Experimental challenges towards the detection of relic neutrinos with unstable nuclei

Réunions plénières du GDR NEUTRINO
SESSION 2009 du 27 au 28 avril 2009

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Outline

- State of Art
- The expected rate of the relic neutrinos on beta instable elements
- Gravitational clustering effect that might enhances the interaction rate.
- Possible experimental approach for the detection relic neutrinos
- Conclusions

The Cosmological Relic Neutrinos

We know that Cosmological Relic Neutrinos (CRN) are weakly-clustered

$\sim 1\sec > BigBang$	Date of birth
$\bar{n}_{\nu_i 0} = \bar{n}_{\bar{\nu}_i 0} = \frac{3}{22}\bar{n}_{\gamma 0} = 53cm^{-3}$	density per flavour
$T_{\nu,0} = \left(\frac{4}{11}\right)^{1/3} T_{\gamma 0} = 1.95K$	temperature
$\bar{p}_{\nu_i 0} = \bar{p}_{\bar{\nu}_i 0} = 3T_{\nu,0} = 5\times 10^{-4}eV$	mean kinetic energy
$\lambda = \frac{1}{\bar{p}_{\nu_i}} = \frac{0.12cm}{\left\langle p/T_{\nu,0\,\bar{p}_{\nu_i 0}} \right\rangle}$	Wave function extension

The detection methods proposed so far!

- Coherent neutrino scattering off a torsion balance: more than 15 o.of m. were missing in sensitivity.

- Annihilation of EECν off relic neutrinos: a neutrino source of $E=10^{22}$eV was required

- An accelerator as large as the earth circumference to increase the energy in the c.m.r and subsequently interaction rate.

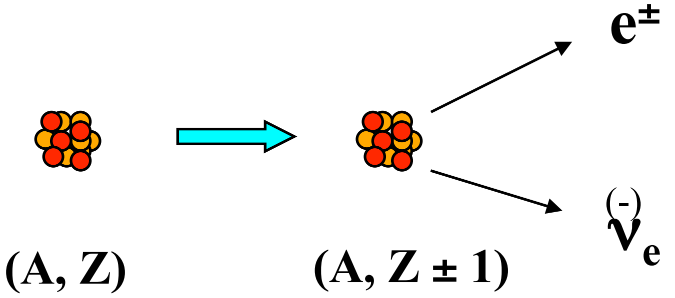
All those methods require unrealistic experimental apparatus or astronomical neutrino sources not yet observed and not even hypothesized.

For recent reviews on this subject see:
A.Ringwald "Neutrino Telescopes" 2005 – hep-ph/0505024
G.Gelmini G. B. Gemini Phys.Scripta T121:131-136,2005

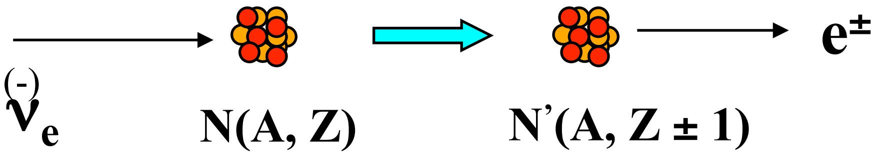
How to detect relic neutrinos

A process without energy threshold

Beta decay



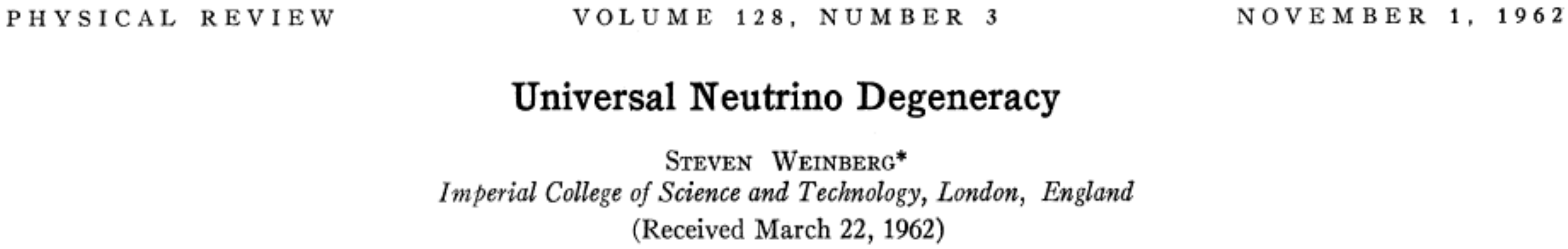
Neutrino Capture on a
Beta decaying nucleus



Since $M(N)-M(N')=Q_\beta>0$ the ν interaction on beta instable nuclei is always energetically allowed no matter the value of the incoming ν energy.

In this case the phase space does not put any energetic constraint to the neutrino CC interaction on a beta instable nucleus (NCB).

A’ 62 paper by S. Weinberg about *ν* chemical potential



PHYSICAL REVIEW VOLUME 128, NUMBER 3 NOVEMBER 1, 1962

Universal Neutrino Degeneracy

Steven Weinberg*
Imperial College of Science and Technology, London, England

(Received March 22, 1962)

In the original idea a large neutrino chemical potential (μ) could distort the electron (positron) spectrum near the endpoint energy

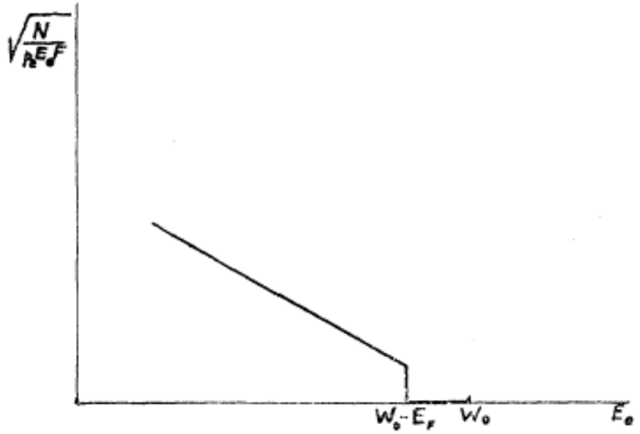


FIG. 1. Shape of the upper end of an allowed Kurie plot to be expected in a β^+ decay if neutrinos are degenerate up to energy E_F, or in a β^- decay if antineutrinos are degenerate.

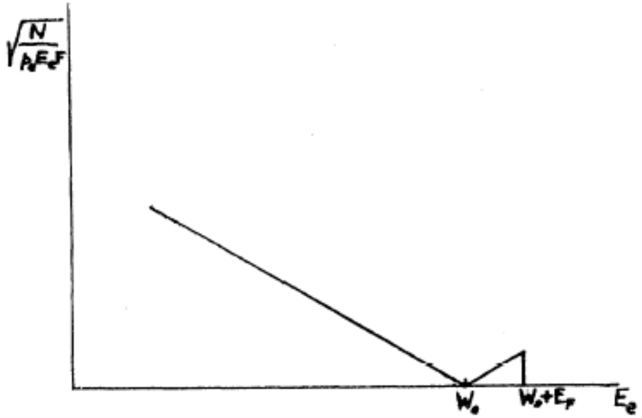


FIG. 2. Shape of the upper end of an allowed Kurie plot to be expected in a β^- decay if neutrinos are degenerate up to energy E_F, or in a β^+ decay if antineutrinos are degenerate.

NCB Cross Section (I)

NCB $$\sigma_{\mathrm{NCB}} v_\nu = \frac{G_\beta^2}{\pi} p_\mathrm{e} E_\mathrm{e} F(Z, E_\mathrm{e}) C(E_\mathrm{e}, p_\nu)_\nu$$

$$E_\mathrm{e} = E_\nu + Q_\beta + m_\mathrm{e} = E_\nu + m_\nu + W_\mathrm{o}$$

Where $F(Z, E_\mathrm{e})$ the Fermi function and $C(E_\mathrm{e}, p_\nu)_\nu$ the nuclear shape factor which is an angular momentum weighted average of nuclear state transition amplitudes.

