New limits on the Pauli-forbidden transitions obtained with the CTF and Borexino detector

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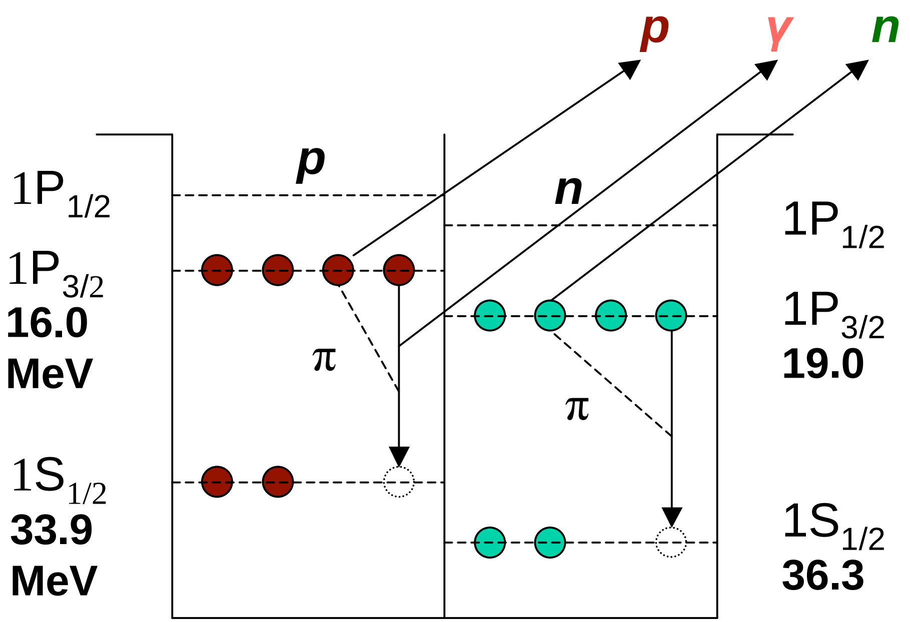
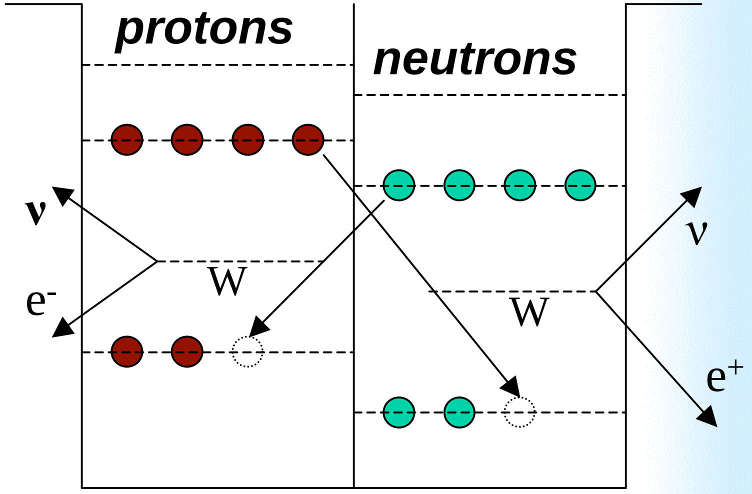
The nucleon level scheme of ^{12}C in a simple shell model





The non-Paulian transitions of P-shell nucleons to the filled S-shell were searched for in nuclei of **^{12}C** contained in the scintillator and **^{16}O** in the water shield of the CTF detector.

The excitation energy of **$^{12}C^{NP}$** corresponds to the difference of the binding energies on S- and P-shells and is comparable with separation energies of nucleons.

The approach consisted of a search for **γ, *n*, *p* and α's** emitted in a NP transitions of P-shell nucleons to the filled $1S_{1/2}$ shell in nuclei. Similarly, the Pauli-forbidden $\beta^{\pm}$ -decay processes were searched for.

Q-value release in the transitions

Energy release in the transitions is the difference between the binding energies of the final and initial nuclei – e.g. **$^{12}C \rightarrow ^{11}B^{NP}+p$** process:

$$Q(^{12}C \rightarrow ^{11}B^{NP}+p)=M(^{12}C) - M(^{11}B^{NP}) - m_p = -E_b(^{12}C)+E_b(^{11}B^{NP})$$

The binding energy of non-Paulian nuclei with 3 p’s or n’s on the S-shell can be evaluated considering the binding energy of ordinary nucleus $E_b(^{11}B)$ and the difference between the E_b of nucleons on S-shell and the separation energy $S_{p,n}$.

$$E_b(^{11}B^{NP}{}_{p,n}) \approx E_b(^{11}B) + E_{p,n}(1S_{1/2}) - S_{p,n}(^{11}B)$$

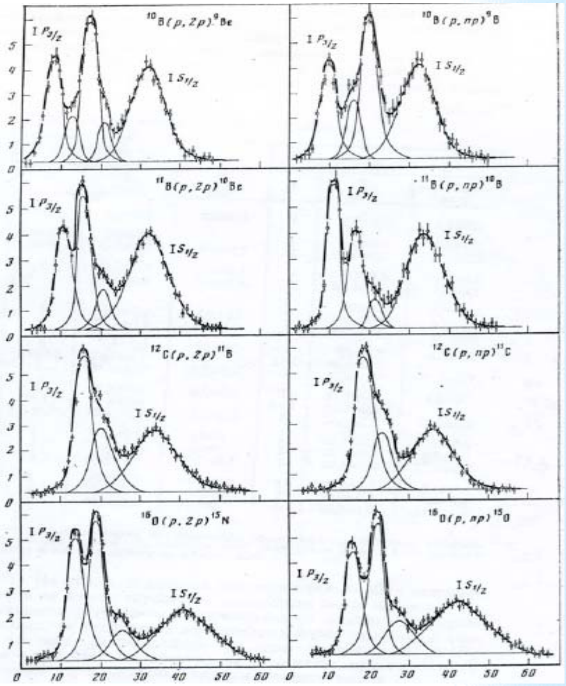
The binding energies of the nuclei and the nucleons separation energies are well known.
The binding energies of nucleons on the shells are not so precise.

$-E_b(^{12}C) = 92.16;$ $E_b(^{11}B) = -76.20;$
$E_p(^{11}B,1S_{1/2})=-33.5\pm0.9;$ $E_n(^{11}B,1S_{1/2})=-34.5\pm1.0;$
$S_p(^{11}B)=11.2;$ $S_n(^{11}B)=10.7;$

Q=6.3±1.0 MeV if $^{11}B^{NP}{}_{3p}$ is in the final state and Q=7.5±1.0 MeV in the case of $^{11}B^{NP}{}_{3n}$.

The nucleon binding energy of the P- and S- shells

Nucleus	$^{9}Be_{4}$	$^{11}B_{5}$	$^{12}C_{6}$	$^{16}O_{8}$
S_p	16.9	11.2	16.0	12.3
S_n	16.6	10.7	18.7	15.7
S_α	2.5	8.7	7.4	7.2
S_d	16.7	15.8	25.2	20.7
$1P_{3/2}(p)$	17.0(0.2)	11.8(0.5)	16.0(0.2)	18.0(0.3)
$1P_{3/2}(n)$	18.1(0.5)	11.7(0.6)	19.0(0.3)	22.0(0.4)
$1S_{1/2}(p)$	28.7(0.5)	33.5(0.9)	33.9(0.9)	39.8(0.9)
$1S_{1/2}(n)$	29.2(0.8)	34.5(1.0)	36.3(0.6)	42.2(1.0)
E_b	58.16	76.20	92.16	127.62



Belostotsky et.al., PAN,41(1985)1425

The nucleon binding energies of P- and *S*-shells for the light nuclei were measured while studying (***p***,***2p***) and (***p***,***np***) 1 GeV proton scattering reactions. The measured values for the **$1S_{1/2}$** shell of **^{12}C** are **En($1S_{1/2}$,^{12}C) =36.3±0.6 MeV** and **Ep($1S_{1/2}$,^{12}C) = 33.9±0.9 MeV**.
These values significantly differ from value $E_p(1S_{1/2},{}^{12}C)$ =39±1 MeV extracted from (***e,ep***)-scattering [*Lapikas et al., PRC 61(2000)*]. We used the data which give the more conservative limits on NP transitions.

Energy released in the possible reactions

Channel	Q, MeV	E detected
$^{12}\mathrm{C}\rightarrow{}^{12}\mathrm{C}^{NP}+\gamma$	17.5 ±1	~17.5
$^{16}\mathrm{O}\rightarrow{}^{16}\mathrm{O}^{NP}+\gamma$	21.8 ±1	~ 21.8
$^{12}\mathrm{C}\rightarrow{}^{11}\mathrm{B}^{NP}+p$	(6.4÷7.8) ±1	2.0÷4.7
$^{12}\mathrm{C}\rightarrow{}^{11}\mathrm{C}^{NP}+n$	(4.5÷6.5) ±2	2.2
$^{12}\mathrm{C}\rightarrow{}^{8}\mathrm{Be}^{NP}+\alpha$	3.0 ±1	0.06÷0.23
$^{12}\mathrm{C}\rightarrow{}^{12}\mathrm{N}^{NP}+e^{-}+\nu$	18.9 ±2	0.0÷18.9
$^{12}\mathrm{C}\rightarrow{}^{12}\mathrm{B}^{NP}+e^{+}+\nu$	17.8 ±2	0.0÷17.8

E.M.

STRONG

WEAK

The signature of the transitions with two particle in the final state is a gaussian peak in the measured spectrum. In the case of neutrino emission the flat $\beta^{\pm}$ - spectra are registered.

To find the response of the scintillator detector (detected energy) one have to take into account the recoil energy of nuclei and quenching factor.

The transitions with Q<0

$^{12}\mathrm{C}\rightarrow{}^{10}\mathrm{B}^{NP}+\mathrm{d}$	-(0.6÷1.5)
$^{12}\mathrm{C}\rightarrow{}^{9}\mathrm{B}^{NP}+\mathrm{t}$	-(4÷5)
$^{12}\mathrm{C}\rightarrow{}^{9}\mathrm{Be}+{}^{3}\mathrm{He}$	-(13÷15)
$^{12}\mathrm{C}\rightarrow{}^{6}\mathrm{Li}+{}^{6}\mathrm{Li}^{NP}$	-(6÷9)
$^{12}\mathrm{C}\rightarrow{}^{6}\mathrm{Li}^{NP}+{}^{4}\mathrm{He}+\mathrm{d}$	-(12÷14)

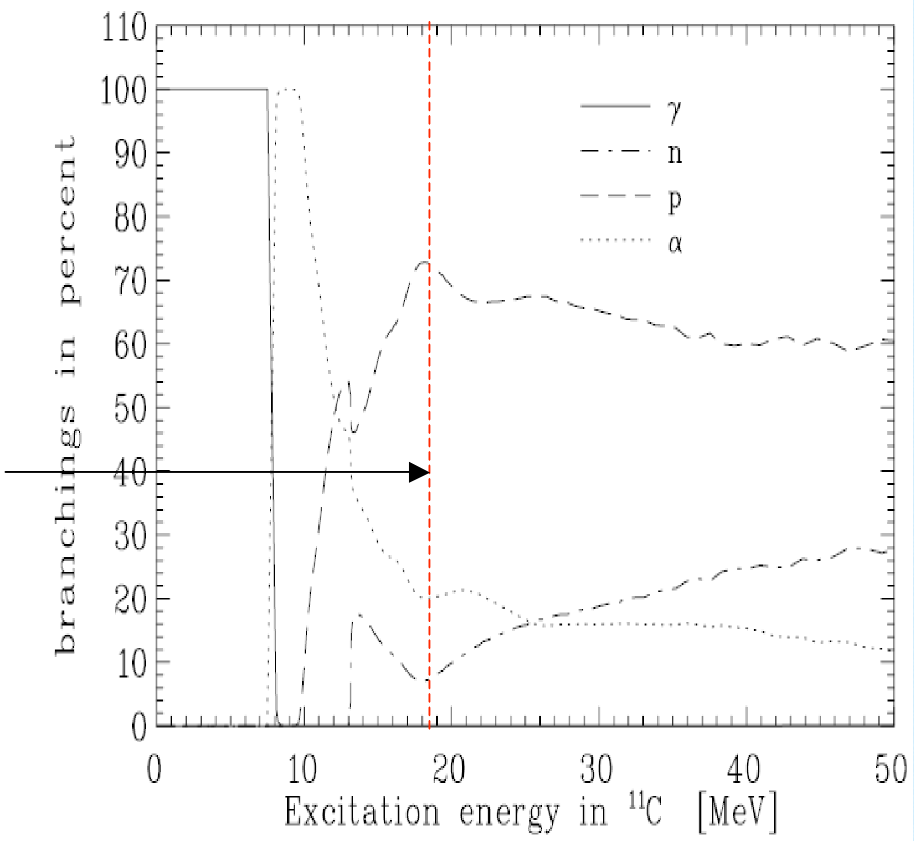
Branching ratio of de-excitation modes

The prediction of the branching ratio for the γ-,*p*-,*n*-,α-emission and NP nucleus in the final state is complicate task. From experimental point of view the search for PEP violation is close to search for nucleon disappearance or decay into invisible channels e.g. n→3v.

