THE NUCLEAR MATRIX ELEMENTS OF 0νββ DECAY AND THE NUMEN PROJECT AT INFN-LNS

F. Cappuzzello

The NUMEN collaboration


Collaborations

INFN LNF
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CERN
BROKHAVEN NATIONAL LABORATORY
INSTITUTE OF MODERN PHYSICS, CHINESE ACADEMY OF SCIENCES, LANZHOU, CHINA
RCNP, OSAKA UNIVERSITY, OSAKA, JAPAN

Spokespersons: F. Cappuzzello (cappuzzello@lns.infn.it) and C. Agodi (agodi@lns.infn.it)
Search for $0\nu\beta\beta$ decay. A worldwide race

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Isotope</th>
<th>Lab</th>
<th>Status</th>
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<td>GERDA</td>
<td>$^{76}\text{Ge}$</td>
<td>LNGS</td>
<td>Phase I completed Migration to Phase II</td>
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<td>SNOLAB</td>
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<tr>
<td>SuperNEMO demonstrator</td>
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<td>LSM</td>
<td>R&amp;D / Construction</td>
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<tr>
<td>Candles</td>
<td>$^{48}\text{Ca}$</td>
<td>Kamioka</td>
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<td>AMoRe</td>
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<td>[Korea]</td>
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<td>MOON</td>
<td>$^{100}\text{Mo}$</td>
<td>[Japan]</td>
<td>R&amp;D</td>
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</table>
New physics for the next decades

but
requires

Nuclear Matrix Element (NME)!

\[ |M^{\beta\beta0\nu}_\varepsilon|^2 = \left| \left\langle \Psi_f | \hat{O}^{\beta\beta0\nu}_\varepsilon | \Psi_i \right\rangle \right|^2 \]

✓ Calculations (still sizeable uncertainties): QRPA, Large scale shell model, IBM ..... E. Caurier, et al., PRL 100 (2008) 052503
N. L. Vaquero, et al., PRL 111 (2013) 142501
J. Barea, PRC 87 (2013) 014315

✓ Measurements (still not conclusive for 0νββ):
  \((\pi^+, \pi^-)\)
  single charge exchange \((^3\text{He},t)\)
  electron capture
  transfer reactions ...

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

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
A new experimental tool: DCE
Heavy-ion DCE

1. Induced by strong interaction

2. Sequential nucleon transfer mechanism 4\textsuperscript{th} order:
   - Brink’s Kinematical matching conditions \cite{Brink1972}

3. Meson exchange mechanism 2\textsuperscript{nd} order

4. Possibility to go in both directions
0νββ vs HI-DCE

1. **Initial and final states:** Parent/daughter states of the 0νββ are the same as those of the target/residual nuclei in the DCE;

2. **Spin-Isospin mathematical structure** of the transition operator: Fermi, Gamow-Teller and rank-2 tensor together with higher L components are present in both cases;

3. **Large momentum available:** A linear momentum as high as 100 MeV/c or so is characteristic of both processes;

4. **Non-locality:** both processes are characterized by two vertices localized in two valence nucleons. In the ground to ground state transitions in particular a pair of protons/neutrons is converted in a pair of neutrons/protons;

5. **In-medium** processes: both processes happen in the same nuclear medium, thus quenching phenomena are expected to be similar;

6. Relevant **off-shell propagation** in the intermediate channel: both processes proceed via the same intermediate nuclei off-energy-shell even up to 100 MeV.
About the reaction mechanism
Factorization of the charge exchange cross-section

for single CEX:

\[
\frac{d\sigma}{d\Omega}(q, \omega) = \hat{\sigma}_\alpha(E_p, A) F_\alpha(q, \omega) B_T(\alpha) B_P(\alpha)
\]

\[
\hat{\sigma}(E_p, A) = K(E_p, 0) |J_{ST}|^2 N_{ST}^D
\]

unit cross-section

\[\beta\text{-decay transition strengths (reduced matrix elements)}\]

generalization to DCE:

\[
\frac{d\sigma}{d\Omega_{DCE}}(q, \omega) = \hat{\sigma}_{\alpha}^{DCE}(E_p, A) F_{\alpha}^{DCE}(q, \omega) B_T^{DCE}(\alpha) B_P^{DCE}(\alpha)
\]

\[
\hat{\sigma}_{\alpha}^{DCE}(E_p, A) = K(E_p, 0) |J'_{ST}|^2 N_{ST}^D
\]
The unit cross section

Single charge-exchange

\[ \hat{\sigma}(E_p, A) = K(E_p, 0) |J_{ST}|^2 N_{ST}^D \]

