Experimental investigations in neutrino physics and in searches for rare and/or hypothetical processes in nuclear physics

5. Exotic processes: decays of electron with violation of electric charge and charge non-conserving beta decays

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Contents

The subject is quite exotic. Absolute majority of people (including physicists) are satisfied with the electric charge conservation, and we do not observe disappearance of matter in our common life.

But it does not mean that we will not face unexpected things – at some level, with increase of experimental sensitivity.

L.B. Okun:
Although we do not today have a noncontradictory phenomenological model to describe the violation of the charge conservation law and/or the Pauli principle, it would be wrong for experimentalists to abandon their tests of these fundamental positions of modern physics. If something in fundamental physics *can* be tested, then it absolutely *must* be tested.
[L.B. Okun, Sov. Phys. Uspekhi 32 (1989) 543]

We should know, to what degree we can trust law of charge conservation (CC) and matter stability.

Gauge invariance $\rightarrow$ CC
Weinberg theorem: CC $\leftrightarrow$ $m_\gamma=0$
[S. Weinberg, Phys. Rev. B 135 (1964) 1049]

(with $m_\gamma \neq 0$ Maxwell equations $\rightarrow$ Proca equations)

Some theories predict these effects (extra dimensions, oscillations to mirror world).

Searches for invisible decays of matter start to be more and more popular, in particular, in relation with extra dimensions.

Probably, our world is a brane inside higher-dimensional space.
Particles can escape from the brane to extra dimensions.
This is predicted to be a generic property of massive matter [V.A. Rubakov et al., PRD 62 (2000) 105011; JHEP 08 (2000) 041; Phys. Uspekhi 44 (2001) 871; N. Arkani-Hamed et al., PLB 429 (1998) 263, Phys. Today, February (2002) 36].

N. Arkani-Hamed, S. Dimopoulos, G. Dvali (2002):
"The presence and properties of the extra dimensions will be investigated by looking for any loss of energy from our 3-brane into the bulk"

Charge and matter could be conserved for the whole space but violated for our 3-d brane. Thus, we could expect disappearance of *e, p, n*, ...

S.L. Dubovsky, JHEP 01 (2002) 012:
$\tau(p \to nothing) = 9.2 \cdot 10^{34}$ yr $\quad\quad \tau(e \to nothing) = 9.0 \cdot 10^{25}$ yr

Disappearance of *e, p*, … means charge non-conservation (CNC) …
So, how possible CNC processes were searched for:

1. Indirect limits

1. **A.A. Pomansky, Neutrino'1976 Conf. – 1977, p. 671:**
   if electric current in the Earth's atmosphere is caused by *e* decay, using current J=200 A and number of electrons in the Earth $N_e=2\times10^{51}$, one obtains: $\tau(e)>5\times10^{22}$ yr;

2. **R.A. Lyttleton, H. Bondi, Proc. Roy. Soc. A 252 (1959) 313:**
   if expansion of Universe is caused by charge imbalance of 2×10^{-18}, from age of Universe 10^{10} yr one gets: $\tau(e)>10^{28}$ yr;

3. **Limits on mass of γ quantum:**
   $m_\gamma<6\times10^{-16}$ eV – data on magnetic field of Jupiter
   [L. Devis et al., Phys. Rev. Lett. 35 (1975) 1402];
   $m_\gamma<2\times10^{-27}$ eV – data on intergalactic magnetic fields
   [G.V. Chibisov, Sov. Phys. Uspekhi 19 (1976) 624];
   this gives: $\tau(e)>10^{27}$ yr and $\tau(e)>10^{51}$ yr, respectively.

Other manifestations of $m_\gamma\neq0$:
- dependence of velocity of γ on E_γ;
- deviation from n=2 in Coulomb law $F \sim 1/r^n$;
- others, see: 1. A.S. Goldhaber et al., Rev. Mod. Phys. 43 (1971) 277
2. L.C. Tu et al., Rep. Prog. Phys. 68 (2005) 77
3. A.S. Goldhaber et al., Rev. Mod. Phys. 82 (2010) 939

2. Direct experiments to search for charge non-conserving (CNC) effects

Decays of electron

$e^- \rightarrow \nu_e + \gamma$

$e^- \rightarrow$ ***invisible****

$e^- \rightarrow$ ***invisible**** **with excitation of nuclear levels**

CNC β decay

Disappearance of p (pp, ppp, etc.) – next lecture

* **invisible = decay to $\nu_e$anti-$\nu_e\nu_e$ or other weakly interacting particles or disappearance into extra dimensions**

