Investigation of double beta decay of $^{58}\text{Ni}$ with the Obelix spectrometer

N.I. Rukhadze (JINR, Dubna) on behalf of Obelix collaboration

JINR Dubna, Russia
IEAP, CTU Prague, Czech Republic
LSM Modane, France

Medex’17, Prague, May 31, 2017
SEARCH FOR DOUBLE BETA DECAY

At present $2\nu2\beta^-$ decay was detected in 11 nuclei:
$^{48}\text{Ca}$, $^{76}\text{Ge}$, $^{82}\text{Se}$, $^{96}\text{Zr}$, $^{100}\text{Mo}$, $^{116}\text{Cd}$, $^{128}\text{Te}$, $^{130}\text{Te}$, $^{136}\text{Xe}$, $^{150}\text{Nd}$, $^{238}\text{U}$
and $2\nu\text{EC/EC}$ in $^{130}\text{Ba}$ was detected in geochemical experiment.

Double beta decay to excited states of daughter nuclei are accompanied by emission of $\gamma$-quanta in de-excitation of excited states. These $\gamma$-quanta may be detected by low background HPGe detectors with high efficiency and good energy resolution.

$2\nu2\beta^-$ decay to excited states was detected in $^{100}\text{Mo} - ^{100}\text{Ru} (0^+_1, 1130.3 \text{ keV})$ and $^{150}\text{Nd} - ^{150}\text{Sm} (0^+_1, 740.4 \text{ keV})$.

$^{100}\text{Mo} - ^{100}\text{Ru} (0^+_1, 1130.3 \text{ keV})$ decay was detected in several experiments, including measurements performed at LSM, Modane with the Obelix HPGe spectrometer

Investigation of 2νββ decay of $^{100}$Mo-$^{100}$Ru to excited states

Metallic foil of enriched $^{100}$Mo with a total mass of 2 505 g was measured in Marinelli bobbin with the OBELIX spectrometer for 2 288 hours.

$^{100}$Mo → $0^+$, 1130 keV $^{100}$Ru* observable γ590.8+γ539.5 keV

$^{100}$Mo → $2^+$, 540 keV $^{100}$Ru observable γ539.5 keV

$T_{1/2} (0^+_1, 1130.3 \text{ keV}) = [7.5 \pm 0.6(\text{stat.}) \pm 0.6(\text{sys.})] \times 10^{20} \text{ yr (90 \% CL)}$

* R. Arnold et al., *Nuclear Physics A* 925 (2014) 25
Laboratoire Souterrain de Modane

Fréjus Tunnel at the French-Italian border

**Depth** - 1800 m of rock (4800 mwe)

**Muons flux** - 4 muons / m² x day⁻¹
(2x10⁶ reduction factor)

**Neutrons flux** - 3000 fast neutrons (>1MeV) per m² and per day
(1000 reduction factor)
Detector Obelix*

P type coaxial HPGe detector Canberra in U-type ultra low background cryostat located at LSM, France (4800 m w.e.)

- **Sensitive volume**: 600 cm$^3$
- **Efficiency**: ~160%
- **Peak / Compton**: 83
- **Energy resolution**: ~1.2 keV at 122 keV ($^{57}$Co), ~2 keV at 1332 keV ($^{60}$Co)
- **Distance from cap**: 4 mm
- **Entrance window**: Al, 1.6 mm

- ~12 cm arch. Pb
- ~20 cm low active Pb
- Radon free air

JINR Dubna, Russia, IEAP, CTU Prague, Czech Republic, LSM Modane, France

Configurations of the Obelix passive shielding

PbI ~ 12 cm of archeological lead
(activity of < 60 mBq/kg)
(~7 cm can be removed)

