Search for Baryon and charge violations with nuclei

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Search for Baryon and Lepton Number Violation, Sept. 20-22, 2007, LBL, Berkeley

Searches for invisible decays of matter start to be more and more popular.

This is related 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. Usp. 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"

Thus, we could expect disappearance of *e, p, n*, ...

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

In addition to searches for *e, p, n,* etc. decays into invisible, one could also mention:

(1) Limit on Br($\mu^+ \to$ *invisible*) < $5.3 \cdot 10^{-3}$ [S.N.Gninenko, 0707.3492]

(2) Limit on Br(o-Ps $\to$ *invisible*) < $4.2 \cdot 10^{-7}$ from the ETH-INR experiment [A. Badertsher et al., PRD 75(2007)032004]

(3) Do we already see disappeared energy and momentum in HERA? [V.Andreev et al., PLB 561(2003)241]

see also in arXiv:
0601028, 0601037,
0602028, 0607020,
0610041, 0612302,
0701050 +
EPJC 51(2007)543

?

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Isolated electrons and muons in events with missing transverse momentum at HERA

H1 Collaboration

Abstract

A search for events with a high-energy isolated electron or muon and missing transverse momentum has been performed at the electron–proton collider HERA using an integrated luminosity of 13.6 pb^{-1} in $e^- p$ scattering and 104.7 pb^{-1} in $e^+ p$ scattering. Within the Standard Model such events are expected to be mainly due to W boson production with subsequent leptonic decay. In $e^- p$ interactions one event is observed in the electron channel and none in the muon channel, consistent with the expectation of the Standard Model. In the $e^+ p$ data a total of 18 events are seen in the electron and muon channels compared to an expectation of 12.4 ± 1.7 dominated by W production (9.4 ± 1.6). Whilst the overall observed number of events is broadly in agreement with the number predicted by the Standard Model, there is an excess of events with transverse momentum of the hadronic system greater than 25 GeV with 10 events found compared to 2.9 ± 0.5 expected. The results are used to determine the cross-section for events with an isolated electron or muon and missing transverse momentum.

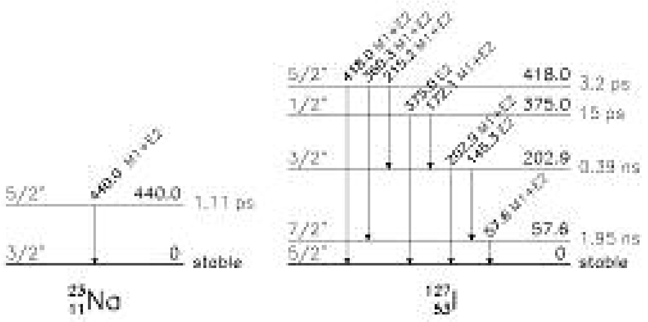
Disappearance of *e, p*, … means charge non-conservation …

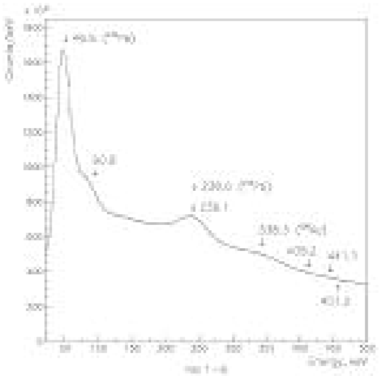
Several our experiments to search for decay of electron:

(1) $e^- \to \nu_e + \gamma$ – one is looking for γ with $E_\gamma \approx m_e c^2/2$ = 255.5 keV
LNGS (3600 m w.e.), low-background 6.5 kg DAMA LXe scintillator (99.5% ^{129}Xe), no 255 keV peak after 8336 h:
$\tau(e^- \to \nu_e + \gamma) > 2.0 \cdot 10^{26}$ yr (best limit in 2000-2002) [P.Belli et al., PRD 61(2000)117301]
(consequence: $m_\gamma < 2.0 \cdot 10^{-15}$ eV)

(2) $e^- \to$ *invisible* – one is looking for energy release in detector = bounding energy of electron on specific shell
LNGS, low-background ~100 kg NaI DAMA set-up, low energy threshold (~2 keV), 8 e^- on L shell (E_b~5 keV) instead of usual 2 e^- on K shell, no peak after 5364 h:
$\tau(e^- \to \mathit{invisible}) > 2.4 \cdot 10^{24}$ yr (best current limit) [P.Belli et al., PLB 460(1999)236]

(3) $e^- \to$ *invisible* with excitation of nuclear levels ($E_{exc} < m_e c^2 - E_b$) – one is looking for deexcitation γ quanta





Data with:

DAMA NaI – $\tau > (1.5\text{-}2.4) \cdot 10^{23}$ yr
[P.Belli et al., PRC 60(1999)065501]

