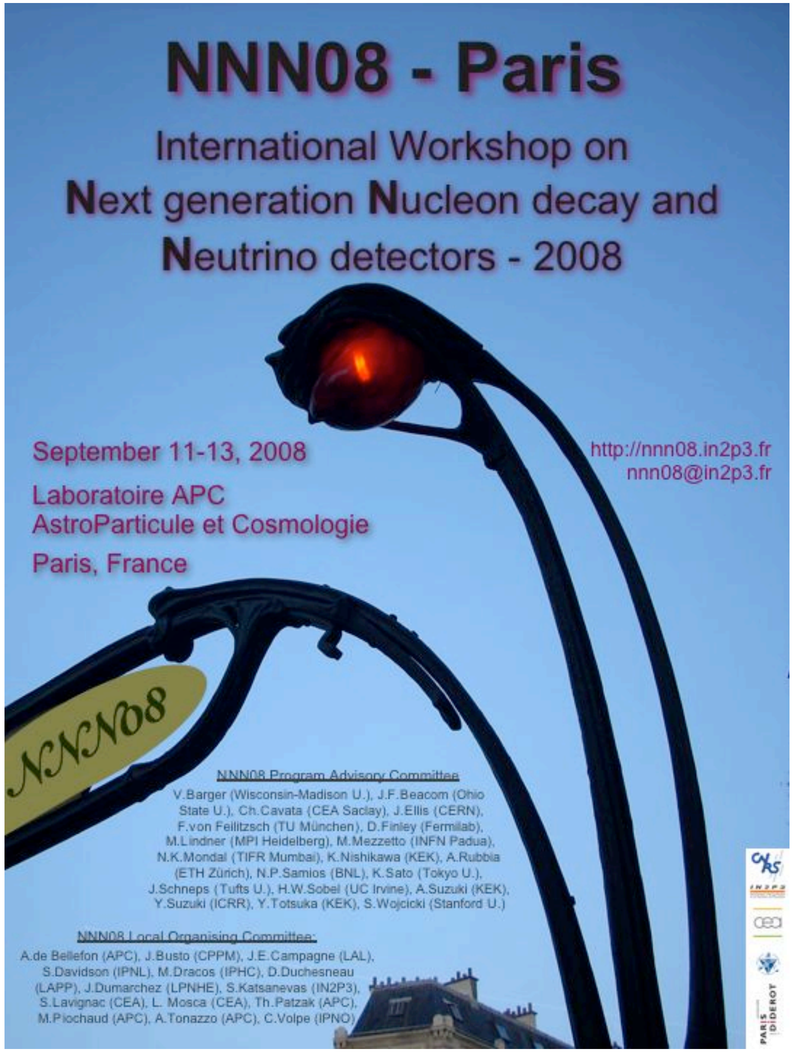
A process to detect neutrinos of vanishing kinetic energy by means of unstable target nuclei



NNN08 - Paris

International Workshop on
Next generation **N**ucleon decay and
Neutrino detectors - 2008

September 11-13, 2008

Laboratoire APC
AstroParticule et Cosmologie

Paris, France

http://nnn08.in2p3.fr
nnn08@in2p3.fr

NNN08 Program Advisory Committee

V.Barger (Wisconsin-Madison U.), J.F.Beacom (Ohio State U.), Ch.Cavata (CEA Saclay), J.Ellis (CERN), F.von Feilitzsch (TU München), D.Finley (Fermilab), M.Lindner (MPI Heidelberg), M.Mezzetto (INFN Padua), N.K.Mondal (TIFR Mumbai), K.Nishikawa (KEK), A.Rubbia (ETH Zürich), N.P.Samios (BNL), K.Sato (Tokyo U.), J.Schneps (Tufts U.), H.W.Sobel (UC Irvine), A.Suzuki (KEK), Y.Suzuki (ICRR), Y.Totsuka (KEK), S.Wojcicki (Stanford U.)

NNN08 Local Organising Committee:

A.de Bellefon (APC), J.Busto (CPPM), J.E.Campagne (LAL), S.Davidson (IPNL), M.Dracos (IPHC), D.Duchesneau (LAPP), J.Dumarchez (LPNHE), S.Katsanevas (IN2P3), S.Lavignac (CEA), L. Mosca (CEA), Th.Patzak (APC), M.Piochaud (APC), A.Tonazzo (APC), C.Volpe (IPNO)

M. Messina, ***University of Bern and LHEP, Switzerland***

A.G. Cocco, G.Mangano and M.M., JCAP06(2007)015

Outline

- The methods proposed so far for the Cosmological Relic Neutrinos detection.
- A new process to detect Cosmological Relic Neutrinos.
- Guide lines about cross section calculations.
- Gravitational clustering effect that might enhances the interaction rate.
- Conclusions
- Outlook

The longstanding question

Is it possible to make a measurement of the Cosmological Relic Neutrinos?

