Exotic structure far from stability

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**Neutron-rich nuclei**

- **r-process nucleosynthesis** - at the origin of one-half of the A>60 stable nuclei.
- Properties of thousands of nuclei located between the valley of beta-stability and the neutron drip line have to be investigated.

- \((n,\gamma)\) and \((\gamma,n)\) rates.
- \(\alpha\)- and \(\beta\)-decay half-lives.
- Rates of \(\beta\)-delayed neutron emission.
- Probabilities for neutron-induced, spontaneous and \(\beta\)-delayed fission.

**Structure of neutron-rich nuclei:**
- Weak binding of the outermost neutrons.
- Coupling between bound states and the particle continuum.
- Diffuse neutron densities.
- Formation of the neutron skin and halo structures.
Neutron-rich nuclei: evolution of shell structure

HFB: SLy6 interaction

Suppression of shell effects, the disappearance of spherical magic numbers, the onset of deformation and shape coexistence in nuclei with large N/Z ratio.

Neutron single-particle levels for $^{42}$Si, $^{44}$S, and $^{46}$Ar as functions of the quadrupole deformation (RHB-NL3).
Quadrupole collectivity in N=28 nuclei\[\rightarrow\] angular momentum projection and configuration mixing \[\text{Phys. Rev. C 65, 024304 (2002)}\]

HFB \[\rightarrow\] Gogny D1S interaction: potential energy surfaces

Angular momentum projected potential energy surfaces for: I=0, 2, 4, 6 and 8.

Small energy differences between coexisting minima \[\rightarrow\] correlation effects beyond the mean-field approximation are important!
Angular momentum projected configuration mixing:

1. Constrained axially symmetric HFB calculations with the constraint on the mass quadrupole moment.

2. Restoration of the rotational symmetry -> rotational energy correction: energy gain ~ to the quadrupole deformation of the intrinsic state.

3. Configuration mixing -> Generator Coordinate Method
CORRELATIONS BEYOND MEAN-FIELD IN NEUTRON-RICH Mg NUCLEI

Angular Momentum Projected Generator Coordinate Method

HFB mean-field potential energy surfaces

Gogny D1S interaction

- angular momentum projection & configuration mixing
The lowest two AMPGCM states for $I = 0^+, 2^+, 4^+, 6^+$, in an energy vs quadrupole moment diagram. The projected PES is for $I=0^+$. 

$B(E2, 0^+_1 \rightarrow 2^+_1)$ in $^{20-40}\text{Mg}$
Reduction of the spin-orbit potential in neutron-rich nuclei

Relativistic Mean-Field framework → the spin-orbit potential originates from the addition of two large fields: the field of the vector mesons (short range repulsion), and the scalar field of the sigma meson (intermediate attraction).

\[
V_{s.o.} \approx \frac{1}{r} \frac{\partial}{\partial r} V_{ls}(r) = \frac{m}{m_{eff}} (V - S)
\]

The relative error for spin-orbit splittings in doubly magic nuclei.

Radial dependence of the spin-orbit term of the single neutron potential.
Reduced energy spacings between spin-orbit partners

\[ \Delta E_{ls} = E_{n,l,\text{j}=l-1/2} - E_{n,l,\text{j}=l+1/2} \]

Radial Dirac wave-functions of spin-orbit doublets.
Extrapolations far from stability?

Two-neutron separation energies for the chain of tin isotopes.

Neutron skin along the chain of tin isotopes.

Constraints on the isovector channel of effective nuclear interactions?
Self-consistent methods based on Density Functional Theory (DFT)

Next-generation universal energy density functionals constrained by bulk properties of nuclei, nuclear matter and nuclear excitations.


Improved description and more reliable predictions on properties of exotic nuclei far from stability!
Microscopic description of weakly bound neutron-rich nuclei

consistent treatment of both the many-body correlations and the continuum of positive energy states and decay channels

**GAMOW SHELL MODEL** -> multiconfigurational shell model that includes a consistent description of bound states and the particle continuum (resonances and the nonresonant scattering background).