DAMA LXe – $\tau > (1.1\text{-}3.7) \cdot 10^{24}$ yr
[P.Belli et al., PLB 465(1999)315]

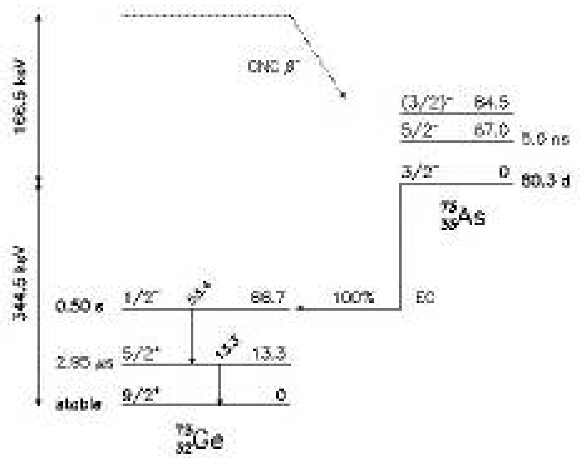
(best current limits)

(4) CNC β decay

Usual beta decay: $(A,Z) \rightarrow (A,Z+1) + e^{-} + \nu_e$
CNC beta decay: $(A,Z) \rightarrow (A,Z+1)$ + (some massless particle: γ, Majoron, etc.) + ν_e

Thus, extra 511 keV are available which makes energetically possible decay of (A,Z) to ground state or excited levels of $(A,Z+1)$ otherwise forbidden

Example: $^{73}Ge \rightarrow {}^{73}As$
CC β energetically forbidden, CNC β allowed



One looks for decay of unstable ^{73}As in Ge detector
Baksan Neutrino Observatory (660 m w.e.),
low-background HP Ge detector 952 g,
$\delta(^{73}Ge)$=7.73%, t=15288 h
Real-time approach at the first time in the CNC β searches (instead of usual chemical separation of daughter products).
$\tau_{CNC\text{-}\beta}(^{73}Ge \rightarrow {}^{73}As) > 2.6 \cdot 10^{23}$ yr
[A.A.Klimenko et al., PLB 535(2002)77]

Other our searches:
DAMA, $^{136}Xe \rightarrow {}^{136}Cs$: $\tau > 1.3 \cdot 10^{23}$ yr [R.Bernabei et al., Beyond the Desert 2003, p.365]
LENS, $^{115}In \rightarrow {}^{115m}Sn$: $\tau > 4.1 \cdot 10^{20}$ yr [C.M.Cattadori et al., NPA 748(2005)333]
DAMA, $^{139}La \rightarrow {}^{139}Ce$: $\tau > 1.0 \cdot 10^{18}$ yr [R.Bernabei et al., Ukr. J. Phys. 51(2006)1037]
However, it was impossible to reach level of $\sim 10^{26}$ yr based on SAGE&GALLEX data

Anonymous referee of one of our article on electron decays, 1999-2000
(we wrote in introduction something like this: "*limits on electron decays are on the level of 10^{23} yr while limits on proton decay are 10 orders of magnitude better*"):

"Where did you see that limit on p decay is 10^{33} yr? Look into PDG – it is 10^{23}-10^{25} yr"

To our big surprise, we really saw the following status of p decay limits in PDG'2000 [EPJC 15(2000)1]:

Baryon Particle Listings

p

p MEAN LIFE

A test of baryon conservation. See the "*p* Partial Mean Lives" section below for limits that depend on decay modes. *p* = proton, *n* = bound neutron.

LIMIT (years)	*PARTICLE*	*DOCUMENT ID*		*TECN*
>1.6 × 10^{25}	***p, n***	[14,15] EVANS	77	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>3 × 10^{23}	*p*	[15] DIX	70	CNTR
>3 × 10^{23}	*p, n*	[15,16] FLEROV	58	

[14] Mean lifetime of nucleons in ^{130}Te nuclei.
[15] Converted to mean life by dividing half-life by ln(2) = 0.693.
[16] Mean lifetime of nucleons in ^{232}Th nuclei.

This fully changed our relation to the subject:
while it was absolutely hopeless to reach 10^{33} yr in our small and middle scale experiments,
we could try to improve limits on the 10^{23}-10^{25} yr level!

This started our involvement in *N*, *NN* and *NNN* decays …

Many thanks to anonymous referee!