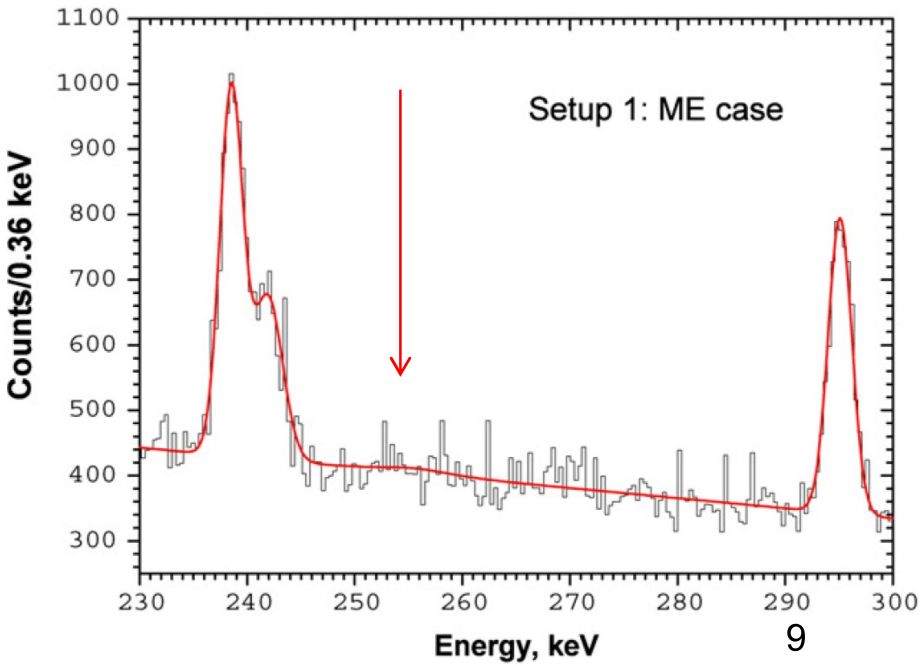
Search for decay $e^- \to \nu_e + \gamma$

One is looking for γ with $E_\gamma \approx m_e c^2/2$ = 255.5 keV because ν_e and γ both are massless so kinematically equivalent (should be taken into account: binding energy on atomic shell and Doppler broadening of the peak)

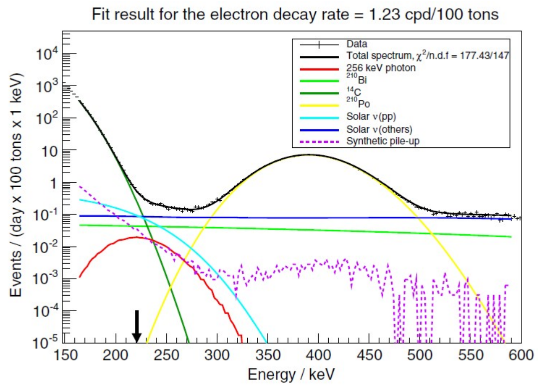
Electron decays in a detector itself but also in surrounding materials (main contribution gives 1st process)

Last experiments:

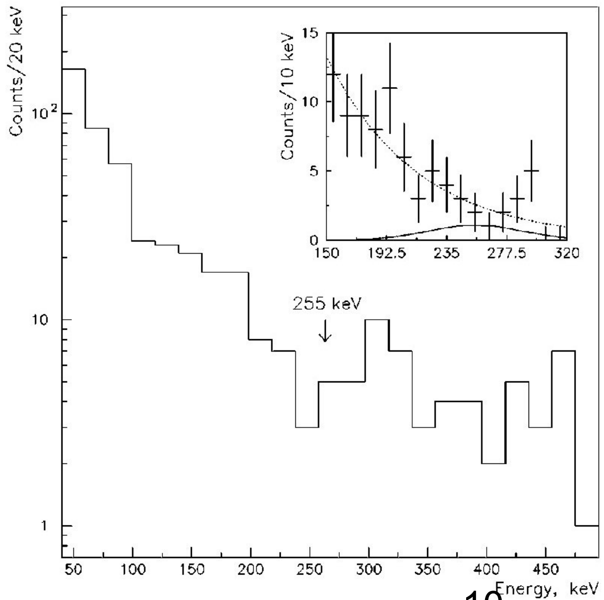
1) H.V. Klapdor-Kleingrothaus et al., Phys. Lett. B 644 (2007) 109: 5 HP Ge detectors (12 kg), underground measurements in Laboratori Nazionali del Gran Sasso (Italy, 3600 m w.e.), 1995-2003. Peak at 255 keV is absent, only limit: $\tau(e^- \to \nu_e + \gamma) > 1.0e26$ yr



2) M. Agostini et al., Phys. Rev. Lett. 115 (2015) 231802:
BOREXINO, LNGS, liquid scintillator 278 t (inner volume), 2212 PMTs, 408 d (2012-2013)
$\tau(e^- \to \nu_e + \gamma) > 6.6e28$ yr – the best to-date limit



3) P. Belli et al., Phys. Rev. D 61 (2000) 117301:
DAMA, liquid Xe (scintillator) 6.5 kg, 8336 h
decay of e^- on different atomic shells of Xe and decay in surrounding Cu, Pb shield; no peak at 255 keV
$\tau(e^- \to \nu_e + \gamma) > 2.0e26$ yr – best limit in 2000



Consequence:
$\tau(e^- \to \nu_e + \gamma) = 10^{-25}(m_Z/m_\gamma)^2$ yr
[J.C. Huang, J. Phys. G 13 (1987) 273]
m_Z=91.2 GeV $\Rightarrow$ m_γ<2.0e–15 eV

Search for decay $e^- \to$ *invisible*

Examples of «invisible» modes:
- decays to 2 neutrino and 1 antineutrino
- disappearance into extra dimensions

If an electron disappears on atomic shell, the created hole will be filled by electrons from higher atomic shells. Cascade of X rays and Auger electrons will be emitted in the deexcitation process. Total energy released = binding energy E_B of disappeared e^- on the shell.