Applications to systems with several valence neutrons.

Multipole response of exotic nuclei

Excited states in weakly bound nuclei $\rightarrow$ 2qp space:
- states with both nucleons in discrete bound levels
- nucleon in a bound level and nucleon in the continuum
- states with both nucleons in the continuum

Relativistic QRPA $\rightarrow$ formulated in the canonical basis of the relativistic Hartree-Bogoliubov model.

CANONICAL BASIS: diagonalizes the density matrix $\rightarrow$ always localized
It describes both the bound states and the positive energy continuum.

Fully self-consistent RQRPA: In both the ph and pp channels the same strength parameters are used in the RHB and RQRPA calculations $\rightarrow$ essential for the decoupling of spurious states.
Evolution of IV dipole strength in Oxygen isotopes

Effect of pairing correlations on the dipole strength distribution

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

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

Transition densities
In light nuclei the onset of dipole strength in the low-energy region is caused by non-resonant independent single particle excitations of the loosely bound neutrons.

$m_1$ (up to 15 MeV) divided by the TRK sum rule

centroid energy of the low-lying dipole strength in $O$ isotopes
Evolution of isovector dipole strength in Sn isotopes:

Transition densities


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


<table>
<thead>
<tr>
<th>$^{132}$Sn at 7.6 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>28.2% $2d_{3/2} \rightarrow 2f_{5/2}$</td>
</tr>
<tr>
<td>21.9% $2d_{5/2} \rightarrow 2f_{7/2}$</td>
</tr>
<tr>
<td>19.7% $2d_{3/2} \rightarrow 3p_{1/2}$</td>
</tr>
<tr>
<td>10.5% $1h_{11/2} \rightarrow 1i_{13/2}$</td>
</tr>
<tr>
<td>3.5% $2d_{5/2} \rightarrow 3p_{3/2}$</td>
</tr>
<tr>
<td>1.9% $1g_{7/2} \rightarrow 2f_{5/2}$</td>
</tr>
<tr>
<td>1.5% $1g_{7/2} \rightarrow 1h_{9/2}$</td>
</tr>
<tr>
<td>0.6% $1g_{7/2} \rightarrow 2f_{7/2}$</td>
</tr>
<tr>
<td>0.6% $2d_{3/2} \rightarrow 3p_{3/2}$</td>
</tr>
</tbody>
</table>

Distribution of the neutron particle-hole configurations for the peak at 7.6 MeV (1.4% of the EWSR)
In heavier nuclei low-lying dipole states appear that are characterized by a more distributed structure of the RQRPA amplitude.

Among several single-particle transitions, a single collective dipole state is found below 10 MeV and its amplitude represents a coherent superposition of many neutron particle-hole configurations.
Resonance at Particle Threshold in $^{208}$Pb

Experimental and theoretical $B(E1)$ strength distributions

Quasiparticle Phonon Model (QPM) -> the configuration space includes two- and three-phonon states up to exc. energies 13 and 16 MeV, respectively.

Isoscalar dipole compression and toroidal modes

Isoscalar GMR in spherical nuclei $\rightarrow$ nuclear matter compression modulus $K_{nm}$.

Giant isoscalar dipole oscillations $\rightarrow$ additional information on the nuclear incompressibility.

$$\hat{Q}_{1\mu}^{T=0} = \sum_{i=1}^{A} \gamma_0 (r^3 - \eta r) \ Y_{1\mu}(\theta_i, \varphi_i)$$

ISGDR strength distributions in $^{208}$Pb. Effective interactions with different $K_{nm}$.

The low-energy strength does not depend on $K_{nm}$!

toroidal dipole moment: poloidal currents on a torus

Toroidal dipole strength distributions.