Our activity in the nucleon(s) decays:

(1) Analysis of experiments with heavy water at the Bugey (also Krasnoyarsk, Rovno) nuclear reactors (aimed to measure σ of *d* disintegration by ν from reactor).
Because *d=pn*, if *p* disappears or decays into anything in *d*, we will have free *n*.
Conservatively supposing that all *n* in 267 kg D_2O target at Bugey are created by *p* decay/disappearance, we get:
$\tau(p \to anything) > 4 \cdot 10^{23}$ yr at 95% C.L. [V.I.Tretyak et al., PLB 505(2001)59]
(in my opinion, this is the best current limit on *p* decay independent on channel)

(2) After publication of the first SNO data in 2002 (1000 t of D_2O instead of 267 kg in Bugey, underground location, pure materials, etc.), using number of free *n* in the SNO volume and subtracting contribution from Solar ν, we have:
$\tau(p \to invisible) > 3.5 \cdot 10^{28}$ yr at 90% C.L. [Yu.G.Zdesenko & VIT, PLB 553(2003)135].
It is for *invisible* modes, not for *anything* because μ veto switched off the SNO in case of energetic events.
This limit was improved further by the SNO Collaboration in 2004 to the best current limit:
$\tau(p \to invisible) > 2.1 \cdot 10^{29}$ yr, searching for γ with E_γ=6–7 MeV after deexcitation of ^{15}N

(3) Search for decay of radioactive nuclei which will be created in a detector in result of nucleon(s) decay into *invisible* (*invisible* means disappearance or decay into ν's, etc.)

$n \to invisible$:	$(A,Z) \to (A-1,Z)$	**If mother (A,Z) was embedded in a**
$p \to invisible$:	$(A,Z) \to (A-1,Z-1)$	**detector, and daughter is unstable,**
$nn \to invisible$:	$(A,Z) \to (A-2,Z)$	**efficiency for its decay will be $\varepsilon \approx 1$.**
$pn \to invisible$:	$(A,Z) \to (A-2,Z-1)$	**This is a big advantage.**
$pp \to invisible$:	$(A,Z) \to (A-2,Z-2)$	

Example: for *nn* decays existed only two limits in 2000:
$\tau(nn \to \nu_\mu \nu_\mu) > 6.0 \cdot 10^{24}$ yr, $\tau(nn \to \nu_e \nu_e) > 1.2 \cdot 10^{25}$ yr – from the Frejus data: the whole Earth was source of decaying *nn* pairs, emitted ν_μ or ν_e should go to 700 t iron detector and to fire it. Efficiency – tiny value.

Our first work with above mentioned approach:
LNGS, DAMA 6.5 kg low-background LXe detector (99.5% ^{129}Xe), 8336 h

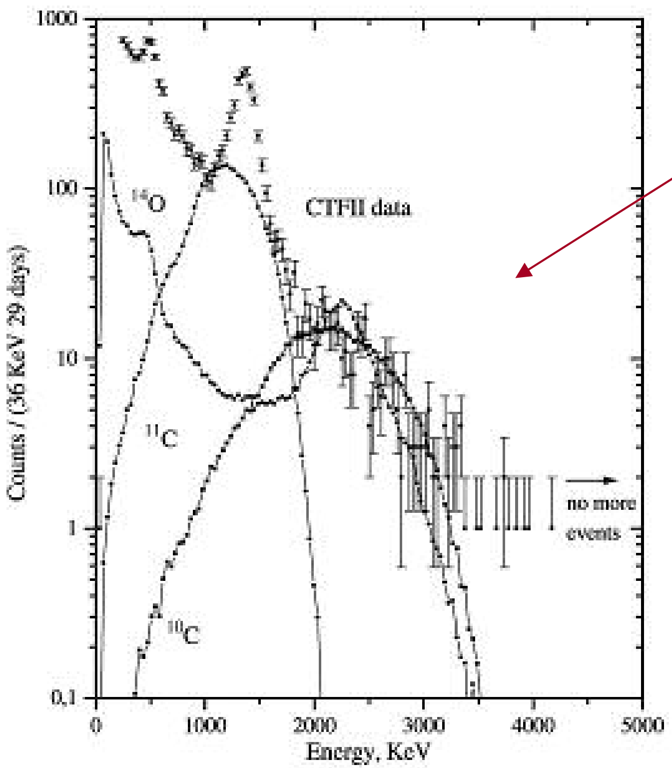
p:	$^{129}Xe \to ^{128}I$	$(T_{1/2}=24.99$ m, β^-, β^+, EC$)$	$\tau(p \to invisible) > 1.9 \cdot 10^{24}$ yr
pp:	$^{129}Xe \to ^{127}Te$	$(T_{1/2}=9.4$ h, $\beta^-)$	$\tau(pp \to invisible) > 5.5 \cdot 10^{23}$ yr
nn:	$^{129}Xe \to ^{127}Xe$	$(T_{1/2}=36.41$ d, EC$)$	$\tau(nn \to invisible) > 1.2 \cdot 10^{25}$ yr

$\tau(nn)$ – the same or better than the Frejus limits, but also valid for all *invisible* channels ($\nu_\mu\nu_\mu$, $\nu_e\nu_e$, $\nu_\tau\nu_\tau$, disappearance, etc.) – with 6.5 kg detector instead of 700 t
$\tau(pp)$ – established for the first time
[R.Bernabei et al., PLB 493(2000)12]