The BRs of de-excitation modes when **neutron disappears from the $1S_{!/2}$ state in ^{12}C** were obtained by Kamyshkov and Kolbe (PRD67(2003)).

The branching ratios at E_{exc} = 23 MeV obtained of the one-step emission are:

γ(0.7%), n(14%), p(64%) and α(21%).



The similar BRs one have to expect for the forbidden P- to S-shell transitions. Because the structure ^{12}C^{NP} nucleus differs from ^{11}C one, **the separate limits on the probabilities for each of the possible NP transitions were obtained**. These values can be compared with the rate for the normal reactions for the case of *p*- or *n*-hole in S-shell.

The mean lifetime limit

The lower limit on NP transitions of nucleons from P-shell to the occupied $1S_{1/2}$-shell can be obtained as:

$$\tau \geq \varepsilon_{\Delta E} \frac{N_N N_{p,n}}{S_{\lim}} T$$

$\varepsilon_{\Delta E}$ is the efficiency of registering an event in the energy interval ΔE,
N_N is the number of nuclei under consideration,
$N_{p,n}$ is the number of nucleons (p and/or n) for which the NP transitions are possible,
T is the time of measurements, and
S_{lim} is the upper limit on the number of candidate events registered in the ΔE interval.

S_{lim} can be evaluated as

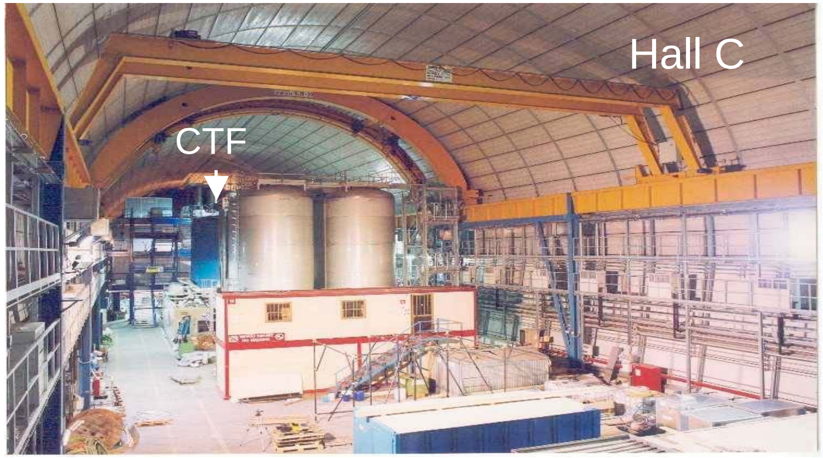
$$S_{\lim}(1\sigma) = 1.1\sqrt{3.3\sigma[keV]B[KeV^{-1}]}$$

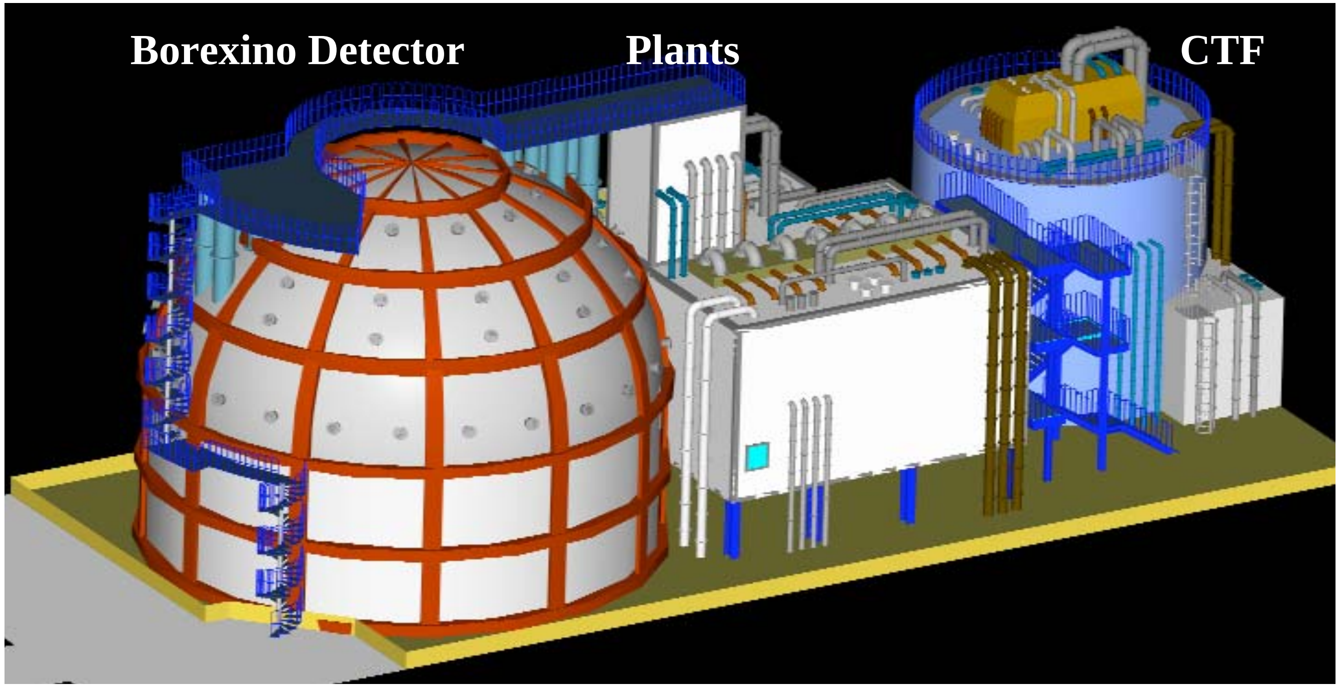
where σ **(E)** is the energy resolution and ***B*(E)** is background level of the detector.

e.g. **100 t** of carbon consists of $N_N \approx 5\text{x}10^{30}$ ^{12}C nuclei and $N_N N_{p+n} \approx 4\text{x}10^{31}$ nucleons on the P-shell.

For **T=1** year, $\varepsilon_{\Delta E}=1$ and **B= 0** ($S_{\lim}$=2.44 for 90% c.l.) the lower limit is $\tau \geq 1.6 \cdot 10^{31}$ y

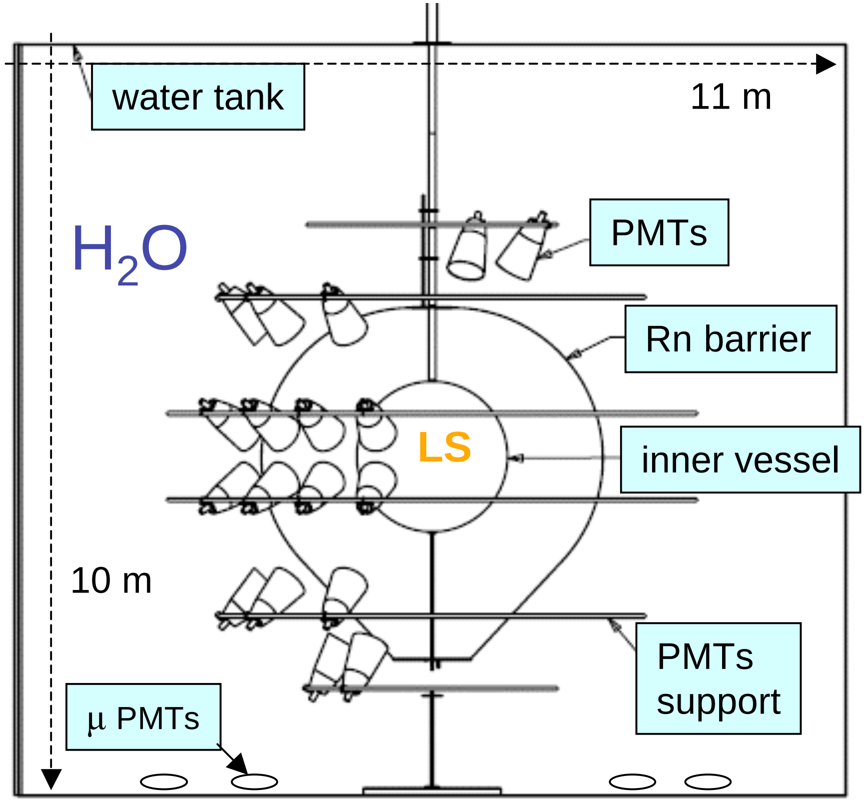
CTF and Borexino detector at the Laboratori Nazionali del Gran Sasso

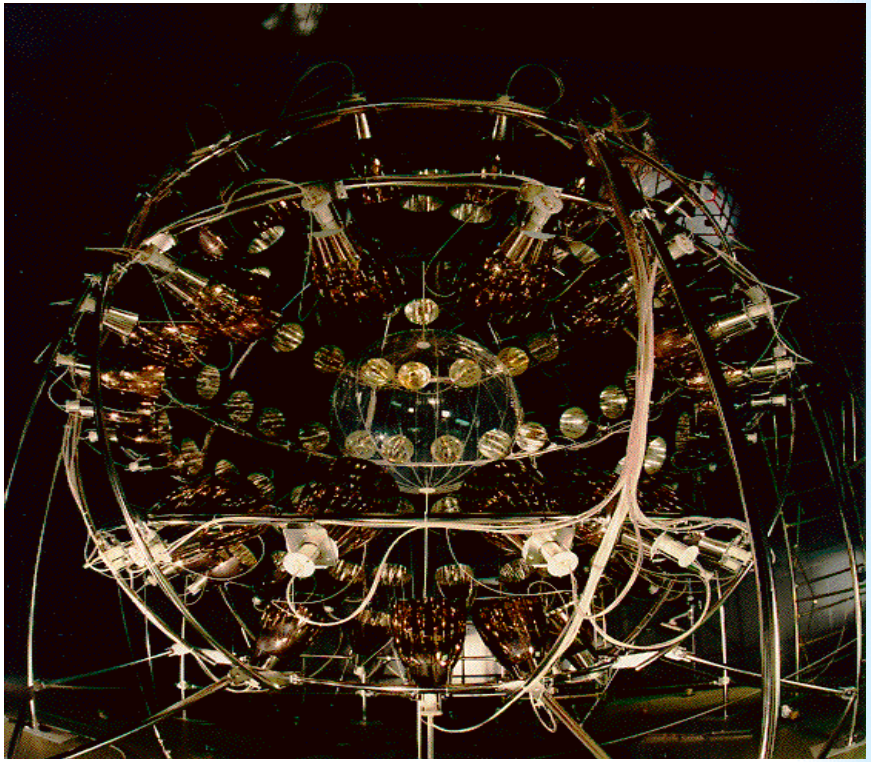




Borexino and CTF are placed in hall C. Mountains provide the shield about 3500 m.w.e.

