Experimental challenges towards the detection of relic neutrinos with unstable nuclei

CERN workshop on the detection of relic neutrinos

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Outline

- The expected rate of the relic neutrinos on beta instable elements
- Gravitational clustering effect that might enhances the interaction rate.
- Possible experimental techniques in view of a possible experiment for the relic neutrino detection
- Conclusions

NCB Cross Section Evaluation

specific cases

Isotope	Q_β (keV)	Half-life (sec)	$\sigma_{\rm NCB}(v_\nu/c)$ $(10^{-41}\ \mathrm{cm}^2)$
^{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 $0^+ \rightarrow 0^+$

Isotope	Decay	Q (keV)	Half-life (sec)	$\sigma_{\rm NCB}(v_\nu/c)$ $(10^{-41}\ \mathrm{cm}^2)$
^{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 $\boldsymbol{\sigma}_{\mathbf{NCB}}\ \boldsymbol{t}_{\mathbf{1/2}}$

Relic Neutrino Detection

The cosmological relic neutrino capture rate is given by

$$\lambda_\nu = \int \sigma_{\rm NCB} v_\nu \frac{1}{\exp(p_\nu/T_\nu)+1} \frac{d^3 p_\nu}{(2\pi)^3}$$

$$\boldsymbol{T_\nu = 1.7 \cdot 10^{-4}\ \mathrm{eV}}$$

after the integration over neutrino momentum and inserting numerical values we obtain:

$$2.85 \cdot 10^{-2}\, \frac{\sigma_{\rm NCB} v_\nu / c}{10^{-45} \mathrm{cm}^2}\, \mathrm{yr}^{-1}\ \ \mathrm{mol}^{-1}$$

In the case of Tritium we estimate that 7.5 neutrino capture events
per year are obtained using a total mass of 100 g

Relic Neutrino Detection (I)

signal to background ratio

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

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

In the case of Tritium $\lambda_\nu(^3H) = 0.66 \cdot 10^{-23} \lambda_\beta(^3H)$ is obtained under

the assumption $m_\nu=0$, $n_\nu \sim 50/cm^3$ in the full energy range.

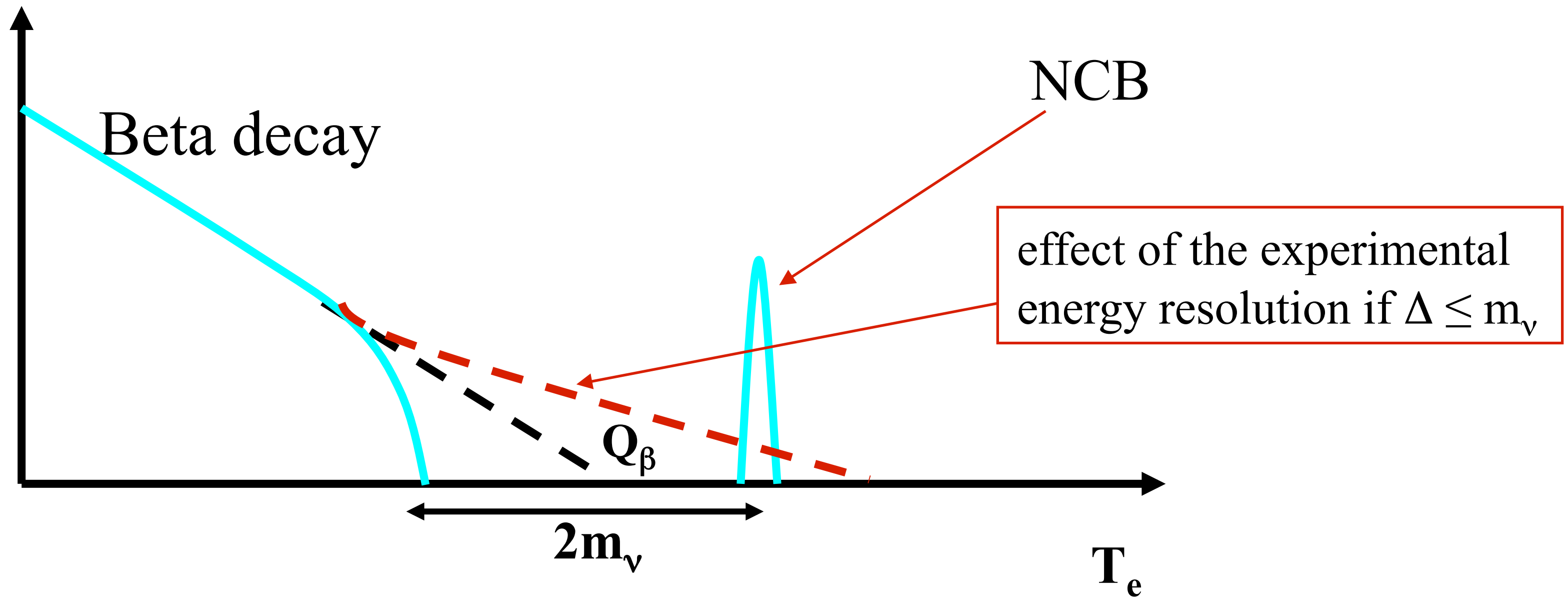
So far we considered the worst condition to calculate the CRN interaction rate. In fact, in cas the neutrino mass is different from zero any energy resolution enhances the signal over background ration and furthermore the Fermi momentum distribution, considered so far, does not describe any neutrino density increase due to gravitational effect.