It is more convenient to focalize our attention on the interaction rate:

$$\lambda_\nu = \frac{G_\beta^2}{2\pi^3} \int_{W_\mathrm{o}+2m_\nu}^{\infty} p_\mathrm{e} E_\mathrm{e} F(Z, E_\mathrm{e}) C(E_\mathrm{e}, p_\nu)_\nu \cdot E_\nu p_\nu f(p_\nu)\, \mathrm{d}E_\mathrm{e},$$

NCB Cross Section (II)

The most difficult part of the rate estimation is the nuclear shape factor calculation:

$$C(E_e, p_\nu)_\beta = \sum_{k_e, k_\nu, K} \lambda_{k_e}\left[M_K^2(k_e, k_\nu) + m_K^2(k_e, k_\nu) - \frac{2\mu_{k_e} m_e \gamma_{k_e}}{k_e E_e} M_K^2(k_e, k_\nu) m_K^2(k_e, k_\nu)\right]$$

Where λ_{ke}, μ_{ke} and γ_{ke} are the Coulomb coefficients, k_e and k_ν are the electron and neutrino radial wave function indexes ($k=j+1/2$), $K=L-1$ represents the nuclear transition multipolarity ($|k_e - k_\nu| \leq K \leq |k_e + k_\nu|$) and, M^2 and m^2 are nuclear matrix element. Their calculation is the main source of uncertainty for σ_{NCB}.

On the other hand, the NCB (see previous slide) and the corresponding beta decay rates are strongly related thanks to the following formula:

$$\lambda_\beta = \frac{G_\beta^2}{2\pi^3} \int_{m_e}^{W_o} p_e E_e F(Z, E_e) C(E_e, p_\nu)_\beta E_\nu p_\nu \, \mathrm{d}E_e$$

$$C(E_e, p_\nu)_\nu = C(E_e, -p_\nu)_\beta$$

NCB Cross Section (III)

The beta decay rate provides a relation that allows to express the mean shape factor:

$$\overline{C}_\beta = \frac{1}{f}\int_{m_e}^{W_o} p_e E_e F(Z, E_e) C(E_e, p_\nu)_\beta E_\nu p_\nu \, dE_e,$$

in terms of observable quantities: $ft_{1/2} = \frac{2\pi^3 \ln 2}{G_\beta^2 \overline{C}_\beta}$, $f = \int_{m_e}^{W_o} F(Z, E_e) p_e E_e E_\nu p_\nu \, dE_e$.

then if we derive G_β in terms of $\overline{C}_\beta$ and of $ft_{1/2}$ and replace it in the expression of the NCB cross section:

$$\sigma_{NCB} v_\nu = \frac{G_\beta^2}{\pi} p_e E_e F(Z, E_e) C(E_e, p_\nu)_\nu$$

we obtain

$$\sigma_{NCB} v_\nu = 2\pi^2 \ln 2 p_e E_e F(Z, E_e) \frac{C(E_e, p_\nu)_\nu}{ft_{1/2} \overline{C}_\beta}$$

So the σ_{NCB} can be calculated in terms of well measured quantities and of $C(E_e, p_\nu)_\nu$ and $\overline{C}_\beta$ which depend on the same nuclear transition matrix elements.

NCB Cross Section

a new parameterization

It is convenient to introduce

$$\mathcal{A} = \int_{m_e}^{W_\circ} \frac{C(E'_e, p'_\nu)_\beta}{C(E_e, p_\nu)_\nu} \frac{p'_e}{p_e} \frac{E'_e}{E_e} \frac{F(E'_e, Z)}{F(E_e, Z)} E'_\nu p'_\nu dE'_e$$

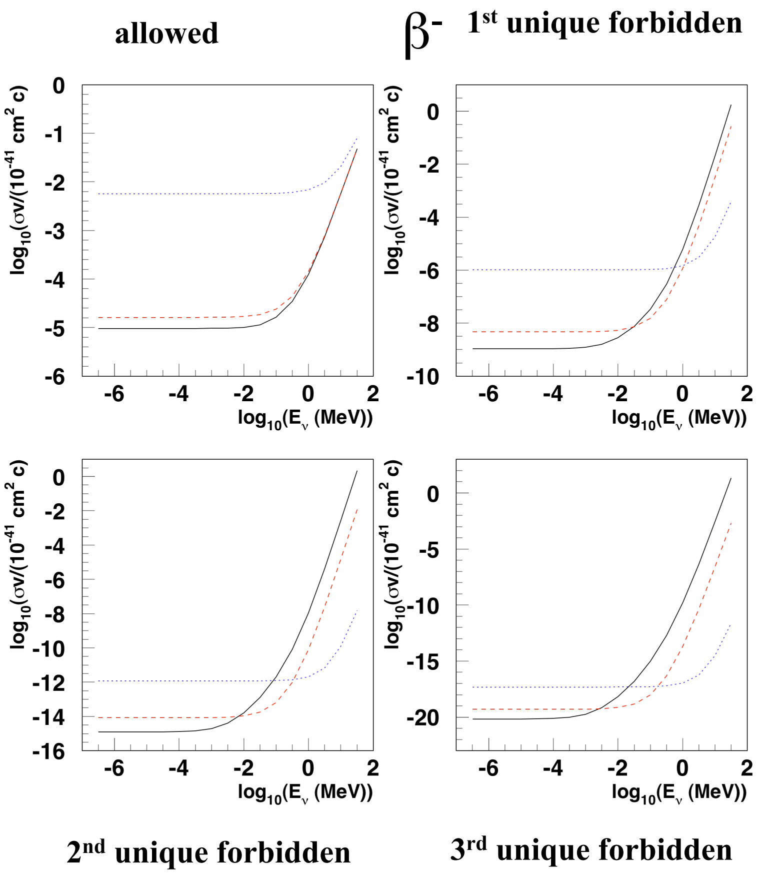
where *A* depends only by E_ν . Then if we introduce *A* in the cross section expression we have:

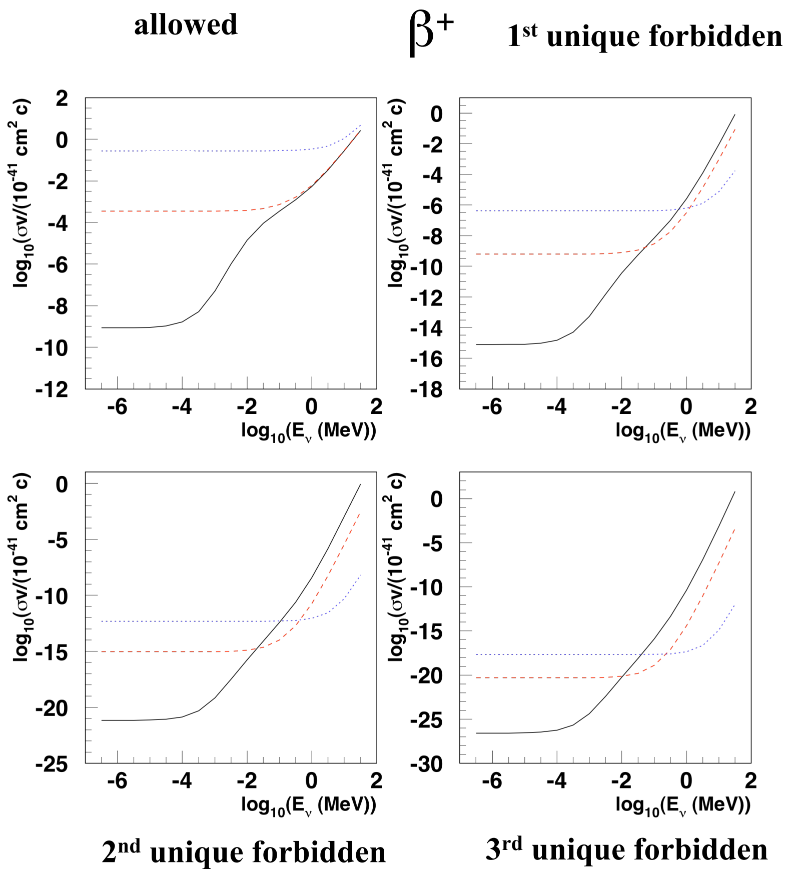
$$\boxed{\sigma_{\mathrm{NCB}} v_\nu = \frac{2\pi^2 \ln 2}{\mathcal{A}\, t_{1/2}}}$$

Thus σ_{NCB} can be easily calculated in terms of the decay half-life of the corresponding beta decay process and of the quantity *A* where the neutrino energy dependency is hidden.