PbII ~ 20 cm of low-active lead
(activity of 5 - 20 Bq/kg)
Double beta decay of $^{58}\text{Ni}$


$$2\nu\text{ECEC} : \ ^{58}\text{Ni} + 2e^- \rightarrow ^{58}\text{Fe}(2^+_1) + 2\nu_e + 2\gamma_{\text{shell}} + \gamma(810.8 \text{ keV})$$

$$2\nu\text{ECEC} : \ ^{58}\text{Ni} + 2e^- \rightarrow ^{58}\text{Fe}(2^+_2) + 2\nu_e + 2\gamma_{\text{shell}} + \gamma(1674.8 \text{ keV})$$

$$\rightarrow \ ^{58}\text{Fe}(2^+_2) + 2\nu_e + 2\gamma_{\text{shell}} + \gamma(810.8 \text{ keV}) + \gamma(864.0 \text{ keV})$$

$$2\nu\text{EC},\beta^+ : \ ^{58}\text{Ni} + e^- \rightarrow ^{58}\text{Fe}(\text{g.s.}) + 2\nu_e + e^+ + \gamma_{\text{shell}} + 2\gamma(511 \text{ keV})$$

$$0\nu\text{ECEC} : \ ^{58}\text{Ni} + 2e^- \rightarrow ^{58}\text{Fe}(\text{g.s.}) + \gamma_K + \gamma_L + \gamma(1918.3 \text{ keV})$$
**Measurement of $^{58}\text{Ni}$**

**Run 1 - 2014**

15.10.2014 - 11.11.2014

$T_1=2348724 \text{ s} = 652.4 \text{ h}$


$T_2=1758647 \text{ s} = 488.5 \text{ h}$

$T = 1141 \text{ h} = 47.5 \text{ d}$

**Sample of natural nickel with a mass of $\sim 21.7 \text{ kg}$, containing $\sim 68\%$ of $^{58}\text{Ni}$**

**Theoretical prediction:**

$T_{1/2}(2\nu\beta^+\text{EC}, 0^+\rightarrow 0^+) = 8.6 \times 10^{25} \text{ y}$

$T_{1/2}(2\nu\text{EC/EC}, 0^+\rightarrow 0^+) = 6.1 \times 10^{24} \text{ y}$

$T_{1/2}(0\nu\text{EC/EC radiative}) = 2 \times 10^{35} - 3 \times 10^{36} \text{ y}$

**Run 2 - 2015**

28.08.2015 - 17.09.2015

$T = 1639946 \text{ s} = 456 \text{ h} = 19 \text{ d}$

**Existing experimental limits:**

$T_{1/2} (2\nu\beta^+\text{EC}, 0^+\rightarrow 0^+) > 7.0 \times 10^{20} \text{ y (68\%CL)}$

$T_{1/2} (2\nu\beta^+\text{EC}, 0^+\rightarrow 2_1^+) > 4.0 \times 10^{20} \text{ y (68\%CL)}$

$T_{1/2} (2\nu\text{EC/EC}, 0^+\rightarrow 2_1^+) > 4.0 \times 10^{19} \text{ y (90\%CL)}$

$T_{1/2} (2\nu\text{EC/EC}, 0^+\rightarrow 2_2^+) > 4.0 \times 10^{19} \text{ y (90\%CL)}$

$T_{1/2} (0\nu\text{EC/EC radiative}) > 2.1 \times 10^{21} \text{ y (90\%CL)}$

**Run 3 - 2017**

07.04.2017 - ….. (in progress)

$T = 3760800 \text{ s} = 1044.7 \text{ h} = 43.5 \text{ d}$

$T_{1/2} (0\nu\text{EC/EC radiative}) > 2.1 \times 10^{21} \text{ y (90\%CL)}$
Measurement of $^{58}\text{Ni}$
Measurement of $^{58}\text{Ni}$
Background of the Obelix spectrometer

<table>
<thead>
<tr>
<th>E [keV]</th>
<th>Nuclide</th>
<th>Counts/kg·day</th>
</tr>
</thead>
<tbody>
<tr>
<td>238</td>
<td>$^{212}\text{Pb}$</td>
<td>0.60±0.25</td>
</tr>
<tr>
<td>295</td>
<td>$^{214}\text{Pb}$</td>
<td>0.24±0.05</td>
</tr>
<tr>
<td>352</td>
<td>$^{214}\text{Pb}$</td>
<td>0.20±0.09</td>
</tr>
<tr>
<td>583</td>
<td>$^{208}\text{Tl}$</td>
<td>0.18±0.07</td>
</tr>
<tr>
<td>609</td>
<td>$^{214}\text{Bi}$</td>
<td>0.21±0.06</td>
</tr>
<tr>
<td>911</td>
<td>$^{228}\text{Ac}$</td>
<td>0.25±0.05</td>
</tr>
<tr>
<td>969</td>
<td>$^{228}\text{Ac}$</td>
<td>0.20±0.04</td>
</tr>
<tr>
<td>1460</td>
<td>$^{40}\text{K}$</td>
<td>0.34±0.05</td>
</tr>
<tr>
<td>2615</td>
<td>$^{208}\text{Tl}$</td>
<td>0.17±0.06</td>
</tr>
</tbody>
</table>