Relic Neutrino Detection (II)
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



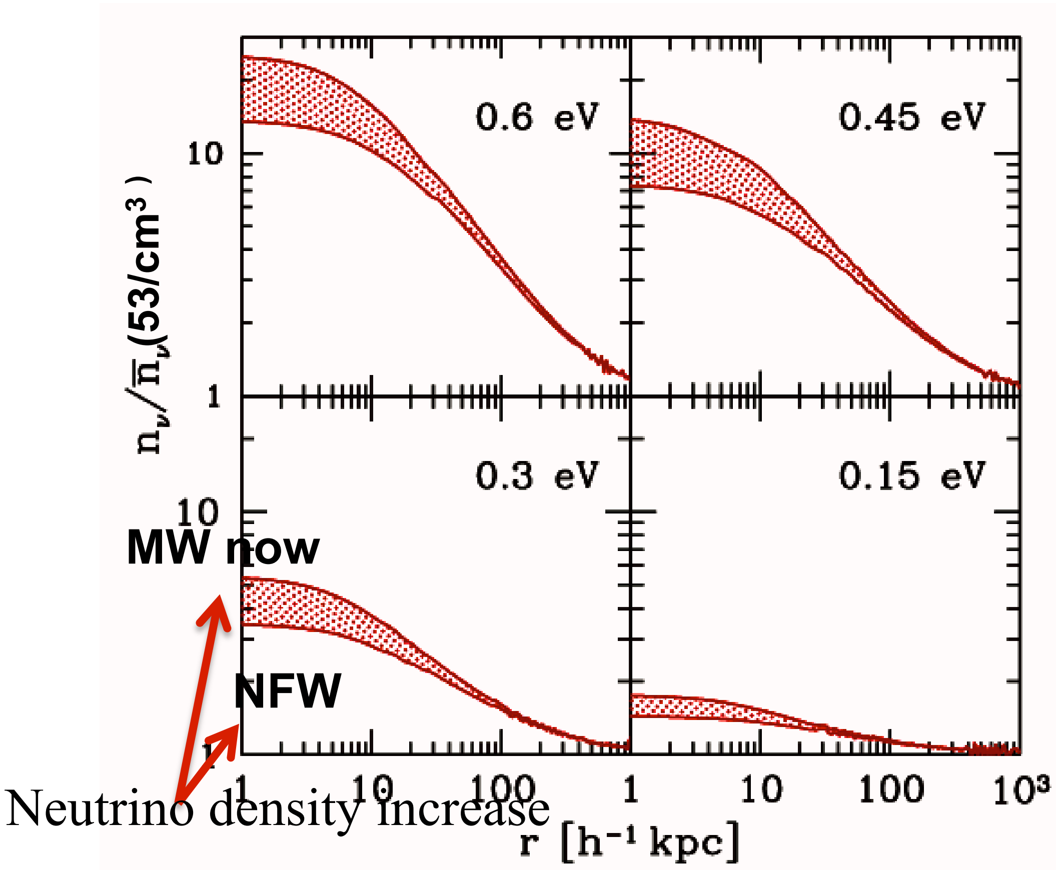
Relic Neutrino Detection

discovery potential

As an example, given a neutrino mass of 0.7 eV and an energy resolution at the beta decay endpoint of 0.2 eV a signal to background ratio of 3 is obtained. In the case of 100 g mass target of Tritium it would take one and half year to observe a 5σ effect.