NCB Cross Section

as a function of E_ν, Q_β and forbiddance level





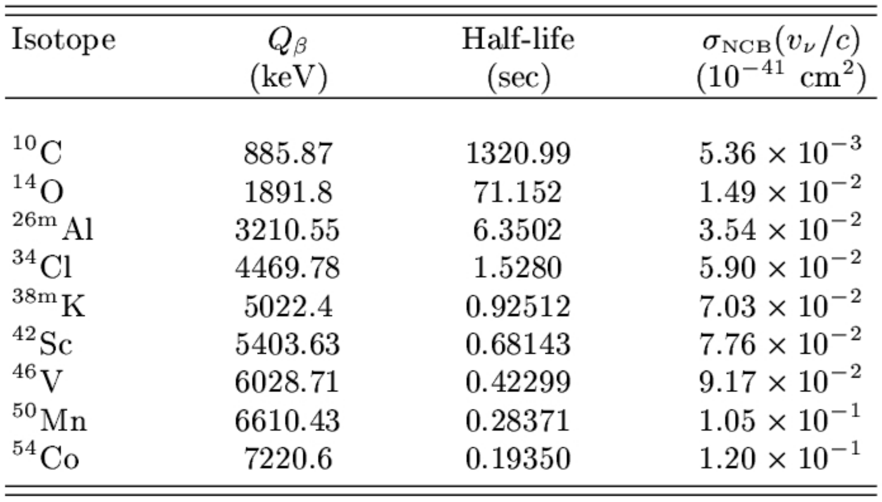
——— Q_β = 1 keV

- - - - Q_β = 100 keV

········ Q_β = 10 MeV

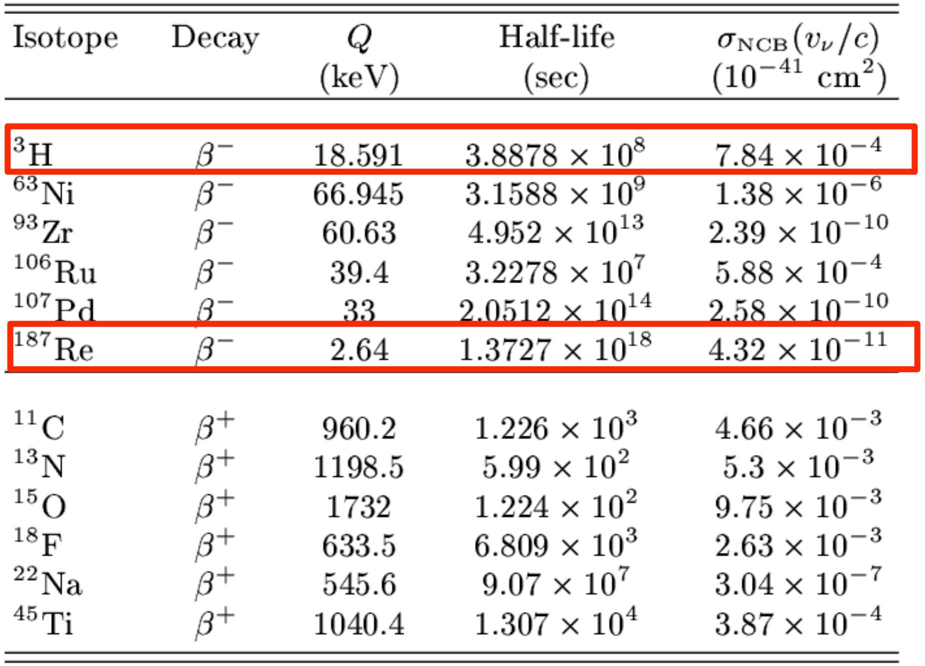
NCB Cross Section Evaluation

specific cases



Isotope	Q_β (keV)	Half-life (sec)	$\sigma_{\mathrm{NCB}}(v_\nu/c)$ (10^{-41} cm^2)
^{10}C	885.87	1320.99	5.36×10^{-3}
^{14}O	1891.8	71.152	1.49×10^{-2}
^{26m}Al	3210.55	6.3502	3.54×10^{-2}
^{34}Cl	4469.78	1.5280	5.90×10^{-2}
^{38m}K	5022.4	0.92512	7.03×10^{-2}
^{42}Sc	5403.63	0.68143	7.76×10^{-2}
^{46}V	6028.71	0.42299	9.17×10^{-2}
^{50}Mn	6610.43	0.28371	1.05×10^{-1}
^{54}Co	7220.6	0.19350	1.20×10^{-1}

Super-allowed $0^+ \to 0^+$



Isotope	Decay	Q (keV)	Half-life (sec)	$\sigma_{\mathrm{NCB}}(v_\nu/c)$ (10^{-41} cm^2)
^{3}H	β^-	18.591	3.8878×10^{8}	7.84×10^{-4}
^{63}Ni	β^-	66.945	3.1588×10^{9}	1.38×10^{-6}
^{93}Zr	β^-	60.63	4.952×10^{13}	2.39×10^{-10}
^{106}Ru	β^-	39.4	3.2278×10^{7}	5.88×10^{-4}
^{107}Pd	β^-	33	2.0512×10^{14}	2.58×10^{-10}
^{187}Re	β^-	2.64	1.3727×10^{18}	4.32×10^{-11}
^{11}C	β^+	960.2	1.226×10^{3}	4.66×10^{-3}
^{13}N	β^+	1198.5	5.99×10^{2}	5.3×10^{-3}
^{15}O	β^+	1732	1.224×10^{2}	9.75×10^{-3}
^{18}F	β^+	633.5	6.809×10^{3}	2.63×10^{-3}
^{22}Na	β^+	545.6	9.07×10^{7}	3.04×10^{-7}
^{45}Ti	β^+	1040.4	1.307×10^{4}	3.87×10^{-4}

Nuclei having the highest product $\boldsymbol{\sigma_{\mathrm{NCB}}\, t_{1/2}}$

NCB Cross Section

the major results of our paper

- **Exist a process (NCB) that allows in principle the detection of neutrino of vanishing energy!**

- **The cross section (times the neutrino velocity) does not vanish when the neutrino energy becomes negligible!**

- **We evaluated thousands of cross section for neutrino interaction on beta unstable nuclei!**

- **The detection of the relic neutrinos has been downscaled from a principle problem to a technological challenge.**

Probing low energy neutrino backgrounds with neutrino capture on beta decaying nuclei JCAP 0706:015,2007,
Low Energy Antineutrino Detection Using Neutrino Capture on EC Decaying Nuclei, arXiv:0903.1217

Relic Neutrino Detection

signal to background ratio

The ratio between capture (λ_ν) and beta decay rate (λ_β) is obtained using the previous expressions:

$$\frac{\lambda_\nu}{\lambda_\beta} = \frac{2\pi^2 n_\nu}{\mathcal{A}}$$

Then, if we evaluate $\lambda_\nu/\lambda_\beta$ for ^{3}H in the full energy range of the β decay spectrum, with the assumption that $m_\nu=0$, $n_\nu \sim 53/\text{cm}^3$ we get a value to small to be considered in an experimental framework ($0.66\ 10^{-23}$).

So far we considered the worst condition to calculate the CRN interaction rate. In fact, in case the neutrino mass is different from zero any energy resolution enhances the signal over background ratio and furthermore the Fermi momentum distribution, assumed so far, does not describe any gravitational clustering effect that in case of non zero neutrino mass will happen.