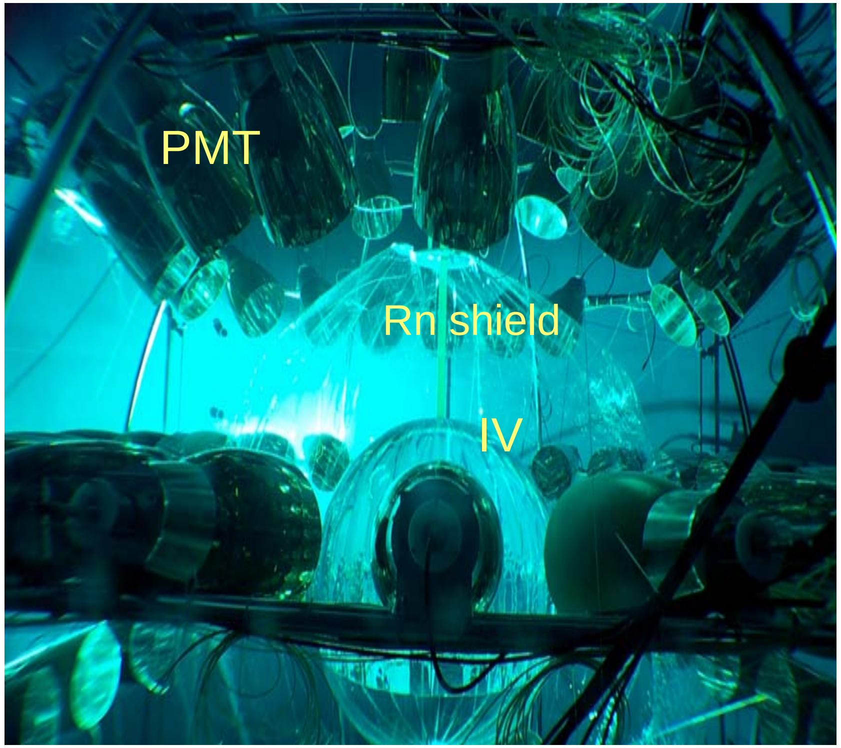
Borexino Counting Test Facility

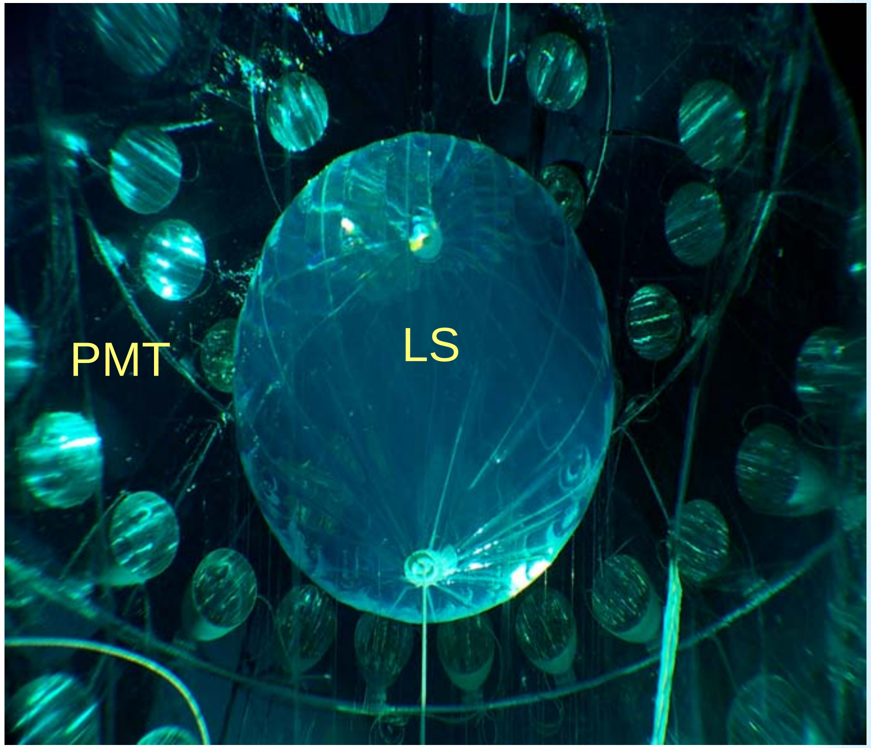




CTF is a prototype of the Borexino detector. The CTF consists of an external cylindrical water tank with **1000 t of water** serving as passive shielding for **4.2 m^3 of LS** contained in a nylon vessel of **Ø2.0 m**. The additional nylon screen between the scintillator vessel and PMTs takes the part of barrier against penetration of external radon. The scintillation light is collected with **100 PMTs** placed inside the water tank. The PMTs with light concentrators provide a total optical coverage of **21%.** The water volume is instrumented with a **Cherenkov muon veto system**.

Borexino Counting Test Facility

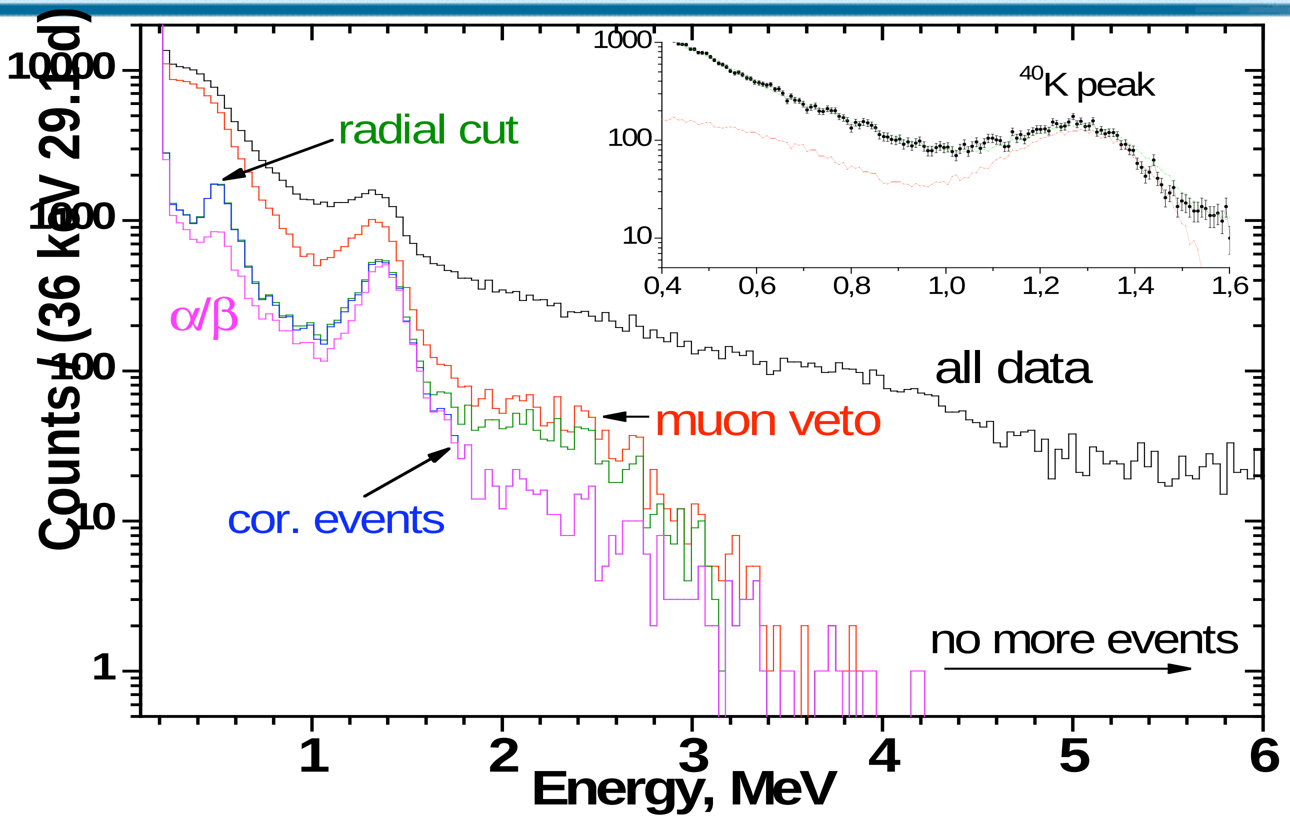




The scintillator de-excitation time is $\tau_1 \approx 5$ ns, which permits a **space resolution σ ~10 cm at 1 MeV.** The energy of an event is measured using the total collected charge from all PMT's. The LY corresponds to 3.5 pe/ (MeV PMT) for 1 MeV electron. The charge response of the detector can be approximated by a Gaussian with the relative resolution $\sigma/E = \sqrt{3.8 \cdot 10^{-3}/E[MeV] + 2.3 \cdot 10^{-3}}$. For events uniformly distributed over the detector's volume **σ_E = 78 keV at 1 MeV.**

Because LS is surrounded by water shield the reaction $^{16}\mathbf{O} \rightarrow {}^{16}\mathbf{O}^{NP} + \gamma$ can be searched for.

The CTF energy spectrum measured during 29 days



The peak at **1.46 MeV** is due to γ's from **^{40}K** decays outside the scintillator.

1.The muon veto system **(muon cut)** suppressed the background rate and **no events with E> 4.5 MeV were detected.**

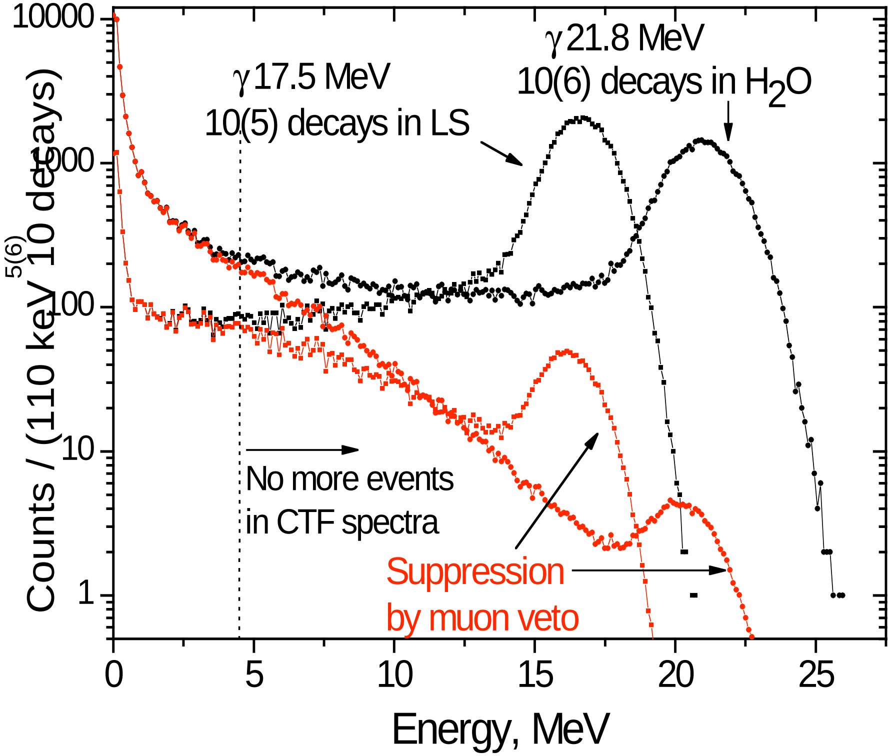
2.The **radial cut (R < 1 m)** reduces the surface background events mainly due to the ^{40}K decays outside the inner vessel.

3.The **time-correlated events** occurring in the **time window 8.2 ms** can also be removed.

