Realistic Nuclear Shell Model and Double-Beta Decay: the STRENGTH project

Nunzio Itaco

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SM&FT 2017 - The XVII Workshop on Statistical Mechanics and nonpertubative Field Theory

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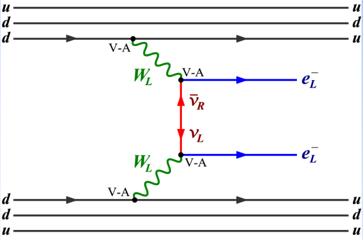
The detection of the $0\nu\beta\beta$ decay is nowadays one of the main targets in many laboratories all around the world, triggered by the search of ”new physics” beyond the Standard Model.

- Its detection
  - would correspond to a violation of the conservation of the leptonic number
  - may provide more informations on the nature of neutrinos (neutrino as a Majorana particle, determination of its effective mass, ..).

The neutrinoless double β-decay

The inverse of the $0\nu\beta\beta$-decay half-life is proportional to the squared nuclear matrix element (NME).
This evidences the relevance to calculate the NME



$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2 \langle m_\nu\rangle^2$$

- $G^{0\nu}$ is the so-called phase-space factor, obtained by integrating over she single electron energies and angles, and summing over the final-state spins
- $\langle m_\nu\rangle = \mid \sum_k m_k U_{ek}^2 \mid$ effective mass of the Majorana neutrino, U_{ek} being the lepton mixing matrix
- $M^{0\nu} = M_{GT}^{0\nu} - \left(\frac{g_V}{g_A}\right)^2 M_F^{0\nu} - M_T^{0\nu}$

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The calculation of the NME

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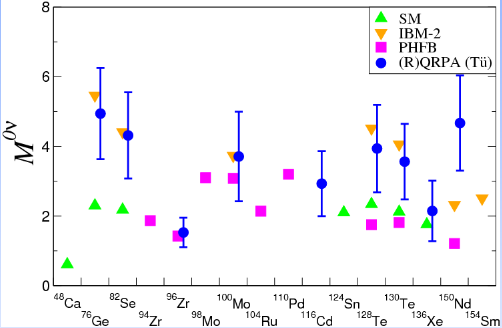

- The spread of nuclear structure calculations evidences inconsistencies among results obtained with different models

Our aim is to compute the $0\nu\beta\beta$-decay NME for ^{76}Ge, ^{82}Se, ^{130}Te, and ^{136}Xe.

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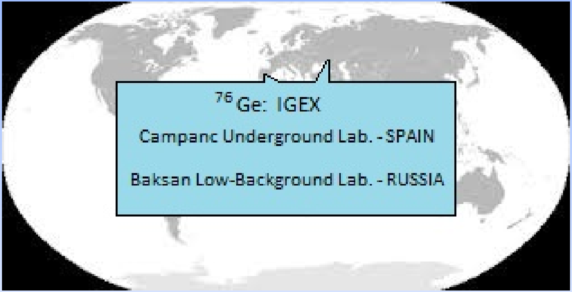

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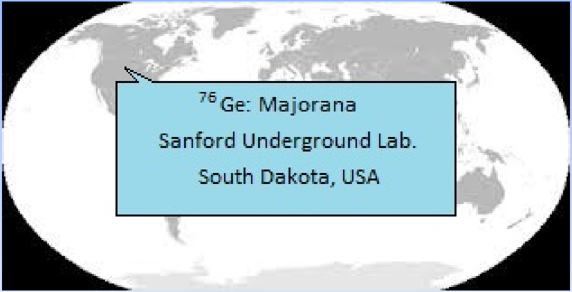

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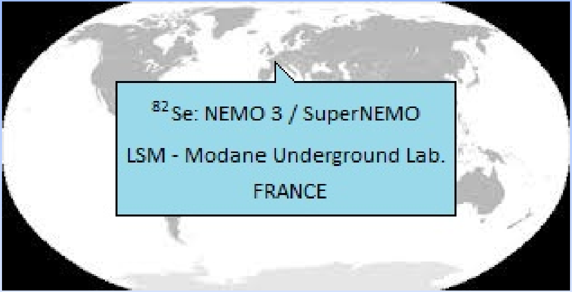