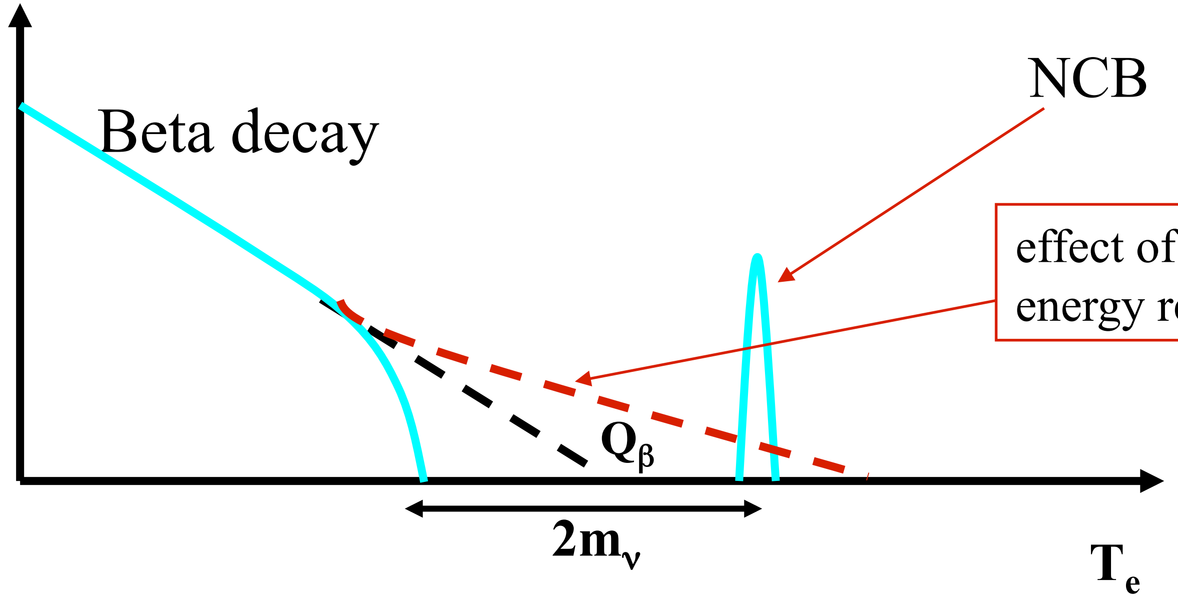
Relic Neutrino Detection (III)

signal to background ratio

As a general result for a given experimental resolution Δ the signal (λ_ν) to background (λ_β) ratio is given by

$$\frac{S}{B} = \frac{9}{2}\zeta(3)\left(\frac{T_\nu}{\Delta}\right)^3 \frac{1}{(1+2m_\nu/\Delta)^{3/2}}\left[\frac{1}{\sqrt{2\pi}}\int_{\frac{2m_\nu}{\Delta}-\frac{1}{2}}^{\frac{2m_\nu}{\Delta}+\frac{1}{2}} e^{-x^2/2}dx\right]^{-1}$$

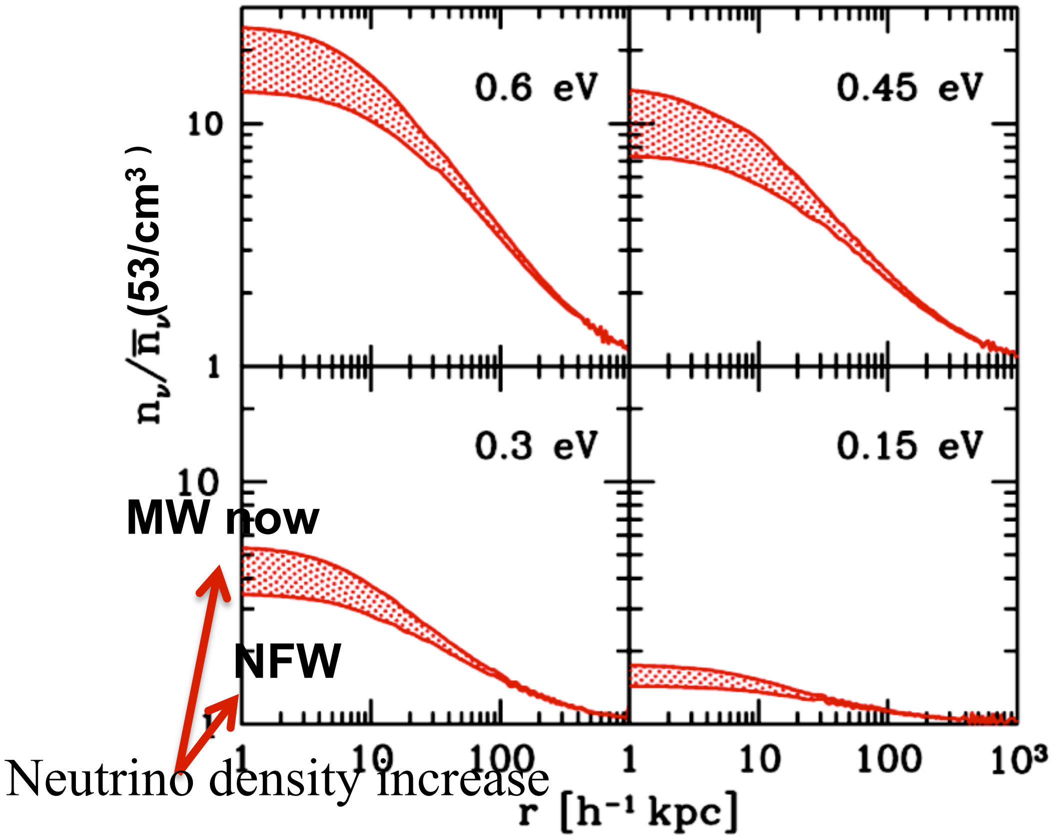
where the last term is the probability for a beta decay electron at the endpoint to be measured beyond the $2m_\nu$ gap.



effect of the experimental energy resolution if $\Delta \leq m_\nu$

Possible effects enhancing the NCB (I)

A.Ringwald and Y.Y.Wong (JCAP12(2004)005) made predictions about the CRN density by using an N-body simulation under two main assumptions. In one they considered the clustering of the CRN under the gravitational potential given by the Milk Way matter density as it is today. The second prediction was made considering a gravitational potential evolving during the Universe expansion (Navarro, Franck White). In both cases the neutrinos were considered as spectators and not participating to the potential generation.



MW now

NFW

Neutrino density increase

Possible effects enhancing the NCB (II)

In table the number of events per year are reported if we assume the target mass of 100 g of Tritium

m_ν(eV)	FD (events/yr)	NFW (events/yr)	MW (events/yr)
0.6	7.5	90	150
0.3	7.5	23	33
0.15	7.5	10	12

In table the amount of target masses are reported for 7.5 events observed per year.

m_ν(eV)	mass/year (FD)	mass/year (NFW)	mass/year (MW)
0.6	100 g	8 g	5 g
0.3	100 g	33 g	25 g
0.15	100 g	75 g	62 g