4.The **α/β discrimination** can be applied to eliminate the contribution from α particles.

Transitions $^{12}C \rightarrow {}^{12}C^{NP}+\gamma$ and $^{16}O \rightarrow {}^{16}O^{NP}+\gamma$ with γ-emission

The response functions of the CTF for decays in the LS and in the water shield before and after muon veto suppression.



The limits on the probability of NP transitions with γ-emission are based on the fact of observing no events with energy higher than 4.5 MeV.

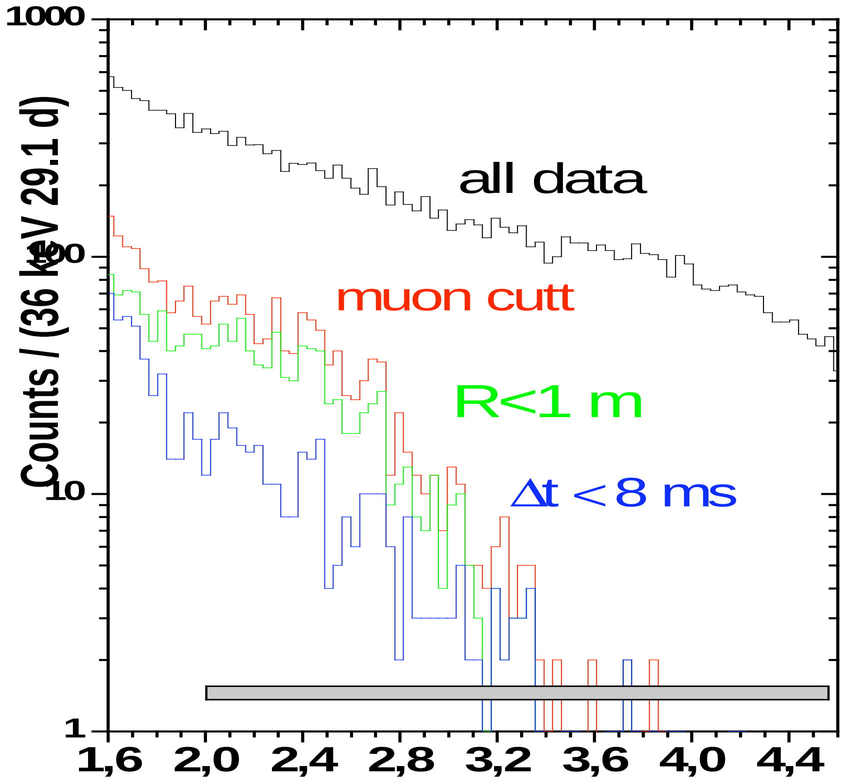
The efficiency of **17.5 MeV** γ detection $\varepsilon_{\Delta E} = 4.3 \cdot 10^{-2}$ was determined in a MC simulation, taking into account the suppression of the high energy events in LS by the muon veto.

The number of ^{12}C nuclei in **4.17 t** of LS is $N_{12C}=1.89 \cdot 10^{29}$. The number of nucleons on the P-shell is $N_n=8$, the total data taking time is **T=0.08 y**, and the upper limit on the number of candidate events is $S_{lim}=2.44$ with 90% c.l.

The obtained limit is $\tau(^{12}C) \geq 2.1 \cdot 10^{27}$ y

The ^{16}O has 8 nucleons on its $1P_{3/2}$ and 4 nucleons on its $1P_{1/2}$ shell. The uniformly distributed γ's were simulated in the 1m-thick layer of water ($N_{16O}=9.8 \cdot 10^{29}$). The values of $\varepsilon_{\Delta E}$ were calculated for **E=21.8 MeV**, **26 MeV** and for the two γ-quanta in the cascade (21+5 MeV). The worst possible efficiency $\varepsilon_{\Delta E} = 5.6 \cdot 10^{-3}$ was adopted. **The limit is**: $\tau(^{16}O) \geq 2.1 \cdot 10^{27}$ **y**

Limits on NP transitions with proton emission $^{12}C\rightarrow{}^{12}B^{NP}+p$



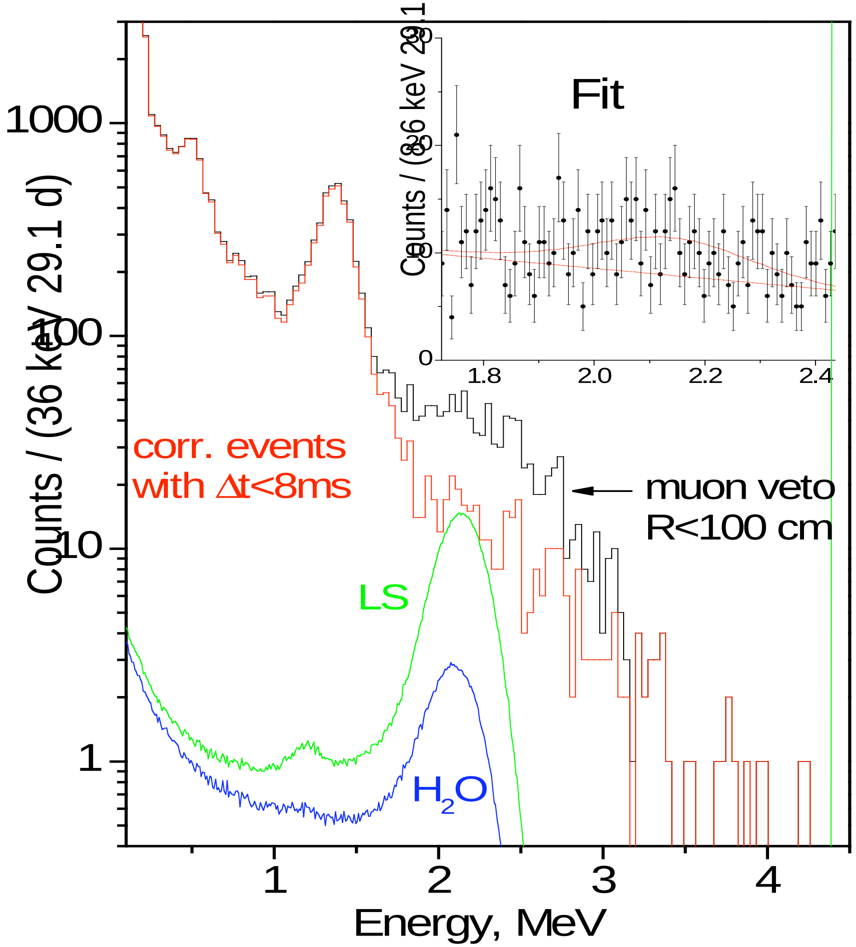
The energy of the proton released in these NP transitions is in **E_p= 5.8(7.2)±1 MeV.** The LY for a proton corresponds to an electron energy of **E_e=2.8(3.9)±0.5 MeV.**

It means that the proton peak can be found in the energy interval **2.0-4.7 MeV**. The uncertainty of the peak position is few times higher than energy resolution of CTF2 (σ_E =130 keV for E_e = 2 MeV) and covers errors of quenching factor determination.

The data obtained after muon veto, radial and correlated events cuts were analyzed.

S_{lim} was defined as the number of events N inside the 2σ window ($\varepsilon_{\Delta E}$=0.68) which can be excluded at a given confidence level: $S_{lim}= (N+1.28(N)^{1/2})$. This procedure was used for the wide energy interval **2.0-4.7 MeV**. The maximum value of **S_{lim}=130** was obtained for the energy interval 2.0-2.26 MeV. Taking into account the efficiency of radial cut (**$\varepsilon_{\Delta E}$=0.8**) the **lower limit** ***$\tau(^{12}C\rightarrow{}^{12}B^{NP}+p)\geq 5.0\cdot 10^{26}$* y** was obtained.

Transitions with neutron emission: $^{12}C \rightarrow ^{11}C^{NP}+n$ and $^{16}O \rightarrow ^{15}O^{NP}+n$

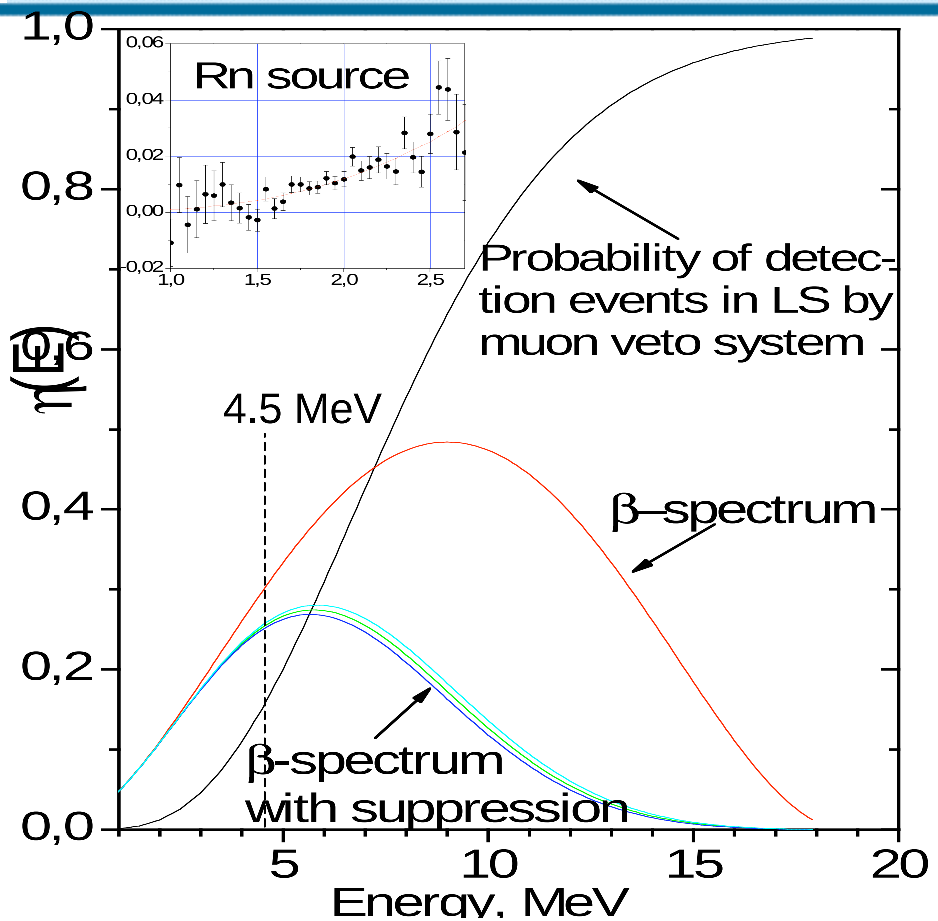


The neutron energy lies in the range (2÷18) MeV, then they are thermalized in LS or water and are captured by protons with lifetime ~250 μs. The cross section of capture **n+p→d+γ** is 0.3 b which is 2-3 orders larger than the capture on the ^{12}C and ^{12}O nuclei.

Capture of thermal neutrons is followed by **2.2 MeV γ**-emission. **The background level at this energy was used to obtain an upper limit on the number of γ's with 2.2 MeV energy.** Because protons, scattered during the neutron thermalization, can be registered by the detector, **the correlated events with Δ t<8 ms were not cut out in the data selection.**

Experimental background was modeled as a linear function plus the contributions of 2.2 MeV γ's originating from LS and water. The obtained limit on the number of captured neutrons **S≤2.7 /(d·t)** gives the limit on NP transitions with neutron emission **$\tau \geq 3.7 \cdot 10^{26}$ y.**

$\beta^{\pm}$-transitions: $^{12}C \rightarrow {}^{12}N^{NP} + e^- + \nu$ and $^{12}C \rightarrow {}^{12}B^{NP} + e^+ + \nu$



The limits on the probability of NP $\beta^{\pm}$-transitions were again based on the fact of observing no events with Ee>4.5 MeV not accompanied by a muon veto signal.

