Nuclear Physics in Spain:

Structure and Reactions (Theory)

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Spanish nuclear physics network: ific.uv.es/gamma/refinu

RESEARCH TOPICS

- Lepton Scattering: IEM-Madrid, UCM-Madrid, Granada, Sevilla.

- Reactions & Structure of Halo nuclei: IEM-Madrid, Sevilla, Huelva, Granada

- Nuclear Structure (models & methods): IEM-Madrid, UCM-Madrid, Sevilla, Huelva.

- Nuclear Structure (microscopic calculations): IEM-Madrid, UCM-Madrid, UAM-Madrid, Cantabria, Granada, Barcelona, Sevilla

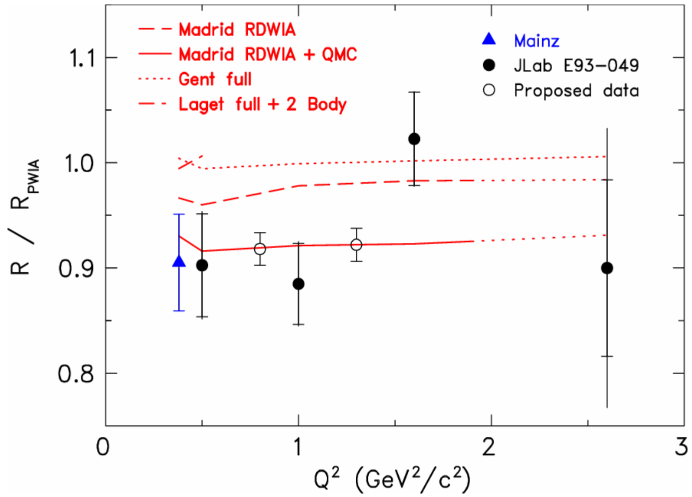
- Nuclear Matter: Barcelona, Sevilla.

Lepton scattering

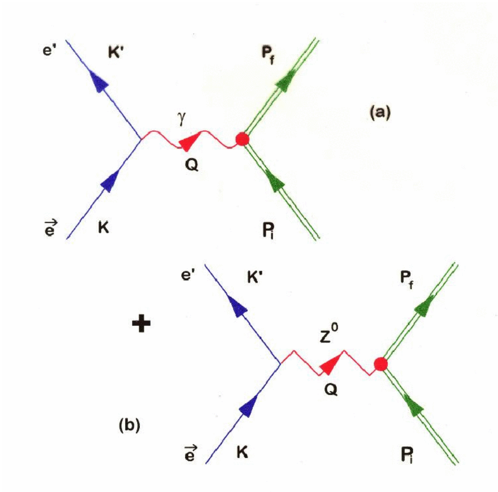
- Relativistic description of (e,e'N) processes. (Granada, Sevilla, IEM, UCM)
- Effect of meson exchange currents (Granada)
- Effect of long range and short range correlations (Granada)
- Neutrino-nucleus scattering. (Sevilla, Granada, UCM)

Electron and Neutrino-Nucleus Scattering Reactions

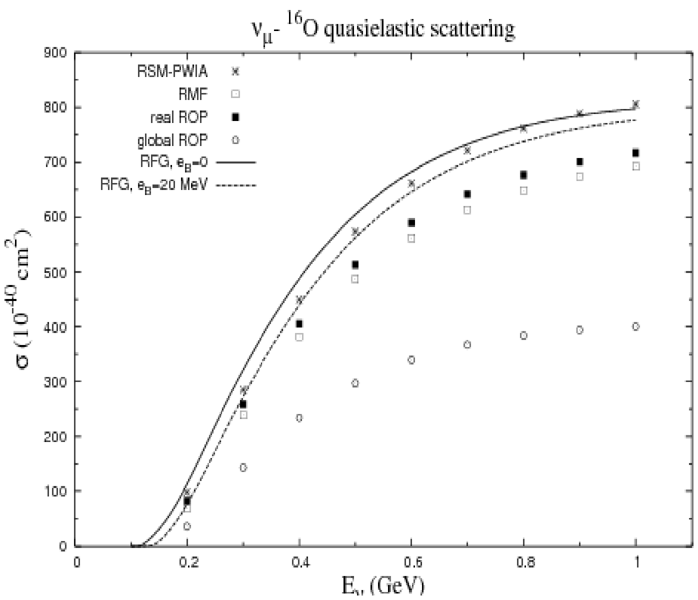
•***Exclusive (e,e'p) processes:*** **relativistic versus non-relativistic descriptions, cross sections, em responses and polarization observables. Medium effects in nucleon f.f.?**



•***Inclusive (e,e') processes:*** **Description of quasielastic (QE) and Delta peaks, Meson Exchange Currents, Parity violating (PV) electron scattering: information on nucleon form factors (strangeness) & couplings in the SM.**

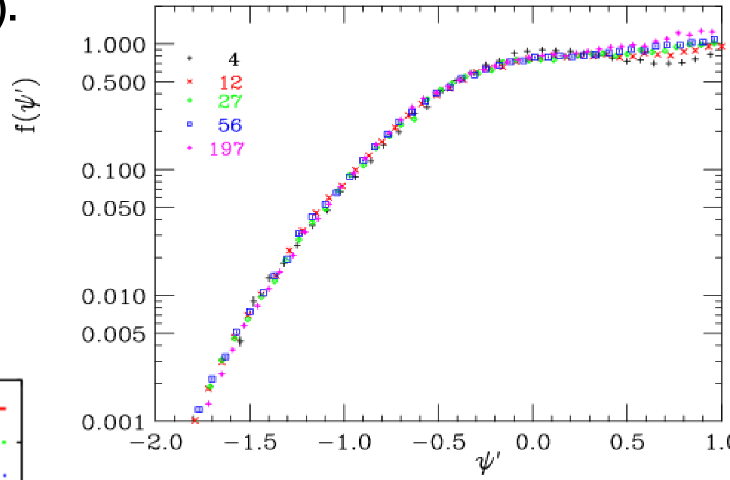


•***Charged and Neutral-current neutrino-nucleus scattering:*** **Relativistic Distorted Wave Impulse Approximation (RDWIA) and effects of final state interactions (FSI). Complement to PV experiments.**