- Observation of absorption dips in the Extremely Energetic Cosmic neutrino (EECν, $E_\nu > 10^{22}$ eV) spectra due to the annihilation with Cosmologic Relic Neutrinos (CRN) in a Z^0.

Neutrino of such a high energy are not even foreseen today.

- Observation of macroscopic forces due to coherent elastic scattering of CRN off target material in torsion balances. This effect is at second order in G^2_F as shown by N. Cabibbo and L. Maiani (Phys. Lett. 114B(1982)115)

The effect exists at the first order in G_F only if a strong nu anti-nu asymmetry or neutrino and target polarization is present. However in order to be able to make the measurement we need accelerometers with a sensitivity improvement of 15 order of magnitude.

Is it possible to make a measurement of the Cosmological Relic Neutrinos?

- Observation of interactions of extremely high energy particles from terrestrial accelerator beams with CRN.

In this case energy beam required is of $E_{beam}>10^7$ TeV and the accelerator would be as long as the earth circumference.

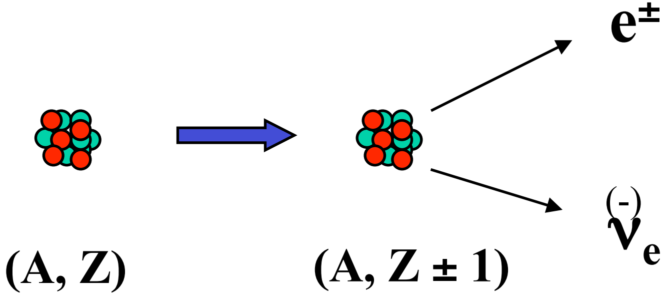
Summarizing: all methods proposed so far require unrealistic experimental apparatus or astronomical neutrino sources not yet observed.

Reviews on this subject see:
A.Ringwald "Neutrino Telescopes" 2005 – hep-ph/0505024
G.Gelmini hep-ph/0412305

Our proposal

A process without energy threshold

Beta decay

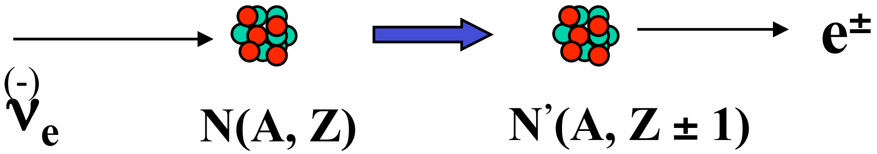


$e^{\pm}$

(A, Z) → $(A, Z \pm 1)$

$\overset{(-)}{\nu}_e$

Neutrino Capture on a
Beta decaying nucleus



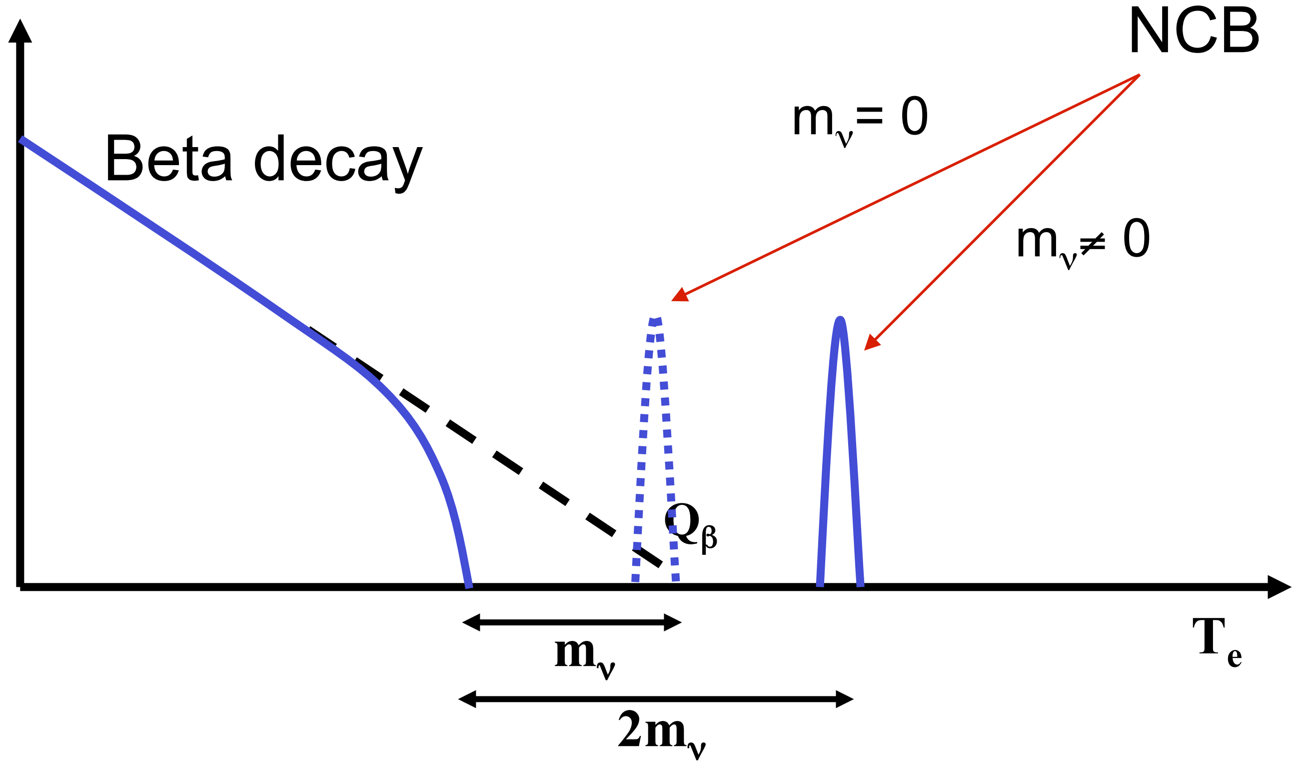
$\overset{(-)}{\nu}_e$ → $N(A, Z)$ → $N'(A, Z \pm 1)$ → $e^{\pm}$