Because high energy events in LS can be seen by muon veto system the corresponding efficiency have to be taken into account.

The limits on the lifetime of neutrons or protons (**$N_{n,n}$=4**) in with respect to the $\beta^{\pm}$- transitions are:

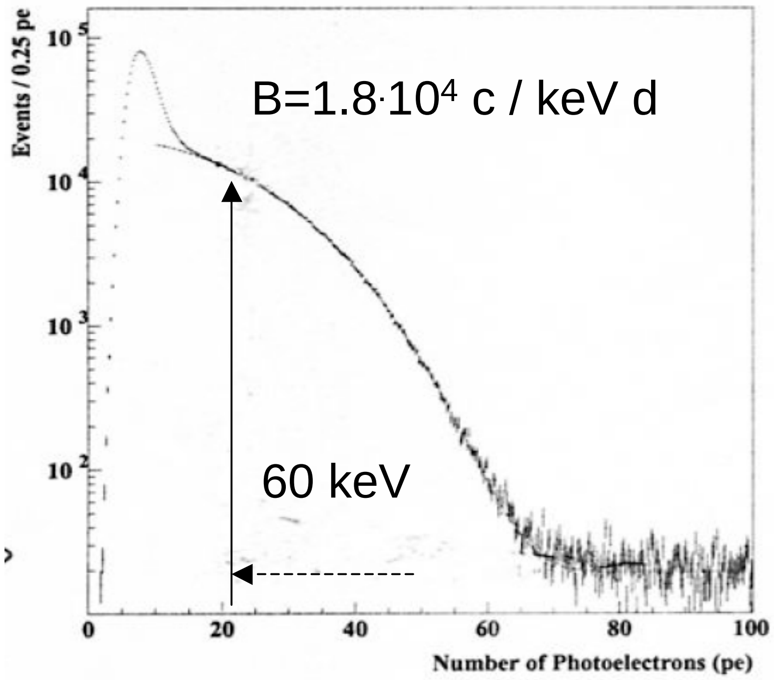
$\tau(^{12}C \rightarrow {}^{12}N^{NP} + e^- + \nu) \geq 7.6 \cdot 10^{27}$ y

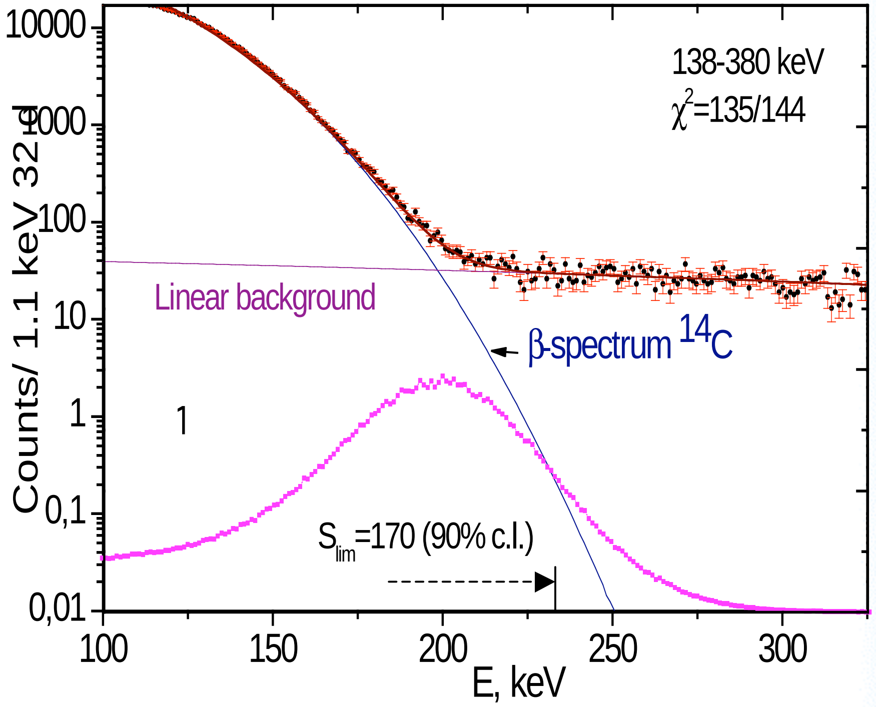
and

$\tau(^{12}C \rightarrow {}^{12}B^{NP} + e^+ + \nu) \geq 7.7 \cdot 10^{27}$ y

The energies release in the reaction **$^{12}C \rightarrow {}^{12}B^{NP}$+e-+ν**, **Q=17.8 MeV**, was calculated by assuming that the E_b of the neutron in $1S_{1/2}$- shell in **^{12}B** nuclei is close to the value for **^{11}B**. In the case of **$^{12}C \rightarrow {}^{12}N^{NP} + e^+ + \nu$** reaction, the value of **$E_p(S_{1/2}, {}^{12}N)$** was approximated by the mean value of the binding energies for two neighboring nuclei ^{12}C and ^{16}O (**Q=18.9 MeV**).

Limit on the NP transition with α-emission: $^{12}C \rightarrow {}^{8}Be^{NP} + \alpha$





The calculation of binding energies of $^{8}Be^{NP}$ give **Q=3.0±0.9 MeV**. Taking into account the recoil of ^{8}Be and the LY for α's one can expect the peak in the range **(60 – 230) keV.** The dominant part of the background in this range is the **β-activity of ^{14}C**.

At the energy **E_e=230 keV** the value **S_{lim} =170** was obtained for γ's appearing in $e \rightarrow \nu\gamma$ decay. The limit on NP transition with α-emission is **$\tau \geq 5.2 \cdot 10^{26}$ y.**

If **$E_e \approx 60$ keV** the limit is weaker. Measurements with low threshold (≈20keV) were performed. At E_e=60 keV, the number of counts in the interval 2σ is **$(6.6\pm0.2)10^{4}$ d^{-1}**, where error includes both systematic and statistic effects. This value leads to the limit **$\tau \geq 6.1 \cdot 10^{23}$ y.**

CTF results (EPJ, C37 (2004) 421)

Channel	E_0, MeV	ΔE, MeV	**CTF** T_{lim},y	Previous limits
$^{12}\mathrm{C}\rightarrow{}^{12}\mathrm{C}^{NP}+\gamma$	17.5	≥ 4.5	$2.1\cdot 10^{27}$	$4.2\cdot 10^{24}$ NEMO-II
$^{16}\mathrm{O}\rightarrow{}^{16}\mathrm{O}^{NP}+\gamma$	21.8	≥ 4.5	$2.1\cdot 10^{27}$	$1.0\cdot 10^{32}$Kamiokande
$^{12}\mathrm{C}\rightarrow{}^{11}\mathrm{B}^{NP}+p$	4.8-8.2	2.0-4.7	$5.0\cdot 10^{26}$	$1.7\cdot 10^{25}$ Ejiri et al. $6.9\cdot 10^{24}$ DAMA (Na+I)
$^{12}\mathrm{C}(^{16}\mathrm{O})\rightarrow{}^{11}\mathrm{C}^{NP}+n$	2.2	1.7-2.5	$3.7\cdot 10^{26}$	$1.0\cdot 10^{20}$ Kishimoto et al
$^{12}\mathrm{C}\rightarrow{}^{8}\mathrm{Be}^{NP}+\alpha$	1.0-3.0	0.07-0.23	$6.1\cdot 10^{23}$	-
$^{12}\mathrm{C}\rightarrow{}^{12}\mathrm{N}^{NP}+e^{-}+\nu_e$	18.9	≥ 4.5	$7.6\cdot 10^{27}$	$3.1\cdot 10^{24}$ NEMO,$\sim 8\cdot 10^{27}$LSD
$^{12}\mathrm{C}\rightarrow{}^{12}\mathrm{B}^{NP}+e^{+}+\nu_e$	17.8	≥ 4.5	$7.7\cdot 10^{27}$	$2.6\cdot 10^{24}$ NEMO-II

The limits on NP in ^{12}C with γ-emission are stronger than obtained with NEMO-2 detector.

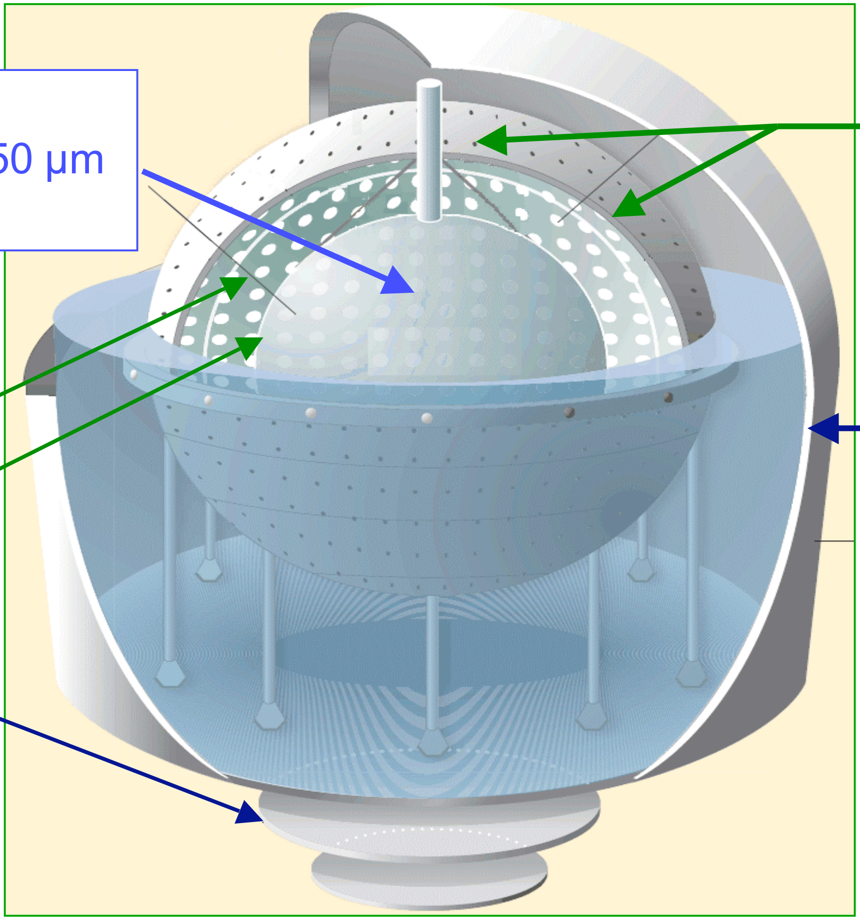
The limits on hadrons emission are stronger than ones obtained with the 300 kg ELEGANTV (E_p >18 MeV) and 100 kg DAMA (E_p >10 MeV) detectors for $^{23}\mathrm{Na}\rightarrow{}^{22}\mathrm{Ne}^{NP}+p$, $^{127}\mathrm{I}\rightarrow{}^{126}\mathrm{Te}+p$.

The limits on NP $\beta^{\pm}$-transitions are 10^3 times stronger than the one obtained by NEMO-2.

The data available from the LSD detector allowed to obtain the comparable limit.

To compare the results for different nuclei and different energy threshold one have to estimate the rate of normal non-forbidden transitions.