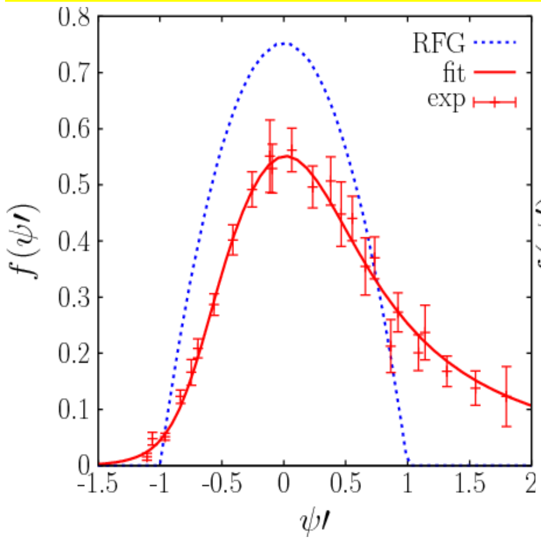
Scaling in lepton-nucleus scattering

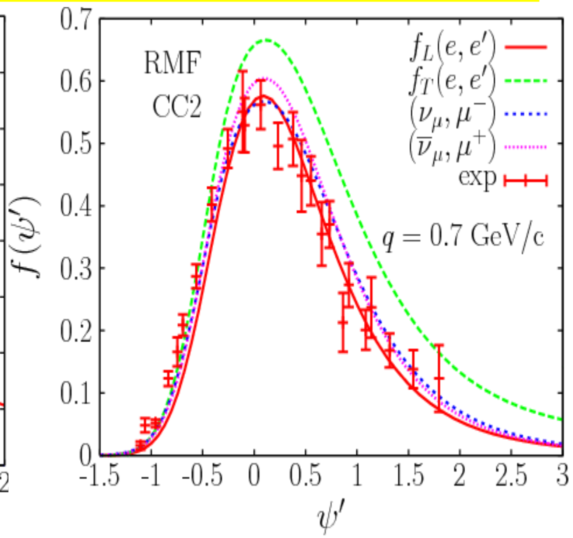
•World (e,e') data fulfill scaling and superscaling behavior (independence on the transfer momentum and the nucleus).

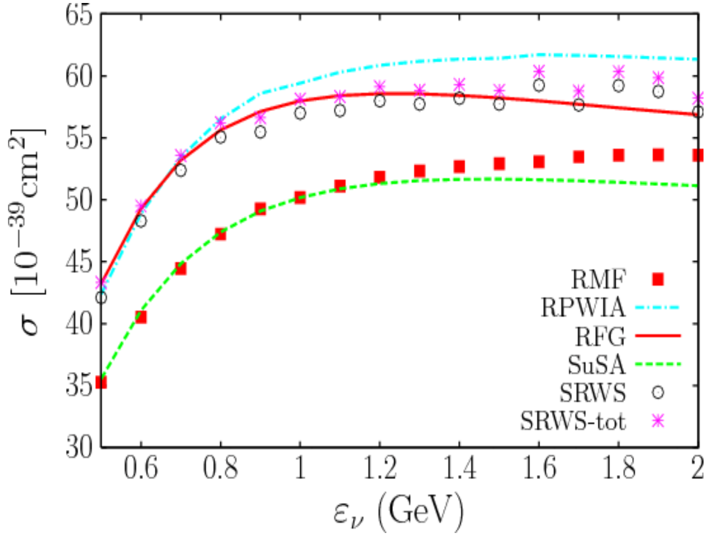


•Data lead to an asymmetrical superscaling function which is reproduced with a description of the reaction mechanism based on the Relativistic Mean Field (RMF).

•Universality of the scaling function: it can be used to predict neutrino-nucleus cross sections. Consistency with RMF calculat.







•SuSA (Superscaling Approach): essential to analyze neutrino oscillation experiments (MiniBooNE, Minos, K2K)

Reactions & Structure of Halo Nuclei

.

•Few body models for 2-body and 3-body halo nuclei (IEM, Sevilla)

•Resonant and non-resonant continuum description (IEM, Sevilla, Huelva)

•Continuum discretization methods (Huelva, Sevilla)

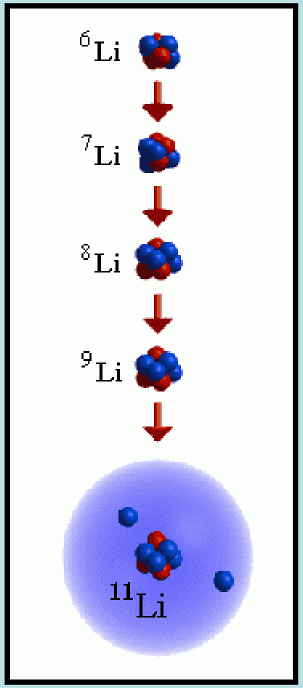
•Scattering, break-up and transfer reactions for halo nuclei (Sevilla)