Possible effects enhancing the NCB

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.



Possible effects enhancing the NCB

Probing low energy neutrino backgrounds
JCAP06(2007)015

Table 3. The number of NCB events per year for 100 g of ^{3}H, taking into account the effect of gravitational clustering in the neighbourhood of the Earth, compared to the case of a standard homogeneous Fermi–Dirac distribution with $T_\nu = 1.7 \times 10^{-4}$ eV (FD). We show for some value of neutrino mass the results for a Navarro, Frenk and White profile (NFW) and for present day mass distribution of the Milky Way (MW), using the local neutrino densities computed in [36].

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

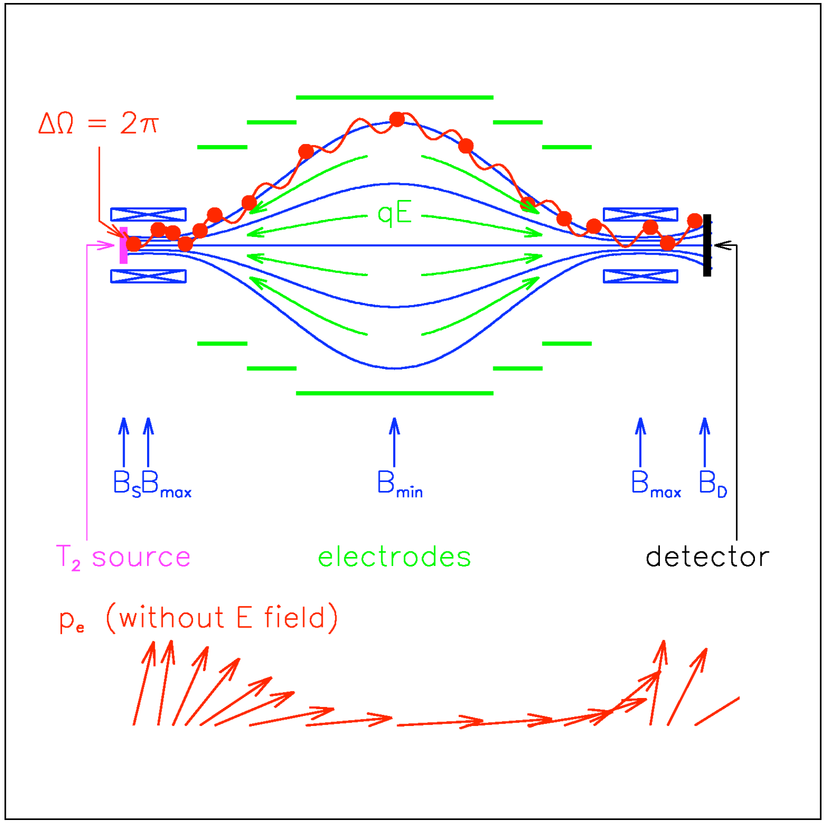
Statistical significance with increased density

In the table is reported the mass needed in order to have a 5 sigma evidence of NCB (on Tritium target) in one year for different neutrino clustering model.

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

One possible experimental approach (I)
KATRIN

The beta electrons, isotropically 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. Therefore the spectrometer acts as an integrating high-energy pass filter. 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 :



