Realistic shell-model and double-beta decay for ^{130}Te and ^{136}Xe

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Cortona, 2017 October 4th

This talk is based on the paper

Phys. Rev. C **95**, *064324 (2017)*,
Calculation of Gamow-Teller and two-neutrino double-β decay properties for ^{130}Te and ^{136}Xe with a realistic nucleon-nucleon potential

by

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- L. D.A., *INFN - Sezione di Napoli*;

Outline

1. About the $0\nu\beta\beta$ decay

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Introduction

The experimental discovery of neutrinoless double-β ($0\nu\beta\beta$) decay is nowadays one of the main targets in many laboratories all around the world.
It would have deep implications: "new physics" beyond the Standard Model.

The $0\nu\beta\beta$ can occur only if neutrino is its own antiparticle $\Rightarrow$
$\Rightarrow$ neutrino is a Majorana particle!

- Then, it would correspond to a violation of the lepton number conservation $\Rightarrow$ $\Delta L \neq 0$.
- Moreover, from a measured lifetime, it would be possible to determine an averaged neutrino mass $\Rightarrow$ $\langle m_\nu \rangle = \sum_i U_{ei}^2 m_i$, obtaining informations on the absolute neutrino mass scale and, potentially, on the neutrino mass hierarchy.

The nuclear matrix element

The inverse half-life of the $0\nu\beta\beta$ decay,

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}|M^{0\nu}|^2\langle m_\nu\rangle^2 ,$$

is proportional to

- $G^{0\nu}$, the so-called phase-space factor (obtained by integrating over the single electron energies and angles, and summing over the final-state spins);
- $\langle m_\nu\rangle^2$, the (squared) averaged neutrino mass;
- $|M^{0\nu}|^2$, where $M^{0\nu}$ is the nuclear matrix element (NME).

The NMEs are quite complicated to compute, due to the entanglement of nuclear and neutrino physics.
The available numerical estimations, due to different models, agree to within factors of two or three.
It is, indeed, a crucial point to choose proper candidate nuclei and models.

The best candidates for the $0\nu\beta\beta$ decay

Experimentally, twelve isotopes have been observed undergoing a $2\nu\beta\beta$ decay. They are:

$$^{48}\text{Ca}\,,\quad ^{76}\text{Ge}\,,\quad ^{78}\text{Kr}\,,\quad ^{82}\text{Se}\,,\quad ^{96}\text{Zr}\,,\quad ^{100}\text{Mo}\,,$$

$$^{116}\text{Cd}\,,\quad ^{128}\text{Te}\,,\quad ^{130}\text{Te}\,,\quad ^{136}\text{Xe}\,,\quad ^{150}\text{Nd}\,,\quad ^{238}\text{U}\,.$$

Among these, only the following are expeted to undergo a $0\nu\beta\beta$ decay:

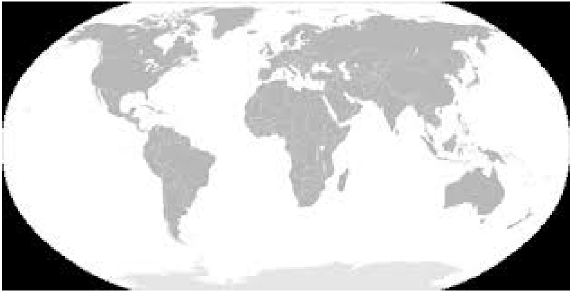
$$^{76}\text{Ge}\,,\quad ^{130}\text{Te}\,,\quad ^{136}\text{Xe}\,;$$

$$^{82}\text{Se}\,,\quad ^{100}\text{Mo}\,,\quad ^{116}\text{Cd}\,;$$

$$^{48}\text{Ca}\,,\quad ^{96}\text{Zr}\,,\quad ^{150}\text{Nd}\,.$$

This is due to some factors as, e.g., the Q-value of the reaction, the theoretical phase-space factor $G^{0\nu}$, and the isotopic abundance.