Integral count rate [30-3000 keV]:

2011 – **173 counts/kg · d**
2014 – **73 counts/kg · d**
2017 - **95 counts/kg · d** (after the detector was repaired by Canberra)
Measurement of $^{58}\text{Ni}$

Sample: natural Ni (~68% of $^{58}\text{Ni}$)
Total mass: ~21.7 kg
The investigations of double beta decay ($\beta^+\text{EC}, \text{EC/EC}$)
Regions of interest: 511 keV, 811 keV, 864 keV, 1675 keV, 1918 keV

Run1 (2014) T=47.5 d

Run2 (2015) T=19 d
Activity of $^{58}$Co in nickel sample at the start of measurements in 15/10/2014 was

$$A^{(58}\text{Co}) = 5.4 \pm 0.5 \text{ mBq/kg}$$
Counting rate [30 – 2900 keV] 95 counts/day•kg

T=44d

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<td>0.25 ± 0.06</td>
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<td>0.25 ± 0.06</td>
</tr>
<tr>
<td>969</td>
<td>$^{228}\text{Ac}$</td>
<td>0.20 ± 0.06</td>
</tr>
<tr>
<td>1124</td>
<td>$^{22}\text{Na}$</td>
<td>1.1 ± 0.1</td>
</tr>
<tr>
<td>1460</td>
<td>$^{40}\text{K}$</td>
<td>0.34 ± 0.05</td>
</tr>
<tr>
<td>2615</td>
<td>$^{208}\text{Tl}$</td>
<td>0.20 ± 0.06</td>
</tr>
</tbody>
</table>
Cosmogenic isotopes in 2017

**57**Co

Gaussian fit results (CL=90%):
Intensity: 121.5 ± 38.9 cnt
Position: 122.52 ± 0.13 keV
Sigma: 0.41 ± 0.17 keV

**54**Mn

Gaussian fit results (CL=90%):
Intensity: 50.3 ± 14.1 cnt
Position: 835.30 ± 0.34 keV
Sigma: 0.71 ± 0.21 keV

**60**Co

Gaussian fit results (CL=90%):
Intensity: 81.8 ± 10.7 cnt
Position: 1332.96 ± 0.16 keV
Sigma: 0.76 ± 0.15 keV

**56**Co

Gaussian fit results (CL=90%):
Intensity: 1.0 ± 1.6 cnt
Position: 847.99 ± 0.00 keV
Sigma: 0.00 ± 0.00 keV
Measurement of $^{58}$Ni at 2017 (third run)

$T = 43.5\text{d} (3760800\text{s})$
Simulation was performed using ROOT-VMC-GEANT4 DPGE package in the energy region of 0.05-5 MeV.
811 keV ROI


Counts

$10^2$

$10$

$1$

Energy, keV

Measurements:
- 2014
- 2015
- 2017
811 keV

HPGe spectrum: fit

Gaussian fit results (CL=90%):

Intensity: -0.1 ± 11.3 cnt
Position: 811.20 ± 0.00 keV
Sigma: 0.75 ± 0.00 keV

N_{EXCL}=11 events
## Preliminary results for double beta decay of $^{58}\text{Ni}$