Usually Ge and NaI detectors were used in such searches.

K shell: $E_B(\mathrm{Ge}) = 11.1$ keV

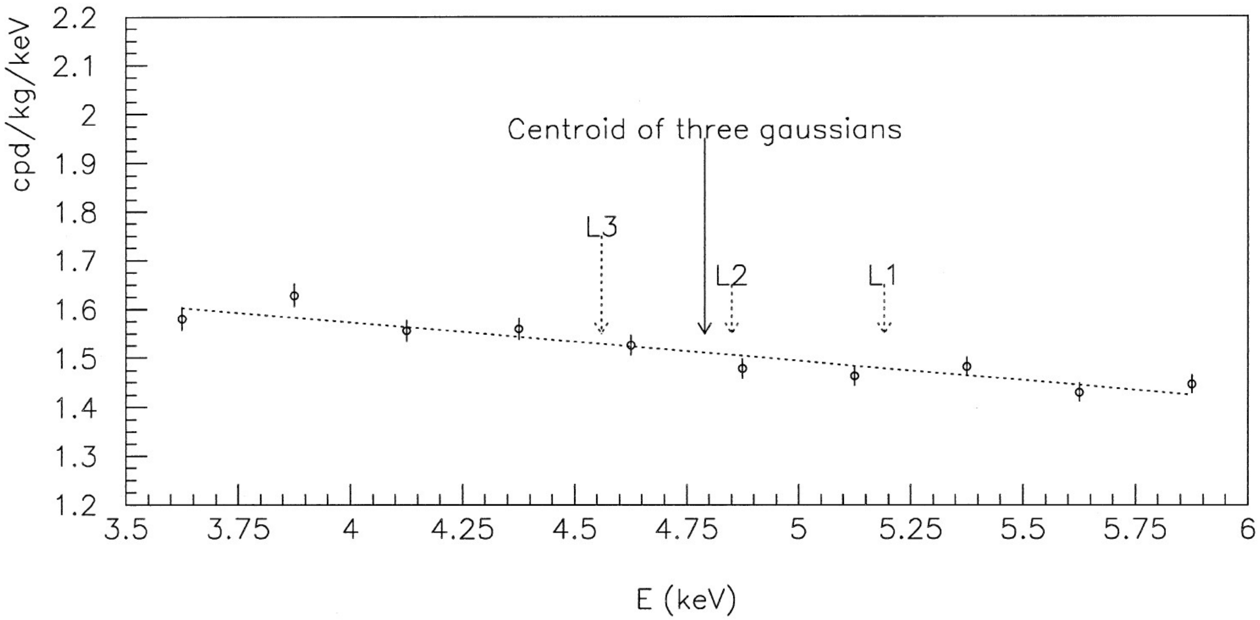
$E_B(\mathrm{I}) = 33.2$ keV

The **best limit** was obtained in:
P. Belli et al., Phys. Lett. B 460 (1999) 236

Gran Sasso, DAMA NaI(Tl) scintillators 9x9.7 = 87.3 kg, 5364 h, low background set-up. Low energy threshold (2 keV).

Low threshold allowed – **at the first time** – to search for decays not of 2 electrons on atomic K shell, as usually before, but **8 electrons on L shell** of I atom ($E_B \cong 5$ keV).

$\tau(e^- \rightarrow \textit{invisible}) > 2.4e24$ yr – 1 order of magnitude better than previous best limit



Recent work of Majorana collaboration:
N. Abgral et al., Eur. Phys. J. C 76 (2016) 619 + arXiv:1612.00886