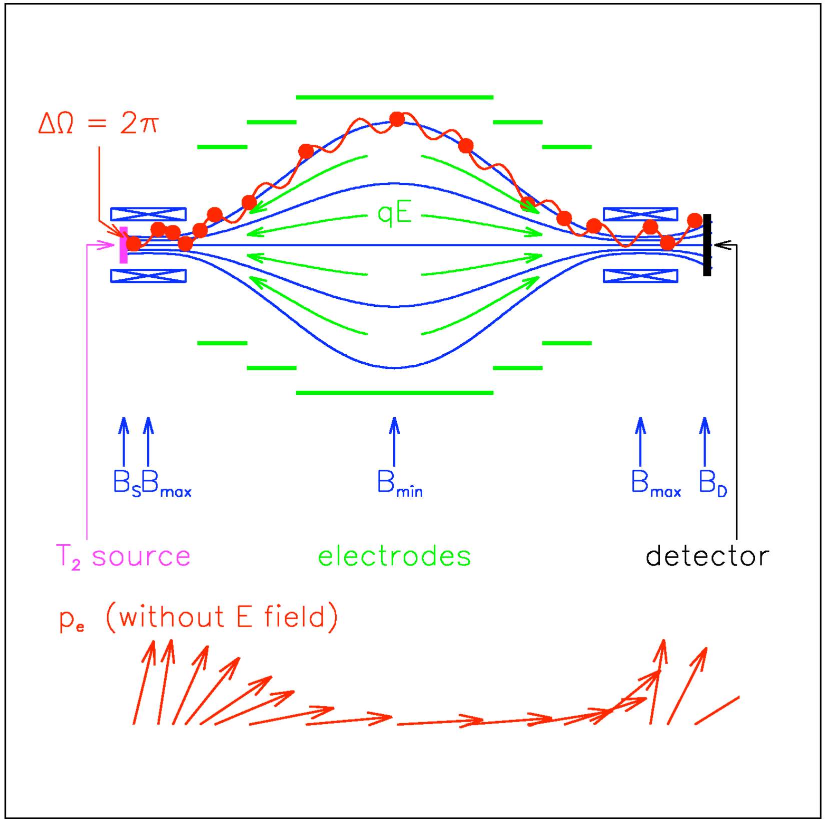
No background has been considered so far!

Possible experimental solutions

One possible experimental approach (I)
KATRIN

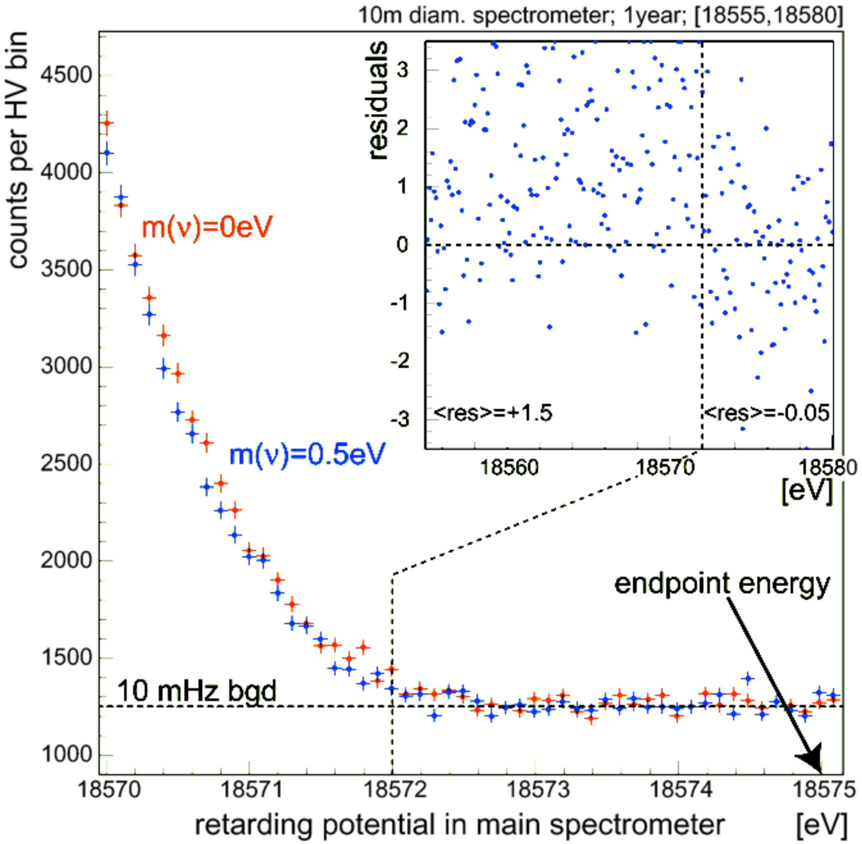
The beta electrons, isotropicaly emitted at the source, are transformed into a broad beam of electrons flying almost parallel to the magnetic field lines. This parallel beam of electrons is running against an electrostatic potential formed by a system of cylindrical electrodes. All electrons with enough energy to pass the electrostatic barrier are reaccelerated and collimated onto a detector, all others are reflected. The relative sharpness of this filter is given by the ratio of the minimum magnetic field B_{min} in the center plane and the maximum magnetic field B_{max} between beta electron source and spectrometer :

$$\frac{\Delta E}{E} = \frac{B_{\min}}{B_{\max}}$$



One possible experimental approach

1 year data data taking
and 0.2 eV resolution



KATRIN collaboration foresees in a second step the following upgrade:

- **spectrometer with larger diameter 7 m to 9 m**
- **larger diameter source vessel 7 cm to 9 cm.**
- **10 Hz overall background rate**

How far can it be?

If we consider:

- ***Katrin sensitivity foreseen in the second experimental phase***

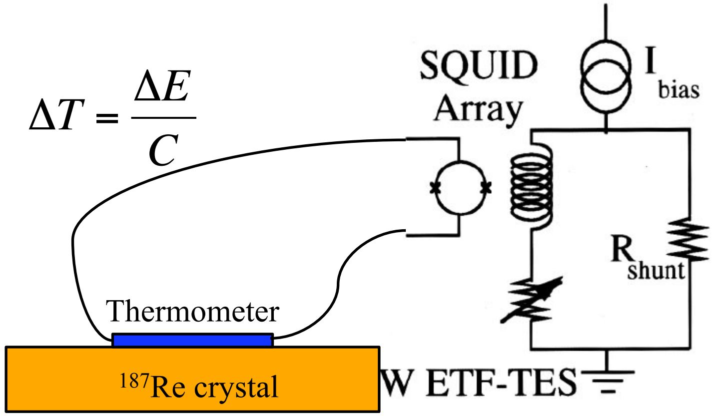
  0.2 eV energy resolution

  0. 1 mHz detector background rate (only 1 o.o.m. better than KATRIN has foreseen)
- ***the cross section value we calculated (7.7 10^{-45} cm^{2}c)***
- ***NFW(MW) density assumption,***
- ***0.6 eV for the neutrino mass***
- ***we need 16(10) g of T to get 15 NCB events, 12 events of background and so 5 sigma evidence in one year (we neglected the background from beta decay: 1/20 (1/30).)***

Another experimental solution to detect the CRN

MARE detector

$$\Delta T = \frac{\Delta E}{C}$$



The key issue of the read-out system are the very low noise SQUID amplifier

$$\Delta V = V_{bias} \cdot A \cdot \frac{\Delta T}{T}$$

MARE collaboration claims that can achieve a resolution of part of eV. This would match our request but much larger mass with respect to the case of Tritium is needed since the cross section of NCB on ^{187}Re is lower. The MARE collaboration foresees to have in ~2011 100000 micro calorimeters of 1-5 mg mass each. This is still 4-6 order of magnitude far from the mass we need but in principle this detector technology can be scaled up easily.