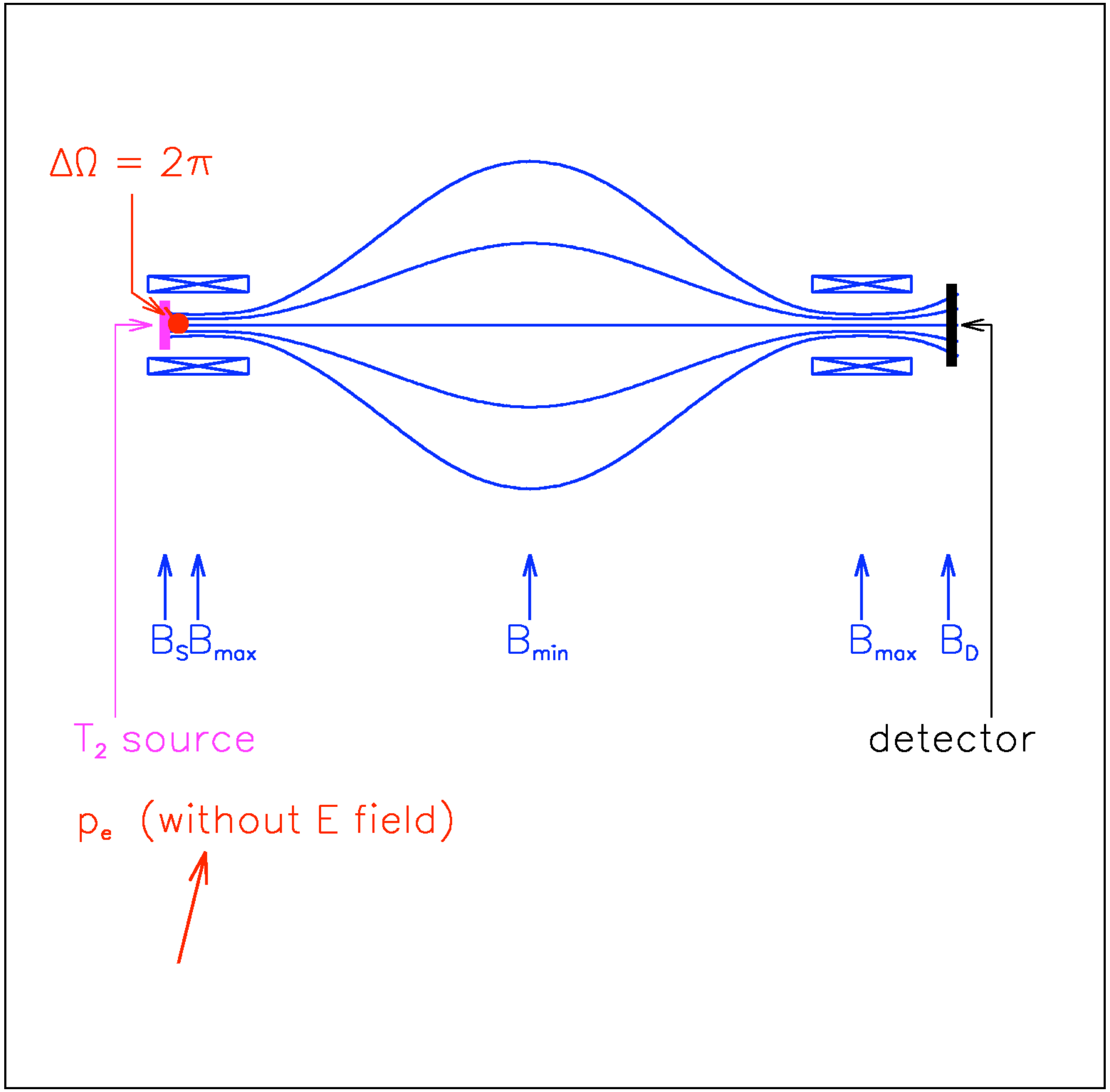
$$\frac{\Delta E}{E} = \frac{B_{\min}}{B_{\max}}$$

One possible experimental approach (II) KATRIN

The focalization capability of the magnetic field is based on the fact:

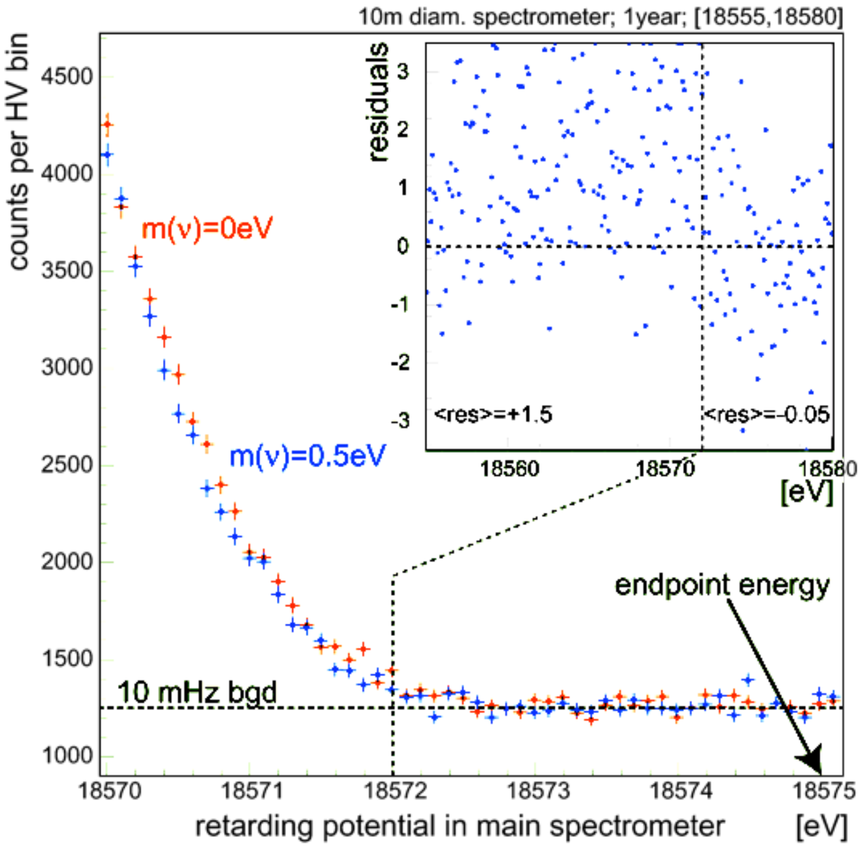
$$\vec{F} = \vec{\nabla}(\vec{\mu} \cdot \vec{B})$$

thus the cyclotron energy is transformed in longitudinal motion



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.**
- **1 mHz overall background rate**

How far can it be?

If we consider:

- ***KATRIN sensitivity foreseen in the second experimental phase***
  0.2 eV energy resolution
  1 mHz detector background rate
- ***the cross section value we calculated (7.7 10^{-45} cm^2c)***
- ***NFW(MW) density assumption,***
- ***0.6 eV for the neutrino mass***
- ***we need 59(35) g of ^2T to get 55 NCB events, 125 background events and so we have almost 5 sigma evidence in one year (we neglected the background from beta decay: ~1/6 (1/10) of the signal)***

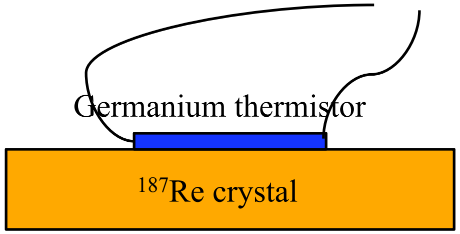
If we consider:

- ***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^2c)***
- ***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

The detector is based on the technology of micro bolometers made of ^{187}Re crystals read-out by high sensitivity resistor. The micro calorimeter are at ~10 mK temperature. The detection principle is based on the fact that given the very low heat capacitance C also a small amount of energy release in the ^{187}R crystal can provoke a measurable ΔT:



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

MARE collaboration claim they can achieve resolution of part of eV. This would match our request but much large mass with respect to the case of tritium is needed since the cross section of NCB on ^{187}Re is lower. The collaboration MARE 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

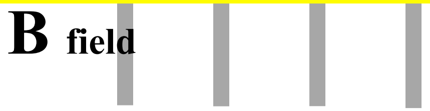
Geometrically-Metastable Superconducting Strips Detectors

