Pairing in Covariant Density Functional Theory

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Relativistic pairing in nuclear matter

Applications of RHB-theory in finite nuclei

Applications of rel. QRPA-theory in finite nuclei

Rel. methods beyond mean field

General remarks about nuclear pairing

1) There is plenty of experimental evidence
2) In principle pairing is a small effect ($\Delta \ll M$)
3) Most important close to the Fermi surface
4) Smearing of the Fermi surface ($v^2$)
5) Gap in the spectrum $E_k = \sqrt{(\varepsilon_k - \lambda)^2 + \Delta^2}$
6) Influence on response functions (e.g. moments of inertia)
7) Phase transition normal fluid $\rightarrow$ superfluid (with $\lambda, \omega, T$)
8) Few exp. data on details of pairing (one parameter $\Delta$)
9) Crucial quantity: pairtransfer matrix elements

$$J^{(2)} = \sum_v \frac{|\langle v | J_x | 0 \rangle|^2}{E_v - E_0} \approx \sum_{k<k'} \frac{|\langle k | J_x | k' \rangle|^2 (u_k v_{k'} - v_k u_{k'})}{E_k + E_{k'}}$$
Relativistic Pairing:

One has to quantize the meson fields:

Fermion fields: \[ \int d^3 r \, \hat{\psi}(\alpha \, p - \beta m) \hat{\psi} \]

Meson fields: \[ \sum_{\mu} \omega_{\mu} a_{\mu}^{+} a_{\mu} \]

Interaction: \[ - \sum_{\mu} \hat{\psi} \Gamma_{\mu}^{\mu} \hat{\psi} \phi_{\mu} \]

Eliminate the meson operators: \[ \phi_{\mu}(r) = \frac{g_{\mu}}{4\pi} \int d^3 r^{' \prime} \frac{e^{-m_{\mu}|r - r^{' \prime}|}}{|r - r^{' \prime}|} \hat{\psi}(r^{' \prime})\Gamma_{\mu}^{\mu} \hat{\psi}(r^{' \prime}) \]

Formulation in Green's functions:

Gorkov factorization

\[ \langle \psi_{1}^{+} \psi_{2}^{+} \psi_{3} \psi_{4} \rangle \approx \langle \psi_{1}^{+} \psi_{4} \rangle \langle \psi_{2}^{+} \psi_{3} \rangle - \langle \psi_{1}^{+} \psi_{3} \rangle \langle \psi_{2}^{+} \psi_{4} \rangle + \langle \psi_{1}^{+} \psi_{2}^{+} \rangle \langle \psi_{3} \psi_{4} \rangle \]

<table>
<thead>
<tr>
<th>direct term</th>
<th>exchange term</th>
<th>pairing term</th>
</tr>
</thead>
</table>

17.11.2005  
Pairing degree of freedom in nuclei and the nuclear medium, INT, Nov.2005
Relativistic Hartree Bogoliubov (RHB)

Unified description of mean-field and pairing correlations

\[
\begin{pmatrix}
\hat{h}_D - m - \lambda & \hat{\Delta} \\
-\hat{\Delta}^* & -\hat{h}_D + m + \lambda
\end{pmatrix}
\begin{pmatrix}
U_k(r) \\
V_k(r)
\end{pmatrix}
= E_k
\begin{pmatrix}
U_k(r) \\
V_k(r)
\end{pmatrix}
\]

Dirac hamiltonian
chemical potential
pairing field
quasiparticle energy
quasiparticle wave function

\[ h_D(\vec{r}') = \bar{\alpha}(\vec{p} - \vec{V}(\vec{r}')) + \beta(m - S(\vec{r}')) + V(\vec{r}') \]

\[ \Delta_{ab}(\vec{r}, \vec{r}') = \frac{1}{2} \sum_{c,d} V_{abcd}^{pp}(\vec{r}, \vec{r}') \kappa_{cd}(\vec{r}, \vec{r}') = \begin{pmatrix}
\Delta_{++} & 0 \\
0 & 0
\end{pmatrix} \]