(4) The same approach was used in joint efforts with BOREXINO Collaboration: LNGS, Counting Test Facility (prototype of full BOREXINO set-up), 4.2 t of high-pure $C_{16}H_{18}$ liquid scintillator + 1000 t of high-pure water around, 698 h

n:	$^{12}C \rightarrow {}^{11}C$ ($T_{1/2}$=20.38 m, β^+, EC)	$\tau(n \rightarrow invisible) > 1.8 \cdot 10^{25}$ yr
p:	$^{13}C \rightarrow {}^{12}B$ ($T_{1/2}$=20.4 ms, β^-)	$\tau(p \rightarrow invisible) > 1.1 \cdot 10^{26}$ yr
nn:	$^{12}C \rightarrow {}^{10}C$ ($T_{1/2}$=19.2 s, β^+)	
	$^{16}O \rightarrow {}^{14}O$ ($T_{1/2}$=70.60 s, β^+)	$\tau(nn \rightarrow invisible) > 4.9 \cdot 10^{25}$ yr
pp:	$^{13}C \rightarrow {}^{11}Be$ ($T_{1/2}$=13.8 s, β^-)	$\tau(pp \rightarrow invisible) > 5.0 \cdot 10^{25}$ yr

[H.O.Back et al., PLB 563(2003)23]



Very conservative limits, when all events in some energy region were ascribed to the *N* or *NN* decays

$\tau(nn \rightarrow invisible)$ was the best current limit up to:
KamLAND (2006): $>1.4 \cdot 10^{30}$ yr

$\tau(pp \rightarrow invisible)$ is still the best current limit

(5) Analysis of old radiochemical experiment on the p and n disappearance in ^{39}K [E.L.Fireman, R.I.Steinberg, J.C.Evans, 1977] :

1710 kg of $KC_2H_3O_2$ ($9.7\cdot10^{27}$ atoms of ^{39}K), Homestake mine (4400 m w.e.), exposition ~1 yr.
p decay in ^{39}K: $^{39}\mathrm{K} \to {}^{38}\mathrm{Ar} \to$ 22.2% emission of $n \to {}^{37}\mathrm{Ar}$
n decay in ^{39}K: $^{39}\mathrm{K} \to {}^{38}\mathrm{K} \to$ 20.4% emission of $p \to {}^{37}\mathrm{Ar}$
Extraction and detection of radioactive ^{37}Ar (rate 0.3±0.6 atom/day).
With 19 p and 20 n in ^{37}Ar it gives: $\tau_p=\tau_n>1.1\cdot10^{26}$ yr.

However, the same data can be used to set limits on the disappearance of the np and nn pair in ^{39}K:
$pn\to invisible$: $^{39}\mathrm{K}\to{}^{37}\mathrm{Ar}$
$nn\to invisible$: $^{39}\mathrm{K}\to{}^{37}\mathrm{K} \to$ EC with $T_{1/2}$=1.2 s $\to {}^{37}\mathrm{Ar}$

$\tau(nn\to invisible)>4.2\cdot10^{25}$ yr
$\tau(pn\to invisible)>2.1\cdot10^{25}$ yr – the best current limit

[V.I.Tretyak et al., JETP Letters 79(2004)106]

(6) Search for tri-nucleon decays into *invisible*

K.S. Babu et al., Phys. Lett. B 570 (2003) 32:
new theory in which processes with ΔB=1 and ΔB=2 are forbidden but with ΔB=3 allowed

LNGS (3600 m w.e.), DAMA low-background LXe detector,
6.5 kg, 68.8% ^{136}Xe, measurements over 8824 h

Decay	Daughter nucleus	Subsequent decays
n	^{135}Xe	$^{135}\mathrm{Xe} \xrightarrow{\beta^-} {}^{135}\mathrm{Cs}$ *
p	^{135}I	$^{135}\mathrm{I} \xrightarrow{\beta^-} {}^{135}\mathrm{Xe} \xrightarrow{\beta^-} {}^{135}\mathrm{Cs}$ *
nn	^{134}Xe	Stable
np	^{134}I	$^{134}\mathrm{I} \xrightarrow{\beta^-} {}^{134}\mathrm{Xe}$
pp	^{134}Te	$^{134}\mathrm{Te} \xrightarrow{\beta^-} {}^{134}\mathrm{I} \xrightarrow{\beta^-} {}^{134}\mathrm{Xe}$
nnn	^{133}Xe	$^{133}\mathrm{Xe} \xrightarrow{\beta^-} {}^{133}\mathrm{Cs}$
nnp	^{133}I	$^{133}\mathrm{I} \xrightarrow{\beta^-} {}^{133}\mathrm{Xe} \xrightarrow{\beta^-} {}^{133}\mathrm{Cs}$
npp	^{133}Te	$^{133}\mathrm{Te} \xrightarrow{\beta^-} {}^{133}\mathrm{I} \xrightarrow{\beta^-} {}^{133}\mathrm{Xe} \xrightarrow{\beta^-} {}^{133}\mathrm{Cs}$
ppp	^{133}Sb	$^{133}\mathrm{Sb} \xrightarrow{\beta^-} {}^{133}\mathrm{Te} \xrightarrow{\beta^-} {}^{133}\mathrm{I} \xrightarrow{\beta^-} {}^{133}\mathrm{Xe} \xrightarrow{\beta^-} {}^{133}\mathrm{Cs}$ **

* ^{135}Cs is not stable, but has $T_{1/2} = 2.3 \cdot 10^6$ yr and breaks the decay chain.
** Given here only the main part of the chain.