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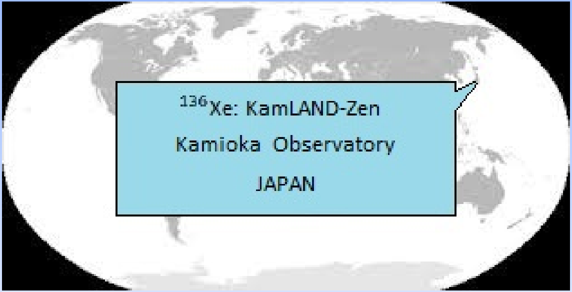
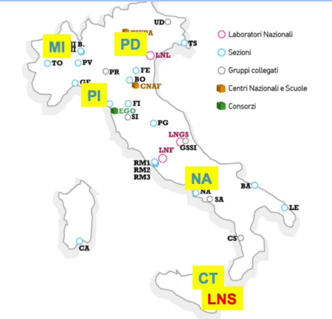


STRENGTH project

STructure and REactions of Nuclei: towards a Global THeory

- started in 2014
- different & complementary expertise in the fields of nuclear structure and reaction dynamics with hadronic probes
- challenges arising from the Radioactive Ion Beam Facilities



- Catania
- LNS Catania
- Milano
- Napoli
- Padova
- Pisa

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Development and application of models for nuclear structure studies

- Shell model
- Density functional theory
- Microscopic and algebraic cluster models

$\Rightarrow$ effective interactions to account for the reduction of the degrees of freedom explcitly considered to solve the many-body problem

STRENGTH project: nuclear structure

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STRENGTH project: reaction dynamics

Dynamics of nuclear excitations and reaction mechanisms

- Heavy ion collisions from the Coulomb barrier up to the Fermi energies involving different reaction mechanisms: semi-classical or micorscopic theories
- Collisions dominated by peripheral, direct mechanisms $\Rightarrow$ transfer, charge exchange and breakup direct reactions
- Optical potentials for total reaction cross section calculations, elastic scattering and knockout involving light exotic nuclei

STRENGTH project

Some numbers to summarize

26 researchers

$\simeq$ 280 papers
$\simeq$ 220 talks
$\simeq$ 25 thesis

The STRENGTH Units provide a relevant contribution to the nuclear physics community through the organization of meetings, workshops and schools

- GGI lectures on Frontiers in Nuclear and Hadronic Physics, Florence
- Summer school Rewriting nuclear physics textbooks, Pisa
- Incontri Nazionali di Fisica Nucleare
- International SPES Workshops
- ...

An example: ^{19}F

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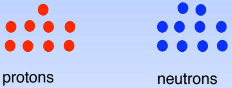

- 9 protons & 10 neutrons interacting
- spherically symmetric mean field (e.g. harmonic oscillator)
- 1 valence proton & 2 valence neutrons interacting in a truncated model space

The degrees of freedom of the core nucleons and the excitations of the valence ones above the model space are not considered explicitly.

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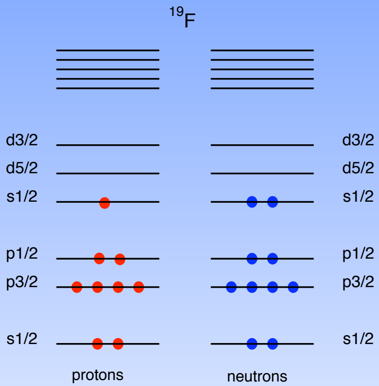

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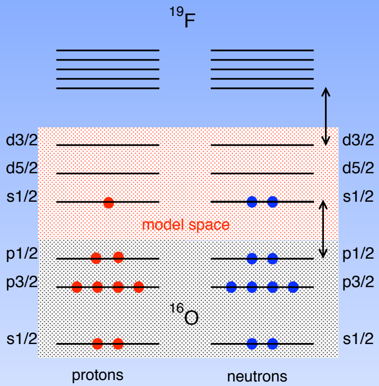

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Effective shell-model hamiltonian

The shell-model hamiltonian has to take into account in an effective way all the degrees of freedom not explicitly considered

Two alternative approaches

- phenomenological
- microscopic

$$V_{NN} \ (+V_{NNN}) \Rightarrow \text{many-body theory} \Rightarrow H_{\text{eff}}$$

Definition

The eigenvalues of H_{eff} belong to the set of eigenvalues of the full nuclear hamiltonian

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Workflow for a realistic shell-model calculation

1. Choose a realistic *NN* potential (*NNN*)
2. Determine the model space better tailored to study the system under investigation
3. Derive the effective shell-model hamiltonian and operators by way of a many-body theory
4. Calculate the physical observables (energies, e.m. transition probabilities, ...)