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).

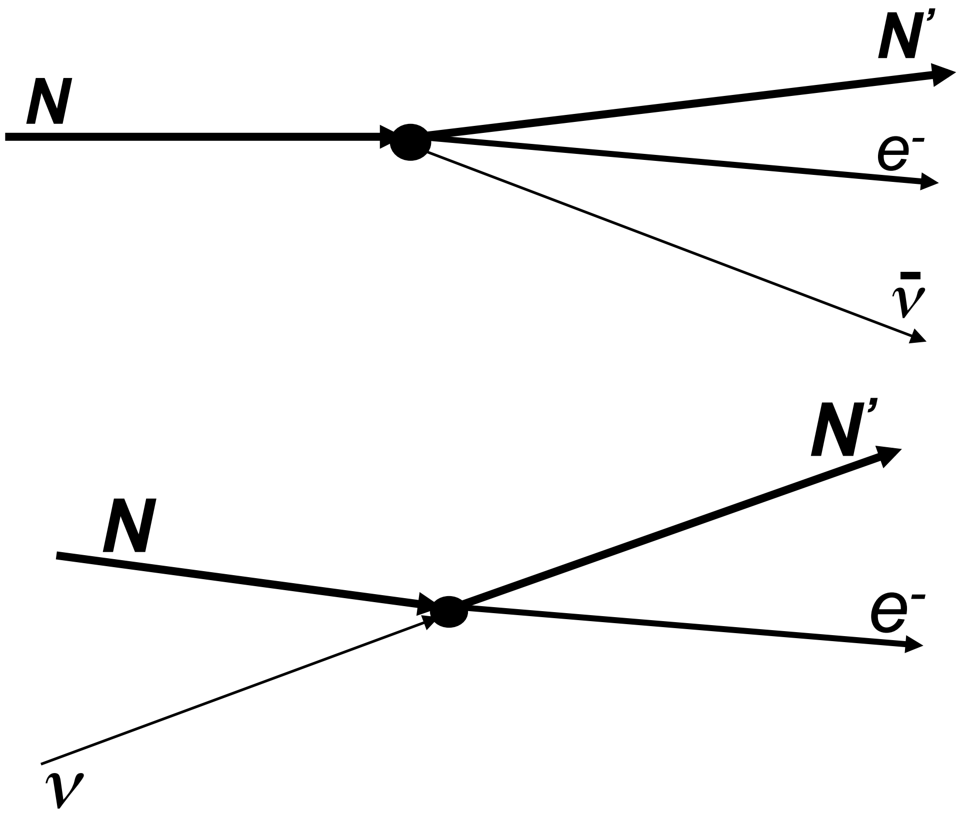
NCB signature

Neutrino masses of the order of 1 eV are compatible with the present picture of our Universe



The events induced by Neutrino Capture have a unique signature: a gap of $2m_\nu$ between the NCB electron energy and the energy of beta decay electrons at the endpoint.

How to evaluate NCB cross section



The invariant amplitudes of the two processes are the same (due to ν crossing).
This fact allows to evaluate the NCB cross section in an easy way.