Detection Principle

$T > T_C$

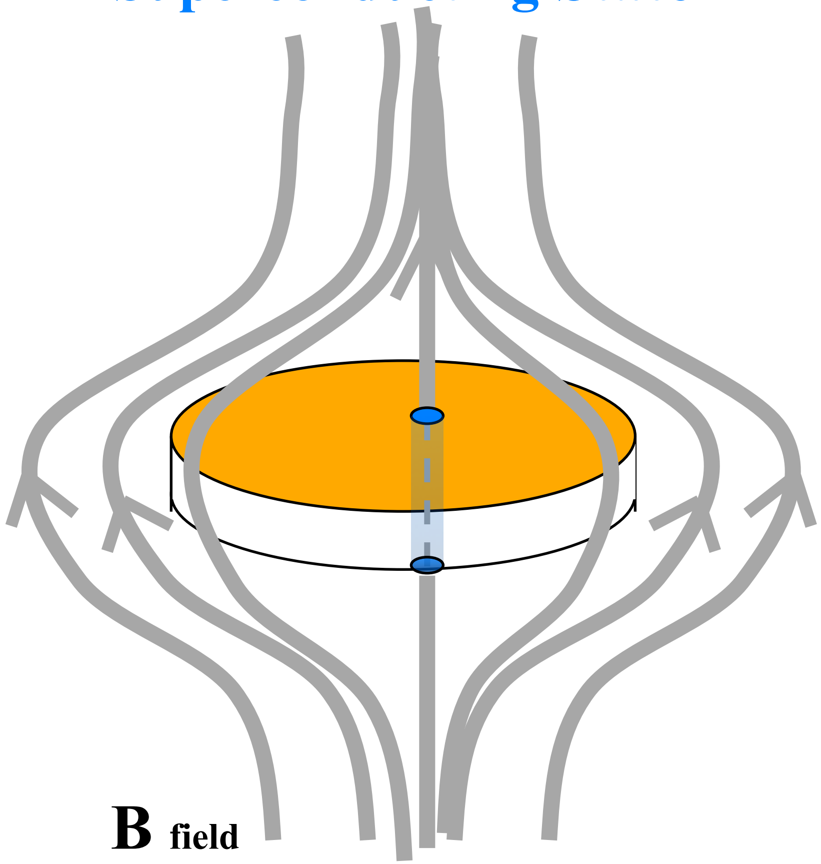
Normal State

When a superconductor strip is placed in an increasing perpendicular field, its transition to the normal state is delayed by an energy barrier that prevents spontaneous flux penetration. As suggested and proven in the literature reported later the Gibbs free energy depends on the applied magnetic field, on the aspect ration of the strip, and on the size of the multi-quantum flux tube that may enter into the strip From the point of view of particle detection the most important aspect that we have to consider is the fact that the flux nucleation can also be provoked by the energy release of a charged particle. (NIM A 370 (1996) 104, NIM A 373 (1996) 65 and reference therein.)

