The nuclear matrix elements of $0\nu\beta\beta$ decay and the NUMEN project at INFN-LNS

MEDEX'17 meeting "Matrix Elements for the Double beta decay EXperiments"

PRAGUE, May 29 - June 2, 2017
Physics case tutorial
Double $\beta$-decay

\[ \frac{A}{Z}X_N \rightarrow \frac{A}{Z-2}Y_{N+2} + 2e^- + (2\bar{\nu}) \]

- Process mediated by the \textit{weak interaction} observable in even-even nuclei where the single $\beta$-decay is energetically forbidden

- The role of the \textit{pairing force}
Double $\beta$-decay

**Two-neutrino double beta decay**

Observed in 11 nuclei since 1987

1. Within standard model
2. $T_{1/2} \approx 10^{19}$ to $2 \times 10^{21}$ yr

\[
1/T_{1/2}^{2\nu} (0^+ \rightarrow 0^+) = G_{2\nu} |M^{\beta\beta 2\nu}|^2
\]

**Neutrinoless double beta decay**

Still not observed

E. Majorana, Il Nuovo Cimento 14 (1937) 171
W. H. Furry, Phys Rev. 56 (1939) 1184

1. Beyond standard model
2. Access to effective neutrino mass
3. Violation of lepton number conservation
4. CP violation in lepton sector
5. A way to leptogenesis and GUT

\[
1/T_{1/2}^{0\nu} (0^+ \rightarrow 0^+) = G_{0\nu} \left|M^{\beta\beta 0\nu}\right|^2 \frac{\langle m_\nu \rangle^2}{m_e^4}
\]
<table>
<thead>
<tr>
<th>Experiment</th>
<th>Isotope</th>
<th>Lab</th>
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</thead>
<tbody>
<tr>
<td>GERDA</td>
<td>$^{76}$Ge</td>
<td>LNGS [Italy]</td>
</tr>
<tr>
<td>CUORE</td>
<td>$^{130}$Te</td>
<td>LNGS [Italy]</td>
</tr>
<tr>
<td>Majorana</td>
<td>$^{76}$Ge</td>
<td>SURF [USA]</td>
</tr>
<tr>
<td>KamLAND-Zen</td>
<td>$^{136}$Xe</td>
<td>Kamioka [Japan]</td>
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<tr>
<td>EXO/nEXO</td>
<td>$^{136}$Xe</td>
<td>WIPP [USA]</td>
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<tr>
<td>CUPID - Lucifer</td>
<td>$^{82}$Se, $^{100}$Mo</td>
<td>LNGS [Italy]</td>
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<tr>
<td>SNO+</td>
<td>$^{130}$Te</td>
<td>Sudbury [Canada]</td>
</tr>
<tr>
<td>SuperNEMO</td>
<td>$^{82}$Se (or others)</td>
<td>LSM [France]</td>
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<tr>
<td>CANDLES</td>
<td>$^{48}$Ca</td>
<td>Kamioka [Japan]</td>
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<tr>
<td>COBRA</td>
<td>$^{116}$Cd</td>
<td>LNGS [Italy]</td>
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<tr>
<td>DCBA</td>
<td>many</td>
<td>[Japan]</td>
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<tr>
<td>AMoRe</td>
<td>$^{100}$Mo</td>
<td>[Korea]</td>
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<tr>
<td>MOON</td>
<td>$^{100}$Mo</td>
<td>[Japan]</td>
</tr>
<tr>
<td>PandaX-III</td>
<td>$^{136}$Xe</td>
<td>[China]</td>
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</table>
New physics for the next decades

but

requires

Nuclear Matrix Element (NME)!

\[ |M_{\beta\beta0}\rangle^2 = \left| \langle \Psi | \hat{O}_{\beta\beta0} | \Psi \rangle \right|^2 \]


✓ Measurements (still not conclusive for 0\nu\beta\beta):

(\pi^+, \pi^-)

single charge exchange (\(^3\)He,t), (d,\(^2\)He)
electron capture
transfer reactions
muon nucleus scattering ...