•Reactions of astrophysical interest (Sevilla, Granada, IEM)

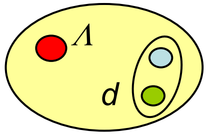
Three-body halo nuclei

Quantum halo states:

✓Systems with a large cluster configuration
✓Large spatial extension (small cluster binding)
✓Large fraction of the wave function in the classically forbidden region

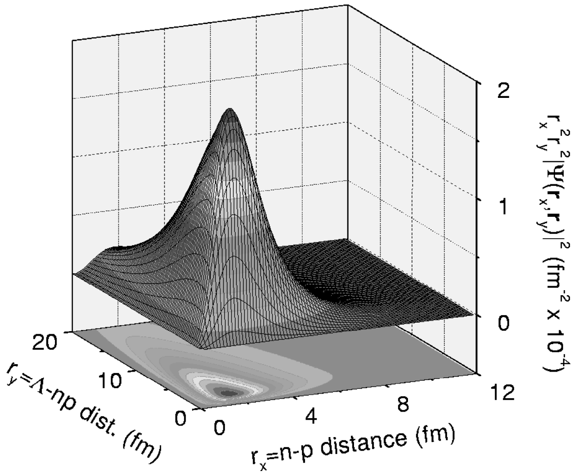


Hypertriton= $n + p + \Lambda$



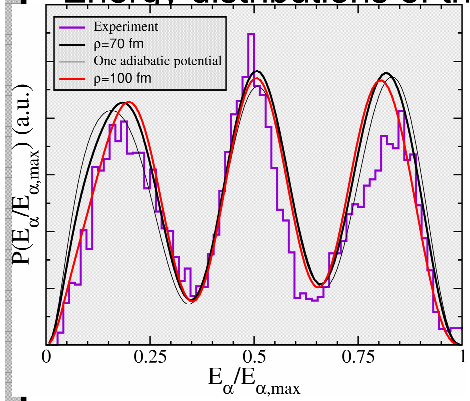
$$\left\langle r^2_{\Lambda-d} \right\rangle^{1/2} = 11.7 \text{ fm}$$

$$S_\Lambda = 0.13 \pm 0.05 \text{ MeV}$$



Three-body techniques applied to continuum wave functions and resonances

✓Direct decay versus sequential decay
✓Energy distributions of the fragments after decay



1^+ resonance in ^{12}C

$^{12}C \rightarrow \alpha+\alpha+\alpha$

Energy distribution of the α particles after decay

Future:

Reactions with astrophysical interest:

✓Two-nucleon radiative capture processes: $\alpha(2n,\gamma)^6$He, ^{15}O(2p,γ)^{17}Ne, α(2α,γ)^{12}C, α(α+n,γ)^{9}Be ….
✓Nuclear reactions at very low energies: ^{7}Be(d,n)^{8}B, ^{10}Be(d,p)^{11}Be, ^{10}Be(d,p)^{11}Be* …

Extension of the method to four-body systems

✓^{9}Be(α,n) ^{12}C, ^{12}C(n,γ) ^{13}C, ^{12}C(α,γ)^{16}O ….

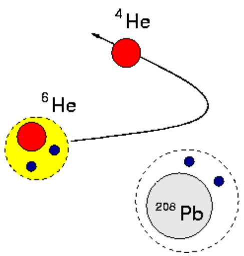
Continuum effects in the scattering of halo nuclei

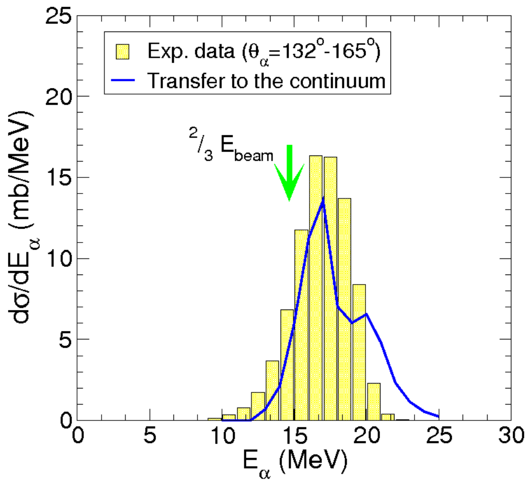
Reactions with exotic nuclei:

✓Large breakup probability
✓Strong coupling to unbound states
✓Requires:
1) Appropriate representation of the continuum:
⇨Orthogonal polynomials, continuum bins, etc
2) Suitable reaction models:
⇨CDCC
⇨Transfer to the continuum
⇨Faddeev techniques

^{6}He + ^{208}Pb breakup: α energy distribution

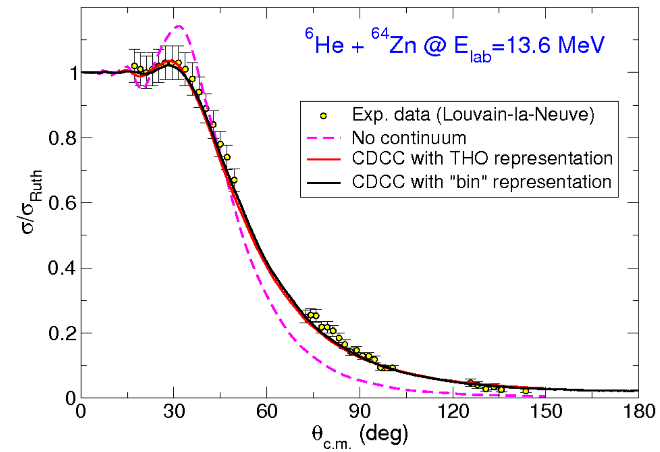
✓Louvain-la-Neuve data
✓Reaction model ⇒ transfer to the continuum