13 HPGe total volume 1890 cm^3, 1140 h, Sanford Underground Research Facility, 4400 m w.e., low background set-up.

Search for peak at 11.1 keV

$\tau(e^- \rightarrow$ *invisible*$) > 1.2e24$ yr

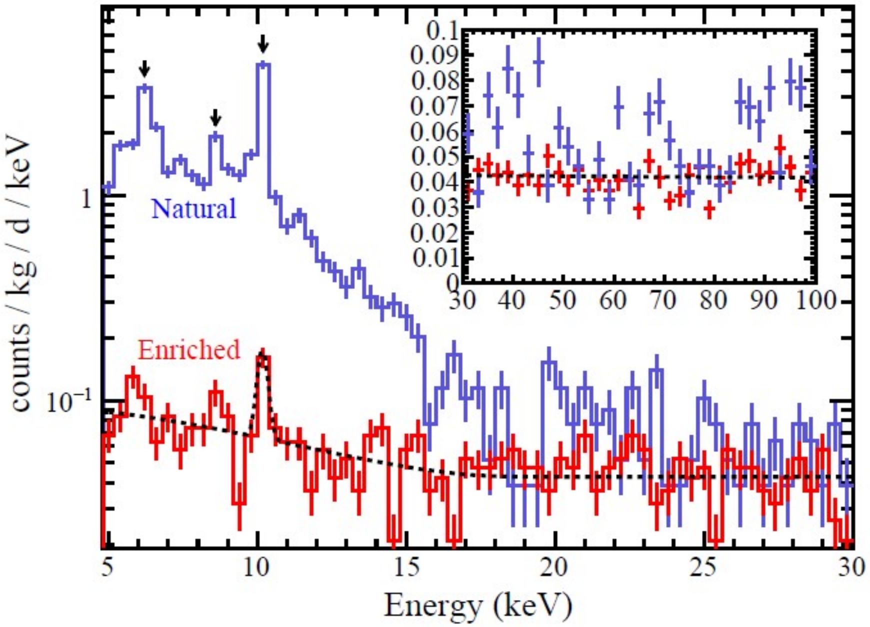
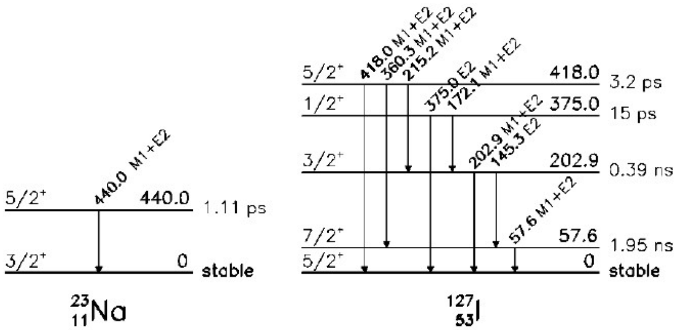
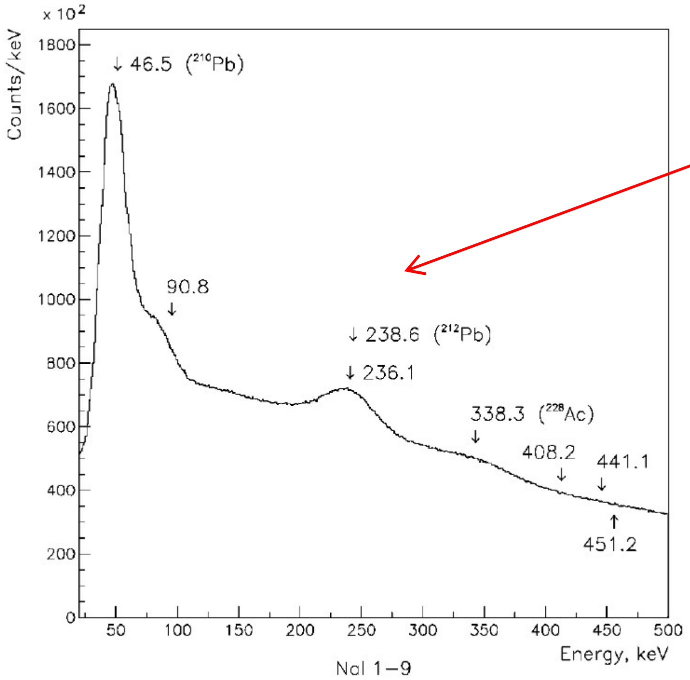


FIG. 1. (Color online) Energy spectra from 195 kg d of natural (blue) and 478 kg d of enriched (red) detector data. A fit of the background model (linear + tritium beta spectrum + ^{68}Ge K-shell) to the enriched spectrum is also shown (dotted black). The background rate and slope, along with the tritium and K-shell rate were floated in the fit. The background fit χ^2/NDF is 75.7/85. Cosmogenic isotopes in the natural detectors produce peaks at 10.36 keV (^{68}Ge), 8.9 keV (^{65}Zn), and 6.5 keV (^{55}Fe) on top of a tritium beta decay continuum. The FWHM of the 10.4 keV peak is ~0.25 keV. The spectrum shown does not include a T/E cut acceptance correction.

Search for decay $e^- \to$ *invisible* with excitation of nuclear levels

Electron disappears but neighboring nucleus is left in excited state. Levels with energies $E_{exc} < m_e c^2 - E_B$ could be excited. One should search for γ quanta emitted in deexcitation process.