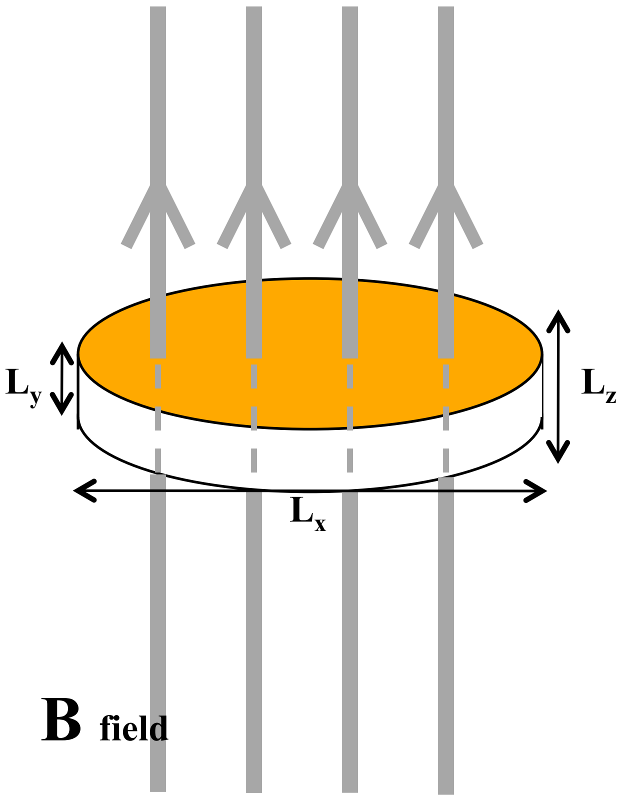
A new experimental options

Geometrically-Metastable Superconducting Strips Detectors

Detection Principle

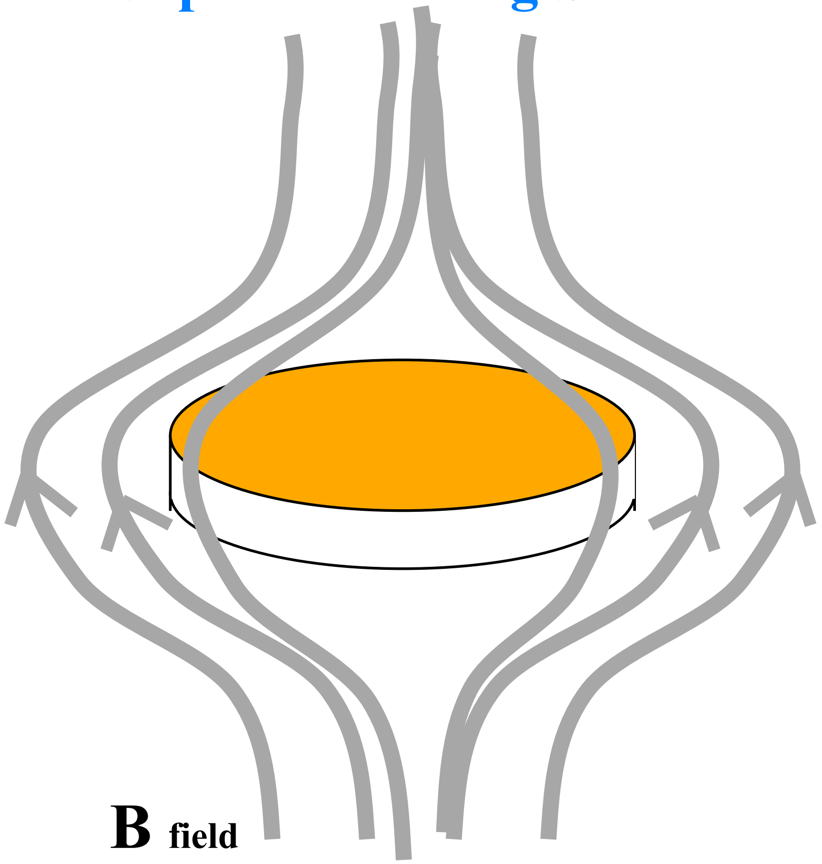
$T > T_C$

Normal State



$T < T_C$

Superconducting State



(NIM A 370 (1996) 104, NIM A 373 (1996) 65 and reference therein.)

A new experimental options

Geometrically-Metastable Superconducting Strips Detectors

Detection Principle

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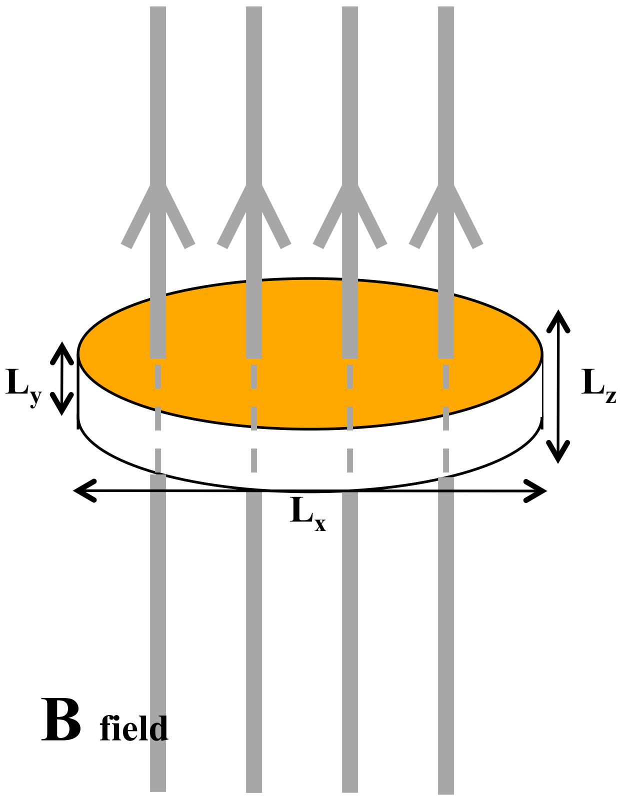
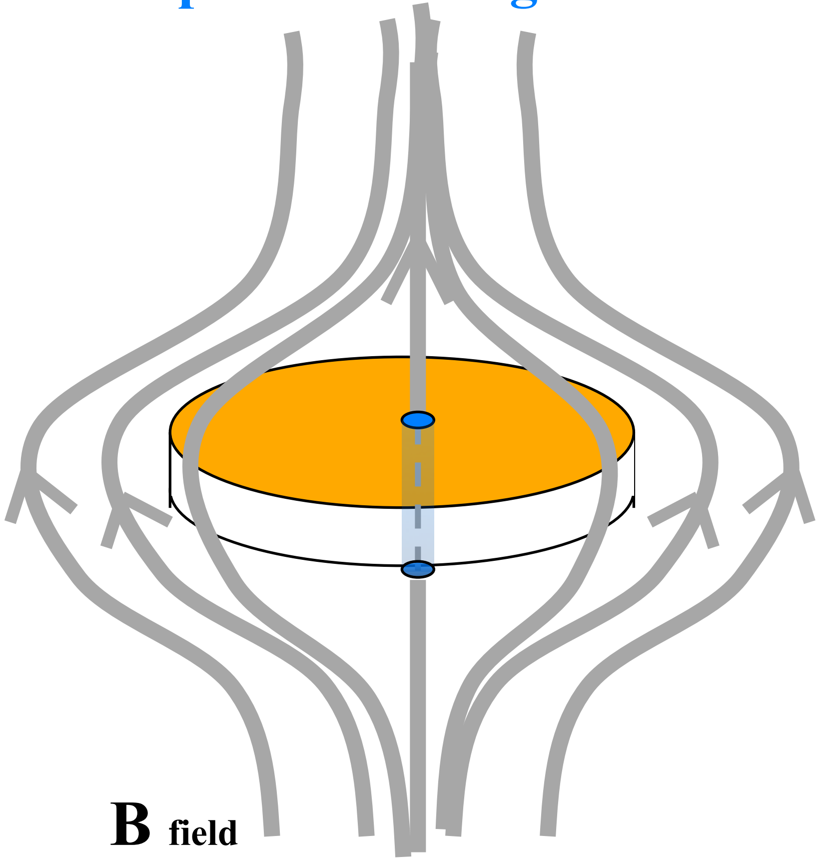
Normal State