^{6}He+^{64}Zn elastic scattering

✓Three-body model for ^{6}He (α + n + n)
✓ ^{6}He continuum represented by energy bins expressed in hyperspherical coordinates
✓ Reaction model: Continuum Discretized CC (CDCC)



Future:

➔ Extension to other 3-body exotic nuclei of current interest (^{11}Li, ^{14}Be,etc)
➔ Application to planned experiments at existing and new facilities:

- **SPIRAL-II**:spectroscopy to unbound states
- **ISOLDE**: ^{11}Be(d,p)^{12}Be, ^{11}Be(d,t)^{10}Be, ^{9}Li(d,p)^{10}Li,...
- **FAIR(HISPEC):** 19C Extreme halo scattering

Nuclear structure: models & methods

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- Interacting boson model approach (IEM, Sevilla, Huelva)

- Soluble models for the pairing interaction (IEM, Sevilla, Huelva)

- Quantum phase transitions in collective nuclei (IEM, Sevilla, Huelva)

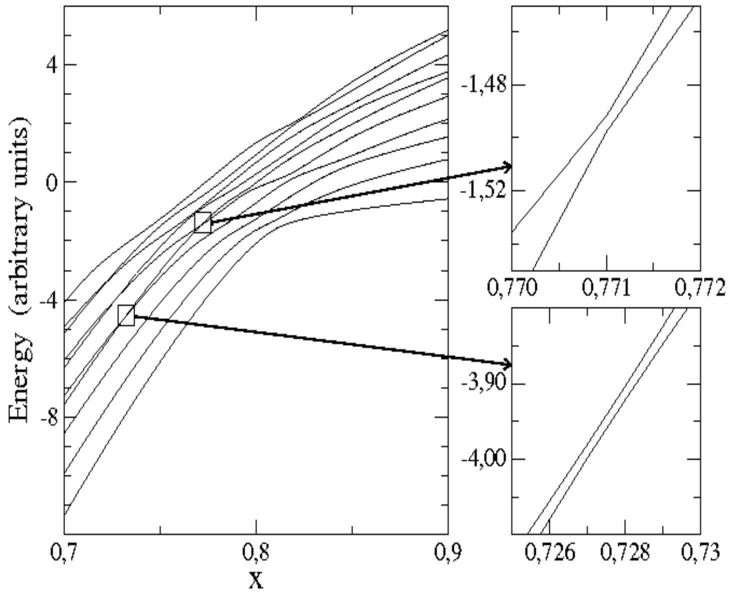
- Chaos in nuclei. Spectral fluctuations in energy levels. (UCM)

Level repulsion and level crossings in the phase diagram of the IBM

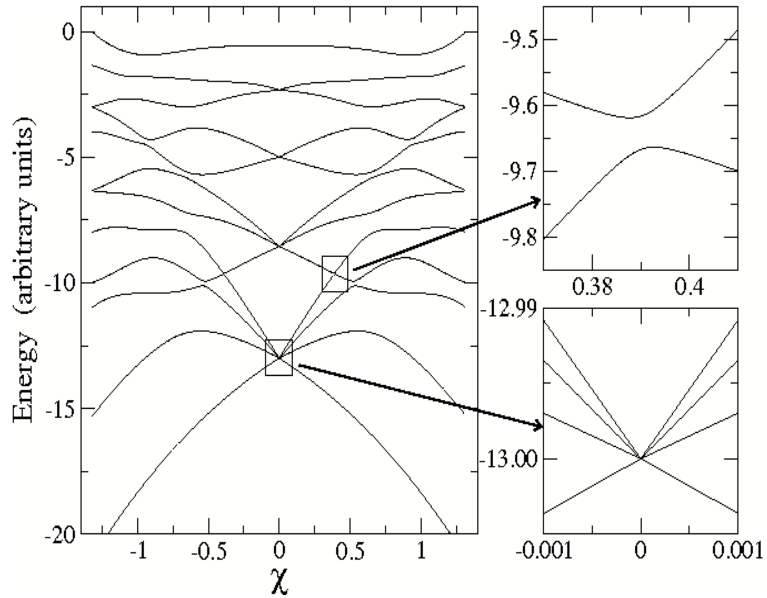
Nature of the Quantum Phase Transitions in the IBM as determined by the existence of quantum integrability or quantum chaos.

- First order phase transitions are due to level repulsion or level crossings in the O(6) critical symmetry point.
- The second order phase transition is due to quantum integrability.