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Computational challenges

Model-space size

major shell 50-82 $\Rightarrow 10^9$ basis states
major shell 50-82 + $g_{9/2}, h_{11/2} \Rightarrow 10^{25}$ basis states !!

3 nucleon force V_{NNN}

- χPT $\Rightarrow V_{NN} + V_{NNN}$
- diagonalization $\Rightarrow$ same # of basis states, but less sparse H_{eff}

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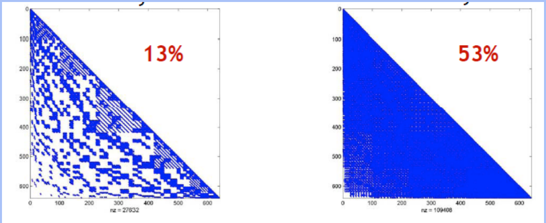


^{20}Ne
sd-shell
640 stati di base

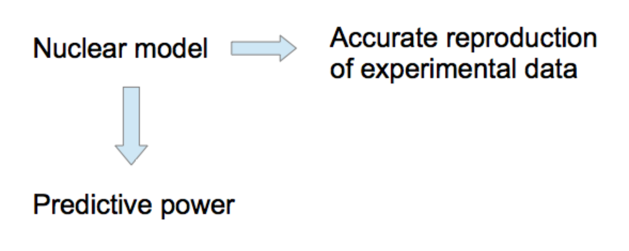
Shell-model code KSHELL

- OpenMP-MPI hybrid
- M scheme & Thick-Restart Lanczos method
- scalability tested up to 8192 cores ⇒ FX10 supercomputer (University of Tokyo)

GALILEO

MARCONI

Nuclear models and predictive power



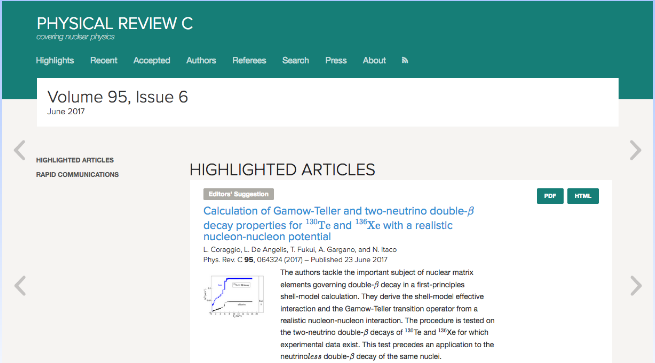
In the last 20 years realistic shell-model calculations have been widely employed with success to explore various regions of the nuclear landscape

Realistic shell-model calculations

Realistic shell-model calculations for ^{130}Te and ^{136}Xe

$\Downarrow$

Check this approach calculating observables related to the GT strengths and $2\nu\beta\beta$ decay and compare the results with data.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HIGHLIGHTED ARTICLES

RAPID COMMUNICATIONS

HIGHLIGHTED ARTICLES

Editors' Suggestion

PDF HTML

Calculation of Gamow-Teller and two-neutrino double-β decay properties for ^{130}Te and ^{136}Xe with a realistic nucleon-nucleon potential

L. Coraggio, L. De Angelis, T. Fukui, A. Gargano, and N. Itaco

Phys. Rev. C **95**, 064324 (2017) – Published 23 June 2017

The authors tackle the important subject of nuclear matrix elements governing double-β decay in a first-principles shell-model calculation. They derive the shell-model effective interaction and the Gamow-Teller transition operator from a realistic nucleon-nucleon interaction. The procedure is tested on the two-neutrino double-β decays of ^{130}Te and ^{136}Xe for which experimental data exist. This test precedes an application to the neutrino*less* double-β decay of the same nuclei.