Gogny D1S
Pairing in nuclear matter

RMF+BCS

Gap equation:

\[ \Delta(p) = -\frac{1}{4\pi^2} \int_0^\infty \nu_{pp}(p,k) \frac{\Delta(k)}{\sqrt{(\varepsilon(k) - \lambda)^2 + \Delta^2(k)}} k^2 dk \]

\[ \nu_{pp}(p,k) = \frac{g_\omega^2}{2E^*(p)E^*(k)} \frac{m^* + p^2 + k^2 - (E^*(p) - E^*(k))^2}{pk} \ln\left(\frac{(p + k)^2 + m_\omega^2}{(p - k)^2 + m_\omega^2}\right) \]

e.g.:
Pairing matrix elements:

\[ v_{pp}(k,p=0.8) \]

\[ k [fm^{-1}] \]

\[ \sigma = 520 \text{ MeV} \]
\[ \sigma = 390 \text{ MeV} \]
All relativistic forces, e.g. NL1, NL2, NL3 ... overestimate nuclear pairing by a factor 3, because they do not have a cut off in momentum space.
Relativistic structure of pairing:

\[
H = \begin{pmatrix}
    m+V-S & \sigma p & \Delta_{++} & \Delta_{+-} \\
    \sigma p & -m-V-S & \Delta_{+-} & \Delta_{--} \\
    \Delta_{++} & \Delta_{+-} & -m-V+S & -\sigma p \\
    \Delta_{+-} & \Delta_{--} & -\sigma p & m+V+S
\end{pmatrix}
\]

\[
\Rightarrow \Delta_{--} \ll \Delta_{++} \ll \sigma p
\]

therefore we neglect \( \Delta_{++} \)
The pairing gap at the Fermi surface

free NN-forces, which reproduce the phase shift in the $^1S_0$ channel give pairing similar to the Gogny force

maximal pairing at the Fermi surface:

<table>
<thead>
<tr>
<th>Potential</th>
<th>$\Delta_F$(MeV)</th>
<th>$k_F$(fm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bonn A</td>
<td>2.80</td>
<td>0.76</td>
</tr>
<tr>
<td>Bonn B</td>
<td>2.84</td>
<td>0.76</td>
</tr>
<tr>
<td>Bonn C</td>
<td>2.83</td>
<td>0.76</td>
</tr>
<tr>
<td>Gogny $D1S$</td>
<td>2.78</td>
<td>0.80</td>
</tr>
</tbody>
</table>
Contributions of the various mesons in the Bonn-potential to pairing:

Occupation Probability $\nu^2$

(in momentum space)

$\nu^2$ vs $k$ (fm$^{-1}$)

- $k = 0.1$ fm$^{-1}$
- $k = 0.8$ fm$^{-1}$
- $k = 1.2$ fm$^{-1}$
Wave functions of the Cooper pair in momentum space:

\[
\chi(k) = \frac{\Delta(k)}{2 \sqrt{[\epsilon(k) - \lambda]^2 + \Delta^2(k)}}.
\]
Wave functions of the Cooper pair in r-space:

\[ \chi(r) = \left\langle \Phi | \psi_\uparrow^\dagger \left( \vec{R} + \frac{1}{2} \vec{r} \right) \psi_\downarrow^\dagger \left( \vec{R} - \frac{1}{2} \vec{r} \right) | \Phi \right\rangle \]

\[ k_F = 0.8 \text{ fm}^{-1} \]
Influence of the repulsive core in Bonn-pot.:
Coherence length:

\[ \xi^2 = \frac{\int d^3 r |\chi(r)|^2 r^2}{\int d^3 r |\chi(r)|^2} \]


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Is the gap caused by the repulsive part of the force?

\[
\Delta(p) = -\frac{1}{4\pi^2} \int_0^\infty \nu_{pp}(p, k) \frac{\Delta(k)}{\sqrt{(\varepsilon(k) - \lambda)^2 + \Delta^2(k)}} k^2 dk
\]
Relativistic Hartree Bogoliubov (RHB)

\[ E[\rho, \kappa] = E_{\text{RMF}}[\rho] + E_{\text{Gogny}}[\kappa] \]

\[ \hat{h} = \frac{\delta E'_{\text{RMF}}}{\delta \hat{\rho}} \]

\[ \hat{\Delta} = \frac{\delta E_{\text{GOG}}}{\delta \hat{\kappa}} \]