NCB Cross Section

a new parameterization

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

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

The nuclear shape factors C_β and C_ν depend on nuclear matrix elements but it can be shown that a simple relation holds:

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

It is convenient to define
$$\mathcal{A} = \int_{m_e}^{W_o} \frac{C(E'_e,p'_\nu)_\beta}{C(E_e,p_\nu)_\nu} \frac{p'_e}{p_e} \frac{E'_e}{E_e} \frac{F(E'_e,Z)}{F(E_e,Z)} E'_\nu p'_\nu dE'_e$$

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

NCB Cross Section Evaluation

The case of Tritium

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

we obtain $\sigma_{\mathrm{NCB}}(^3\mathrm{H}) \frac{v_\nu}{c} = (\ 7.7 \pm 0.2\ ) \times 10^{-45}\ \mathrm{cm}^2$

where the uncertainty is due to Fermi and Gamow-Teller matrix element knowledge.

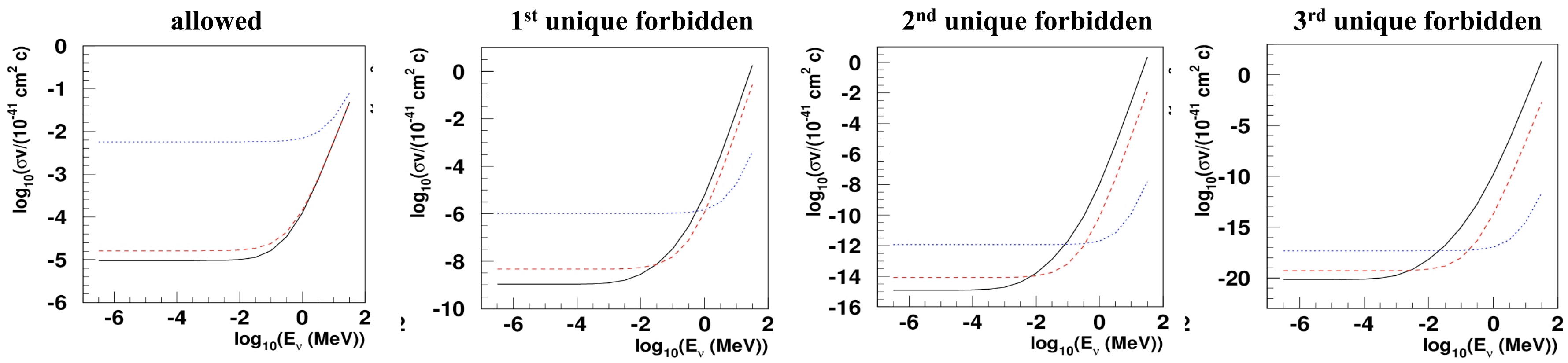
Using shape factors ratio $\sigma_{\mathrm{NCB}} v_\nu = \frac{2\pi^2 \ln 2}{\mathcal{A}\ t_{1/2}}$

$$\sigma_{\mathrm{NCB}}(^3\mathrm{H}) \frac{v_\nu}{c} = (\ 7.84 \pm 0.03\ ) \times 10^{-45}\ \mathrm{cm}^2$$

where the uncertainty is due only to uncertainties on Q_β and $t_{1/2}$

NCB Cross Section

as a function of E_ν, Q_β and forbiddance level



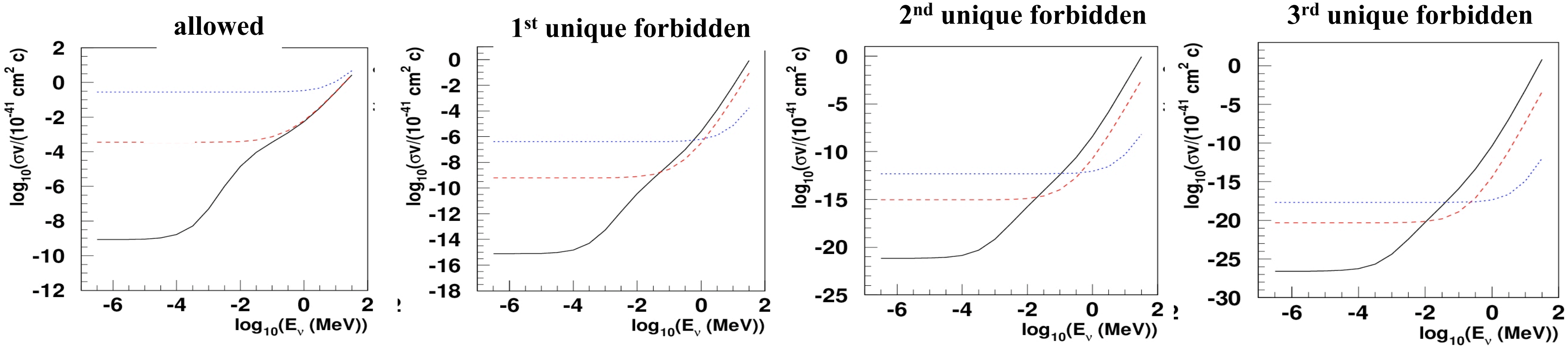
β^- (top)