\( J_{ST} \) Volume integral of the \( V_{ST} \) potential

Double charge-exchange

\[ \hat{\sigma}_{DCE}^\alpha(E_p, A) = K(E_p, 0) |J'_{ST}|^2 N_{ST}^D \]

\( J'_{ST} \) Volume integral of the \( V_{ST}G_{V_{ST}} \) potential,
where \( G = \sum_n \frac{|n\rangle\langle n|}{E_n - (E_i + E_f)/2} \) is the intermediate channel propagator (including off-shell)

\[ \hat{\sigma}_{DCE}^\alpha(E_p, A) \text{ is the Holy Graal} \]

If known it would allow to determine the NME from DCE cross section measurement, whatever is the strenght fragmentation.
The volume integrals

Nuclear spin and isospin excitations

Franz Osterfeld

Reviews of Modern Physics, Vol. 64, No. 2, April 1992

✓ Volume integrals are larger at smaller energies

✓ They enter to the fourth power in the unit cross section!

✓ GT-F competition at low energy

FIG. 15. Energy and momentum dependence of the free nucleon-nucleon $t_p$ matrix. The upper part of the figure shows the energy dependence of the central components of the effective $t_p$ matrix at zero-momentum transfer (including direct and exchange terms). The $G$-matrix interaction of Bertsch et al. (1977) was used below 100 MeV and joined smoothly to the $t_p$ matrix above 100 MeV. The lower figures show the momentum dependence of the 135-MeV $t_p$ matrix for natural-left figure) and unnatural-right figure) parity transitions. Isoscalar and isovector central (C), spin-orbit (LS), and tensor (T) components are shown. From Petrovich and Love (1981).
Methodology for NME

$0\nu\beta\beta$ - decay

\[
1/T_{1/2}^{0\nu} (0^+ \rightarrow 0^+) = G_{0\nu}|M_{\beta\beta0\nu}|^2 \left| \langle m_\nu \rangle \right|^2
\]

$Q_{EC} = 923$ keV

$Q_{\beta^-\beta^-} = 2039.00(5)$ keV

$Q_{\beta^-} = 2962$ keV

$J^{\pi} = 1^+$

$1^+ \ 120.258(1)$ keV

$1^+ \ 86.787(1)$ keV

$1^+ \ 44.425(1)$ keV

DCE @ INFN-LNS
The Superconducting Cyclotron (CS) at LNS

The LNS K800 Superconducting Cyclotron
in operation since 1994

It can accelerate from Hydrogen to Uranium
Maximum nominal energy is 80 MeV/u

INFN-LNS: nuclear physics and accelerators
<table>
<thead>
<tr>
<th>Optical characteristics</th>
<th>Measured values</th>
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</thead>
<tbody>
<tr>
<td>Maximum magnetic rigidity</td>
<td>1.8 T m</td>
</tr>
<tr>
<td>Solid angle</td>
<td>50 msr</td>
</tr>
<tr>
<td>Momentum acceptance</td>
<td>-14.3%, +10.3%</td>
</tr>
<tr>
<td>Momentum dispersion for (k=)</td>
<td>3.68</td>
</tr>
</tbody>
</table>

**Achieved resolution**

- Energy \(\Delta E/E \sim 1/1000\)
- Angle \(\Delta \theta \sim 0.2^\circ\)
- Mass \(\Delta m/m \sim 1/160\)

F. Cappuzzello et al., *MAGNEX: an innovative large acceptance spectrometer for nuclear reaction studies*, in Magnets: Types, Uses and Safety (Nova Publisher Inc., NY, 2011) pp. 1–63.
(\(^{18}\text{O},^{18}\text{Ne}\)) DCE reactions at LNS

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

First pilot experiment

\[0^\circ < \theta_{\text{lab}} < 10^\circ \quad Q = -5.9 \text{ MeV}\]

- \(^{18}\text{O}\) and \(^{18}\text{Ne}\) belong to the same multiplet in \(S\) and \(T\)
- Very low polarizability of core \(^{16}\text{O}\)
- Sequential transfer processes very mismatched \(Q_{opt} \sim 50 \text{ MeV}\)
- Doubly magic target
\[ 40\text{Ca}(^{18}\text{O},^{18}\text{Ne})^{40}\text{Ar} \]

**Projectile**

Super-allowed transition
GT strength not fragmented

**Target**

GT strength not much fragmented

Y. Fujita, private communication
Pauli blocked for F and GT
Experimental Set-up

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

Diagram:

- $^{18}\text{O} + ^{40}\text{Ca}$
- $^{16}\text{O} + ^{42}\text{Ca}$
- $^{18}\text{F} + ^{40}\text{K}$
- $^{18}\text{Ne} + ^{40}\text{Ar}$
- $^{20}\text{Ne} + ^{38}\text{Ar}$
Particle Identification