Expected chains of radioactive decays were simulated with EGS, and calculated response functions were compared with the experimental spectrum

[R.Bernabei et al., EPJA 27,s01(2006)35]

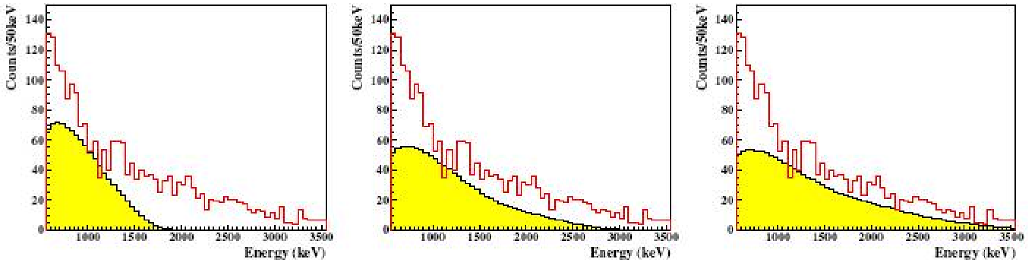


Fig. 3. Comparison between the experimental spectrum measured during 8823.54 h (thick histogram) and the expected signal (colored histogram) for: left) the nnp disappearance with $\tau_{nnp} = 1.4 \cdot 10^{22}$ yr excluded at 90% C.L.; center) the npp disappearance with $\tau_{npp} = 2.7 \cdot 10^{22}$ yr excluded at 90% C.L.; right) the ppp disappearance with $\tau_{ppp} = 3.6 \cdot 10^{22}$ yr excluded at 90% C.L.

Very conservative approach:
expected theoretical curve should not be greater than experimental spectrum

$\tau(nnp \to invisible) > 1.4 \cdot 10^{22}$ yr
$\tau(npp \to invisible) > 2.7 \cdot 10^{22}$ yr
$\tau(ppp \to invisible) > 3.6 \cdot 10^{22}$ yr
all at 90% C.L.

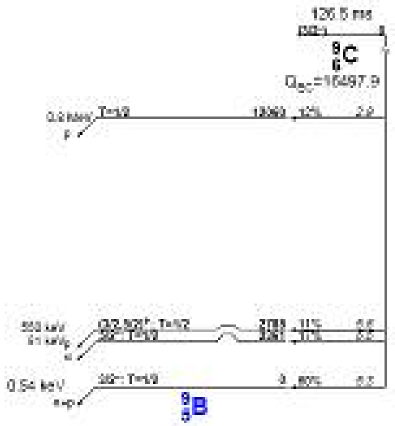
First limits on *NNN* disappearance

Possible search for *NNN* → *invisible* in KamLAND or SNO+ ?

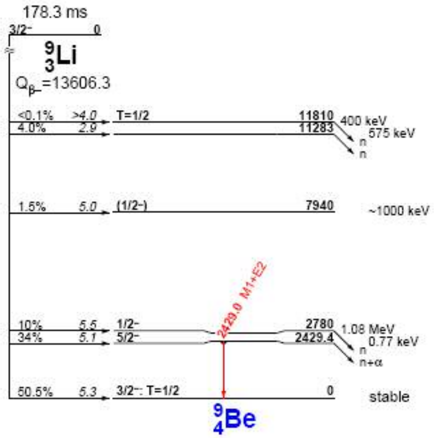
Liquid scintillator: C and H; O in surrounding water

			Daughter decay and *Q* (MeV)	
$^{12}_{6}C$ 98.93%	*nnn* →	$^{9}_{6}C$	EC	=16.4979
	nnp →	$^{9}_{5}B$	$p+2\alpha$	=0.1851
	ppp →	$^{9}_{3}Li$	β^-	=13.6063
$^{13}_{6}C$ 1.07%	*nnn* →	$^{10}_{6}C$	EC	=3.651
	npp →	$^{10}_{4}Be$	β^-	=0.556
	ppp →	$^{10}_{3}Li$	β^-	=20.444
$^{16}_{8}O$ 99.757%	*nnn* →	$^{13}_{8}O$	EC	=17.765
	nnp →	$^{13}_{7}N$	EC	=2.2204
	ppp →	$^{13}_{5}B$	β^-	=13.4372