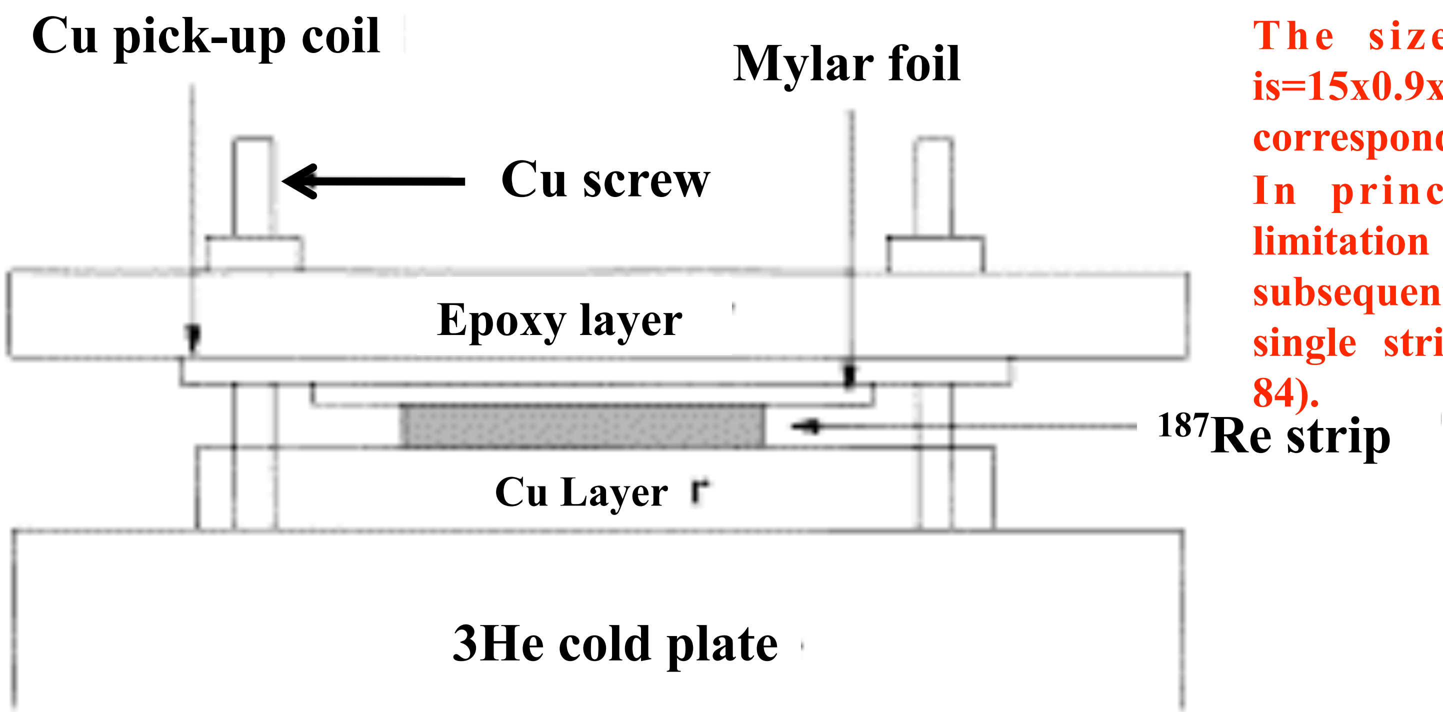


$T < T_C$

Superconducting State



Typical experimental set-up



The size of the Re strip is=15x0.9x0.00025 mm^3 that corresponds to a mass of 7 mg. In principle there are no limitation on the volume and subsequently on the mass of the single strip (NIM A444 (2000) 84).

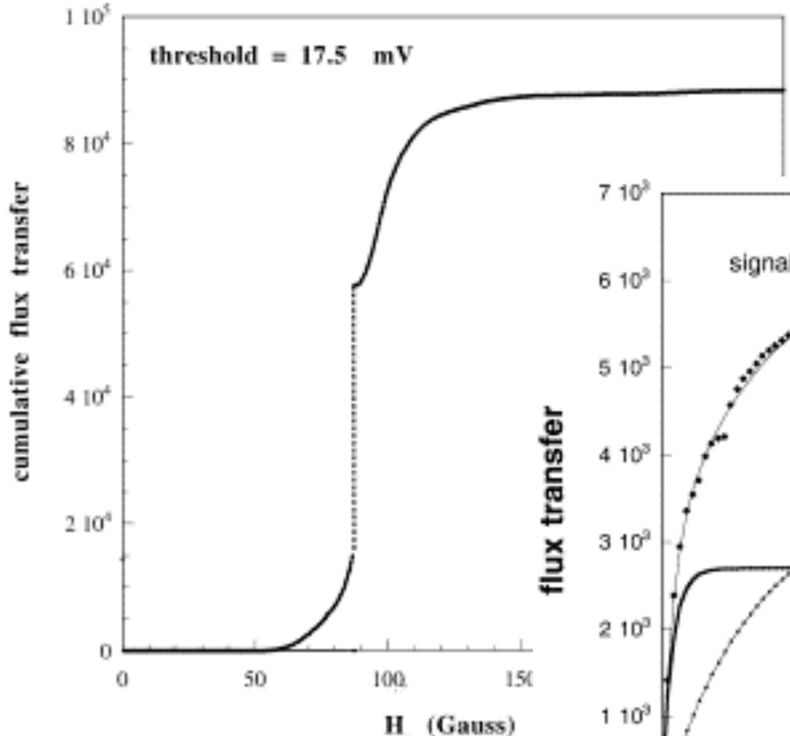
Why the signal is proportional to the energy release?