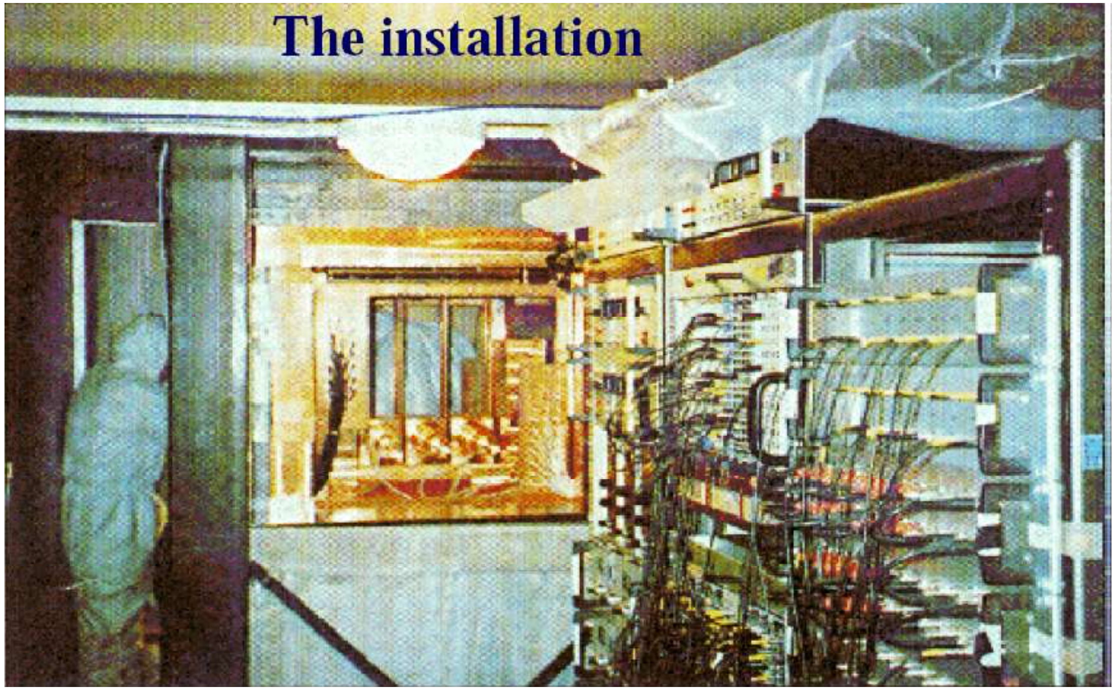


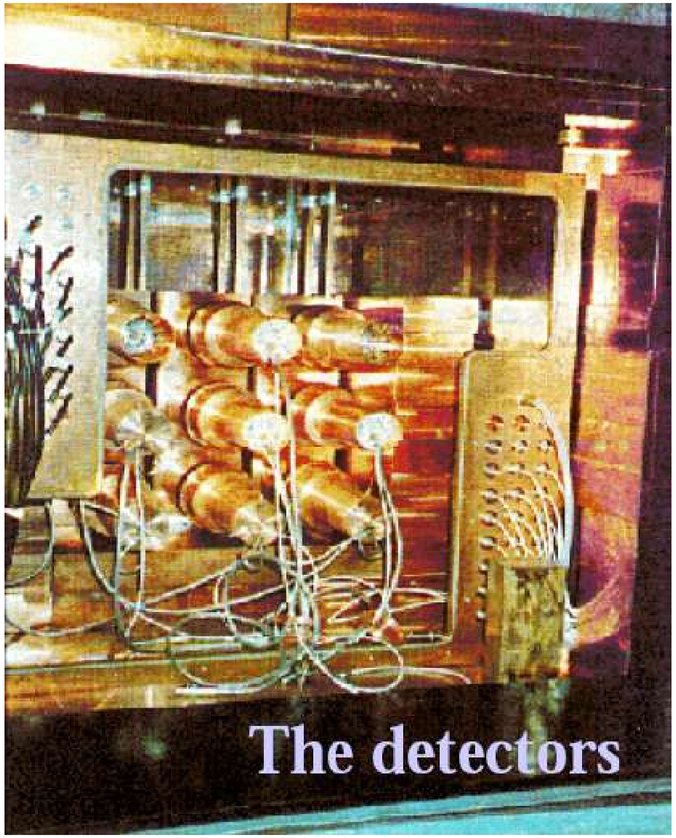
If decay occurs inside detector, one expects peak at energy $E = E_{exc} + E_B$

Example: P. Belli et al., Phys. Rev. C 60 (1999) 065501:
LNGS, DAMA NaI(Tl) 87.3 kg, 9585 h
$\tau >$ (1.5-2.4)e23 y
(up to 2 orders of magnitude better than known before)

P. Belli et al., Phys. Lett. B 465 (1999) 315:
DAMA LXe 6.5 kg, 3039 h
(excitation of levels in ^{129}Xe)
$\tau >$ (1.1-3.7)e24 y (best to-date limits)

~100 kg DAMA NaI installation:





Summary of all experiments on electron decays

(since the first experimental search of Feinberg and Goldhaber in 1959)

20 experiments for $e^- \to \nu_e + \gamma$ and $e^- \to$ invisible
5 experiments for $e^- \to$ *invisible* with excitation of nuclear levels

Table 2: Experimental life-time limits on the electron disappearance with nuclear levels excitation of ^{23}Na, ^{127}I and ^{129}Xe. Best values are in red.