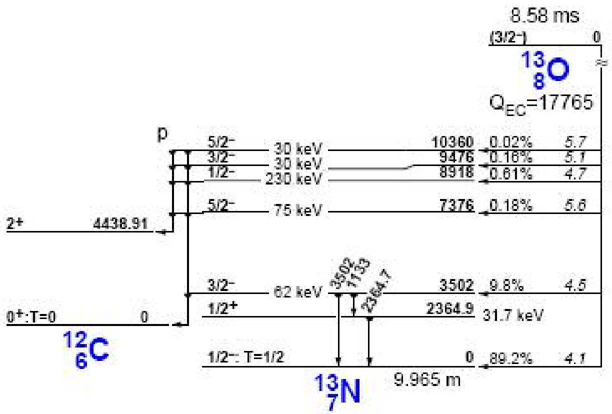
nnn: $^{12}{}_{6}\mathrm{C} \rightarrow {}^{9}{}_{6}\mathrm{C}$



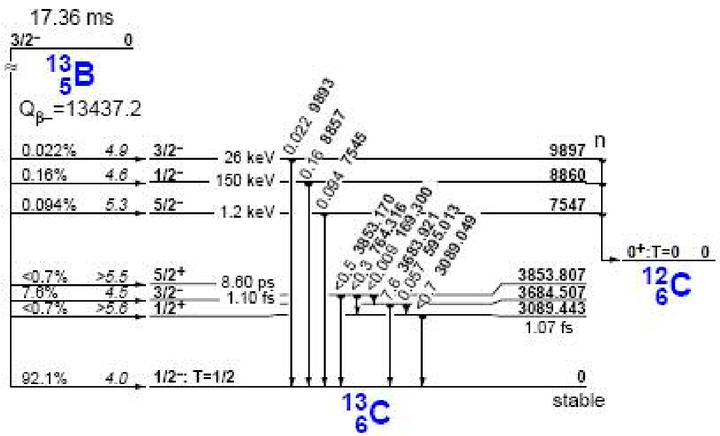
ppp: $^{12}{}_{6}\mathrm{C} \rightarrow {}^{9}{}_{6}\mathrm{Li}$



nnn: $^{16}{}_{8}\mathrm{O} \rightarrow {}^{13}{}_{8}\mathrm{O}$



ppp: $^{16}{}_{8}\mathrm{O} \rightarrow {}^{13}{}_{5}\mathrm{B}$



Conclusions:

In series of experiments, we established limits on probabilities of exotic processes with violation of electric charge and/or *B* number. Mostly these limits were the best world values at the time of publication, some of them were determined at the first time.

The following limits are still alive (i.e. the best current limits, 90% C.L.):

$\tau(e^- \rightarrow invisible) > 2.4 \cdot 10^{24}$ yr

$\tau(e^- \rightarrow invisible$ with excitation of nuclear levels$) > 3.7 \cdot 10^{24}$ yr

$\tau(p \rightarrow anything) > 4 \cdot 10^{23}$ yr

$\tau(pp \rightarrow invisible) > 5.0 \cdot 10^{25}$ yr

$\tau(pn \rightarrow invisible) > 2.1 \cdot 10^{25}$ yr

$\tau(nnp \rightarrow invisible) > 1.4 \cdot 10^{22}$ yr

$\tau(npp \rightarrow invisible) > 2.7 \cdot 10^{22}$ yr

$\tau(ppp \rightarrow invisible) > 3.6 \cdot 10^{22}$ yr

Thank you for attention!

(See Appendix for summary of searches for CNC and *N*, *NN* and *NNN* decays into invisible channels)

Appendix

Summary of searches for charge non-conserving processes and *N*, *NN*, and *NNN* decays into invisible

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

Detector	Volume (cm^3)	Time of measurement (h)	Limit on $\tau_e(e^- \to invisible)$ (yr)	Limit on $\tau_e(e^- \to \nu_e\gamma)$ (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]
HP Ge	135	8850	–	$1.5(1.1){\cdot}10^{25}$	1986 [Avi86]
HP Ge	$3{\times}140$	1662	$2.7(1.7){\cdot}10^{23}$	–	1991 [Reu91]
NaI(Tl)	$17{\times}10570$	2823	$1.2{\cdot}10^{23}$	–	1992 [Eji92]
HP Ge	591	3199	–	$2.4(1.2){\cdot}10^{25}$	1993 [Bal93]
HP Ge	$48{+}2{\times}209$	$13404^a, 7578^b$	$4.3(2.6){\cdot}10^{23}$	$3.7(2.1){\cdot}10^{25}$	1995 [Aha95]
BaF_2	$2{\times}103$	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]
HP Ge	132	12600	$1.3{\cdot}10^{24}$	–	1998 [Kli98]
NaI(Tl)	$9{\times}2643$	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]
HP Ge	437	33233	–	$1.9(1.0){\cdot}10^{26}$ [e]	2007 [Kla07]

[a] For channel $e^- \to invisible$

[b] For channel $e^- \to \nu_e\gamma$

[c] At 84% C.L.