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Final state or Decay transition</th>
<th>$T_{1/2}$, (90% CL)</th>
<th>Previous limits, $T_{1/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta^+\text{EC}$</td>
<td>g.s.</td>
<td>$9.7\times10^{21}$ y</td>
<td>$7.0\times10^{20}$ y (68%CL)*</td>
</tr>
<tr>
<td>$\beta^+\text{EC}$</td>
<td>811 keV</td>
<td>$1.2\times10^{22}$ y</td>
<td>$4.0\times10^{20}$ y (68%CL)*</td>
</tr>
<tr>
<td>$\text{EC/EC}$</td>
<td>811 keV</td>
<td>$1.6\times10^{22}$ y</td>
<td>$4.0\times10^{19}$ y (90%CL)**</td>
</tr>
<tr>
<td>$\text{EC/EC}$</td>
<td>1675 keV</td>
<td>$8.3\times10^{21}$ y</td>
<td>$4.0\times10^{19}$ y (90%CL)**</td>
</tr>
<tr>
<td>$0\nu\text{EC/EC}$ resonant</td>
<td>Radiative 1918 keV</td>
<td>$5.1\times10^{22}$ y</td>
<td>$2.1\times10^{21}$ y (90%CL)***</td>
</tr>
</tbody>
</table>

Future plans of measurements with Obelix

1. Continue our measurement of $^{58}\text{Ni}$ to improve our experimental limits on various double beta decay modes of $^{58}\text{Ni}$ which are now the best.
2. Perform the investigation of double beta decay of $^{82}\text{Se}$ and $^{150}\text{Nd}$ to excited states

$^{82}\text{Se}$ decay scheme

$^{150}\text{Nd}$ decay scheme

$Q_{\beta\beta} = 2997 \text{ keV}$
Thank you for your attention
Additional slides
# Preliminary results

<table>
<thead>
<tr>
<th>Energy</th>
<th>Efficiency</th>
<th>Nexcl</th>
<th>$T_{1/2}$, (90% CL)</th>
<th>Previous limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kb+ (811 keV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>811 keV</td>
<td>1.0%</td>
<td>11.0</td>
<td>$1.2 \times 10^{22}$ y</td>
<td>$4.0 \times 10^{20}$ y (68%CL)*</td>
</tr>
<tr>
<td>Kb+ (g.s.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>511 keV</td>
<td>2.9%</td>
<td>38.0</td>
<td>$0.97 \times 10^{22}$ y</td>
<td>$7.0 \times 10^{20}$ y (68%CL)*</td>
</tr>
<tr>
<td>KK (811 keV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>811 keV</td>
<td>1.4%</td>
<td>11.0</td>
<td>$1.6 \times 10^{22}$ y</td>
<td>$4.0 \times 10^{19}$ y (90%CL)**</td>
</tr>
<tr>
<td>0νKK-resonant (1918 keV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1918 keV</td>
<td>1.2%</td>
<td>3.0</td>
<td>$5.1 \times 10^{22}$ y</td>
<td>$2.1 \times 10^{21}$ y (90%CL)***</td>
</tr>
<tr>
<td>KK (1675 keV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>811 keV</td>
<td>1.0%</td>
<td>14.1</td>
<td>$0.90 \times 10^{22}$ y</td>
<td></td>
</tr>
<tr>
<td>1675 keV</td>
<td>1.3%</td>
<td>13.9</td>
<td>$1.2 \times 10^{22}$ y</td>
<td>$4.0 \times 10^{19}$ y (90%CL)**</td>
</tr>
</tbody>
</table>

Calculation of the limit

\[ T_{1/2}^{LIM} > \ln(2) \times \varepsilon \times M_{TOT} \times O^{(58\text{Ni})} \times T_{\text{EXP}} \times N_{A/A/N_{\text{EXCL}}} \]

<table>
<thead>
<tr>
<th>Параметр</th>
<th>Величина</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA/10^{20}</td>
<td>6022.142</td>
</tr>
<tr>
<td>M_{TOT}^{n}</td>
<td>21754</td>
</tr>
<tr>
<td>O^{(58\text{Ni})}</td>
<td>68.27%</td>
</tr>
<tr>
<td>A</td>
<td>58</td>
</tr>
</tbody>
</table>

K.Zuber

http://wwwarchive.ph.ed.ac.uk/sussp61/lectures/05_Zuber_NeutrinolessDoubleBetaDecay/StAndrews_2006_lect2_orig.ppt
Measurement of La powder at Marinelli backer
Efficiency of the Obelix for different geometries of measurements