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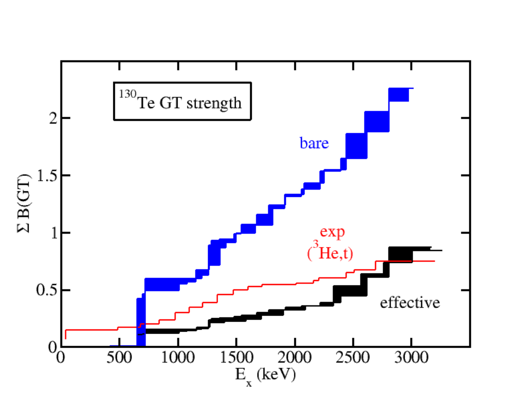
^{130}Te GT^{-} running sums



$$B(\mathrm{GT}) = \frac{\left| \langle \Phi_f | \sum_j \vec{\sigma}_j \vec{\tau}_j | \Phi_i \rangle \right|^2}{2J_i + 1}$$

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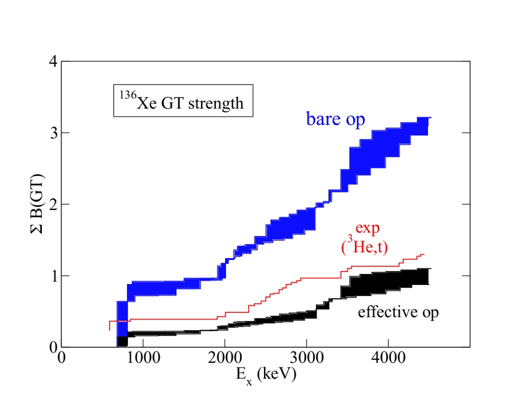
^{136}Xe GT$^-$ running sums



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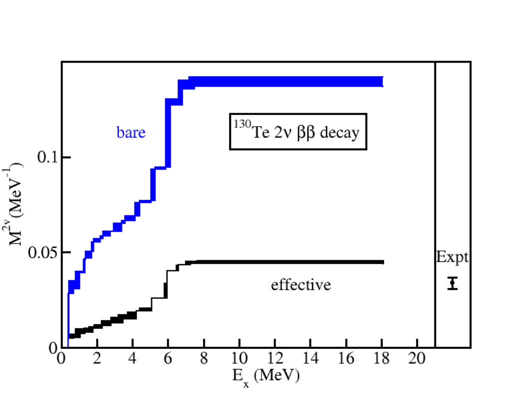
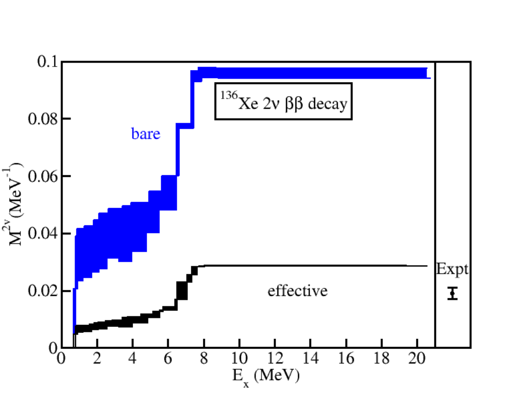
$^{130}\mathrm{Te} \rightarrow ^{130}\mathrm{Xe}$ nuclear matrix element



$$M_{2\nu}^{\mathrm{GT}} = \sum_n \frac{\langle 0_f^+ || \vec{\sigma}\tau^- || 1_n^+ \rangle \langle 1_n^+ || \vec{\sigma}\tau^- || 0_i^+ \rangle}{E_n + E_0}$$

$^{136}Xe \rightarrow ^{136}Ba$ nuclear matrix element



$$M_{2\nu}^{\rm GT} = \sum_n \frac{\langle 0_f^+ || \vec{\sigma}\tau^- || 1_n^+ \rangle \langle 1_n^+ || \vec{\sigma}\tau^- || 0_i^+ \rangle}{E_n + E_0}$$

Conclusions and perspectives

- RSM calculations provide a satisfactory description of observed GT-strength distributions and $2\nu 2\beta$ NME

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- $2\nu\beta\beta$
  - Role of real three-body forces and two-body currents (present collaboration with Pisa group)
  - Evaluation of the contribution of three-body correlations (blocking effect)
- $0\nu\beta\beta$
  - Derivation of the two-body effective operator
  - Calculation of the two-body transition-density matrix elements

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