Nucleus, E_{exc}	Life time limits τ (yr) [Hol87] 90% C.L.	[Eji91] 68% C.L.	[Bel99a] 90% C.L.	[Bel99b] 90% C.L.	[Ber12] 90% C.L.
^{23}Na					
440.0 keV			$1.5 \cdot 10^{23}$		
^{127}I					
57.6 keV	$2.1 \cdot 10^{21}$	$5.8 \cdot 10^{22}$	$2.4 \cdot 10^{23}$		
202.9 keV	$1.9 \cdot 10^{21}$	$5.6 \cdot 10^{22}$	$2.0 \cdot 10^{23}$		
375.0 keV	$2.4 \cdot 10^{21}$		$1.8 \cdot 10^{23}$		
418.0 keV	$2.4 \cdot 10^{21}$		$1.6 \cdot 10^{23}$		$1.2 \cdot 10^{24}$
^{129}Xe					
39.6 keV				$1.1 \cdot 10^{24}$	
236.1 keV				$3.7 \cdot 10^{24}$	
318.2 keV				$2.2 \cdot 10^{24}$	
321.7 keV				$2.5 \cdot 10^{24}$	
411.5 keV				$2.3 \cdot 10^{24}$	

Table 1: Experimental limits on the electron life-time at 68% (90%) C.L. for channels: $e^- \rightarrow invisible$ and $e^- \rightarrow \nu_e \gamma$. Best limits are in red.

Detector	Volume (cm^3)	Time of measurement (h)	Limit on $\tau_e(e^- \rightarrow invisible)$ (yr)	Limit on $\tau_e(e^- \rightarrow \nu_e\gamma)$ (yr)	Year [Ref.]
NaI(Tl)	1287	6.5	$1.0 \cdot 10^{18}$	$1.0 \cdot 10^{19}$	1959 [Fei59]
NaI(Tl)	348	$110^a, 362^b$	$2.0 \cdot 10^{21}$	$4.0 \cdot 10^{22}$	1965 [Moe65]
Ge(Li)	66	1185	$5.3 \cdot 10^{21}$ [c]	–	1975 [Ste75]
NaI(Tl)	1539	515	$2.0 \cdot 10^{22}$	$3.5 \cdot 10^{23}$	1979 [Kov79]
Ge(Li)	130	$3760^a, 3616^b$	$2.0 \cdot 10^{22}$	$3.0 \cdot 10^{23}$	1983 [Bel83]
HPGe	135	8850	–	$1.5(1.1) \cdot 10^{25}$	1986 [Avi86]
HPGe	3×140	1662	$2.7(1.7) \cdot 10^{23}$	–	1991 [Reu91]
NaI(Tl)	17×10570	2823	$1.2 \cdot 10^{23}$	–	1992 [Eji92]
HPGe	591	3199	–	$2.4(1.2) \cdot 10^{25}$	1993 [Bal93]
HPGe	$48 + 2 \times 209$	$13404^a, 7578^b$	$4.3(2.6) \cdot 10^{23}$	$3.7(2.1) \cdot 10^{25}$	1995 [Aha95]
BaF_2	2×103	986	–	$3.2 \cdot 10^{21}$	1996 [Alo96]
Xe^d	2000	$2340^a, 257^b$	$1.5 \cdot 10^{23}$	$2.0(1.0) \cdot 10^{25}$	1996 [Bel96]
HPGe	132	12600	$1.3 \cdot 10^{24}$	–	1998 [Kli98]
NaI(Tl)	9×2643	5354	$4.2(2.4) \cdot 10^{24}$	–	1999 [Bel99]
Xe^d	2000	8336	–	$3.4(2.0) \cdot 10^{26}$	2000 [Bel00]
$C_{16}H_{18}{}^d$	$4.2 \cdot 10^6$	770	–	$-(4.6) \cdot 10^{26}$	2002 [Bac02]
HPGe	437	33233	–	$1.9(1.0) \cdot 10^{26}$ [e]	2007 [Kla07]
$C_9H_{12}{}^d$	$3.2 \cdot 10^8$	9792	–	$-(6.6) \cdot 10^{28}$	2015 [Ago15]
HPGe	84	5316	$-(2.2) \cdot 10^{23}$	–	2016 [Abg16a]
HPGe	1890 (13 HPGe)	1140	$-(1.2) \cdot 10^{24}$	–	2016 [Abg16b]

[a] For channel $e^- \rightarrow invisible$
[b] For channel $e^- \rightarrow \nu_e\gamma$
[c] At 84% C.L.
[d] Liquid scintillator
[e] This result was critisized in [Der07] as being overestimated at $\simeq$5 times

Search for CNC β decays

Usual, charge conserving (CC) β decay: $(A,Z) \rightarrow (A,Z+1)+e^{-}+\nu_e$

Charge non-conserving (CNC) β decay: $(A,Z) \rightarrow (A,Z+1)+\nu_e+\nu_e$

It is supposed that, instead of electron, some non-charged massless particle is emitted in CNC β decay (ν_e, γ, Majoron, etc.).