BOREXINO detector layout and main features



Scintillator:
278 t PC+PPO in a 150 μm
thick nylon vessel

Stainless Steel Sphere:
2212 PMTs
1350 m^3

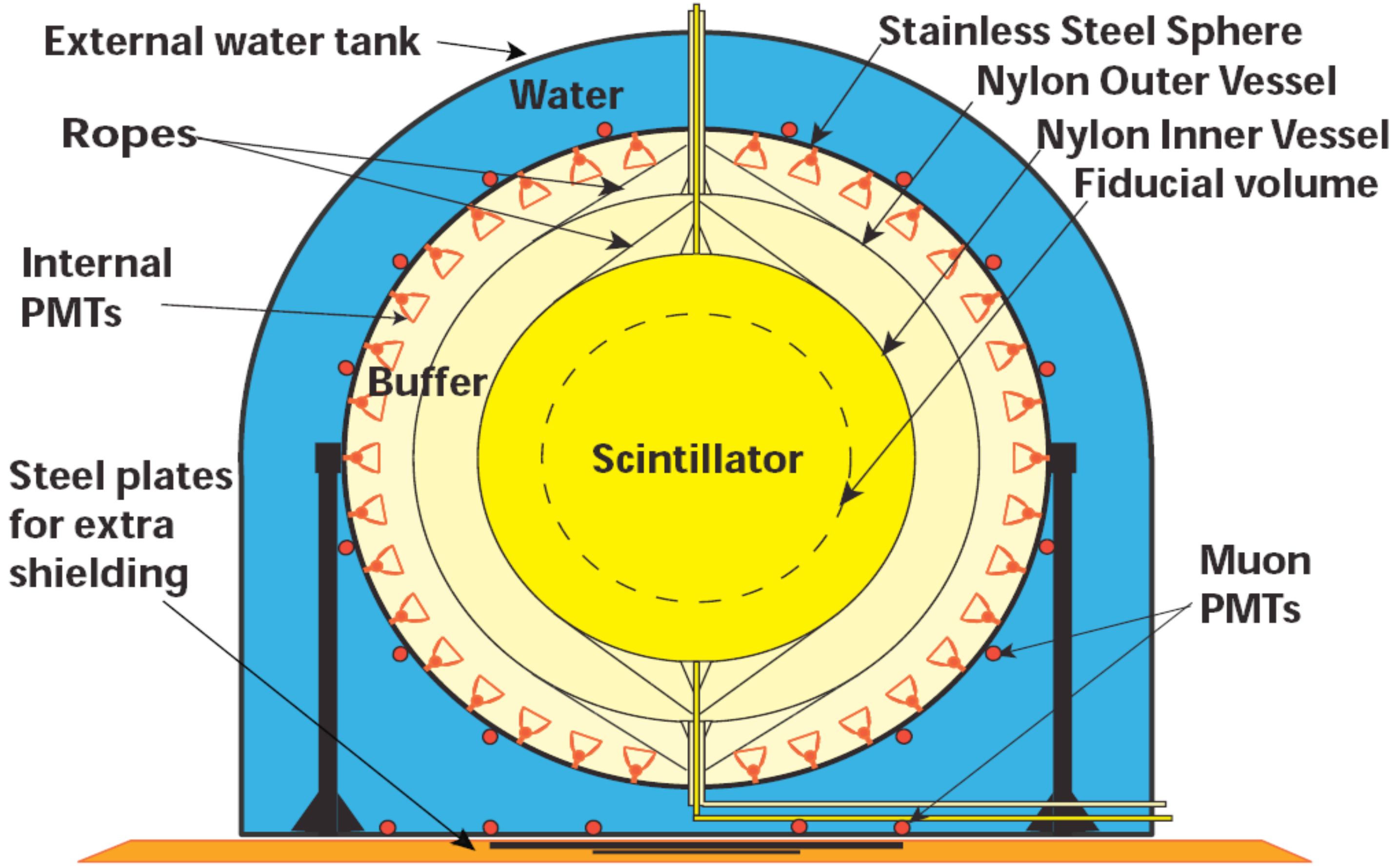
Nylon vessels:
Outer: 5.50 m
Inner: 4.25 m

Water Tank:
γ and ***n*** shield
μ water Čh detector
208 PMTs in water
2100 m^3

Carbon steel plates

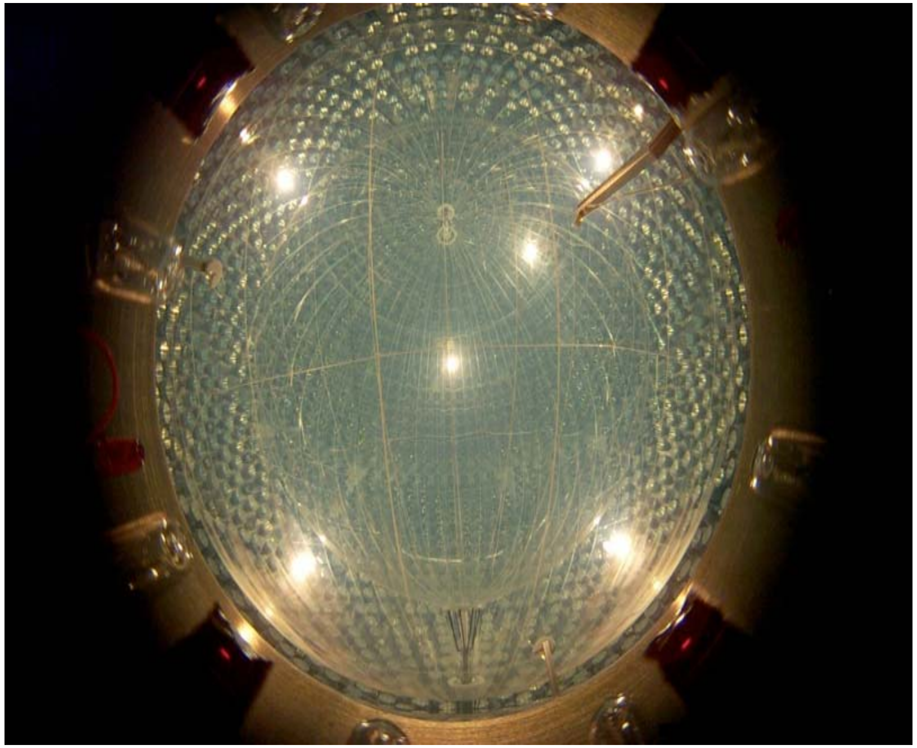
Borexino is a scintillator detector with mass of **278 tons of PC, C_9H_{12}**. The scintillator is contained in a thin nylon vessel and is surrounded by two concentric PC buffers doped a component quenching the PC scintillation light. The two PC buffers are separated by a thin nylon membrane to prevent diffusion of radon. The scintillator and buffers are contained in Stainless Steel Sphere (SSS) with diameter 13.7 m.

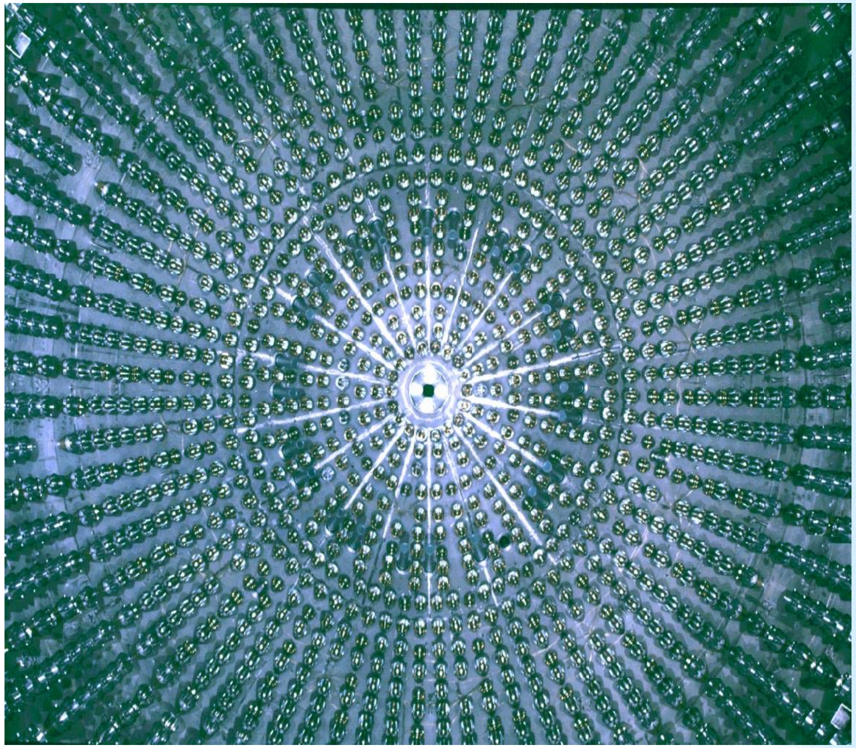
BOREXINO detector layout and main features



The SSS is enclosed in a water tank, containing **2100 tons of water** as an additional shield against external γ's and neutrons. The scintillation light is detected via **2212 PMTs** uniformly distributed on the inner surface of the SSS. Additional **208 PMTs** detect the Cherenkov light radiated by muons in the water shield.

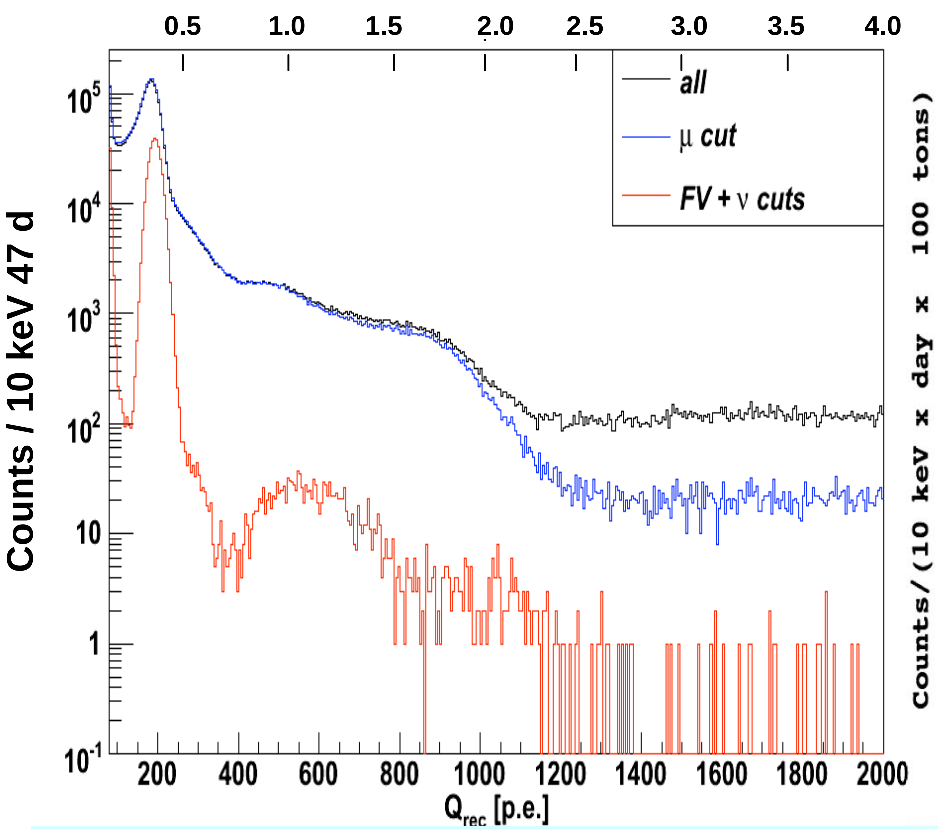
BOREXINO detector layout and main features