β^+ (bottom)

— Q_β = 1 keV

- - - Q_β = 100 keV

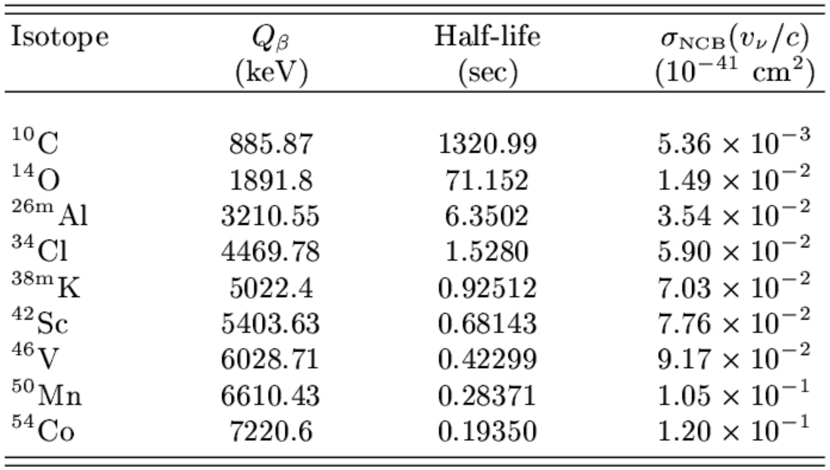
······ Q_β = 10 MeV



An important result is that the cross section does not vanish when the neutrino energy becomes negligible.

NCB Cross Section Evaluation

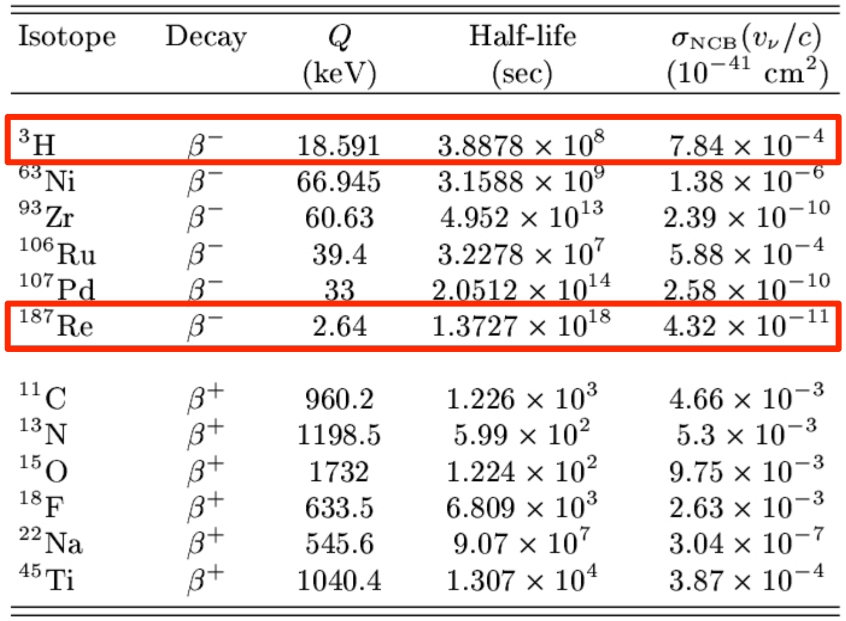
specific cases



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

(very precise measure of Q_β and $t_{1/2}$)



Isotope	Decay	Q (keV)	Half-life (sec)	$\sigma_{\rm NCB}(v_\nu/c)$ (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 $\sigma_{\rm NCB}\ t_{1/2}$ ^{3}H and ^{187}Re rispectivly 3×10^4 s•cm^2 and 6×10^7 s•cm^2.

We calculated cross section for 1272 β^- and 799 β^+ nuclei

Relic Neutrino Detection

The cosmological relic neutrino capture rate is given by

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

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

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 by 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 $m_\nu=0$.