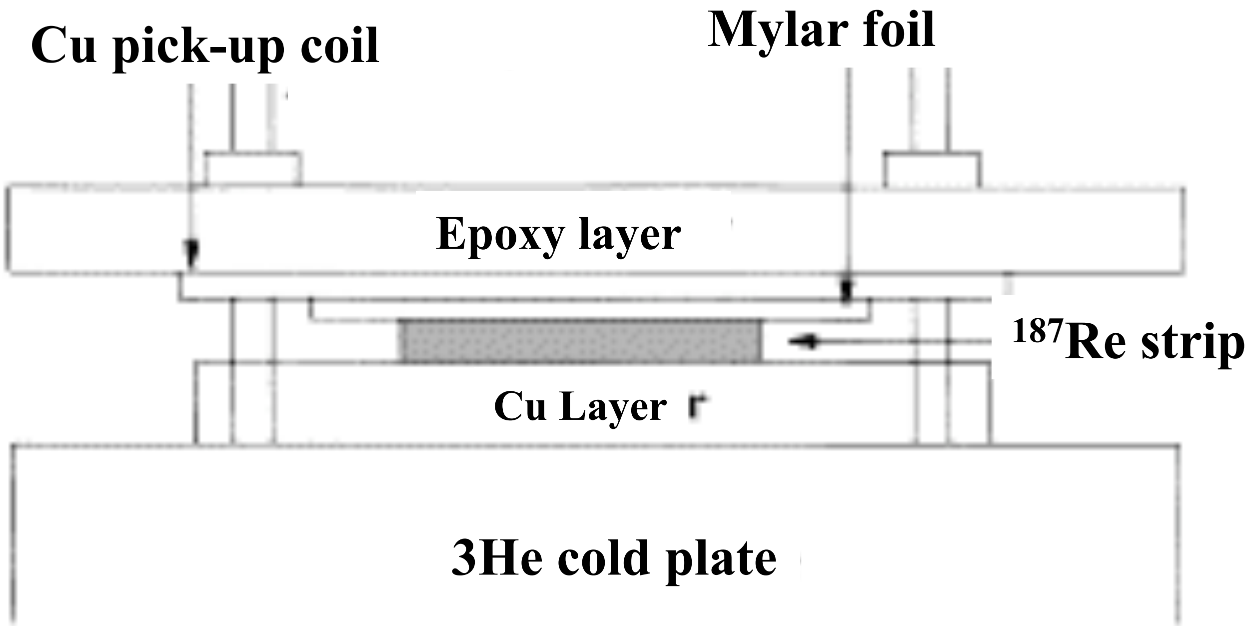
$T < T_C$

Superconducting State



(NIM A 370 (1996) 104, NIM A 373 (1996) 65 and reference therein.)

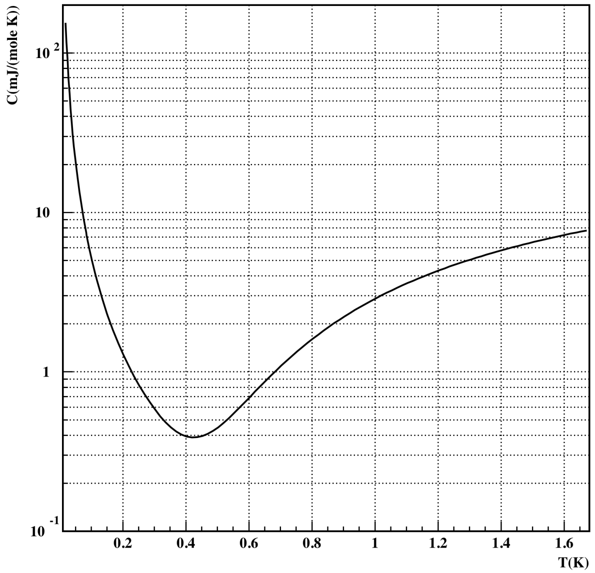
Typical experimental set-up



The size of the Re strip is = 15 x 0.9 x 0.025 mm^3 t corresponding to a mass of 7 mg. NIM A444 (2000) 84).

$$\frac{E_{released}}{L_y S} = \Delta h$$

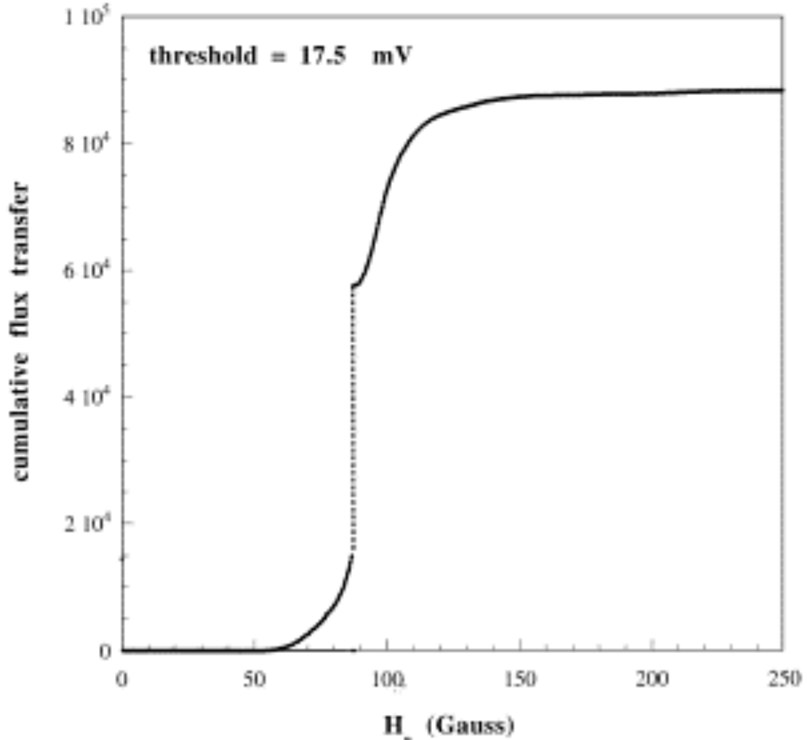
Δh is the variation of enthalpy density in the phase transition.



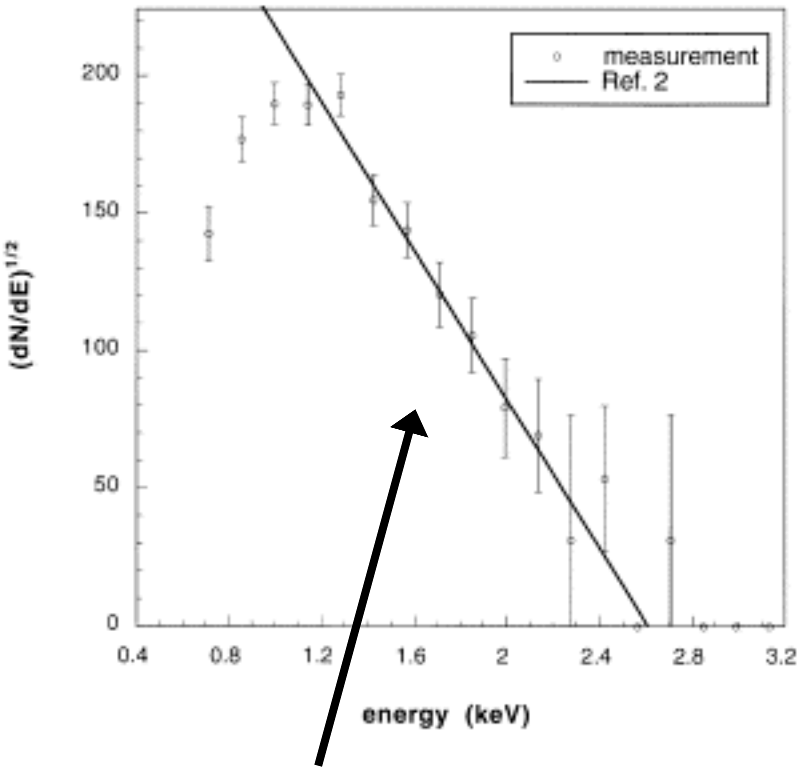
$$V \sim \int \frac{d\phi}{dt} dt = H \cdot S \propto H \cdot \frac{E_{released}}{L_y \Delta h}$$

$$\Delta h = 6.11 keV / \mu m^3$$

Some results from old measurements (I)