In this case we have additional 511 keV in energy (which usually are spent for the electron rest mass). This gives possibility of transitions (to the ground state or excited levels of daughter nucleus), which are usually forbidden because of not sufficient energy release.

Usually limits on probability of CNC β decays were extracted as by-products of measurements of solar neutrinos in radiochemical experiments:

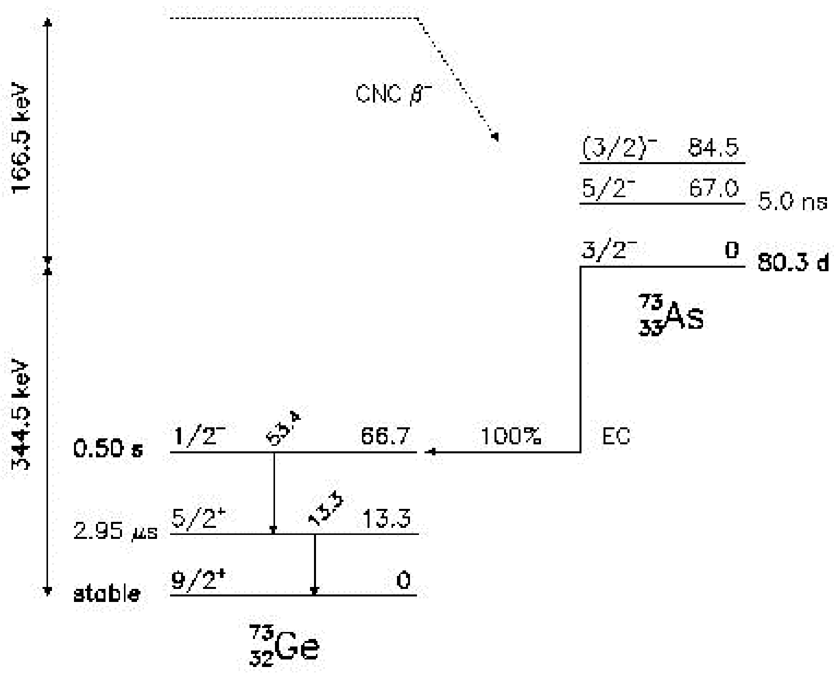
$$(A,Z) + \nu_e \rightarrow (A,Z+1) + e^{-}$$

(both processes give the same daughter nucleus). In radiochemical experiments, it is in principle impossible to determine which process gave (A,Z+1). So, knowledge of limits on CNC β decays was important.

Example: CNC β decay of ^{73}Ge

[A.A. Klimenko et al., Phys. Lett. B 535 (2002) 77]

Baksan Neutrino Observatory (660 m w.e.), low background set-up with active and passive shielding, HP Ge detector of 952 g, $\delta(^{73}\mathrm{Ge})$=7.73%, t=15288 h



1 candidate event:
11.1 keV + 66.7 keV with Δt=1.43 s
Possible background processes in $^{73}\mathrm{Ge}\to{}^{73}\mathrm{As}$:
(p,n), $(\alpha,p3n)$, (ν_e,e^-)

Unique time&energy signature of decay of ^{73}As created in the CNC β decay of ^{73}Ge:

1. **E=11.1 keV – deexcitation of ^{73}Ge atomic shell after K electron capture in ^{73}As;**
2. **E=53.4 keV in few seconds;**
3. **E=13.3 keV in few μs period.**

Real-time approach is used at the first time in the CNC β searches.

$\tau_{CNC\text{-}\beta}(^{73}\mathrm{Ge}\to{}^{73}\mathrm{As}) > 2.6\mathrm{e}23$ yr

Some other searches:

DAMA, $^{136}Xe \to {}^{136}Cs$: $\tau > 1.3 \cdot 10^{23}$ yr
[R.Bernabei et al., Beyond the Desert 2003, p.365]

LENS, $^{115}In \to {}^{115m}Sn$: $\tau > 4.1 \cdot 10^{20}$ yr
[C.M.Cattadori et al., NPA 748 (2005) 333]

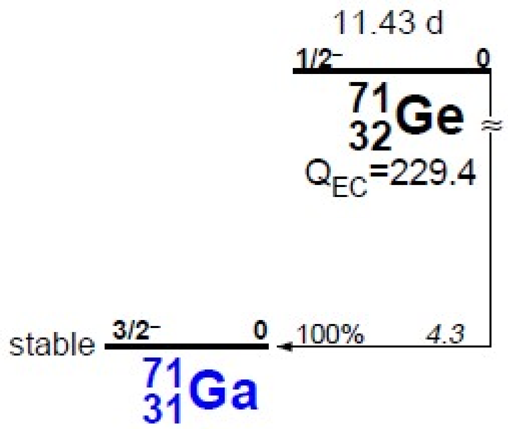
DAMA, $^{139}La \to {}^{139}Ce$: $\tau > 1.0 \cdot 10^{18}$ yr
[R.Bernabei et al., Ukr. J. Phys. 51 (2006) 1037]

