Study of the electron lifetime limit using the Borexino data

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LNGS, October 29, 2015

Outline

Why the electron decay?

There is no experimental evidence for the electric charge non-conservation (CNC)

However, there are some theories (beyond the Standard Model).

Continuous CNC ⇒ astrophysical effects:

- varying α theories;
- theories with non-constant speed of light;

Discrete CNC ⇒ atomic and nuclear effects:

- electron decay into neutral particles due to e.g. U(1) symmetry breaking;
- electron disappearance in extra-dimensional theories;

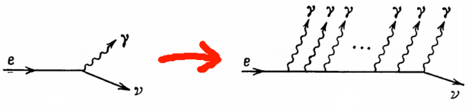
etc.

$e \rightarrow$SM particles

In the Standard model these processes would be followed by a huge amount of bremsstrahlung photons (according to L. B. Okun, Sov. Phys. Usp. **32**, 543 (1989))

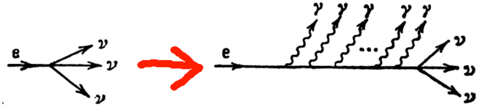
$e \rightarrow \gamma\nu$

- E = 256 keV
- Does not occur in the Standard Model



$e \rightarrow \nu\nu\nu$

- low energy ($\lesssim$ 50 keV)
- model-independent (electron disappearance)

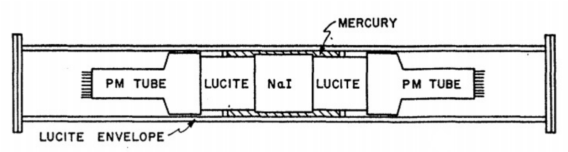


Experiments for the electron decay search

year	experiment	material	decay mode	limit, years	CL
1959	Feinberg, Goldhaber	NaI	$e \to \gamma\nu$	10^{19}	68%
1959	Feinberg, Goldhaber	NaI	$e \to \nu\nu\nu$	10^{17}	68%
1965	Moe, Reines	NaI	$e \to \gamma\nu$	4×10^{22}	68%
1965	Moe, Reines	NaI	$e \to \nu\nu\nu$	2×10^{21}	68%
1975	Steinberg et al.	Ge	$e \to \nu\nu\nu$	5.3×10^{21}	68%
1979	Kovalchuk et al. (Baksan)	NaI	$e \to \gamma\nu$	3.5×10^{23}	68%
1983	Belotti et al.	Ge	$e \to \gamma\nu$	3×10^{23}	68%
1983	Belotti et al.	Ge	$e \to \nu\nu\nu$	2×10^{22}	68%
1986	Avignone III et al.	Ge	$e \to \gamma\nu$	1.5×10^{25}	68%
1993	Balysh et al. (Heidelberg-Moscow)	Ge	$e \to \gamma\nu$	1.63×10^{25}	68%
1995	Aharonov et al. (TWIN)	Ge	$e \to \gamma\nu$	2.1×10^{25}	90%
1995	Aharonov et al. (COSME)	Ge	$e \to \nu\nu\nu$	2.6×10^{23}	90%
1996	Belli et al. (DAMA/LXe)	Xe	$e \to \gamma\nu$	2×10^{25}	68%
1996	Belli et al. (DAMA/LXe)	Xe	$e \to \nu\nu\nu$	1.5×10^{23}	68%
1999	Belli et al. (DAMA)	NaI	$e \to \nu\nu\nu$	$(1.5 - 2.4) \times 10^{23}$	90%
1999	Belli et al. (DAMA)	NaI (L-shell)	$e \to \nu\nu\nu$	2.4×10^{24}	90%
2000	Belli et al. (DAMA/LXe)	Xe	$e \to \gamma\nu$	2×10^{26}	90%
2002	Back et al. (Borexino/CTF-II)	PXE	$e \to \gamma\nu$	4.6×10^{26}	90%
2007	Klapdor-Kleingrothaus et al. (Heidelberg-Moscow)	Ge	$e \to \gamma\nu$	1.93×10^{26}	90%
2012	Bernabei et al. (DAMA/LIBRA)	NaI	e capture	1.2×10^{24}	90%