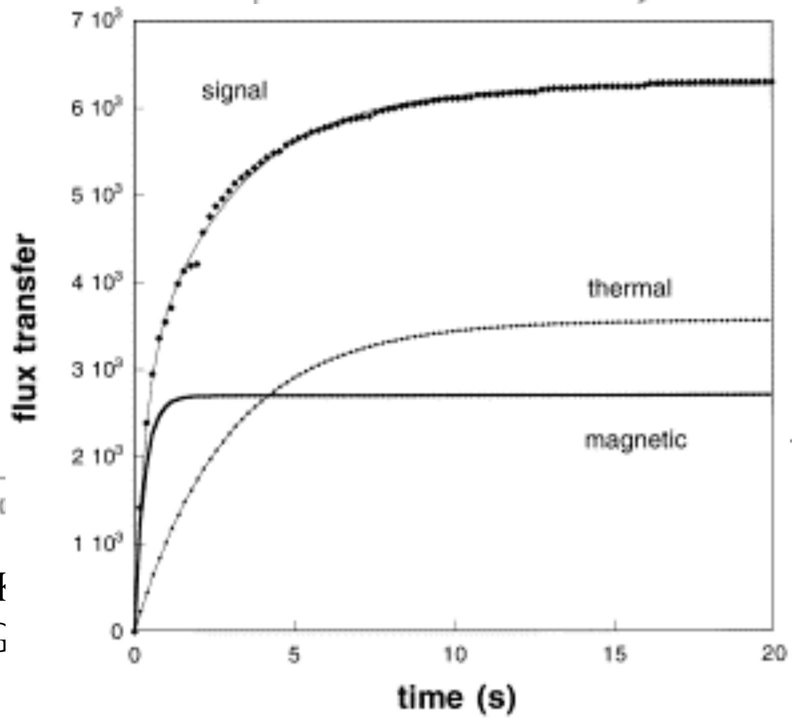
$$\frac{E_{released}}{L_y S} = \Delta h$$

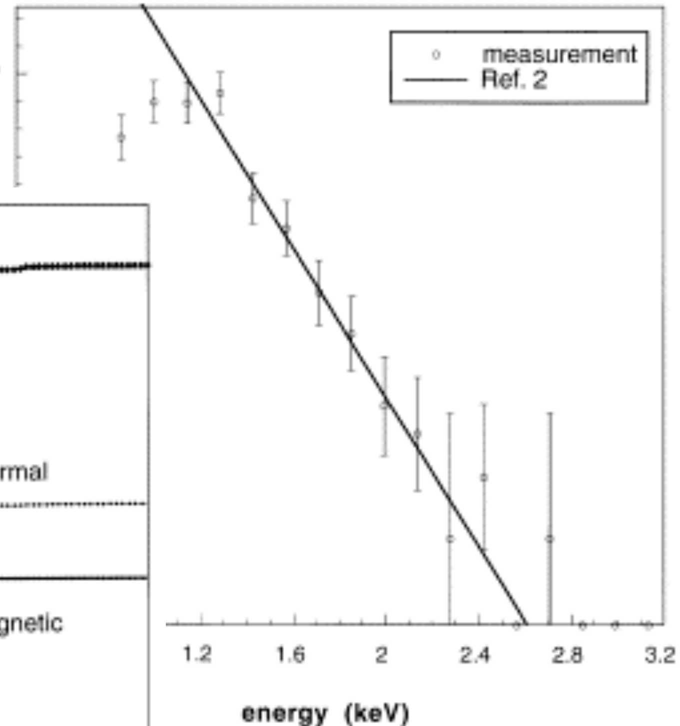
Where Δh is the variation of enthalpy density in the phase transition. The typical volume where the nucleation of flux tube take place is ~ 1-10 μm^3

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

Some results from old measurements







The device was cooled (330mH
B field was ramped from 88 G
well above H_c (210 G).

From the plot it si visible that after ~20 the efficiency drops dow according to: $\varepsilon(t) = \frac{\tau_T}{\Delta t}\left[1 - e^{-\Delta t/\tau_T}\right]$

Why this experimental approach is very promising

•The mass per strip can be increased up to the technological limit of the read-out chain: 1-10 g. The signal rate that can be tolerated are

$\sim 10^5$ Hz with a time response of the read-out electronic on the scale of 10ns.

•The energy resolution envisaged in the literature are at level of eV

if the read-out is realized by means of SQUID amplifier.

•A detector with a full mass of kg is not out of reach even with the present status of the knowledge in the filed of Geometrically Metastable Superconducting Strip Detectors.

Conclusions

- The fact that neutrino has a nonzero mass has renewed the interest on Neutrino Capture on Beta decaying nuclei as a <u>unique tool to detect very low energy neutrino</u>

- 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

- So far we considered only two elements: ^{3}H and ^{187}Re. More elements are under study

- From the point of view of the technological feasibility of the measurement we are only at beginning of the investigation. We are confident that a new technological improvement can soon make this measurement more realistic With a detector KATRIN like or MARE like.
- Furthermore we started to investigate the technology of the Geometrically Metastable Superconducting Strip Detector that appears to be very promising.