Z identification

A. Cunsolo, et al., NIMA484 (2002) 56
A. Cunsolo, et al., NIMA481 (2002) 48
F. Cappuzzello et al., NIMA621 (2010) 419
F. Cappuzzello, et al. NIMA638 (2011) 74

A identification

\[ B_\rho = \frac{p}{q} \]

\[ X_{\text{loc}} \propto \frac{m}{q} E_{\text{resid}} \]
Single CEX $^{40}$Ca($^{18}$O, $^{18}$F)$^{40}$K at 15 MeV/u

$2 \times 10^{-2}$ $^{40}$Ca($^{18}$O, $^{18}$F)$^{40}$K

$2.6^\circ \leq \theta_{lab} \leq 4.6^\circ$

$\frac{d\sigma}{dE_x}$ [mb/MeV]

$1 \times 10^{-2}$

$0.03 + 0.80 \pm 0.09 + g.s.$

$2.27 + 2.39 + 2.73$

$4.38$

$E_x$ [MeV]

$x$-section (2MeV < $E_x$ < 3MeV)

$\approx 0.5$ mb/sr

Extracted $B$(GT) = 0.087$\pm$0.01

$B$(GT) from ($^3$He,t) = 0.083

Y. Fujita

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Single CEX $^{116}$Sn($^{18}$O,$^{18}$F)$^{116}$In at 25 MeV/u

$3.5^\circ \leq \theta_{lab} \leq 4.5^\circ$

Counts/400keV

Excitation Energy (MeV)

$97$ counts in $1$ MeV

Preliminary analysis!

$x$-section (within 1 MeV)

$\approx 0.17$ mb/sr

Extracted upper limit for $B$(GT) < 0.8

$B$(GT) from (d, $^2$He) = 0.4

S.Rakers, et al., PRC 71 (2005) 054313
The role of the transfer reactions

$^{40}\text{Ca}(^{18}\text{O},^{20}\text{Ne})^{38}\text{Ar} @ 270 \text{ MeV}$

$0^\circ < \theta_{\text{lab}} < 10^\circ$

differential cross section $\frac{d\sigma}{d\Omega}(L=0; \theta=0^\circ) \sim 10 \mu\text{b/sr}$

$g.s., L_{\text{max}} = 4$

$g.s. + 2.167 L = 2$

$g.s. + 2.167 L = 6$

$g.s. + 2.167 L = 8$

Suppression of the $^{40}\text{Ca}(^{18}\text{O},^{16}\text{O})^{42}\text{Ca}$ channel

Very weak

Suppression of $L = 0$ in the pair transfer

Suppression of $L > 0$ in the double pair transfer

Less than 1% effect in the DCE cross section
The $^{40}\text{Ar}$ $0^+$ ground state is well separated from the first excited state $2^+$ at 1.46 MeV.
$^{40}\text{Ca}_{\text{g.s.}}(0^+) (^{18}\text{O}, ^{18}\text{Ne})^{40}\text{Ar}_{\text{g.s.}} (0^+) \ @ \ 270 \text{ MeV}$

\[ \frac{d\sigma}{d\Omega_{\text{DCE}}} (q, \omega) = \delta_{\alpha}^{\text{DCE}} (E_p, A) F_{\alpha}^{\text{DCE}} (q, \omega) B_{T}^{\text{DCE}} (\alpha) B_{P}^{\text{DCE}} (\alpha) \]

\[ \frac{d\sigma}{d\Omega_{\text{DCE}}} (q, \omega) = \delta_{\alpha}^{\text{DCE}} (E_p, A) F_{\alpha}^{\text{DCE}} (q, \omega) \]

$B_{T}^{\text{DCE}} (GT) B_{P}^{\text{DCE}} (GT) \leq 0.20$

to be compared with 0.11

Preliminary
Preliminary matrix elements

Pure GT

$$|M_{40Ca \rightarrow 40Ar}^{DCE} (GT)|^2 = 0.42 \pm 0.21$$

Pure F

$$|M_{40Ca \rightarrow 40Ar}^{DCE} (F)|^2 = 0.28 \pm 0.14$$

$$|M^{0\nu\beta\beta} (^{40}Ca)|^2 = 0.37 \pm 0.18$$

Assuming a closure approximation for all multipolarities we get an uncertainty of 20% by changing the closure energy from 0 to 50 MeV