2003	Majorana	Ge	proposed
2005	CUORE	TeO_2	proposed
2012	LENA	?	proposed

NaI experiments

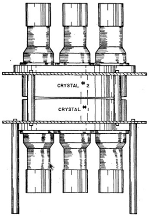


M. K. Moe and F. Reines, Phys. Rev. **140**, 992 (1965)

- $e \to \nu\nu\nu$: dissapearance of an electron from iodide atom K-shell ⇒ photon emission while filling the vacancy ($\mathrm{E}_{max} = 33.2$ keV)
- $e \to \gamma\nu$: monoenergetic photon emission ($\mathrm{E} = 256$ keV)

Feinberg, Goldhaber (1959) - $10^{17}/10^{19}$
Moe, Reines (1965) - $2 \times 10^{21}/4 \times 10^{22}$
Kovalchuk et al. (1979) - 3.5×10^{23}
DAMA (1999) - 2.4×10^{24}

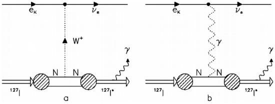
NaI experiments: coincidence techniques



M. K. Moe and F. Reines, Phys. Rev. **140**, 992 (1965)

- filling of K-shell vacancy;
- monoenergetic 256 keV photon.

Moe, Reines (1965) - 7×10^{21}



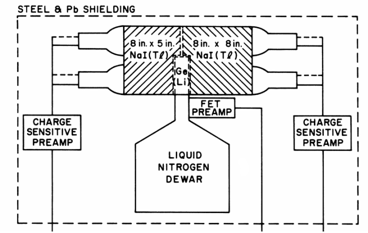
R. Bernabei et al., Eur. Phys. J. C **72**, 1920 (2012)

$$(A, Z) + e^- \rightarrow (A, Z)^* + \nu_e$$

- filling of K-shell vacancy;
- electron capture ⇒ nucleus deexcitation (417.9 keV).

DAMA/LIBRA (2012) - 1.2×10^{24}

Ge detectors



R. I. Steinberg et al., Phys. Rev. D**12**, 2582 (1975)

Electron disappearance from Ge atom K-shell ⇒ $E = 11.1$ keV

- energy resolution is better in comparison with NaI detectors;
- lower background level in the region of interest.

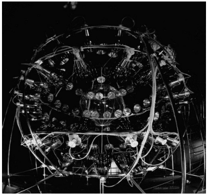
Steinberg et al. (1975) - 5.3×10^{21}
Belotti et al. (1983) - $2 \times 10^{22} / 3 \times 10^{23}$
Avignone III et al. (1986) - 1.5×10^{25}
TWIN, COSME (1995) - $2.6 \times 10^{23} / 2.1 \times 10^{25}$
Heidelberg–Moscow (1993, 2007) - $1.63 \times 10^{25}, 1.93 \times 10^{26}$

Liquid scinlillation detectors

DAMA/LXe

- 6.5 kg of liquid xenon (∼2 litres)
- energy threshold ∼ 17 keV
- energy resolution is comparable to NaI
- background level 0.22×10^{-2} cpd/ton/keV

$1.5 \times 10^{23} / 2 \times 10^{26}$

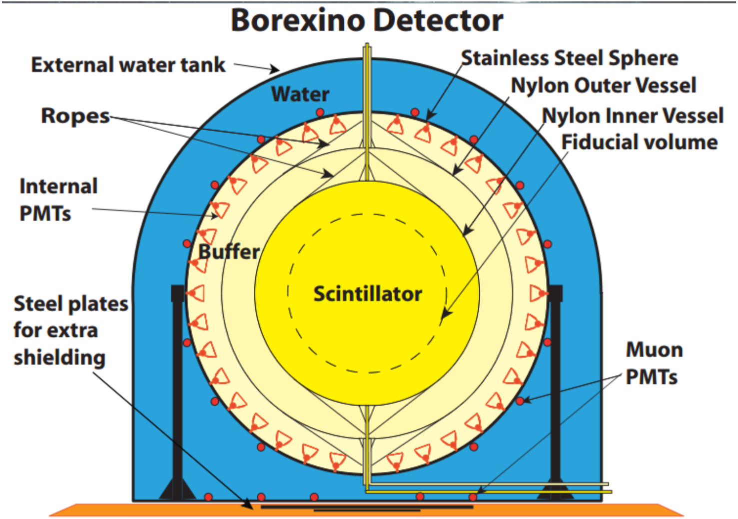


Borexino counting test facility (CTF)