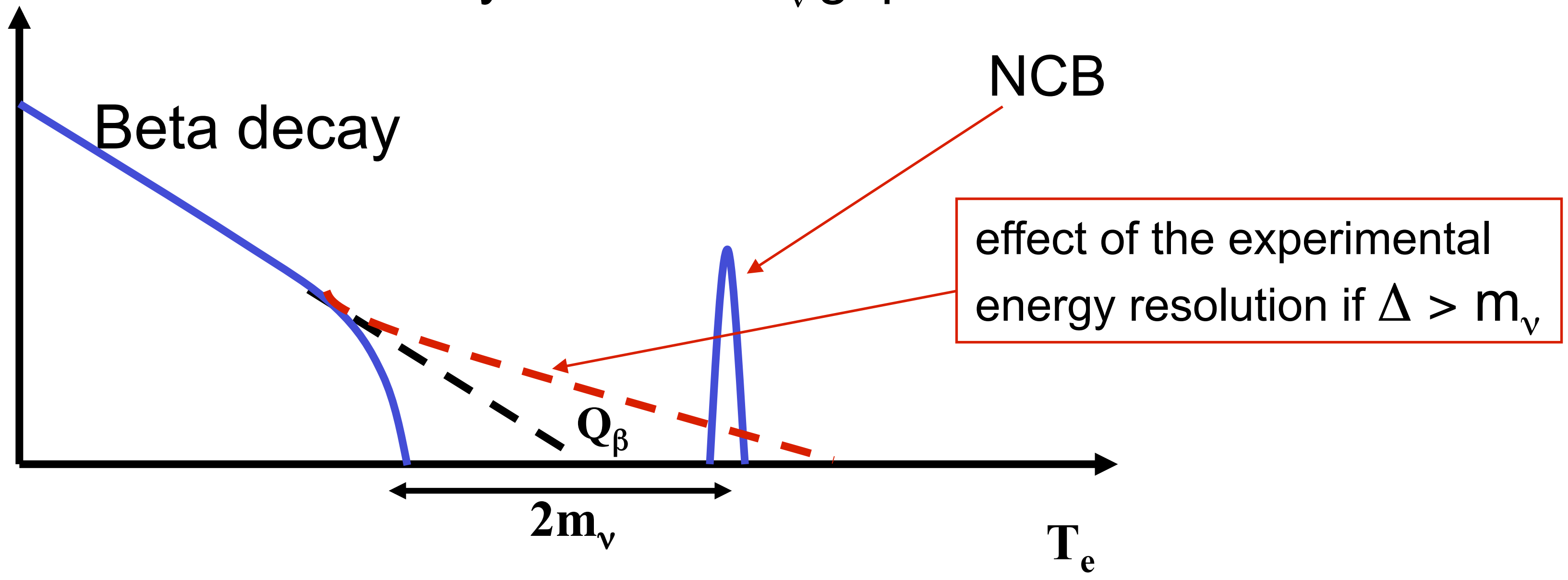
Relic Neutrino Detection (II)

signal to background ratio

As a general result for a given experimental resolution Δ the signal over background ($\lambda_\nu/\lambda_\beta$) 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 Δ > m_ν

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 a half year to observe a 5σ effect.

A larger interaction rate is obtained in case of ν gravitational clustering (A.Ringwald and Y.Y.Wong, JCAP 12(2004)005)

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

Recently another paper was published where our calculation were confirmed. In the paper was also made the hypothesis of a clustering effect that might increase up to a factor 1000 the local neutrino density w.r.t. the cosmological mean value (R. Lazauskas, P. Vogel and C. Volpe, J Phys. G35(2008)025001).

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

- A detailed study of NCB cross section has been performed for a large sample of known beta decays and a method to reduce the uncertainty due to nuclear matrix elements evaluation has been found.

- 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

Outlook

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

- Also elements EC instable show the nice feature of having sizeable cross section for neutrino CC cross section even if the neutrino has very low energy. The properties of those elements as neutrino target are still under evaluation. Soon a new paper will be submitted to a journal where the EC calculation cross section is shown and also a new process is considered for CRN detection.

- 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.
An electrostatic detector like KATRIN could be a possible experimental approach or also a large array of micro calorimeters apparatus like MARE detector. Both technological approach have positive and negative aspect.