Pauli blocking about 0.14 for F and GT

Just to speculate: removing Pauli blocking one can roughly estimate

$$|M^{0\nu\beta\beta} (^{48}Ca)|^2 = 2.6 \pm 1.3$$
Moving towards hot-cases

Caveat

- The \((^{18}\text{O},^{18}\text{Ne})\) 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 \((^{18}\text{O},^{18}\text{Ne})\). \((^{18}\text{Ne},^{18}\text{O})\) requires a radioactive beam \((^{20}\text{Ne},^{20}\text{O})\) or \((^{12}\text{C},^{12}\text{Be})\) have smaller \(B(\text{GT})\)
- In some cases gas target will be necessary, e.g. \(^{136}\text{Xe}\) or \(^{130}\text{Xe}\)
- In some cases the energy resolution is not enough to separate the g.s. from the excited states in the final nucleus → Coincident detection of \(\gamma\)-rays
- A strong fragmentation of the double GT strength is known in the nuclei of interest compared to the \(^{40}\text{Ca}\).
Major upgrade of LNS facilities: NUMEN

- The **CS** accelerator current upgrade (from 100 W to 5-10 kW);
- The **MAGNEX focal plane** detector will be upgraded from 2 khz to 500 khz
- The **MAGNEX** maximum magnetic **rigidity** will be increased
- An **array of detectors for γ-rays** measurement in coincidence with MAGNEX will be built
- The **beam transport line** transmission efficiency will be upgraded from about 70% to nearly 100%
- The **target** technology for intense heavy-ion beams will be developed
- **Nuclear reaction theory** upgrading
The NUMEN goals
The NUMEN goals:

**Constraints to theory**
A new generation of DCE constrained $0\nu\beta\beta$ NME theoretical calculations can emerge

**NUMEN Holy Graal**
Getting $\sigma^{DCE}$ as a predictable function of $E_p$ and $A$

- Requires cross section factorisation
- Experimentally requires large systematics

**Compare sensitivity**
Sensitivity of different half-life experiments
- Requires factorisation
- Sizeable inaccuracies reduced in the ratio
- Does not require systematics

Does not require factorisation
Does not require systematics
Requires reaction theory
The Phases of NUMEN project

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

**Preliminary time table**

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An intense experimental activity in phase 2

<table>
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<tr>
<th>Reaction</th>
<th>Energy (MeV/u)</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
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<tr>
<td>&quot;^116\text{Sn} (^{18}\text{O}, ^{18}\text{Ne}) ^{116}\text{Cd}</td>
<td>15-30</td>
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<tr>
<td>&quot;^116\text{Cd} (^{20}\text{Ne}, ^{18}\text{O}) ^{116}\text{Sn}</td>
<td>15-25</td>
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<tr>
<td>&quot;^116\text{Te} (^{20}\text{Ne}, ^{18}\text{O}) ^{116}\text{Sn}</td>
<td>15-25</td>
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<tr>
<td>&quot;^7\text{Ge} (^{18}\text{O}, ^{18}\text{Ne}) ^{7}\text{Se}</td>
<td>15-30</td>
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<td>&quot;^{10}\text{Cd} (^{18}\text{O}, ^{18}\text{Ne}) ^{10}\text{Pd}</td>
<td>15-30</td>
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An intense R&D activity in phase 2

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<th>Activity</th>
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<th>2017</th>
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<td>Electric field simulations</td>
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<td>Study of positive ions backflow</td>
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<td></td>
<td>Development of read-out system</td>
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<td>Construction of a prototype</td>
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<td></td>
<td>Tests with radioactive-sources and beam</td>
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<td>Design of the final detector</td>
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<td>Design of the final segmented read-out electrode</td>
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<tr>
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<td>Construction of the final detector</td>
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</table>

| PID-wall | Radiation hardness test of SiC CsI | | | |
| | Prototyping different thicknesses and area SiC detectors | | | |
| | Building a SiC-CsI PID module | | | |
| | Developing read-out electronics | | | |
| | Design of the final PID-wall | | | |
| | Construction of the final detector | | | |

| Magnetic rigidity | Magnetic field simulations | | | |
| | Installation or new power supplies | | | |

| Čerenkov \( \gamma \)-ray calorimeter | Prototyping different detector solutions | | | |
| | Radio-active source and in-beam tests | | | |
| | Design of the final detector assembly | | | |
Conclusions and Outlooks

- Many facilities for $0\nu\beta\beta$ half life, but not for the NME
- Pioneering experiments at RCNP (Osaka) and LNS (Catania) are showing that the $(^{18}\text{O},^{18}\text{Ne})$ cross section can be suitably measured
- First results for the $(^{18}\text{O},^{18}\text{Ne})$ are encouraging, showing that quantitative information on $0\nu\beta\beta$ NME are not precluded
- Good to have NME calculations also for $(^{40}\text{Ca},^{40}\text{Ar})$