✓ A new experimental tool: heavy-ion Double Charge-Exchange (DCE)

E. Courrier, et al., PRL 100 (2008) 052503
S.J. Freeman and J.P. Schiffer JPG 39 (2012) 124004
D. Frekers, Prog. Part. Nucl. Phys. 64 (2010) 281
J.P. Schiffer, et al., PRL 100 (2008) 112501

Heavy-ion DCE as surrogate processes

- Induced by strong interaction

- Sequential nucleon transfer mechanism 4th order:

- Meson exchange mechanism 2nd order or even 1st order in the nucleus-nucleus potential

- Possibility to go in both directions

Tiny amount of DGT strength in low lying states

Sum rule almost exhausted by DGT Giant Mode
Differences

- DCE mediated by **strong interaction**, $0\nu\beta\beta$ by **weak interaction**
- DCE includes **sequential transfer mechanism**

Similarities

- **Same initial and final states:** Parent/daughter states of the $0\nu\beta\beta$ decay are the same as those of the target/residual nuclei in the DCE
- **Similar operator:** Fermi, Gamow-Teller and rank-2 tensor components are present in both the transition operators, with tunable weight in DCE
- **Large linear momentum** ($\sim 100$ MeV/c) available in the virtual intermediate channel
- **Non-local** processes: characterized by two vertices localized in a pair of valence nucleons
- **Same nuclear medium**: Constraint on the theoretical determination of quenching phenomena on $0\nu\beta\beta$
- **Off-shell propagation** through virtual intermediate channels
DCE @ INFN-LNS
The LNS laboratory in Catania
Superconducting Cyclotron and MAGNEX spectrometer @ LNS

crucial for the experimental challenges

K800 Superconducting Cyclotron

- In operation since 1996.
- Accelerates from H to U ions
- Maximum energy 80 MeV/u.

MAGNEX spectrometer


Achieved resolution

<table>
<thead>
<tr>
<th>Measured values</th>
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<tbody>
<tr>
<td>Energy $\Delta E/E \sim 1/1000$</td>
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<tr>
<td>Angle $\Delta \theta \sim 0.2^\circ$</td>
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<tr>
<td>Mass $\Delta m/m \sim 1/160$</td>
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</table>

Optical characteristics

<table>
<thead>
<tr>
<th>Measured values</th>
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<tbody>
<tr>
<td>Maximum magnetic rigidity</td>
</tr>
<tr>
<td>Solid angle</td>
</tr>
<tr>
<td>Momentum acceptance</td>
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<tr>
<td>Momentum dispersion for $k= -0.104$ (cm/%)</td>
</tr>
</tbody>
</table>

1.8 T m
50 msr
-14.3%, +10.3%
3.68
**The MAGNEX FPD**

- **Quadrupole**
- **Dipole**
- **1.91 m**

**Scattering Chamber**

**Focal Plane Detector**
- active area $140 \times 20 \text{ cm}^2$

**Ionization drift chamber**, five independent proportional counters, four of which are position-sensitive and a **wall of stopping silicon detectors**

**Pure isobutane; pressure range: 5-100 mbar; 600-800 V, wires $\phi=20 \mu m$**

**Wall of 60 stopping 7 X 5 cm$^2$ Silicon detectors**

**View of the stripped anode**

**Multiwire gas tracker and $\Delta E$ stage**

(\(^{18}\text{O},^{18}\text{Ne}\)) DCE reactions at LNS

First pilot experiment

- \(^{18}\text{O}^7+\) beam from Cyclotron at 270 MeV (10 pnA, 3300 μC in 10 days)
- \(^{40}\text{Ca}\) solid target 300 μg/cm\(^2\)
- Ejectiles detected by the MAGNEX spectrometer (0° < \(\theta_{\text{lab}}\) < 10°)
- Unique angular setting: -2° < \(\theta_{\text{lab}}\) < 10° corresponding to a momentum transfer range from 0.17 fm\(^{-1}\) to about 2.2 fm\(^{-1}\)

\(^{18}\text{O}^{18}\text{Ne}\) reactions at LNS

- \(^{40}\text{Ca}(^{18}\text{O},^{18}\text{Ne})^{40}\text{Ar} @ 270\text{ MeV}\)

\(^{18}\text{O} + ^{40}\text{Ca} \rightarrow ^{16}\text{O} + ^{42}\text{Ca}\) Measured

\(^{18}\text{O} + ^{40}\text{Ca} \rightarrow ^{18}\text{F} + ^{40}\text{K}\) Not measured