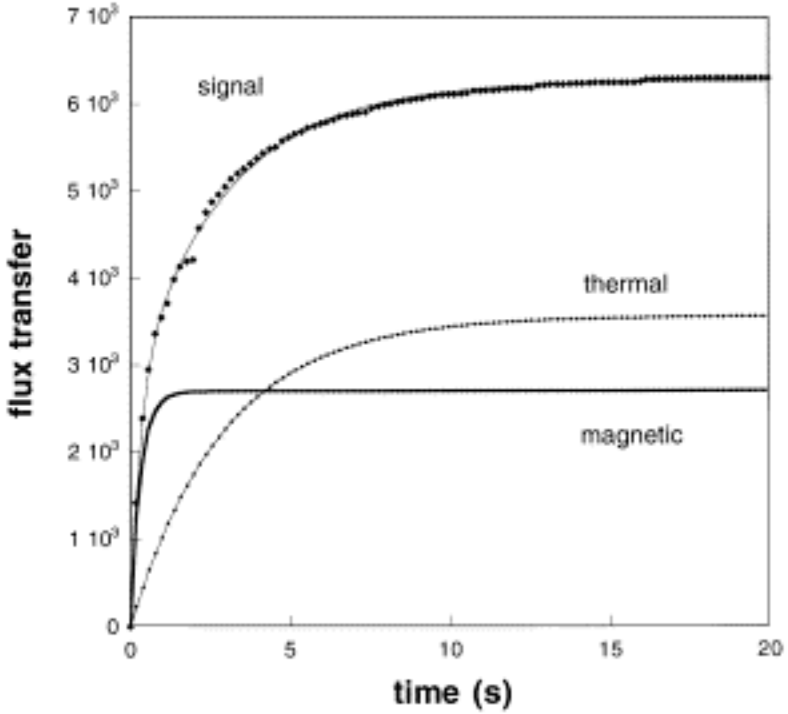


The device was cooled (330mK) at zero field and the B field was ramped from 88 G (16 G/s) up to 250 G, above H$_c$ (210 G).



ΔE=135 eV

Some results from old measurements (II)



From the plot it is visible that after ~20 s the efficiency drops down according to: $\varepsilon(t) = \frac{\tau_T}{\Delta t}\left[1 - e^{-\Delta t/\tau_T}\right]$. After 20 s a new cycle of the B field starts again.

Why this experimental approach is very promising

- **The mass per strip can be increased almost without limit if we keep the aspect ratio of an ellipsoid where one axis is much larger than the other one (1/10). Under this hypothesis 1-10 g per strip is achievable.**

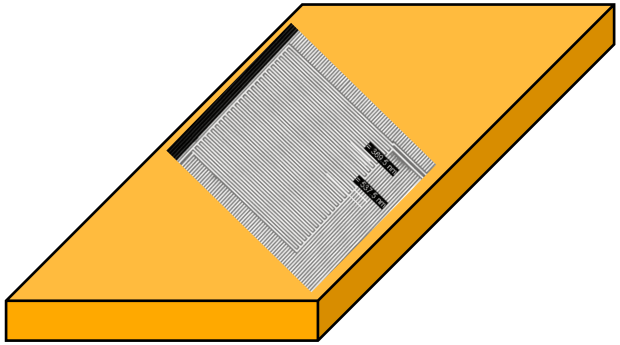
- **The limit of the single detector will be due to the time response of read-out chain. The signal rate that can be tolerated is ~ 10^5 Hz if the time response of the read-out electronic is ~10ns.**

- **A detector with a full mass of 1-10 kg is not out of reach even with the present status of the knowledge in the field of Geometrically-Metastable Superconducting Strip Detectors.**

- **Still under investigation the limiting factors of the ultimate energy resolution**

Bolometer with nano-sensor read-out

Nb=T



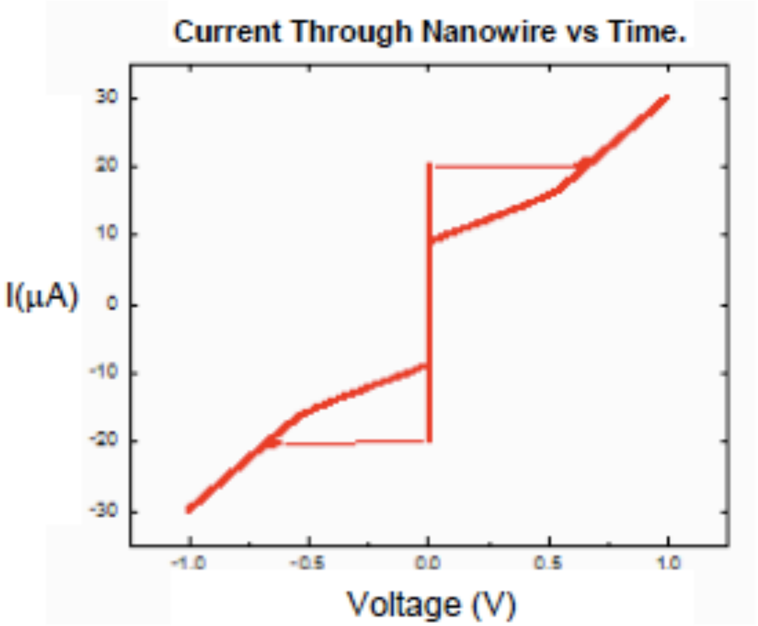
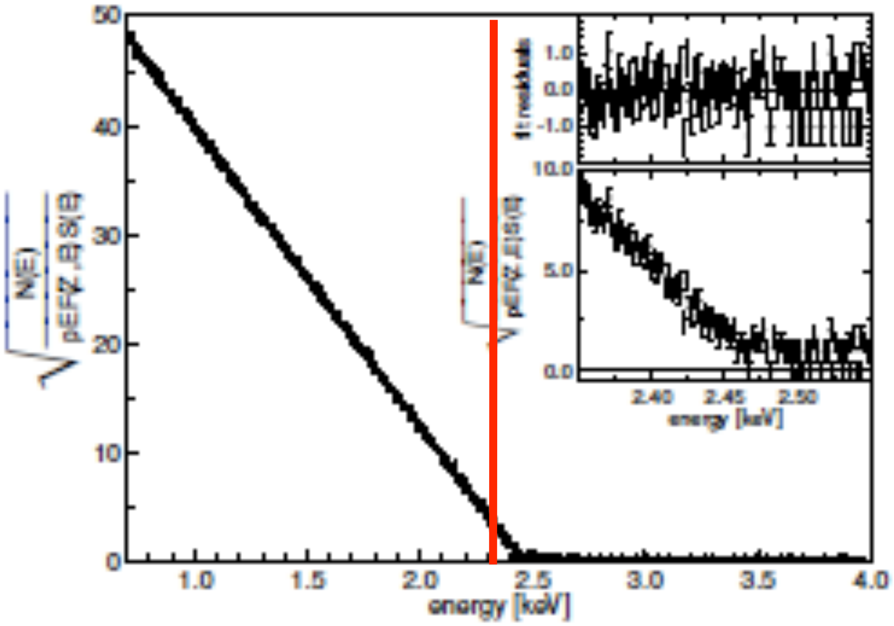


Figure 6: DC IV curve for 200nm wide nanowire detector showing a critical current of approx. 20 μA.



$$\frac{dN}{dt} = 5.6\cdot 10^{11}\,\frac{Hz}{mg}$$

$$N(\Delta E) = \left(\frac{\Delta E}{Q}\right)^3 = \left(\frac{5}{18591}\right)^3 \cong 2\cdot 10^{-11}$$

Conclusions

- The fact that neutrino has a nonzero mass has renewed the interest on Neutrino Capture on Beta decaying nuclei as a unique tool to detect very low energy neutrino
- The relatively high NCB cross section when considered in a favourable scenario could bring cosmological relic neutrino detection within reach in a near future if:
  - neutrino mass is in the eV range
  - an electron energy resolution of 0.1 – 0.2 eV is achieved

- Different technological approaches are under study such as the Geometrically Metastable-Superconducting Strip Detector and the Bolometer with nano-sensor read-out device. Both detector technology appear very promising.