Our aim is to compute the $0\nu\beta\beta$ decay nuclear matrix elements (NMEs) for ^{130}Te and ^{136}Xe.
Those nuclei are currently under experimental investigation:



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INFN Laboratori Nazionali del Gran Sasso (AQ), Italy

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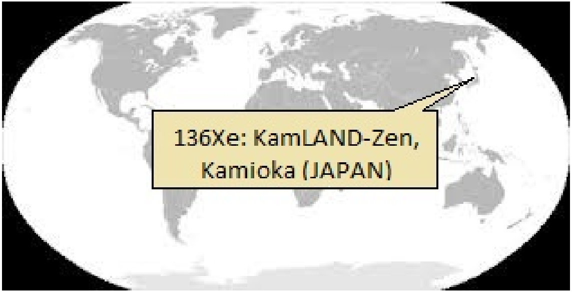

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Framework

Our framework is the realistic shell model, where all the parameters appearing in the SM Hamiltonian and in the transition operators are derived from a realistic free nucleon-nucleon NN potential V_{NN}, theoretically (MBPT).

$\Rightarrow$ No empirical parameters! No quenching of g_A and g_V!

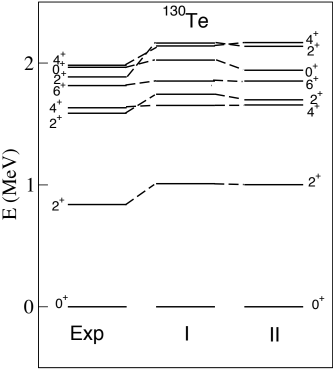
It is a mandatory step, however, to check this approach to calculate properties related to the GT strengths and $2\nu\beta\beta$ decays of ^{130}Te and ^{136}Xe, and compare the results with the available experimental data.

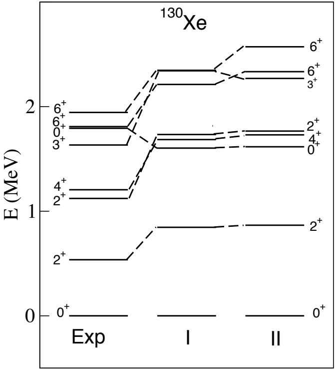
Realistic Shell-Model calculations

Our starting point:

- high-precision NN CD-Bonn potential, V_{NN}. The high-momentum components are smoothed out using the $V_{low\,k}$ approach with a cutoff $\Lambda = 2.6$ fm^{-1};
- core: (doubly-closed) ^{100}Sn;
- model space: five proton and neutron orbitals ($0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$, and $0h_{11/2}$);
- effective hamiltonian: H_{eff} obtained from 3rd order time-dependent perturbation theory;
- effective operators: Θ_{eff} derived consistently with H_{eff} by way of Many-Body Perturbation Theory;

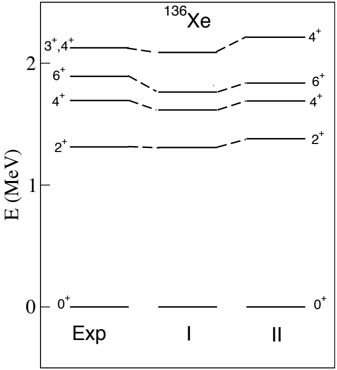
Spectroscopy of ^{130}Te and ^{130}Xe

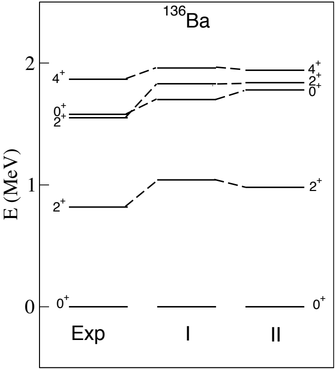




Nucleus	$J_i \to J_f$	$B(E2)_{Expt}$	I	II
^{130}Te				
	$2^+ \to 0^+$	580 ± 20	430	420
	$6^+ \to 4^+$	240 ± 10	220	200
^{130}Xe				
	$2^+ \to 0^+$	1170^{+20}_{-10}	954	876