<table>
<thead>
<tr>
<th>A</th>
<th>( E/A )</th>
<th>( E_{\text{pair}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>expt.</td>
<td>RHB</td>
</tr>
<tr>
<td>132</td>
<td>-8.355</td>
<td>-8.319</td>
</tr>
</tbody>
</table>


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Density functional:

\[ \hat{\rho} = \langle \Phi | \psi^\dagger \psi | \Phi \rangle \]
\[ \hat{\kappa} = \langle \Phi | \psi^\dagger \psi^\dagger | \Phi \rangle \]
\[ \phi = \sigma, \omega^\mu, \rho^\mu, A^\mu \]

\[ E[\hat{\rho}, \hat{\kappa}, \phi] = E_{RMF}[\hat{\rho}, \phi] + E_{pair}[\hat{\kappa}] \]

\[ E_{RMF}[\rho, \phi] = \int d^3r \left\{ H_D(r) + H_{mes}(r) + H_{int}(r) \right\} \]
\[ E_{pair}[\hat{\kappa}] = \langle \Phi | V^{pp} | \Phi \rangle = \frac{1}{2} \text{Tr}(\hat{\kappa} V^{pp} \hat{\kappa}^*) \]

\[ H_D(r) = J(r) + m_N[\rho_s(r) - \rho(r)] \]
\[ H_{mes}(r) = \frac{1}{2} |\nabla \sigma(r)|^2 + \frac{1}{2} m_\sigma \sigma(r)^2 + \ldots \]
\[ H_{int}(r) = g_\sigma \rho_s(r) \sigma(r) + g_\omega j_B^\mu(r) \omega_\mu(r) + \ldots \]

\[ J(r) = -i \sum_i V^\dagger_i(r) \alpha \nabla V(r) \]
renormalized relativistic RHB for zero range pairing

\[ V^{pp} = g(\rho) \delta(r-r') \]

Bulgac, Yu, PRC 65, 051305 (2002)
Niksic, Ring, Vretenar, PRC 71, 044320 (2005)
renormalized $\delta$-pairing in finite nuclei

for density dependent $g(\rho)$ the effective coupling shows a peak at the surface
Applications of pairing in finite nuclei

- Moments of inertia in rotating nuclei
- Halo phenomena at the neutron drip line
- Quasiparticle-RPA for excited states
  - IVGDR in Sn-isotopes
  - Pygmy modes
- Methods beyond mean field
  - projected density functionals (PDFT)
  - relativistic GCM
  - particle vibrational coupling
  - decay width of Giant resonances

Pairing important: Gogny D1S (no free parameter). With Skyrme-forces one needs surface pairing. Does surface pairing compensate for finite range?
Excitation of the superdeformed minimum:

\[ ^{194}\text{Hg} \]

\[ E_x \approx 6.02 \]

\[ \text{Exp}: \quad E_x = 6.02 \]

\[ \text{NL3}: \quad = 6.0 \]

\[ \text{NL1}: \quad = 5.6 \]

\[ \text{Gogny}: \quad = 6.9 \]

\[ \text{Skyrme}: \quad = 5.0 \]

\[ \text{WS}: \quad = 4.6 \]

G. A. Lalazissis, P. Ring, PLB 427 (1998) 225
normal deformed bands in the rare earth region
Neutron halo’s

Mean field theory of halo’s: (RHB in the continuum)

advantages:
* residual interaction by pairing
* self-consistent description
* universal parameters
* polarization of the core
* treatment of the continuum

problems:
* center of mass motion
* boundary conditions at infinity
Densities in Li-isotopes

J. Meng and P. Ring, PRL 77, 3963 (1996)
J. Meng and P. Ring, PRL 80, 460 (1998)

rel. Hartree-Bogoliubov, parameter set NL2
density dependent $\delta$–pairing
(adjusted to Gogny)
canonical basis in Li-isotopes

* eigenstates of the density matrix
* wavefunction has BCS-type

\[ |\Phi\rangle = \prod_n (u_n + v_n a_n^+ a_n^+) |\rangle \]
\[ \epsilon_n = \langle n | h | n \rangle, \quad \Delta_n = \langle n | \Delta | n \rangle \]