- 4 tons of organic liquid scintillator (PXE, $C_{16}H_{18}$ in CTF-II)
- energy threshold ∼ 50 keV (sensitive only to $e \to \gamma\nu$)
- background level 0.15×10^{-2} cpd/ton/keV

4.6×10^{26}

The Borexino detector



Properties

- scintillator: pesudocumene (1,2,4-trimethylbenzene) + PPO (2,5-diphenyloxazole, 1.5 g/l)
- Mass: 278 tons; 75.5 tons fiducial volume
- 2212 PMTs
- Energy threshold: ∼ 50 keV
- specific background level in the region of interest (around the 256 keV photon peak): 0.15 cpd/ton/keV

number of events $S = \sqrt{\Phi}$,

where Φ is integral background:

$$\Phi = 3.3\sigma \cdot B \cdot M \cdot T$$

$$\Longrightarrow$$

The lifetime limit:

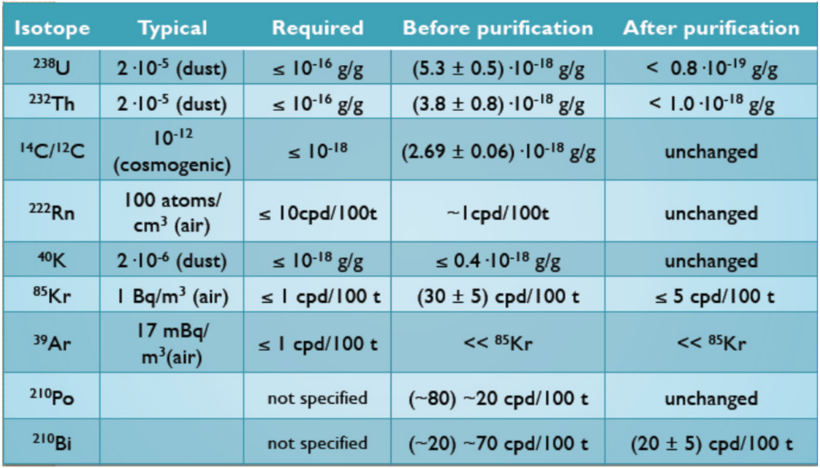
$$\tau \geqslant \epsilon N_e \frac{T}{S}$$

	ϵ	N_e	T, days	B, keV$^{-1}\cdot$ days$^{-1}\cdot$ tons^{-1}	σ, keV	M, tons
CTF-II	0.67	1.36×10^{30}	32.1	1.5	30	4.2
Borexino	0.264	9.19×10^{31}	408	0.15	25	278

⇒ the result can be improved at two orders of magnitude

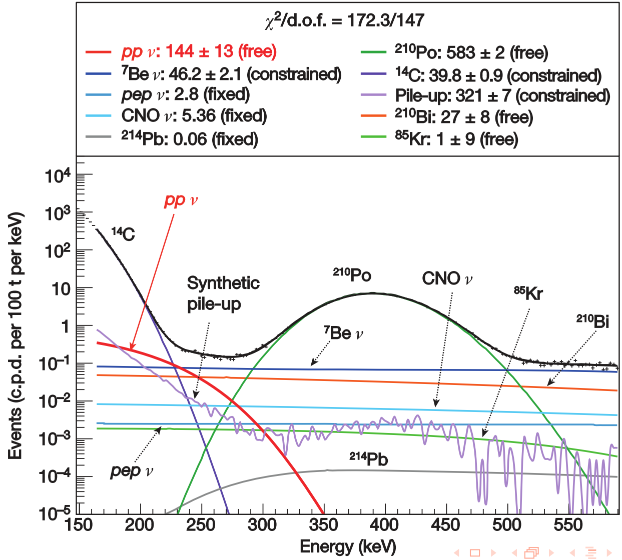
Data set

Borexino Phase II data is being obtained after an extended purification campaign.