[d] Liquid scintillator

[e] This result was critisized in [Der07] as being overestimated at $\simeq$5 times

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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.
^{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	$2.4 \cdot 10^{21}$		$1.6 \cdot 10^{23}$	
^{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				$2.3 \cdot 10^{24}$

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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$\to^{87m}$Sr	RbF, 30 g	CS [a], NaI(Tl)	$> 1.8 \cdot 10^{16}$	$< 3.3 \cdot 10^{-17}$	1960 [Sun60]
^{87}Rb$\to^{87m}$Sr	Rb_2CO_3, 400 g	CS, Ge(Li)	$> 1.9 \cdot 10^{18}$ (90%)	$< 3.0 \cdot 10^{-19}$	1979 [Nor79]
^{71}Ga$\to^{71}$Ge	Ga, 300 kg	CS, prop. counter	$> 2.3 \cdot 10^{23}$ (90%)	$< 9.0 \cdot 10^{-24}$	1980 [Bar80]
^{87}Rb$\to^{87m}$Sr	Rb_2CO_3, 800 g	CS, Si(Li)	$> 7.5 \cdot 10^{19}$ (90%)	$< 7.9 \cdot 10^{-21}$	1983 [Vai83]
^{113}Cd$\to^{113m}$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$\to^{71}$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]
^{73}Ge$\to^{73}$As	Ge, 952 g	RT [b], HPGe	$\geq 2.6 \cdot 10^{23}$ (90%)	$\leq 1.1 \cdot 10^{-8}$	2002 [Kli02]
^{71}Ga$\to^{71}$Ge	[c]		$\geq 1.4 \cdot 10^{27}$ (68%)	$\leq 2.0 \cdot 10^{-27}$	2004 [Tor04]
^{136}Xe$\to^{136}$Cs	Xe, 6.5 kg [d]	RT, LXe	$> 1.3 \cdot 10^{23}$ (90%)	$< 1.1 \cdot 10^{-5}$	2004 [Ber04]
^{115}In$\to^{115m}$Sn	In, 928 g	RT, HPGe	$> 4.1 \cdot 10^{20}$ (90%)	$< 2.4 \cdot 10^{-20}$	2005 [Cat05]
^{139}La$\to^{139}$Ce	$LaCl_3$, 50 g	RT, $LaCl_3$(Ce) scint.	$> 1.0 \cdot 10^{18}$ (90%)	$< 4.7 \cdot 10^{-10}$	2006 [Ber06]

[a] CS means chemical separation of the daughter product
[b] RT means real-time experiment
[c] Using data of [Nor96] and subtracting contribution from Solar neutrinos
[d] 68.8% ^{136}Xe

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Table 4: Lower limits on the life-time for N, NN and NNN decays into invisible channels established in various approaches. The best limits for specific channels are in red.

Nucleon(s) decay		τ limit, yr and C.L.	Year [Ref.]	Short explanation
p	$\rightarrow$ *anything*	$1.2 \cdot 10^{23}$	1958 [Fle58]	Limit on ^{232}Th spontaneous fission
		$3.0 \cdot 10^{23}$	1970 [Dix70]	Search for free n in liquid scintillator enriched in deuterium ($d \rightarrow n+?$)
		$4.0 \cdot 10^{23}$ 95%	2001 [Tre01]	Free n in reactor experiment with D_2O
	$\rightarrow$ *invisible*	$7.4 \cdot 10^{24}$	1977 [Eva77]	Geochemical search for ^{130}Te$\rightarrow ... \rightarrow$^{129}Xe
		$1.1 \cdot 10^{26}$	1978 [Fir78]	Radiochemical search for ^{39}K$\rightarrow ... \rightarrow$^{37}Ar
		$1.9 \cdot 10^{24}$ 90%	2000 [Ber00]	Search for ^{128}I decay in ^{129}Xe detector
		$\simeq 10^{28}$	2002 [Ahm02]	Free n in the SNO D_2O volume
		$1.1 \cdot 10^{26}$ 90%	2003 [Bac03]	Search for ^{12}B decay in CTF detector
		$3.5 \cdot 10^{28}$ 90%	2003 [Zde03]	Free n in the SNO D_2O volume
		$2.1 \cdot 10^{29}$ 90%	2004 [Ahm04]	Search for γ with E_γ=6–7 MeV emitted in ^{15}N deexcitation in SNO detector
n	$\rightarrow$ *anything*	$1.8 \cdot 10^{23}$	1958 [Fle58]	Limit on ^{232}Th spontaneous fission
	$\rightarrow \nu_\mu \bar{\nu}_\mu \nu_\mu$	$5.0 \cdot 10^{26}$ 90%	1979 [Lea79]	Massive liquid scint. detector fired by ν_μ in result of n decays in the whole Earth ^{a,b}
		$1.2 \cdot 10^{26}$ 90%	1991 [Ber91]	Fréjus iron detector fired by ν_μ ^{b}
	$\rightarrow \nu_e \bar{\nu}_e \nu_e$	$3.0 \cdot 10^{25}$ 90%	1991 [Ber91]	Fréjus iron detector fired by ν_e ^{c}
	$\rightarrow \nu_\tau \bar{\nu}_\tau \nu_\tau$	$2.3 \cdot 10^{27}$ 90%	1997 [Gli97]	Search for bremsstrahlung γ with E_γ>100 MeV emitted due to sudden disappearance of n magnetic moment (from Kamiokande data) ^{d}
	$\rightarrow \nu_\tau \bar{\nu}_\tau \nu_\tau \bar{\nu}_\tau \nu_\tau$	$1.7 \cdot 10^{27}$ 90%	1997 [Gli97]	The same approach ^{d}
	$\rightarrow$ *invisible*	$8.6 \cdot 10^{24}$	1977 [Eva77]	Geochemical search for ^{130}Te$\rightarrow ... \rightarrow$^{129}Xe
		$1.1 \cdot 10^{26}$	1978 [Fir78]	Radiochemical search for ^{39}K$\rightarrow ... \rightarrow$^{37}Ar
		$4.9 \cdot 10^{26}$ 90%	1993 [Suz93]	Search for γ with E_γ=19–50 MeV emitted in