J. Meng and P. Ring, PRL 77, 3963 (1996)
Criteria for halo formation:

- increasing level density
- coupling to the continuum
- low orbital angular momentum

W. Pöschl et al., PRL 79 (1997) 3841
Densities in Ne-isotopes

W. Pöschl et al., PRL 79 (1997) 3841

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Giant halo in the Zr region:

J. Meng and P. Ring, PRL 80, 460 (1998)
Relativistic QRPA for excited states:

Small amplitude limit:

\[ \tilde{\rho}(t) = \tilde{\rho}^{(0)} + \delta \tilde{\rho}(t) \]

ground-state density

RRPA matrices:

\[ A_{mnj} = (\epsilon_n - \epsilon_i) \delta_{mn} \delta_{ij} + \frac{\partial h_{mi}}{\partial \rho_{nj}}, \quad B_{mnj} = \frac{\partial h_{mi}}{\partial \rho_{jn}} \]

the same effective interaction determines
the Dirac-Hartree single-particle spectrum
and the residual interaction

Interaction:

\[ \hat{\nabla}^{ph} = \frac{\delta^2 E}{\delta \tilde{\rho} \delta \tilde{\rho}} \quad \hat{\nabla}^{pp} = \frac{\delta^2 E}{\delta \hat{\kappa} \delta \hat{\kappa}} \]
IV-GDR in Sn-isotopes

\[ E_{th} = 15.59 \text{ MeV} \quad E_{th} = 15.53 \text{ MeV} \quad E_{th} = 15.40 \text{ MeV} \quad E_{th} = 15.28 \text{ MeV} \]
\[ E_{exp} = 15.68 \text{ MeV} \quad E_{exp} = 15.59 \text{ MeV} \quad E_{exp} = 15.36 \text{ MeV} \quad E_{exp} = 15.19 \text{ MeV} \]
Experimental indications of the soft dipole mode

HALF-LIFE
- Unknown
- <0.1 s
- 0.1 - 5 s
- 5 - 100 s
- 100 s - 1 h
- 1 h - 1 y
- 1 y - 1 Gy
- Stable

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Photoneutron Cross Sections for Unstable Neutron-Rich Oxygen Isotopes


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Sektion Physik, Ludwig-Maximilians-Universität, D-85748 Garching, Germany
(Received 19 December 2000)

The dipole response of stable and unstable neutron-rich oxygen nuclei of masses A=17 to A=22 has been investigated experimentally utilizing electromagnetic excitation in heavy-ion collisions at beam energies about 600 MeV/nucleon. A kinematically complete measurement of the neutron decay channel in inelastic scattering of the secondary beam properties from a Pb target was performed. Differential electromagnetic excitation cross sections dσ/dΩ were derived up to 30 MeV excitation energy. In contrast to stable nuclei, the deduced dipole strength distribution appears to be strongly fragmented and systematically exhibits a considerable fraction of low-lying strength.

The study of the response of clear or electromagnetic isoscalar strength in the properties of the nuclear ground state and collective excited states allow a full understanding of the giant resonance strength of stable nuclei. The giant resonance strength in light and medium mass nuclei is sensitive to the isospin dependence of the nuclear interaction [5].

Systematic experimental investigations of the response of exotic nuclei, however, are not yet available. For some light halo nuclei, however, a clear electromagnetic excitation energy was interpreted as a threshold effect, involving the valence neutron into the continuum. For example, the 20Ne and 22Ne, a coherent dipole neutron strength against the core was observed [6,7].

The appearance of a collective giant resonance in other nuclei [8-11], for the one-neutron halo nuclei [11], the observed dipole thresholds were interpreted as threshold effects, involving the valence neutron into the continuum.

For some light halo nuclei, however, a clear electromagnetic excitation energy was interpreted as threshold effect, involving the valence neutron into the continuum.

The appearance of a collective giant resonance in other nuclei [8-11], for the one-neutron halo nuclei [11], the observed dipole thresholds were interpreted as threshold effects, involving the valence neutron into the continuum.