First order phase transitions



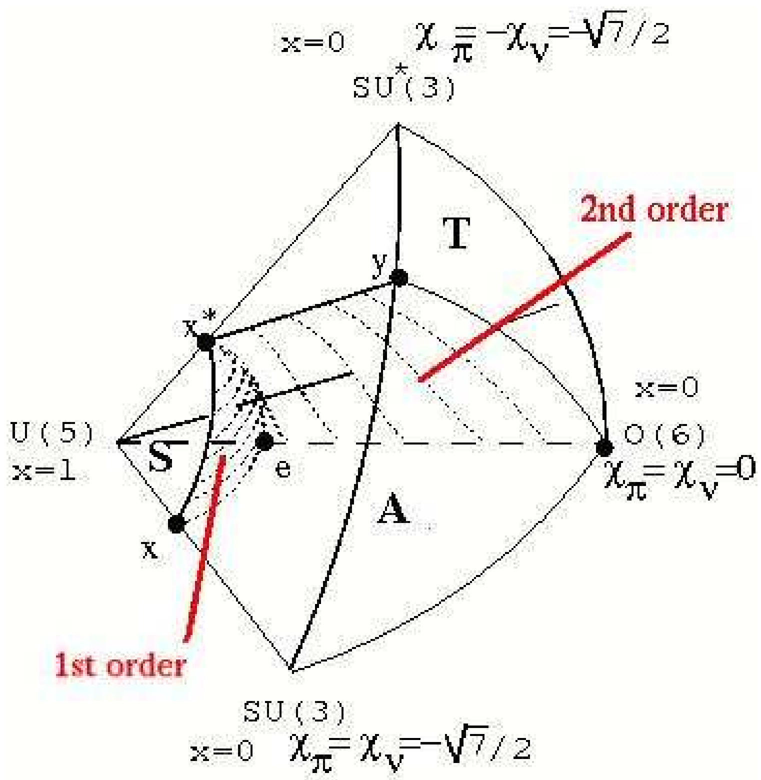
Level repulsion



Level crossing in the O(6) critical point.

Quantum Phase transitions in nuclear systems

Phase diagram of the Proton-Neutron Interacting Boson Model analyzing the properties of quantum phase transitions between spherical, axially deformed and triaxial shapes. Unveiled 1st and 2nd order transitional surfaces.



Future:

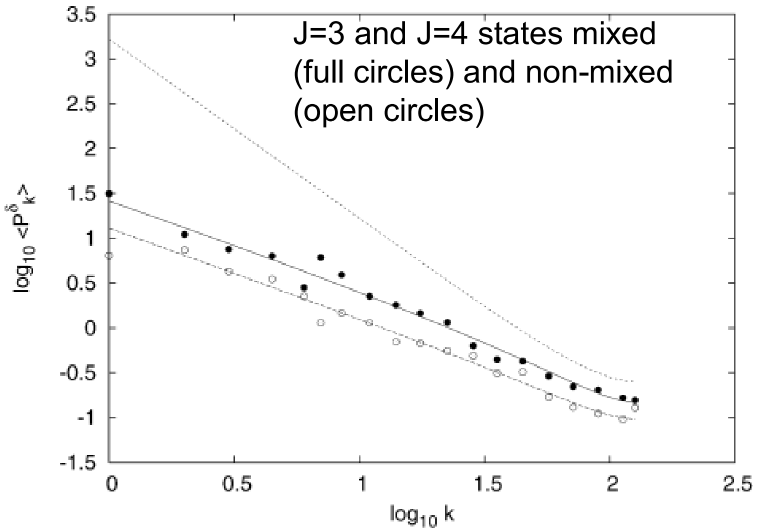
- Look for experimental candidates close to the new transtional surfaces.
- Possible extensions to other two fluid systems. Molecular system (U(3)xU(3)). Spinor condensates.

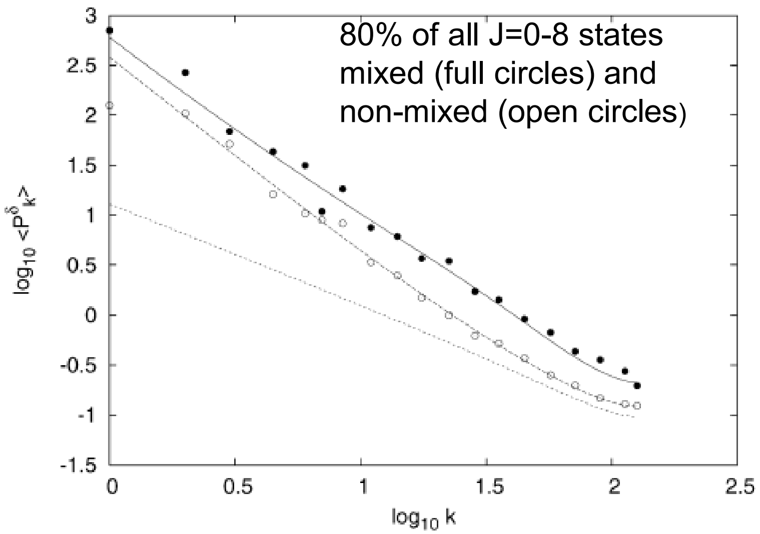
Spectral fluctuations in nuclear energy levels

Power spectrum

$$P_k^\delta = \frac{1}{N}\left|\sum_{q=0}^{N-1} \delta_q \exp(-2\pi qk/N)\right|^2$$

The power spectrum is sensitive to missing levels and symmetry mixing





Application to shell model results of ^{24}Mg:
Theory allows to estimate fraction of missing levels and the number of mixed symmetries

Nuclear structure: microscopic calculations

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- Large shell model calculations (UAM)
- RPA calculations (Granada, Sevilla)
- Relativistic mean field calculations (Cantabria)
- Deformed mean field calculations (UAM, IEM, UCM)
- Beyond the mean field: Configuration mixing (UAM)
- Short range correlations (FHNC method). (Granada)