Isotope	Typical	Required	Before purification	After purification
^{238}U	$2 \cdot 10^{-5}$ (dust)	$\leq 10^{-16}$ g/g	$(5.3 \pm 0.5) \cdot 10^{-18}$ g/g	$< 0.8 \cdot 10^{-19}$ g/g
^{232}Th	$2 \cdot 10^{-5}$ (dust)	$\leq 10^{-16}$ g/g	$(3.8 \pm 0.8) \cdot 10^{-18}$ g/g	$< 1.0 \cdot 10^{-18}$ g/g
^{14}C/^{12}C	10^{-12} (cosmogenic)	$\leq 10^{-18}$	$(2.69 \pm 0.06) \cdot 10^{-18}$ g/g	unchanged
^{222}Rn	100 atoms/cm^3 (air)	$\leq$ 10cpd/100t	~1cpd/100t	unchanged
^{40}K	$2 \cdot 10^{-6}$ (dust)	$\leq 10^{-18}$ g/g	$\leq 0.4 \cdot 10^{-18}$ g/g	unchanged
^{85}Kr	1 Bq/m^3 (air)	$\leq$ 1 cpd/100 t	(30 ± 5) cpd/100 t	$\leq$ 5 cpd/100 t
^{39}Ar	17 mBq/m^3(air)	$\leq$ 1 cpd/100 t	<< ^{85}Kr	<< ^{85}Kr
^{210}Po		not specified	(~80) ~20 cpd/100 t	unchanged
^{210}Bi		not specified	(~20) ~70 cpd/100 t	(20 ± 5) cpd/100 t

Phase II data is successfully used in the pp-neutrino analysis: *Nature*, **512**, *383 – 386 (2014)*



Summary

- From all the previous electron lifetime studies the best result was obtained by the prototype of Borexino, CTF-II
- In comparison with CTF-II, Borexino has lower background level, larger mass and exposure time
- The data set used in the pp-neutrino analysis is suitable for this study because of the same region of interest

1. Overview
   - On the electric charge non-conservation
   - Previous experiments
   - The Borexino experiment

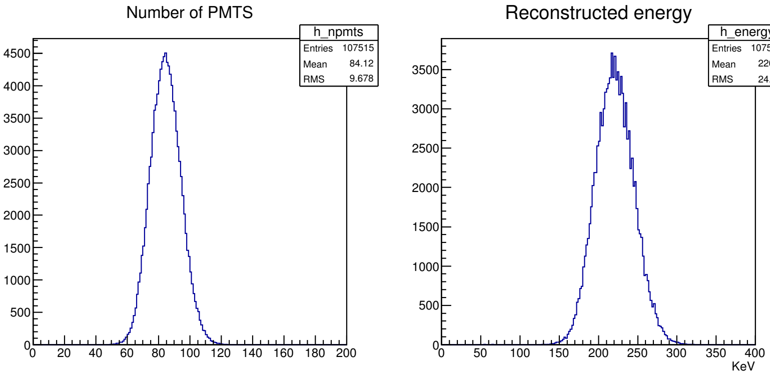
2. Analysis
   - Statistical analysis
   - Systematic errors

Basic steps

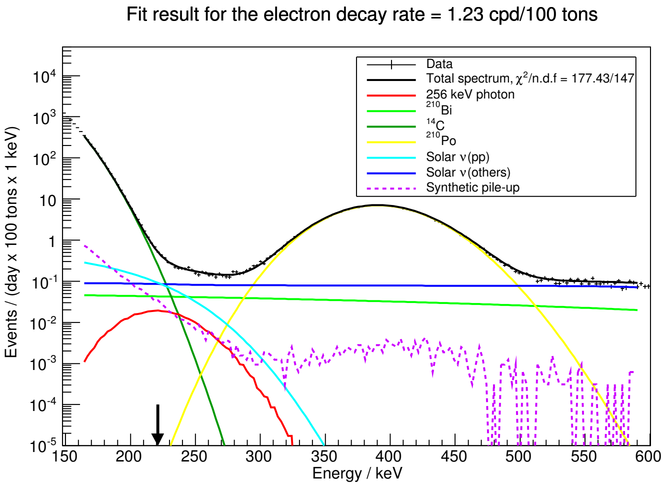
- MonteCarlo sumulation of the signal (256 keV photon) in the detector;
- Spectral fit (150 – 600 keV)
- Obtaining the probability profile ⇒ event number upper limit
- Obtaining the lifetime lower limit
- Study of systematic errors