FIG. 2. Photoneutron cross sections for 16O (upper panel) and for the unstable isotopes 17O (lower panel) as extracted from the measured electromagnetic excitation cross section (symbols). The inset displays the cross section for near the neutron threshold on an expanded energy scale. The thresholds for decay channels involving neutrons (which were not observed in the present experiment) are indicated by arrows.

5442 0031-9007 36 4

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Evolution of IV dipole strength in Oxygen isotopes

RHB + RQRPA calculations with the NL3 relativistic mean-field plus D1S Gogny pairing interaction.

What is the structure of low-lying strength below 15 MeV?

Effect of pairing correlations on the dipole strength distribution

Isovector dipole strength in $^{132}\text{Sn}$.

Distribution of the neutron particle-hole configurations for the peak at 7.6 MeV (1.4% of the EWSR)

$^{132}\text{Sn}$ at 7.6 MeV
- 28.2% $2d_{3/2} \rightarrow 2f_{5/2}$
- 21.9% $2d_{5/2} \rightarrow 2f_{7/2}$
- 19.7% $2d_{3/2} \rightarrow 3p_{1/2}$
- 10.5% $1h_{11/2} \rightarrow 1i_{13/2}$
- 3.5% $2d_{5/2} \rightarrow 3p_{3/2}$
- 1.9% $1g_{7/2} \rightarrow 2f_{5/2}$
- 1.5% $1g_{7/2} \rightarrow 1h_{9/2}$
- 0.6% $1g_{7/2} \rightarrow 2f_{7/2}$
- 0.6% $2d_{3/2} \rightarrow 3p_{3/2}$
* Important points:
- the tail of the GT-strength distribution at low energies
- the position of specific single particle levels (i.e. effective mass)
- effective pairing force in the T=1 and T=0 channel.
- in simple QRPA the lifetimes are too big

* Possible methods to improve the results:
- coupling to surface vibrations (difficult and beyond mean field)
- use of a tensor coupling in the $\omega$-channel (one phenomenological parameter)
- $T=0$ pairing force with Gaussian character (one phenomenological parameter)
The nucleon effective mass $m^*$:

$m^*$ represents a measure of the density of states around the Fermi surface.

**Nonrelativistic mean-field models**

- Effective mass: $m^*/m = 0.8 \pm 0.1$

**Relativistic mean-field models**

- Dirac mass: $m_D = m + S(r)$
- Effective mass: $m^* = m - V(r)$

**Conventional RMF models**

- Spin-orbit splittings + nuclear matter binding

- $0.55m \leq m_D \leq 0.60m$
- $0.64m \leq m^* \leq 0.67m$

Small density of states $\Rightarrow$ overestimated $\beta$-decay lifetimes
Tensor omega-nucleon coupling enhances the spin-orbit interaction.

scalar and vector self-energies can be reduced

\[ V_{SO} = \left[ \frac{1}{4M^2} \frac{1}{r} \frac{d}{dr} (V - S) + \frac{f_V}{2MM} \frac{1}{r} \frac{d\omega}{dr} \right] l \cdot s \]

Cadmium isotopes: $\pi_{1g9/2}$ level is partially empty

$T=0$ pairing has large influence on the $\nu_{1g7/2} \rightarrow \pi_{1g9/2}$ transition which dominates the $\beta$-decay process

An increase of the $T=0$ pairing partially compensates for the fact that the density of states is still rather low. T. Niksic et al, PRC 71, 014308 (2005)

\[ \nu h_{9/2} \rightarrow \pi h_{11/2} \]

G. Martinez-Pinedo and K. Langanke, PRL 83, 4502 (1999)
Correlations beyond mean field

- Conservation of symmetries by projection before variation
- Motion with large amplitude by Generator Coordinates
- Coupling to collective vibrations
  - shifts of single particle energies
  - decay width of giant resonances
Halo wave function in the canonical basis:

\[ |\Phi\rangle = \sum_{N} c_N |N\rangle \]

\[ |\Phi\rangle = c_2 |^5 Li\rangle + c_4 |^7 Li\rangle + c_6 |^9 Li\rangle + c_8 |^{11} Li\rangle + \ldots \]

\[ \hat{P}^N |\Phi\rangle = c_8 |^{11} Li\rangle \]
Projected Density Functionals