Velocity distributions in $^{116}$Sn

Spin-Isospin Resonances and Neutron Skin of Nuclei


Proton-neutron RQRPA calculation
DD-ME1 + Gogny-type pairing
Landau-Migdal $g'_0 = 0.55$

The isotopic dependence of the energy spacings between the GTR and IAS
direct information on the evolution of the neutron skin thickness along the Sn isotopic chain
Proton-rich nuclei and the proton drip-line


Proton-rich nuclei and the proton drip-line

Self-consistent RHB calculations: separation energies, quadrupole deformations, odd-proton orbitals, spectroscopic factors

Ground-state proton emitters

<table>
<thead>
<tr>
<th>N</th>
<th>( S_p )</th>
<th>( \beta_2 )</th>
<th>( p)-orbital</th>
<th>( \nu^2 )</th>
<th>( E_p ) exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^{124} \text{Pm} )</td>
<td>63</td>
<td>-1.00</td>
<td>0.35</td>
<td>5/2(^-)</td>
<td>0.72</td>
</tr>
<tr>
<td>( ^{125} \text{Pm} )</td>
<td>64</td>
<td>-0.81</td>
<td>0.35</td>
<td>5/2(^-)</td>
<td>0.74</td>
</tr>
<tr>
<td>( ^{130} \text{Eu} )</td>
<td>67</td>
<td>-1.22</td>
<td>0.34</td>
<td>5/2(^-)</td>
<td>0.44</td>
</tr>
<tr>
<td>( ^{131} \text{Eu} )</td>
<td>68</td>
<td>-0.90</td>
<td>0.35</td>
<td>5/2(^+)</td>
<td>0.44</td>
</tr>
<tr>
<td>( ^{135} \text{Tb} )</td>
<td>70</td>
<td>-1.15</td>
<td>0.34</td>
<td>3/2(^+)</td>
<td>0.62</td>
</tr>
<tr>
<td>( ^{136} \text{Tb} )</td>
<td>71</td>
<td>-0.90</td>
<td>0.32</td>
<td>3/2(^+)</td>
<td>0.65</td>
</tr>
<tr>
<td>( ^{140} \text{Ho} )</td>
<td>73</td>
<td>-1.10</td>
<td>0.31</td>
<td>7/2(^-)</td>
<td>0.61</td>
</tr>
<tr>
<td>( ^{141} \text{Ho} )</td>
<td>74</td>
<td>-0.90</td>
<td>0.32</td>
<td>7/2(^-)</td>
<td>0.64</td>
</tr>
<tr>
<td>( ^{145} \text{Tm} )</td>
<td>76</td>
<td>-1.43</td>
<td>0.23</td>
<td>7/2(^-)</td>
<td>0.47</td>
</tr>
<tr>
<td>( ^{146} \text{Tm} )</td>
<td>77</td>
<td>-1.20</td>
<td>-0.21</td>
<td>7/2(^-)</td>
<td>0.50</td>
</tr>
<tr>
<td>( ^{147} \text{Tm} )</td>
<td>78</td>
<td>-0.96</td>
<td>-0.19</td>
<td>7/2(^-)</td>
<td>0.55</td>
</tr>
</tbody>
</table>
Mapping the proton drip-line from Z=31 to Z=49

* important for the process of nucleosynthesis during explosive hydrogen burning
* the exact location of the proton drip line determines a possible path of rapid proton capture process
* proton separation energies beyond the drip line -> possible observation of ground state proton radioactivity

The proton drip-line in the sub-Uranium region.

Possible ground-state proton emitters in this mass region?

**Shape coexistence in proton-rich nuclei: $^{186}$Pb**

Evolution of shell structure → low lying $0^+$ states in neutron-deficient Pb nuclei

GCM configuration mixing of angular-momentum and particle-number projected self-consistent HF+BCS states. SLy6 interaction plus density-dependent zero-range pairing.

Particle-number and angular-momentum projected PES up to $I=10^+$.  


GCM spectrum of the lowest positive parity bands with $K=0$. 

Expt.  
Calc.
Modern Nuclear Structure Theory:

Structure and stability of exotic nuclei with extreme proton/neutron asymmetries

Universal microscopic energy density functional -> bulk properties of finite nuclei, extended asymmetric nuclear matter, and nuclear excitations

Link between Nuclear Physics and Astrophysics

Bridge between low-energy, non-perturbative QCD and the phenomenology of finite nuclei