\(^{18}\text{O} + ^{40}\text{Ca} \rightarrow ^{18}\text{Ne} + ^{40}\text{Ar}\) Not measured

\(^{20}\text{Ne} + ^{38}\text{Ar}\) Not measured
$^{40}\text{Ca}(^{18}\text{O},^{18}\text{Ne})^{40}\text{Ar @ 270 MeV}$

$$d\sigma / d\Omega_{DCE} (q, \omega) = \sigma_{DCE}^{DCE}(E_p, A)F_{DCE}(q, \omega)B_{DCE}(\alpha)B_{DCE}^{DCE}(\alpha)$$

$$d\sigma / d\Omega_{DCE} (q, \omega) = \delta_{DCE}^{DCE}(E_p, A)F_{DCE}^{DCE}(q, \omega)$$


Pauli blocking about 0.14 for F and GT
The role of the transfer reaction and the competing processes

Less than 1% effect in the DCE cross section

Single charge exchange

Extracted $B(\text{GT}) = 0.087$

$B(\text{GT})$ from $(^3\text{He},t) = 0.083$

Y. Fujita
Moving towards hot-cases:

Caveat

- The reaction Q-values are normally more negative than in the $^{40}$Ca case.

- The $(^{18}O, ^{18}Ne)$ reaction is particularly advantageous, but it is of $\beta^+\beta^+$ kind.

- None of the reactions of $\beta^-\beta^-$ kind looks like as favourable as the $(^{18}O, ^{18}Ne)$. $(^{18}Ne, ^{18}O)$ requires a radioactive beam. $(^{20}Ne, ^{20}O)$ or $(^{12}C, ^{12}Be)$ have smaller $B(GT)$.

- In some cases gas or implanted target will be necessary, e.g. $^{136}Xe$ or $^{130}Xe$.

- In some cases the energy resolution is not enough to separate the g.s. from the excited states in the final nucleus $\rightarrow$ Coincident detection of $\gamma$-rays.

Much higher beam current is needed.
The NUMEN project

Spokespersons: F. Cappuzzello (cappuzzello@lns.infn.it) and C. Agodi (agodi@lns.infn.it)


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School of Physics and Astronomy Tel Aviv University, Israel

H. Petracsu,

IFIN-HH, Bucarest, Romania

\[ 1/T_{1/2}^{0\nu} (0^+ \rightarrow 0^+) = G_0 \left| M^{\beta\beta 0\nu} \right|^2 \left( \frac{m_\nu}{m_e} \right)^2 \]
A broad view

- TeBe
- CS-upgrade
- SiCILIA INFN call
- Theory
- NUMEN_gr3 (R&D and experiments)
- INFN CSN-III
- NURE
- Other regional projects
Present technology is not enough...

The challenge: to detect with good energy, mass and angular resolutions rare events at very high rates of heavy ions!

- Upgraded set-up to match about 1000 times more beam current than the present
- Substantial change in the technologies used in CS and in the MAGNEX detector
The Goals of the Research Program

Main goal (Holy Grail):
Extraction from measured cross-sections of “data-driven” information on NME for all the systems candidate for 0νββ

Mid-term goals:

- **Constraints** to the existing theories of NMEs
- Model-independent **comparative information** on the sensitivity of half-life experiments
- Complete study of the **reaction mechanism**
Status and perspectives of NUMEN
The Phases of NUMEN project

- **Phase 1**: The experimental feasibility
- **Phase 2**: “hot” cases optimizing the experimental conditions and getting first results (approved)
- **Phase 3**: The facility Upgrade (Cyclotron, MAGNEX, beam lines, .....
- **Phase 4**: The systematic experimental campaign

**Time table**

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<tbody>
<tr>
<td>Phase 1</td>
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<td>Phase 2</td>
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<td>Phase 3</td>
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<tr>
<td>Phase 4</td>
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Recent NUMEN experiments
## Facing some hot cases in Phase 2