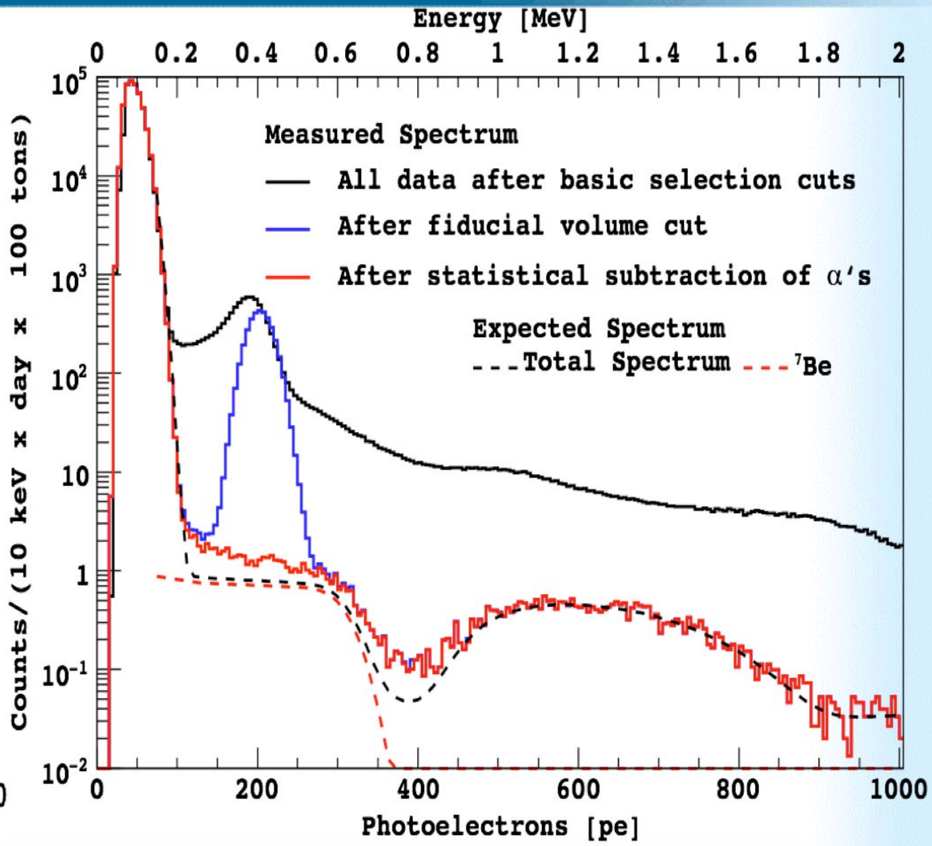




The estimated light output is about **500 pe/MeV** which scales the **energy resolution** as **5%/√ E(MeV).** The main trigger fires when at least **K** PMTs detect one p.e. within a time of 60 ns. The value K = 30 corresponds to an energy threshold of 60 keV and triggering rate = 15 Hz, which is largely dominated by ^{14}C events. Event positions are estimated by analysis of the times of the triggered PMTs. **The position resolution** depends on energy as √ E and it is about **15 cm at 1 MeV**.

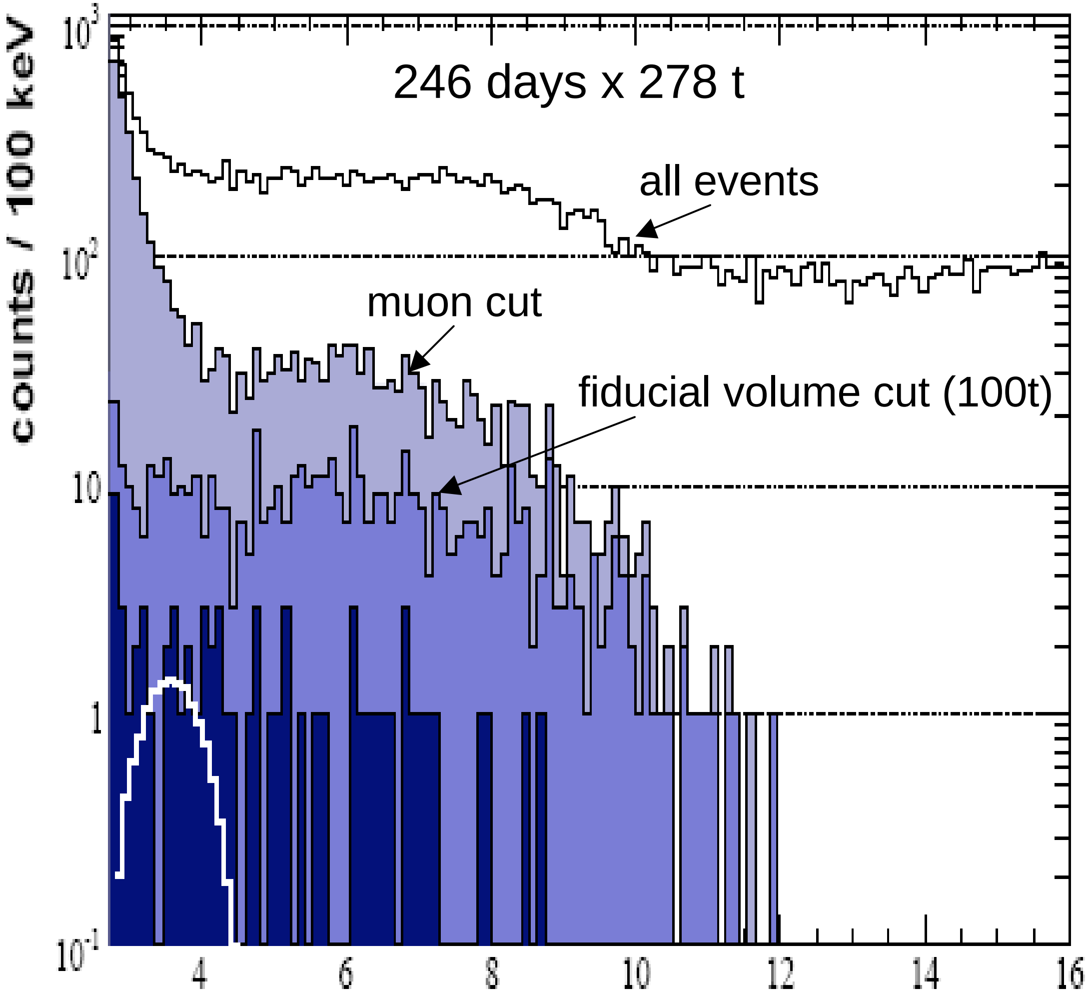
The low energy part of the Borexino spectrum (Phys.Lett. B658(2008)101; Phys.Rev.Lett. 101(2008)091302)





1. **^{14}C** β-spectrum dominates at low energies, isotopic ratio equal to **$^{14}C/^{12}C=(2.7\pm0.6)\cdot10^{-18}$**.
2. **^{210}Po,** giving initially 80 c/(d t), decays successfully with 200 d lifetime.
3. **U and Th** has extremely low concentration level **$(1.6\pm0.1)\cdot10^{-17}$** g/g and **$(6.8\pm1.3)\cdot10^{-18}$** g/g.
4. For natural **K** the upper limit of **$<3\cdot10^{-14}$ g/g**.
5. The concentration of **^{85}Kr** corresponds to **29±14 c/(d·100t)**.
6. The decays of cosmogenic **^{11}C** are observed at the rate of **25 c/(d 100t).**

The high energy part of the spectrum (arXiv:0808.2868[astro-ph])



Event Selection:

1. Only single cluster events are accepted, so to exclude pile-up and fast coincident events.
2. Muon events are rejected by muon veto system.
3. After each muon crossing the scintillator, all events within a time window of 2 ms are rejected.
4. In order to remove the external background, only signals reconstructed within a spherical 100 t fiducial volume are accepted.
5. The time correlated events such as radon induced ^{214}Bi->^{214}Po sequences are identified and removed.

$\tau({}^{12}C \to {}^{12}C^{NP}+\gamma) \geq 2.6 \cdot 10^{31}$ y

Preliminary results from 246 days of Borexino data

The limit on the probability of transitions ${}^{12}C \to {}^{12}C^{NP}+\gamma$ is based on the experimental fact of observing **no events with energy higher than 12 MeV passing muon veto cut**. The lower limit on PEP violating transitions of nucleons from P-shell to the occupied $1S_{1/2}$-shell was obtained using the formula:

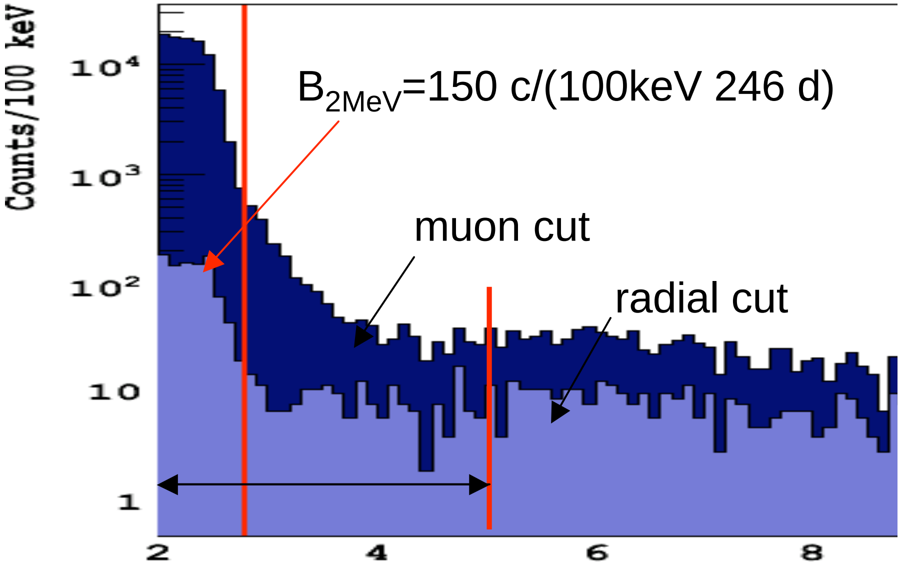
$$\tau \geq \varepsilon_{\Delta E} \frac{N_N N_{p+n}}{S_{\lim}} T = 2.6 \cdot 10^{31}\, y (90\% c.l.)$$

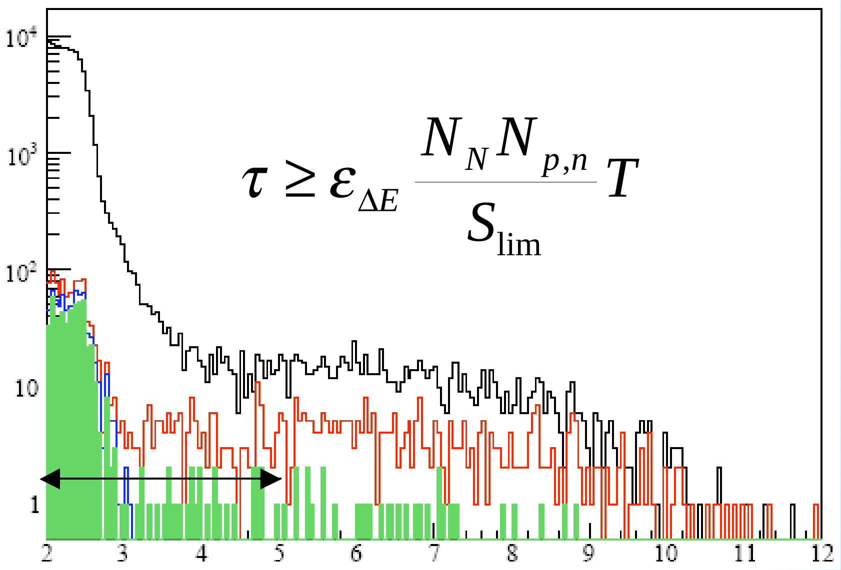
$\varepsilon_{\Delta E} \approx 0.95$ is the efficiency of registering an event in the energy interval ΔE;
$N_{12C} = 1.24 \cdot 10^{31}$ (278 t) is the number of ${}^{12}C$ nuclei under consideration,
$N_{p+n} = 8$ is the number of nucleons for which the non-Paulian transitions are possible,
T = 246 days is the total time of measurements,
$S_{lim} = 2.44$ is the upper limit on the number of candidate events at 90% c.l.

detector	Mass, t	Time, d	$\varepsilon_{\Delta E}$	B, (keV 100 t y)$^{-1}$ at 2 MeV, Muon veto and radial cut
CTF	4.2 / 2.9	29	0.042	420
BOREXINO	278 /100	246	0.95	2.2

The Borexino limit is 4 orders of magnitude stronger than the CTF one because of the large mass, time of measurement and efficiency of registration.