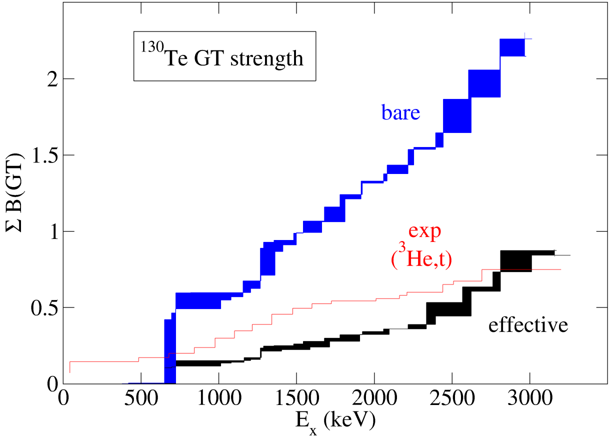
Spectroscopy of ^{136}Xe and ^{136}Ba





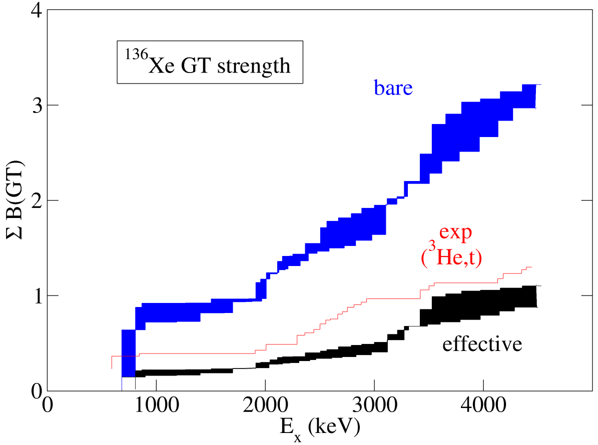
Nucleus	$J_i \rightarrow J_f$	$B(E2)_{Expt}$	I	II
^{136}Xe				
	$2^+ \rightarrow 0^+$	420 ± 20	300	300
	$4^+ \rightarrow 2^+$	53 ± 1	9	11
	$6^+ \rightarrow 4^+$	0.55 ± 0.02	1.58	2.42
^{136}Ba				
	$2^+ \rightarrow 0^+$	800^{+80}_{-40}	590	520

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



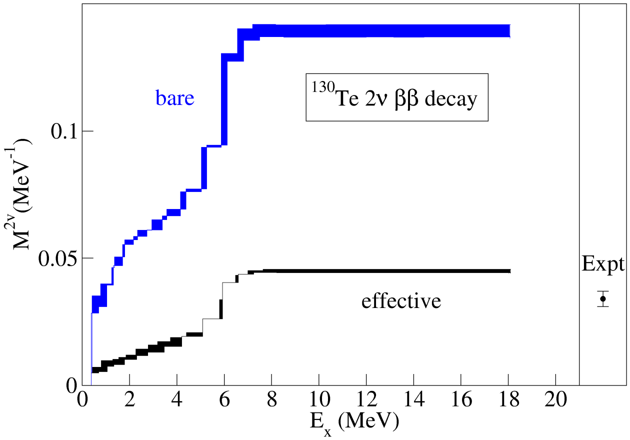
$$B(\mathrm{GT}) = \frac{\left|\langle\Phi_f|\sum_j \vec{\sigma}_j \vec{\tau}_j|\Phi_i\rangle\right|^2}{2J_i+1}$$