\[
\left| \Psi^N \right> = \hat{P}^N \left| \Phi \right> = \delta(\hat{N} - N) \left| \Phi \right> = \int \frac{d\varphi}{2\pi} e^{i\varphi(\hat{N} - N)} \left| \Phi \right>
\]

projected density functional:

\[
E^N[\hat{\rho}, \hat{\kappa}] = \frac{\langle \Phi | \hat{H}\hat{P}^N | \Phi \rangle}{\langle \Phi | \hat{P}^N | \Phi \rangle}
\]

projected HFB-equations (variation after projection):

\[
\begin{pmatrix}
\hat{h}^N & \hat{\Delta}^N \\
-\hat{\Delta}^{N*} & -\hat{h}^{N*}
\end{pmatrix}
\begin{pmatrix}
U_k(r) \\
V_k(r)
\end{pmatrix}
= \begin{pmatrix}
U_k(r) \\
V_k(r)
\end{pmatrix} E_k
\]

J. Sheikh and P. Ring, NPA 665 (2000) 71

analytic expressions

\[
\hat{h}^N = \frac{\delta E^N}{\delta \hat{\rho}}
\]

\[
\hat{\Delta}^N = \frac{\delta E^N}{\delta \hat{\kappa}}
\]
Ne-isotopes

Pairing degree of freedom in nuclei and the nuclear medium.

Halo-formation in Ne-isotopes

Pairing energies

Binding energies

Rms-radii

Generator Coordinate Method (GCM)

\[ \langle \delta \Phi | \hat{H} - q \hat{Q} | \Phi \rangle = 0 \]

Constraint Hartree Fock produces wave functions depending on a generator coordinate \( q \).

GCM wave function is a superposition of Slater determinants.

Hill-Wheeler equation:

\[ \int dq \left[ \langle q | H | q' \rangle - E \langle q | q' \rangle \right] f(q') = 0 \]

with projection:

\[ | \Psi \rangle = \int dq f(q) \hat{P}^N \hat{P}^I | q \rangle \]
GCM without projection:

$^{194}\text{Hg}$

$N_{sh} = 10$

$N_{sh} = 12$

$N_{sh} = 14$

$N_{sh} = 16$

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GCM-wave functions of the lowest states

$N_{sh} = 14$

$^{194}\text{Hg}$
Ang. momentum projected energy surfaces:

$^{194}\text{Hg}$

$N_{sh} = 10$

$N_{sh} = 12$

$N_{sh} = 14$
Vibrational Couplings: energy dependent self-energy:

\[ \Sigma = S + V + \Sigma(\omega) \]

mean field
pole part

RPA-modes

\[ z_\nu = \left[ 1 - \frac{d\Sigma_{\nu\nu}}{d\omega} \bigg|_{\omega = \epsilon_\nu} \right]^{-1} \]
Distribution of single-particle strength in $^{209}$Bi

- $^{209}$Bi $1h9/2$
- $^{209}$Bi $1i13/2$
- $^{209}$Bi $2h11/2$
- $^{209}$Bi $2f5/2$
Level scheme for $^{207}$Pb
Contributions of complex configurations

The full response contains energy dependent parts coming from vibrational couplings.

\[ \text{Self energy} \]

\[ \text{g – phonon amplitudes (QRPA)} \]

\[ \text{ph interaction amplitude} \]

\[ R^e \]

\[ R^e \]

\[ R^e \]

\[ R^e \]
Decay-width of the Giant Resonances

\[ S(E) = -\frac{1}{\pi} \text{Im} \Pi(E + i\Delta) \]

**E1 photoabsorption cross section**

\[ \sigma_{E1}(E) = \frac{16\pi^3 e^2}{9\hbar c} E S_{E1}(E) \]
Conclusions

There is a relativistic formulation of pairing

Pairing is a totally non-relativistic phenomenon
excellent separation of scales!

RHB-model uses Gogny force in the pairing channel

Applications in finite nuclei
- rotational spectra (cranked RHB-theory)
- halo phenomena (continuum RHB theory)
- vibrational excitations (rel. QRPA)

Method beyond mean field:
- Projected funcionals (PDFT)
- Generator Coordinate Method (GCM)
- Particle-Vibrational Coupling (PVC)
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