$\tau(^{12}C\rightarrow{}^{11}B^{NP}+p)\geq 7.1\cdot 10^{29}$ y and $\tau(^{12}C\rightarrow{}^{11}C^{NP}+n)\geq 7.1\cdot 10^{29}$ y





$$\tau \geq \varepsilon_{\Delta E}\frac{N_N N_{p,n}}{S_{\lim}}T$$

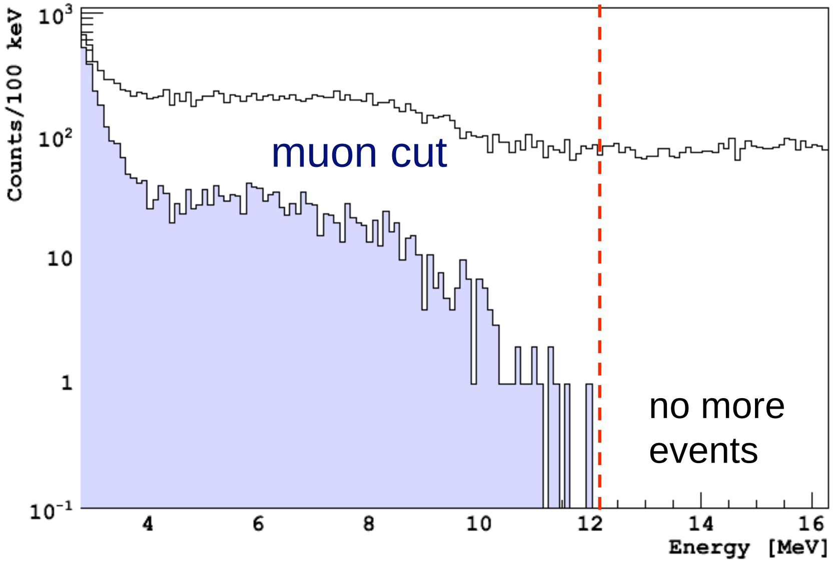
The position of proton peak is expected in the range **2.0÷5.0 MeV.** The **T=246** days **x 100 t** statistics (**N_{12C} = 1.24·10^{31}**) were used. The limit on the number on events ($S_{\lim}$) was found using 1σ-method which is based on the measured background level:

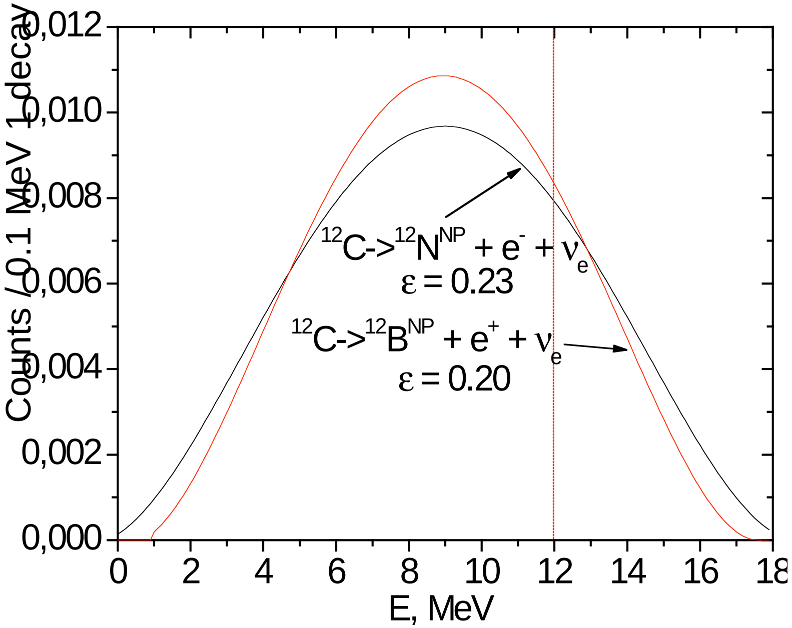
$$S_{\lim}(1\sigma)=1.1\sqrt{3.3\sigma[keV]B[KeV^{-1}]}$$

where **σ(E)=71 keV** is energy resolution and **B(E)=1.5 c/(keV)** is background level.
The maximum value of **$S_{\lim}$=34 for 90% c.l.** was obtained for the interval 2.0-2.24 MeV and it corresponds to the upper limit **$\tau(^{12}C\rightarrow{}^{11}B^{NP}+p)\geq 7.1\cdot 10^{29}$ y**.

The same limit is applicable to **$^{12}C\rightarrow{}^{11}C^{NP}+n$** transitions. The limit can be improved by selection of two consequential events. With criteria (Δt < 2ms and E_1>1MeV and 2.5>E_2>1.5) **24** events were found in **278t x 334days**. The limit is 4 times stronger - **$\tau(^{12}C\rightarrow{}^{11}C^{NP}+n)\geq 3.0\cdot 10^{30}$ y**

$\tau(^{12}C \to ^{12}N^{NP}+e^-+\nu) \geq 3.1\ 10^{30}$ y and $\tau(^{12}C \to ^{12}B^{NP}+e^++\nu) \geq 2.7\ 10^{30}$ y





The limits on the probabilities of NP $\beta^\pm$- transitions were based on the fact of observing no events with energy higher than 12 MeV passing muon veto cut.

The number of $e^\pm$ emitted with E>12 MeV are **$\varepsilon_{\Delta E}$ = 0.23** and **$\varepsilon_{\Delta E}$= 0.20** for transitions **$^{12}C \to ^{12}N^{NP}+e^-+\nu$** and **$^{12}C \to ^{12}B^{NP}+e^++\nu$**, correspondently. The lower limits were obtained as:

$$\tau \geq (\varepsilon_{\Delta E} = 0.23)\frac{(N_{12C} = 1.24\cdot 10^{31} = 278t)(N_p = 4)}{S_{\lim} = 2.44}(T = 0.67y) = 3.1\cdot 10^{30}\, y(at.90\%.c.l.)$$

New limits obtained with the Borexino *(preliminary)*

Channel	E_0, MeV	τ_{lim}, y·n^{-1} BOREXINO	τ_{lim}, y CTF	Previous limits
$^{12}C \to {}^{12}C^{NP} + \gamma$	17.5	2.6·10^{31}	2.1·10^{27}	4.2·10^{24} NEMO-II
$^{16}O \to {}^{16}O^{NP} + \gamma$	21.8		2.1·10^{27}	1.0·10^{32} Kamiokande
$^{12}C \to {}^{11}B^{NP} + p$	4.8-8.2	7.1·10^{29}	5.0·10^{26}	1.7·10^{25} ELEGANTV. 6.9·10^{24} DAMA (Na+I)
$^{12}C \to {}^{11}C^{NP} + n$	2.2	7.1·10^{29}	3.7·10^{26}	1.0·10^{20} Kishimoto et al
$^{12}C \to {}^{8}Be^{NP} + \alpha$	1.0-3.0		6.1·10^{23}	-
$^{12}C \to {}^{12}N^{NP} + e^- + \nu_e$	18.9	3.1·10^{30}	7.6·10^{27}	3.1·10^{24} NEMO-II ~8·10^{27} LSD
$^{12}C \to {}^{12}B^{NP} + e^+ + \nu_e$	17.8	2.7·10^{30}	7.7·10^{27}	2.6·10^{24} NEMO-II

The Borexino results are 3-4 orders of magnitude stronger then CTF ones.

The limits for NP transitions in ^{12}C with γ-,p-,n-,α-, and $\beta^{\pm}$- emissions are the best to date.

The limit on the NP transition in ^{12}C with γ-emission is comparable to the same result for ^{16}O obtained using Kamiokande data for γ BR=1.

Borexino has unique parameters to study NP transitions with low Q (p or α emissions)

The relative strength of the NP transitions to the Normal Transitions

The NP transitions with emission of γ, n or p and ν,e-pair can be induced by electromagnetic, strong and weak interactions. The obtained limits on lifetime can be converted to limits on the rates of transitions ($\lambda^{NP}=\hbar/\tau^{NP}$) and on relative strength of NP-transitions to the normal ones.

Channel	λ^{NP}, $s^{-1}(^{12}C)$	$\Gamma^{NT}=\hbar\lambda^{NT}$	λ^{NT}, $s^{-1}(^{12}C)$	$\lambda^{NP}/\lambda^{NT}$	Previous
$^{12}C\rightarrow{}^{12}C^{NP}+\gamma$	$9.8\cdot10^{-39}$	0.0019 MeV	$2.9\cdot10^{18}$	$\mathbf{\leq3.4\cdot10^{-57}}$	$2.3\cdot10^{-57}$
$^{12}C\rightarrow{}^{11}B(C)^{NP}+p(n)$	$3.6\cdot10^{-37}$	5 MeV	$7.6\ 10^{21}$	$\leq$ $\mathbf{4.7\cdot10^{-59}}$	$1.0\cdot10^{-54}$
$^{12}C\rightarrow{}^{12}N(B)^{NP}+e^{\pm}+v$	$4.1\cdot10^{-38}$	$1.3\cdot10^{-18}$ eV	$2\cdot10^{-3}$	$\leq$ $\mathbf{2.1\cdot10^{-35}}$	$6.5\cdot10^{-34}$

The decay width of nuclear E1 γ-transition from P- to S-shell given by the Weisskopf estimate is **Γ_γ~1.9 keV**. The ratio $\lambda^{NP}/\lambda^{NT}$ is less then **$3.4\cdot10^{-57}$** (90%c.l.)

The width of hadrons emission is 2-3 orders larger width of γ-transition. The measured width of S-hole state in ^{12}C is **$\Gamma_h\approx5$ MeV**. The detection of ***p*** or ***n*** give a more stringent limit on the relative strength of NP transitions then the detection of **γ's** if one can set a similar limit on the lifetime for both decays. The obtained limit is $\lambda^{NP}/\lambda^{NT}\leq$ **$4.7\cdot10^{-59}$.**

The NP β± -transitions are first-order forbidden P→S transitions. The log ft values for such first forbidden transitions range from 6 to 9, conservative value corresponds to life-time ~ **500 sec** or level width **$\Gamma_\beta=\hbar\lambda=\hbar/\tau=1.3\cdot10^{-18}$ eV** or $\lambda^{NP}/\lambda^{NT}\leq$ **$2.1\cdot10^{-35}$**

The limits on the relative strength of NP transitions for strong and weak interactions are the best to date.

Conclusion

Using the unique features of the CTF and Borexino - the extremely low background, large scintillator mass and low energy threshold - new limits on the forbidden transitions of nucleons from the P-shell to the $1S_{1/2}$-shell in ^{12}C with the emission of γ, n, p, α and $\beta^{\pm}$ particles have been obtained:

$\tau(^{12}C \rightarrow ^{12}C^{NP} + \gamma) > 2.6 \cdot 10^{31}$ y,

$\tau(^{12}C \rightarrow ^{11}B^{NP} + p) > 7.1 \cdot 10^{29}$ y,

$\tau(^{12}C \rightarrow ^{11}C^{NP} + n) > 7.1 \cdot 10^{29}$ y,

$\tau(^{12}C \rightarrow ^{11}Be^{NP} + \alpha) > 6.1 \cdot 10^{23}$ y,

$\tau(^{12}C \rightarrow ^{12}N^{NP} + e^{-} + \nu) > 3.1 \cdot 10^{30}$ y,

$\tau(^{12}C \rightarrow ^{12}B^{NP} + e^{+} + \nu) > 2.7 \cdot 10^{30}$ y,

all with 90 % C.L.

These limits on NP transitions in ^{12}C with γ-,p-,n-,α-, and $\beta^{\pm}$- emissions are the best to date and can be improved because ***Borexino is taking data.***

The end.

Thanks for your attention!

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Extra slides

- Comparisons with invisible decay limits
- Borexino spectra
- Is $^{11}C^{NP}$ unstable?
- The rate of EL transitions
- Animation