Backup

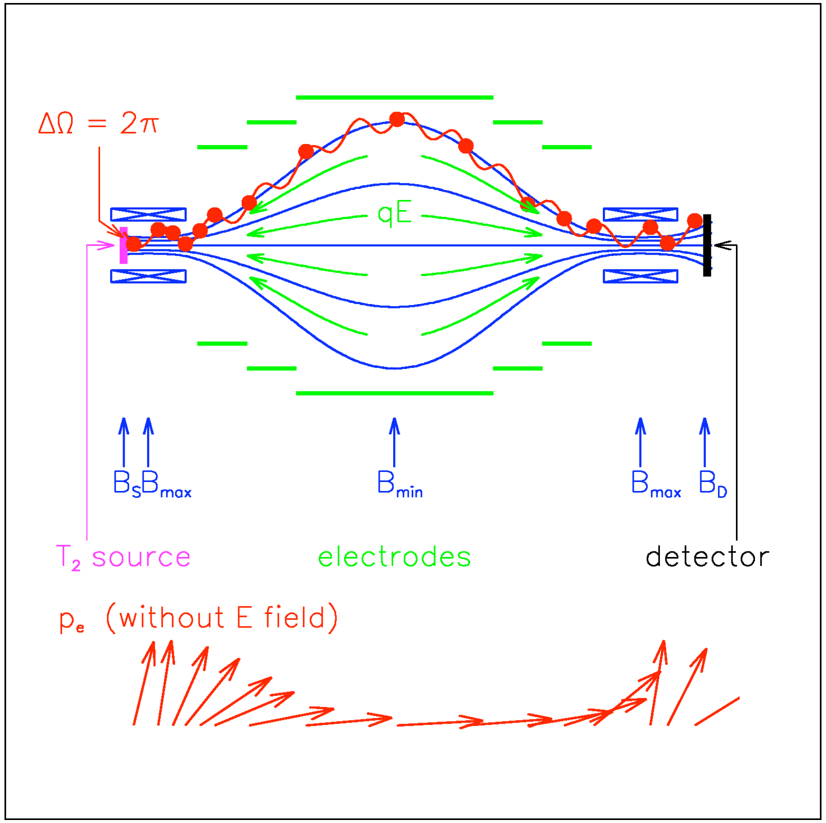
One possible experimental approach (I)

KATRIN detector, the ultimate direct neutrino mass measurement,
aims at direct neutrino mass measurement through the study of the ^{3}H end-point
(Q_β =18.59 keV, $t_{1/2}$ =12.32 y)

The beta electrons are transformed into a broad beam of electrons flying almost parallel to the magnetic field lines. 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.

The electrons are running against an electrostatic potential formed by a system of cylindrical electrodes.

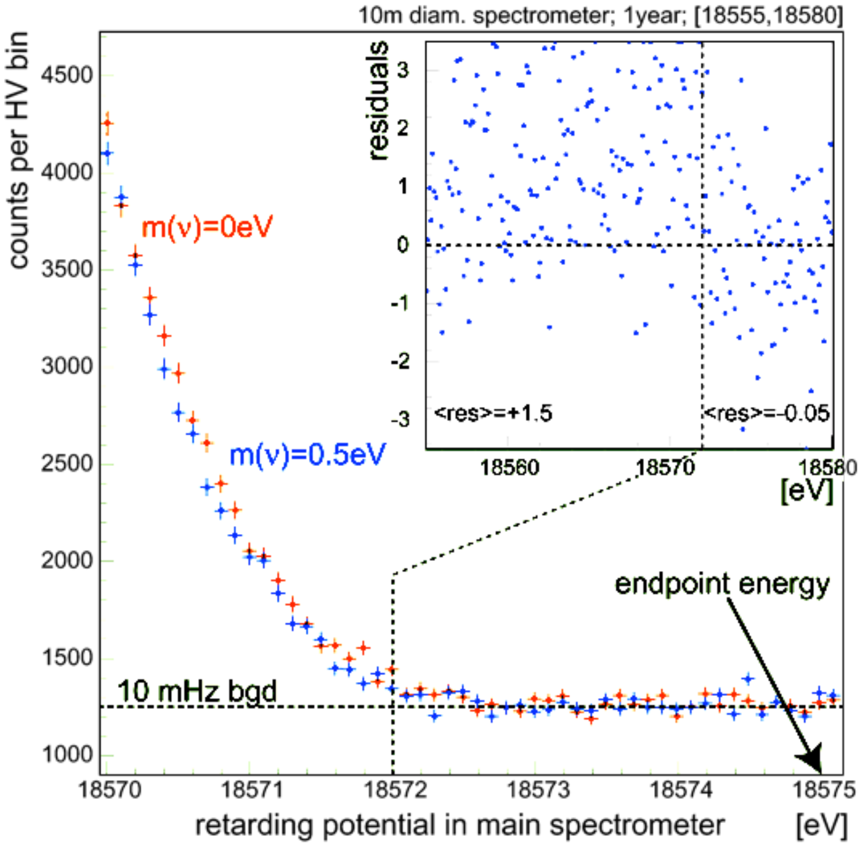
Then all the electrons with enough energy to pass the electrostatic barrier are reaccelerated and collimated onto a detector, all others are reflected. Therefore the spectrometer acts as an integrating high-energy pass filter. The relative sharpness of this filter is given by the ratio of the minimum 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

MC simulation of 1 year data taking



KATRIN phase I

- **Energy resolution 0.93 eV**
- **Tritium mass ~0.1mg**
- **10 mHz overall background rate**
- **first results 2011-2015**

