICAEN, Caen, France)
- A. Raduta (NIPNE, Bucharest-Magurele, Romania)

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M. Di Prima (LNS - INFN, Catania, Italy)

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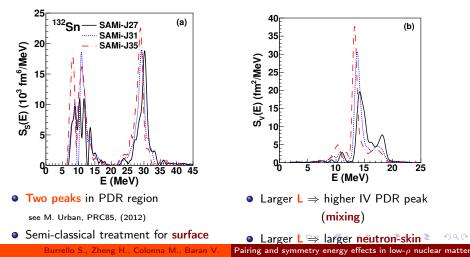
THANK YOU FOR YOUR KIND ATTENTION!

Burrello S., Zheng H., Colonna M., Baran V. Pairing and symmetry energy effects in low- ρ nuclear matter

Coupling of IS-IV modes and influence of interaction terms Comparison with TDHF and future perspectives

Further insight: influence of IV term of the interaction

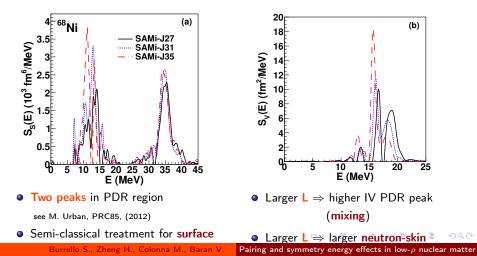
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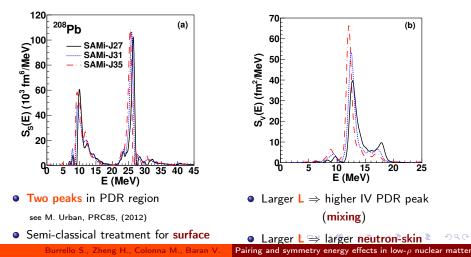
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Further insight: influence of momentum dependence