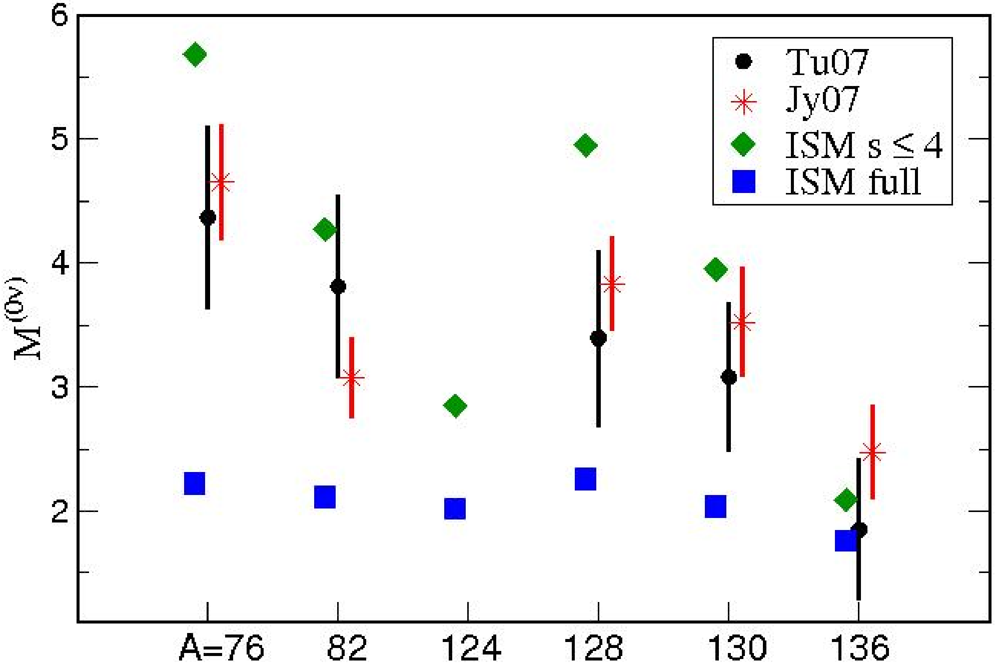
INTERACTING SHELL MODEL

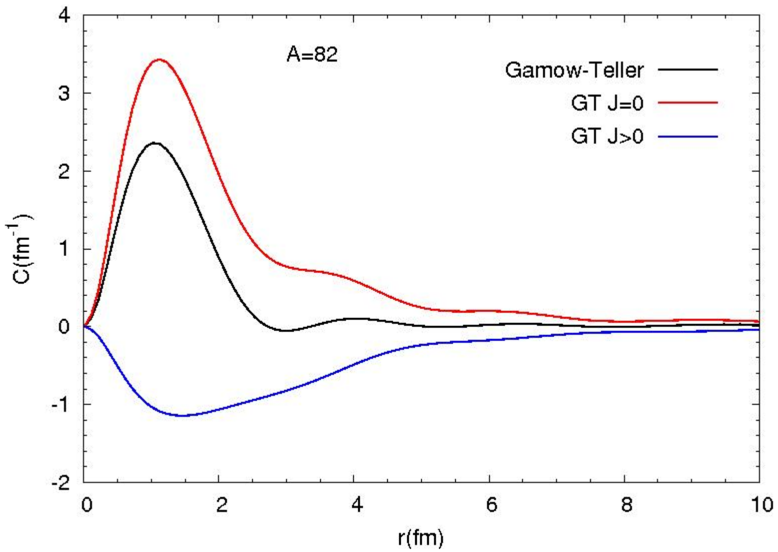
✓ Large scale Shell Model calculations (up to 10^{11} Slater determinants) of the spectroscopic properties of nuclei at the very neutron rich edge: ^{40}Mg, ^{42}Si, ^{44}S, ^{46}Ar

✓ Laboratory frame description of nuclear superdeformation in ^{36}Ar and ^{40}Ca

✓ State-of-the-art calculations of the neutrinoless double beta decay ($0\nu\beta\beta$)

- The importance of a proper treatment of pairing-like correlations to get a correct value for nuclear matrix element (NME)
- The effect of deformation of parent-daughter nuclei on NME
- The effect of the short range correlations
- The dependence of the NME on the internucleonic distance





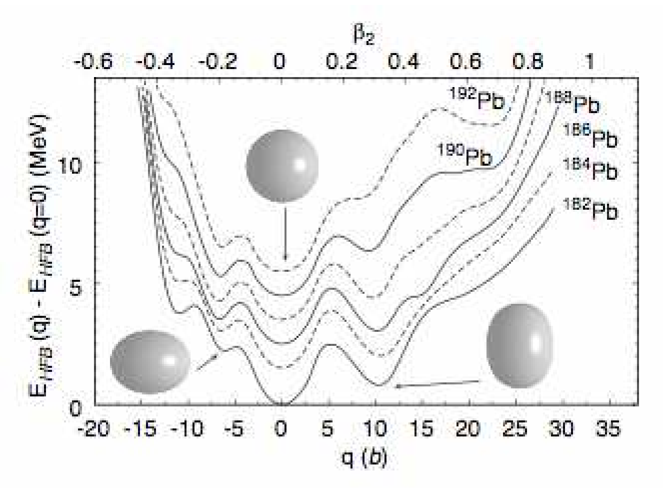
SELF-CONSISTENT MEAN FIELD AND BEYOND

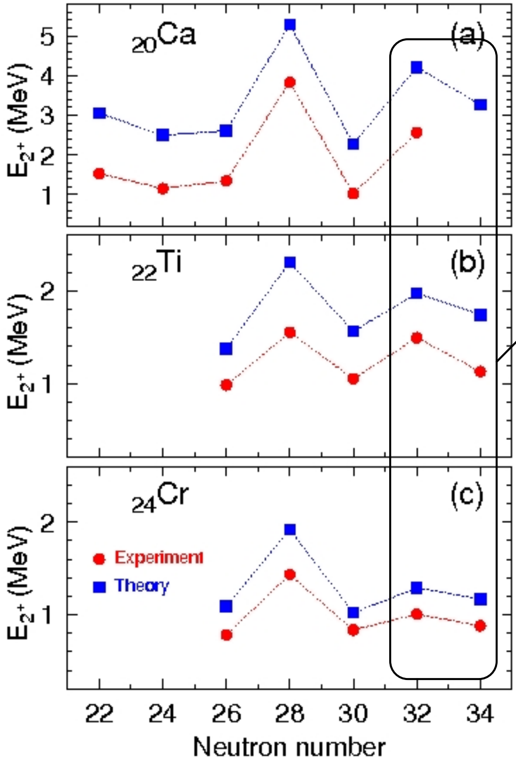
✓ Description of nuclear properties with an 'universal' density-dependent force (Gogny) and state-of-the-art beyond-mean-field calculations.