DAMA, $^{100}Mo \to {}^{100}Tc$: $\tau > 4.5 \cdot 10^{19}$ yr
[P.Belli et al., Nucl. Phys. A 846 (2010) 143]

The best limit was achieved in the SAGE&GALLEX radiochemical solar ν experiment, $^{71}Ga \to {}^{71}Ge$: $\tau > 3.5 \cdot 10^{26}$ yr
[E.B. Norman et al., Phys. Rev. D 53 (1996) 4086]

SAGE&GALLEX:

Usual beta decay $^{71}Ga \rightarrow {}^{71}Ge$ is forbidden, however, if electron is not emitted, ^{71}Ge could appear in result of CNC beta decay (not only because of solar ν capture): $\tau > 3.5 \cdot 10^{26}$ yr
[E.B. Norman et al., Phys. Rev. D 53 (1996) 4086]



Limit was improved to $\tau > 1.4 \cdot 10^{27}$ yr taking into account contribution from flux of solar neutrinos (measured by other experiments)
[M. Torres, H. Vucetich, Mod. Phys. Lett. A 19 (2004) 639]

Summary of all experiments on search for CNC β decay
(11 experiments since 1960)

Table 3: Limits on life-time and CNC admixture in the weak interactions established in direct experiments to search for charge non-conserving β decay. Best limits are in red.

CNC β decay	Target, weight	Technique, detector	τ_{CNC}, yr (C.L.)	ϵ_ν^2	Year [Ref.]
^{87}Rb→^{87m}Sr	RbF, 30 g	CS [a], NaI(Tl)	$> 1.8 \cdot 10^{16}$	$< 3.3 \cdot 10^{-17}$	1960 [Sun60]
^{87}Rb→^{87m}Sr	Rb_2CO_3, 400 g	CS, Ge(Li)	$> 1.9 \cdot 10^{18}$ (90%)	$< 3.0 \cdot 10^{-19}$	1979 [Nor79]
^{71}Ga→^{71}Ge	Ga, 300 kg	CS, prop. counter	$> 2.3 \cdot 10^{23}$ (90%)	$< 9.0 \cdot 10^{-24}$	1980 [Bar80]
^{87}Rb→^{87m}Sr	Rb_2CO_3, 800 g	CS, Si(Li)	$> 7.5 \cdot 10^{19}$ (90%)	$< 7.9 \cdot 10^{-21}$	1983 [Vai83]
^{113}Cd→^{113m}In	$CdCl_2$, 1.5 kg	CS, Si(Li), NaI(Tl)	$> 1.4 \cdot 10^{18}$ (90%)	$< 9.7 \cdot 10^{-18}$	1983 [Roy83]
^{71}Ga→^{71}Ge	$GaCl_3$–HCl, 101 t + Ga, 57 t	CS, prop. counter	$\geq 3.5 \cdot 10^{26}$ (68%)	$\leq 8.0 \cdot 10^{-27}$	1996 [Nor96] [b]
^{73}Ge→^{73}As	Ge, 952 g	RT [c], HPGe	$\geq 2.6 \cdot 10^{23}$ (90%)	$\leq 1.1 \cdot 10^{-8}$	2002 [Kli02]
^{136}Xe→^{136}Cs	Xe, 6.5 kg [d]	RT, LXe	$> 1.3 \cdot 10^{23}$ (90%)	$< 1.1 \cdot 10^{-5}$	2004 [Ber04]
^{115}In→^{115m}Sn	In, 928 g	RT, HPGe	$> 4.1 \cdot 10^{20}$ (90%)	$< 2.4 \cdot 10^{-20}$	2005 [Cat05]
^{139}La→^{139}Ce	$LaCl_3$, 50 g	RT, $LaCl_3$(Ce) scint.	$> 1.0 \cdot 10^{18}$ (90%)	$< 4.7 \cdot 10^{-10}$	2006 [Ber06]
^{100}Mo→^{100}Tc	$^{100}MoO_3$, 1199 g	RT, 4 HP Ge	$> 4.5 \times 10^{19}$ (90%)	$< 2.9 \cdot 10^{-21}$	2010 [Bel10]

[a] CS means chemical separation of the daughter product

[b] Accounting for contribution from the solar neutrinos, the limit for ^{71}Ga was improved to $\tau_{CNC} > 1.4 \times 10^{27}$ yr ($\epsilon_\nu^2 < 2.0 \cdot 10^{-27}$) in [Tor04]

[c] RT means real-time experiment

[d] 68.8% ^{136}Xe

$$\epsilon_\nu^2 = \frac{\tau(n)}{\tau_{CNC}(A,Z)} \frac{W^5(n)}{W^5(A,Z)} \frac{ft_{1/2}(A,Z)}{ft_{1/2}(n)}$$

Conclusions

Searches for CNC processes and e, N, NN, NNN decays into *invisible* is very interesting and important field of research.

Experimental efforts are active.

During the last decade, τ limits for electron decay were improved from $10^{23} - 10^{25}$ yr to $10^{24} - 10^{28}$ yr (in dependence on mode).

The advice of L.B. Okun is followed …

Thank you for attention!