Signal from the 256 keV monoenergetic photon in Borexino

The signal is simulated in GEANT4

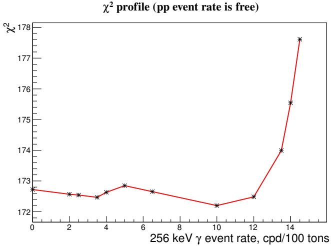


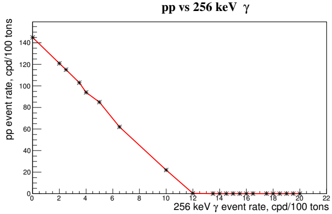
Spectral fit



Strong correlation with ν_{pp} rate!

The ν_{pp} flux is a free parameter





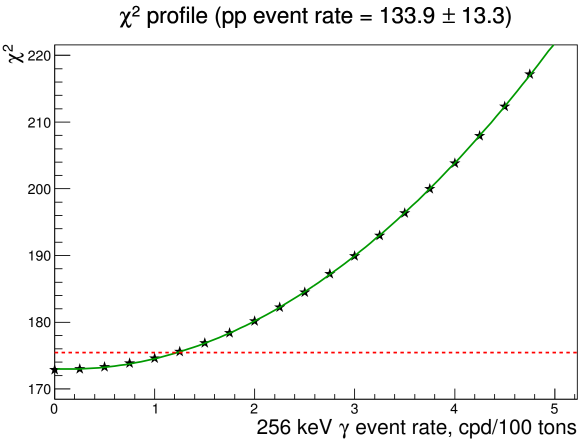
- Event rate upper limit $n_{max} \simeq 12$ cpd/100 tons
- It corresponds to $\Phi_{pp} = 0$ (?!)

Results from radiochemical experiments (SAGE, GALLEX/GNO):

$$\Phi_{pp} = \left(3.40^{+0.46}_{-0.47}\right) \times 10^{10}\ cm^{-2} s^{-1}$$

J. N. Abdurashitov *et al.* [SAGE Collaboration], Phys. Rev. C **80**, 015807 (2009)

χ^2 profile for the constrained Φ_{pp}

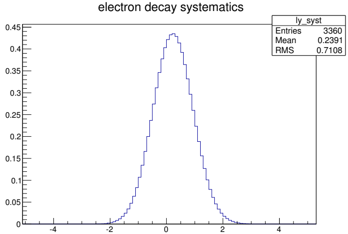


$n \leqslant 1.23$ cpd/ 100 t; $\tau \geqslant 7.2 \times 10^{28}$ years (CL $= 90\%$)

5σ discovery level: $n = 4.5$ cpd/100 t; $\tau = 1.9 \times 10^{28}$ yr

Systematic errors

- choice of energy estimator (number of PMTs hit in the time period of 230 ns and 400 ns) $\Rightarrow$ 8%
- 1% light yield uncertainty $\Rightarrow$ 1%
- 2% fiducial mass uncertainty $\Rightarrow$ $< 0.01\%$



$$n \leqslant 1.33 \text{ cpd}/\ 100 \text{ t}$$

$$\tau \geqslant 6.6 \times 10^{28} \quad \text{years}$$

Conclusion

- Experimental investigating of processes with the electric charge non-conservation e.g. the electron decay is an evident way to search for physics beyond the Standard Model
- Search for the electron decay requires good detector response at low energies, low background level and large statistics
- Borexino detector is an excellent tool to improve the previous result obtained by its prototype
- The new limit on the electron lifetime is obtained

$$\tau_{e\to\gamma\nu} \geqslant 6.6 \times 10^{28} \quad \text{years}$$

$$(\mathrm{CL} = 90\%)$$