✓ Combination of configuration mixing (GCM) techniques with symmetry restored wave functions (particle number and angular momentum projections)

✓ Some recent applications:

- ➢ Shape coexistence in Pb isotopes
- ➢ Appearance or degradation of shell closures in exotic nuclei
- ➢ Shape transitions in Nd isotopes





N=32 is a shell closure while *N*=34 is not in neutron rich nuclei

Signatures of nuclear deformation in beta-decay

Gamow-Teller strength extracted from two complementary methods:

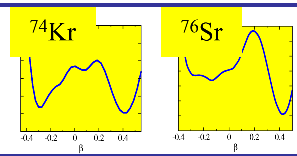
- β-decay
  - Unstable nuclei.
  - Direct method, but energy restrictions.
- Charge exchanged reactions
  - Stable nuclei (at present).
  - No energy restriction, but reaction mechanism involved.

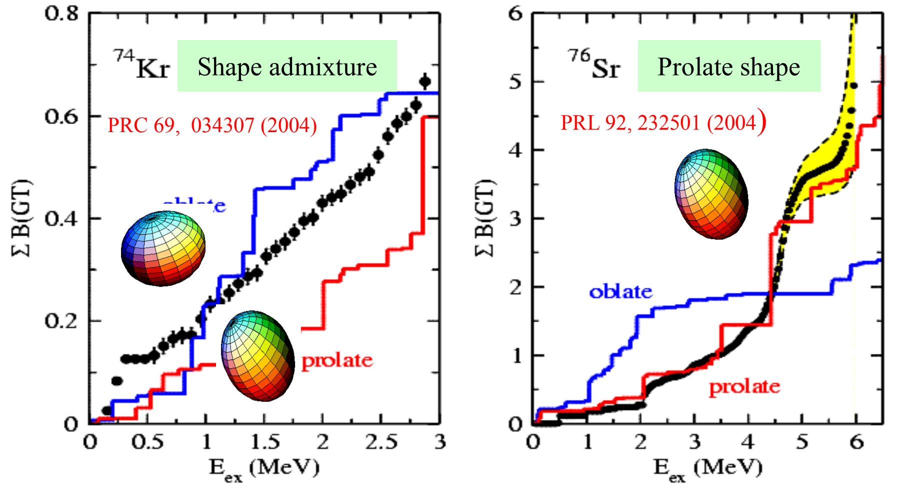
GT strength distributions from selfconsistent deformed Skyrme Hartree-Fock + BCS + pnQRPA calculations:

- Nuclear Structure:
  - Deformation.
- Nuclear Astrophysics:
  - Half-lives of nuclei involved in violent stellar events (waiting points nuclei in rp processes).
- Particle Physics:
  - Double β-decay. Nature of ν (Dirac or Majorana). Absolute ν-masses.

GT strength: Theory vs. Experiment (p-rich nuclei A~70)

Potential energy curves:
Oblate and prolate minima

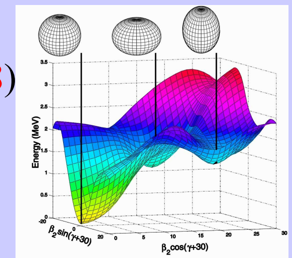




Accumulated GT strength vs. excitation energy of daughter nucleus

Outlook:

- B(GT) in other mass regions (neutron deficient Pb-Hg) (experiment at CERN-ISOLDE-2008)
- Charge exchanged reactions cross sections: Nuclear structure and reaction mechanism.
  Combine information from β-decay and charge exchange reactions on exotic nuclei: EXL-FAIR (GSI).
- Applications to Nuclear Astrophysics and Particle Physics