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



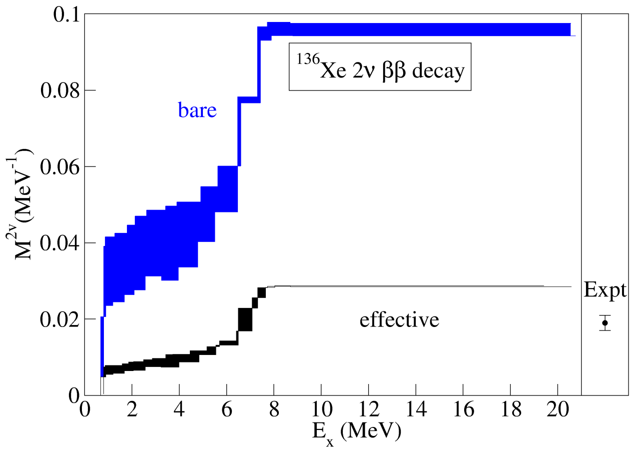
$$B(\mathrm{GT}) = \frac{\left|\langle \Phi_f | \sum_j \vec{\sigma}_j \vec{\tau}_j | \Phi_i \rangle\right|^2}{2J_i + 1}$$

^{130}Te $\rightarrow^{130}$ 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



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

Summary of the results

Experimental and calculated GT strengths and $2\nu\beta\beta$ decay NME (in MeV^{-1}) for ^{130}Te and ^{136}Xe

Nucleus	Expt.	I	II
^{130}Te			
GT strength	0.746 ± 0.045	0.842	0.873
NME	0.034 ± 0.003	0.044	0.046
^{136}Xe			
GT strength	1.33 ± 0.07	0.94	1.13
NME	0.0218 ± 0.0003	0.0285	0.0287

Outlook

Improvements on the $2\nu\beta\beta$ decay calculations:

- estimation of three-body forces contributions;
- role of two-body currents;
  (collaboration with PISA group)
- many-body correlations effects.
  (completed, report in a forthcoming paper)

Perspectives on the $0\nu\beta\beta$ decay:

- calculation of the $0\nu\beta\beta$ NME for ^{130}Te and ^{136}Xe;
  (collaboration with F. Nowacki - IPHC Strasbourg)
- application of our framework to ^{76}Ge and ^{82}Se.
  (forthcoming paper)

Thank you!

Perturbative properties of the effective operator

Decay	1st ord $M_{2\nu}^{GT}$	2nd ord $M_{2\nu}^{GT}$	3rd ord $M_{2\nu}^{GT}$	Expt.
$^{130}\mathrm{Te} \rightarrow ^{130}\mathrm{Xe}$ (I)	0.142	0.040	0.044	0.034 ± 0.003
$^{130}\mathrm{Te} \rightarrow ^{130}\mathrm{Xe}$ (II)	0.137	0.042	0.046	
$^{136}\mathrm{Xe} \rightarrow ^{136}\mathrm{Ba}$ (I)	0.0975	0.0272	0.0285	0.0218 ± 0.0003
$^{136}\mathrm{Xe} \rightarrow ^{136}\mathrm{Ba}$ (II)	0.0942	0.0277	0.0287	

- (I) theoretical SP energies
- (II) empirical SP energies fitted to the observed low-lying states in ^{133}Sb and ^{131}Sn

Matrix elements of the neutron-proton effective GT^- operator

$n_a l_a j_a$ $n_b l_b j_b$	3rd order $\mathrm{GT}^-_{\mathrm{eff}}$	quenching
$0g_{7/2}$ $0g_{7/2}$	-1.239	0.50
$0g_{7/2}$ $1d_{5/2}$	-0.019	
$1d_{5/2}$ $0g_{7/2}$	0.131	
$1d_{5/2}$ $1d_{5/2}$	1.864	0.64
$1d_{5/2}$ $1d_{3/2}$	-1.891	0.61
$1d_{3/2}$ $1d_{5/2}$	1.794	0.58
$1d_{3/2}$ $1d_{3/2}$	-1.023	0.66
$1d_{3/2}$ $2s_{1/2}$	-0.093	
$2s_{1/2}$ $1d_{3/2}$	0.117	
$2s_{1/2}$ $2s_{1/2}$	1.598	0.65
$0h_{11/2}$ $0h_{11/2}$	2.597	0.69