KATRIN phase II

- **Energy resolution 0.2 eV**
- **spectrometer with larger diameter 7 m to 9 m**
- **larger diameter source vessel 7 cm to 9 cm.**
- **1 mHz overall background rate**
- **2015 ->**

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^{2}c)***
- ***NFW(MW) density assumption,***
- ***0.6 eV for the neutrino mass***
- ***we need 59(35) g of ^{2}T 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:

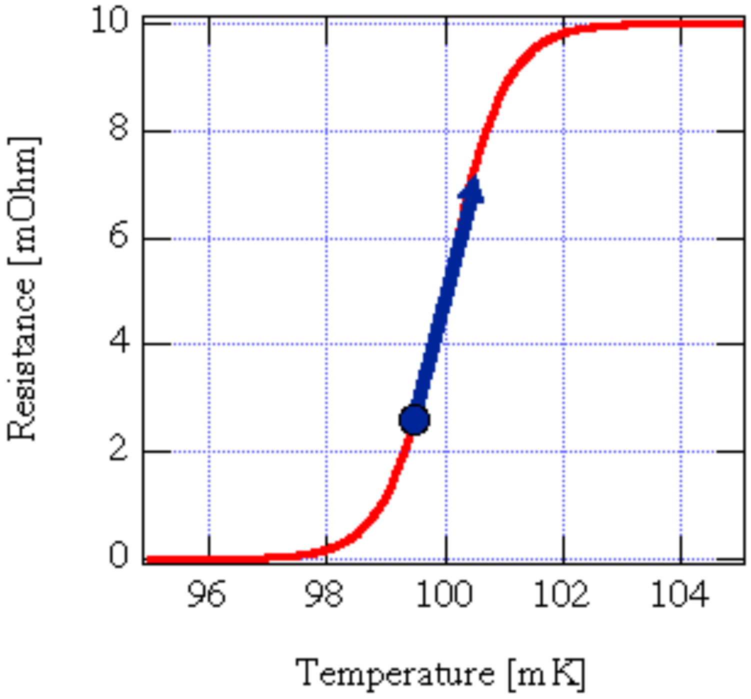
- ***Katrin sensitivity foreseen in the second experimental phase***
  0.2 eV energy resolution
  0. 1 mHz detector background rate (only 1 o.o.m. better than KATRIN has foreseen)
- ***the cross section value we calculated (7.7 10^{-45} cm^{2}c)***
- ***NFW(MW) density assumption,***
- ***0.6 eV for the neutrino mass***
- ***we need 16(10) g of ^{2}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: future experiment based on solid state technology aiming at direct measurement through the study of the ^{187}Re endpoint (Q_β =2.2 keV, $t_{1/2}$ =4.3 10^{10} y), by using micro-bolometers @ 10mK temperature)

The detector is based on the technology of micro bolometers made of ^{187}Re crystals read-out by high sensitivity resistor Transition Edge Resistor (TER):

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: $\Delta T = \frac{\Delta E}{C(T)}$



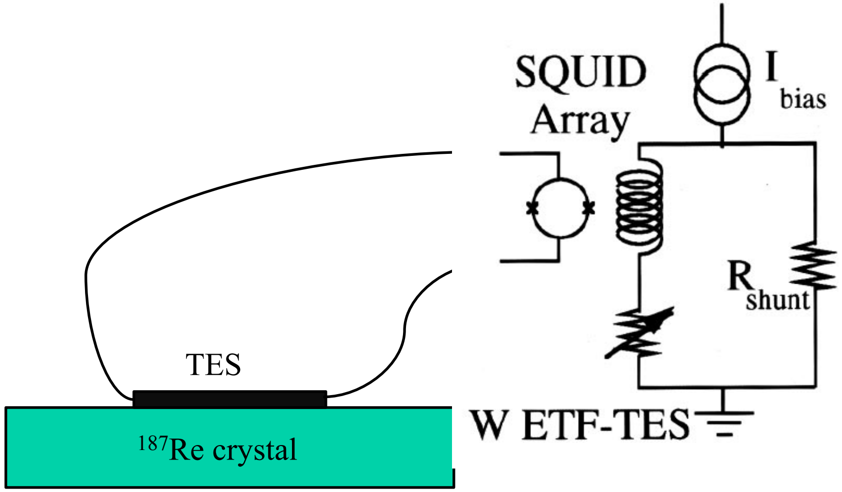
and subsequently an instantaneous TER resistance variation happen such that:

$$V(T) = i \cdot R(T)$$

and the current variation will be measured.

Another experimental solution to detect the CRN

schematic drawing of a bolometer



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

The MARE collaboration claims that they can achieve resolution of part of eV. This would mach 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.