Nuclear matter

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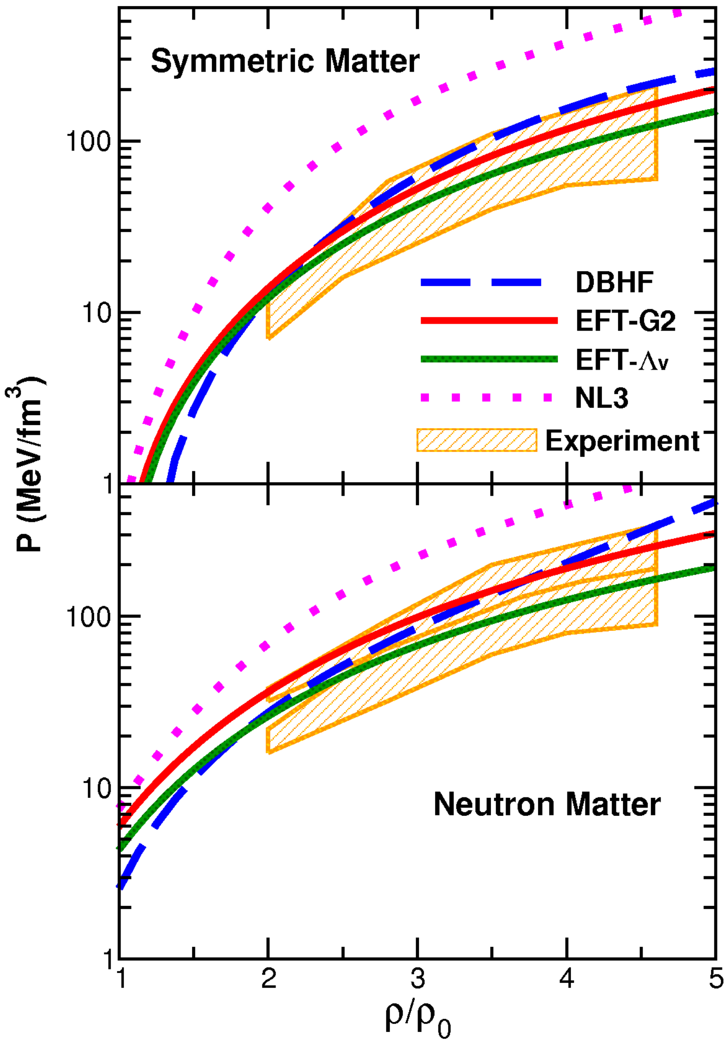
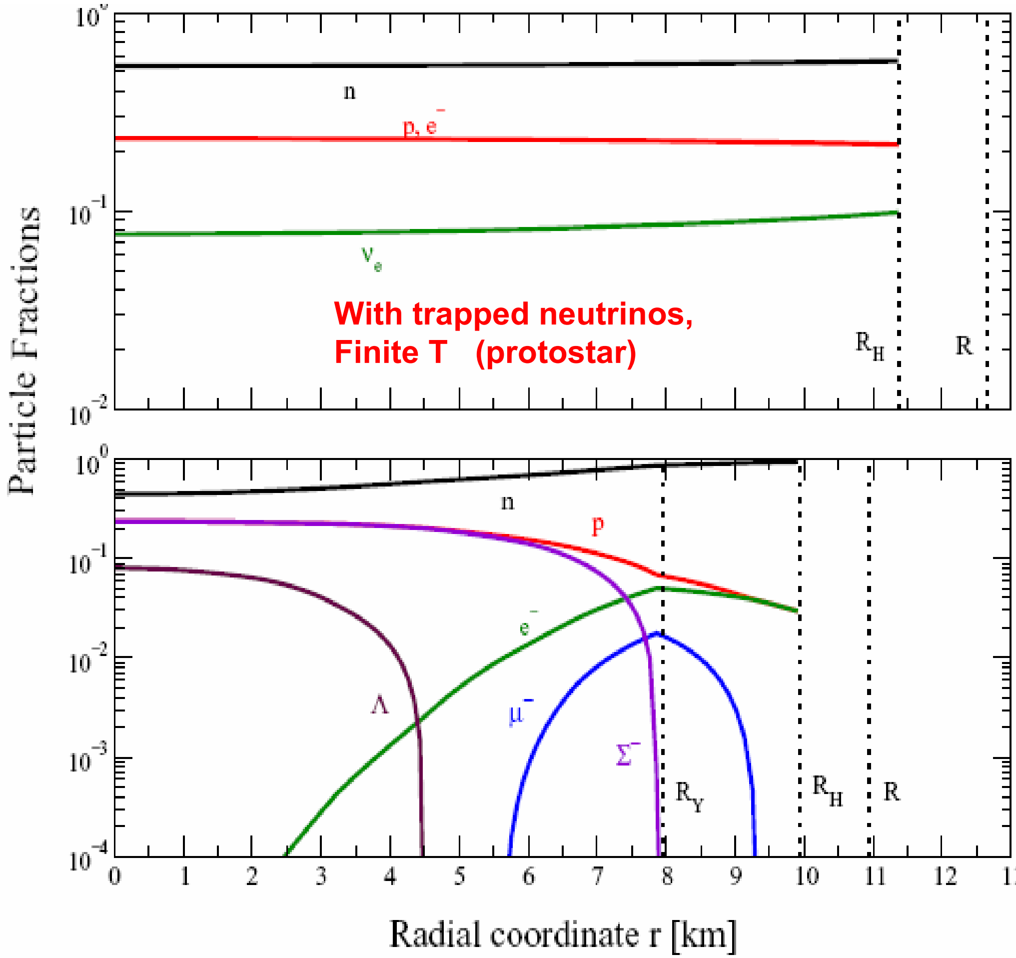
- Equation of state of nuclear matter (Barcelona)
- Symmetry energy in nuclear matter (Barcelona)
- Single-particle properties in the nuclear medium (Barcelona)
- Structure of neutron stars (Barcelona, Sevilla)

EoS of dense nuclear matter : Theory vs HIC data



Composition in the interior of neutron stars.



without neutrinos, T=0 (neutron stars)

Outlook

- Collaboration within theory groups in Spain is increasing
- Collaboration with experimental groups in Spain is increasing
- Participation in large international collaborations is increasing

Relevant facilities	Short term	Long term
Lepton Scattering	TJNL (USA) Mainz	eLISE (FAIR)
Reactions & Structure	GSI, ISOLDE, Louvain, Jyvaskyla, GANIL, Legnaro, …	Super-FRS (FAIR), SPIRAL II, EURISOL Smaller facilties
Nuclear Matter	RHIC (USA) SPS (CERN)	CBM (FAIR) Alice (CERN)