					^{15}O deexcitation in Kamiokande detector
		$1.8\cdot10^{25}$	90%	2003 [Bac03]	Search for ^{11}C decay in CTF detector
		$1.9\cdot10^{29}$	90%	2004 [Ahm04]	Search for γ with E_γ=6–7 MeV emitted in ^{15}O deexcitation in SNO detector
		$5.8\cdot10^{29}$	90%	2006 [Ara06]	Search for correlated decays in KamLAND detector
nn	$\to \nu_\mu\bar{\nu}_\mu$	$6.0\cdot10^{24}$	90%	1991 [Ber91]	Fréjus iron detector fired by ν_μ [e]
	$\to \nu_e\bar{\nu}_e$	$1.2\cdot10^{25}$	90%	1991 [Ber91]	Fréjus iron detector fired by ν_e [f]
	$\to$ *invisible*	$1.2\cdot10^{25}$	90%	2000 [Ber00]	Search for ^{127}Xe decay in ^{129}Xe detector
		$4.9\cdot10^{25}$	90%	2003 [Bac03]	Search for ^{10}C and ^{14}O decay in CTF
		$4.2\cdot10^{25}$	90%	2004 [Tre04]	Radiochemical search for ^{39}K→...→^{37}Ar [g]
		$1.4\cdot10^{30}$	90%	2006 [Ara06]	Search for correlated decays in KamLAND detector
pp	$\to$ *invisible*	$5.5\cdot10^{23}$	90%	2000 [Ber00]	Search for ^{127}Te decay in ^{129}Xe detector
		$5.0\cdot10^{25}$	90%	2003 [Bac03]	Search for ^{11}Be decay in CTF detector
		$1.9\cdot10^{24}$	90%	2006 [Ber06]	Search for decays ^{134}Te→...→^{134}Xe in ^{136}Xe detector
pn	$\to$ *invisible*	$2.1\cdot10^{25}$	90%	2004 [Tre04]	Radiochemical search for ^{39}K→...→^{37}Ar [g]
		$3.2\cdot10^{23}$	90%	2006 [Ber06]	Search for decays ^{134}I→^{134}Xe in ^{136}Xe detector
ppp	$\to$ *invisible*	$3.6\cdot10^{22}$	90%	2006 [Ber06]	Search for decays ^{133}Sb→...→^{133}Cs in ^{136}Xe detector
ppn	$\to$ *invisible*	$2.7\cdot10^{22}$	90%	2006 [Ber06]	Search for decays ^{133}Te→...→^{133}Cs in ^{136}Xe detector
pnn	$\to$ *invisible*	$1.4\cdot10^{22}$	90%	2006 [Ber06]	Search for decays ^{133}I→...→^{133}Cs in ^{136}Xe detector

[a] The result of [Lea79] was reestimated in [Ber91] to be more than one order of magnitude lower

[b] The limit is also valid for $p \to \nu_\mu\bar{\nu}_\mu\nu_\mu$ decay

[c] The limit is also valid for $p \to \nu_e\bar{\nu}_e\nu_e$ decay

[d] $i = e, \mu, \tau$

[e] The limit is also valid for pn and pp decays into $\nu_\mu\bar{\nu}_\mu$

[f] The limit is also valid for pn and pp decays into $\nu_e\bar{\nu}_e$

[g] On the base of the data of [Fir78]

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