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Energy (MeV/u)</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
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</thead>
<tbody>
<tr>
<td>$^{116}\text{Sn} \left( ^{18}\text{O}, ^{18}\text{Ne} \right) ^{116}\text{Cd}$</td>
<td>15-30</td>
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<tr>
<td>$^{116}\text{Cd} \left( ^{20}\text{Ne}, ^{20}\text{O} \right) ^{116}\text{Sn}$</td>
<td>15-25</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$^{130}\text{Te} \left( ^{20}\text{Ne}, ^{20}\text{O} \right) ^{130}\text{Xe}$</td>
<td>15-25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{76}\text{Ge} \left( ^{20}\text{Ne}, ^{20}\text{O} \right) ^{76}\text{Se}$</td>
<td>15-25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{76}\text{Se} \left( ^{18}\text{O}, ^{18}\text{Ne} \right) ^{76}\text{Ge}$</td>
<td>15-30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{106}\text{Cd}\left( ^{18}\text{O}, ^{18}\text{Ne} \right) ^{106}\text{Pd}$</td>
<td>15-30</td>
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</table>
Recent NUMEN R&D
Major upgrade of LNS facilities: The CS accelerator

• The **CS** accelerator current (from 100 W to 5-10 kW);

![Diagram of accelerator with extraction channels]

• The **beam transport line** transmission efficiency to nearly 100%

TDR of the project approved
Cryostat tender started (~4.1M€)
A challenging beam dump inside the MAGNEX hall

Present MAGNEX hall

Future MAGNEX hall
A challenging beam dump inside the MAGNEX hall

85 μA beam of $^{18}$O on Ag

Silver beam dump 20 kW

85 μA beam of $^{20}$Ne on $^{76}$Ge+C

From S. Russo (LNS radioprotection service)
The new focal plane detector
Major upgrade of LNS facilities: MAGNEX

- The **MAGNEX focal plane** detector rate (from 2 kHz to several MHz)

  From multi-wire tracker  |  To micro-pattern tracker

- R&D key issue: MPGD-based tracker at low pressure and wide dynamic range
- INFN-LNS, collaboration with INFN-CT, UNAM, MSU

From wall of 60 Si pad  |  To wall of 2500 SiC-SiC pad telescopes

- A big challenge!
- Call approved by INFN CSN5 (SICILIA)
- collaboration with CNR, STM, FBK

About $10^{14}$ ions to be collected in 10 years
Other upgrades

- The **MAGNEX** maximum magnetic **rigidity** (from 1.8 Tm to 2.5 Tm)

- The **target** technology for intense heavy-ion beams

- An **array of scintillators for γ-rays** measurement in coincidence with MAGNEX
Other upgrades

Electronics for very high rate

A new test bench facility for detector developments

Plan_B for particle identification

- Data Acquisition
- Irradiation tests
- Data Reduction

Simulations
One of the three pillars of NUMEN (formal development and calculations)

**Development of theory**

**Weak Interaction $0\nu 2\beta$ decay and Strong Interaction Analogue**

- Simultaneous $d \rightarrow u$ $\Delta q=+1$ transitions by emission of a virtual weak gauge boson $W^-$
  - $W^-$ decays into electron and Majorana neutrino
- Correlation of the two events by exchange of the virtual $\nu_e \bar{\nu}_e$ pair
- Emission of two electrons ON their mass-shell: $p^2_e = m^2_e$
- Direct observation (GERDA@LNGS...)

**Hadronic Analogue**

- Simultaneous $d \rightarrow u$ $\Delta q=+1$ transitions by emission of a virtual $d\bar{u}$ vector pair $\leftrightarrow \rho^-$ meson
- $\rho^+ \rightarrow \pi^+ + \pi^0$ decay into a pair of pions
- Heavy vector mesons $\rho^*$
- Correlation of the two events by exchange of the virtual qq pair as contained in $\pi^0 \equiv (d\bar{u} + u\bar{d})/\sqrt{2}$
- Emission of two $\pi^-$ OFF their mass-shell: $p^2 \neq m^2_\pi$
- No direct observation

H. Lenske, Genova, May, 2017
Conclusions and Outlooks

- NUMEN represents a challenging perspective for the future of LNS in nuclear science
- The project turns around the MAGNEX and the Cyclotron upgrade toward high intensity
- Results of relevance for $0\nu\beta\beta$ physics already got in the initial campaigns
- A big challenge for nuclear technology and nuclear theory
Conference on Neutrinos and Nuclear Physics (CNNP2017)

15-21 October 2017
Catania (Italy)

http://agenda.infn.it/event/CNNP2017

Registration open