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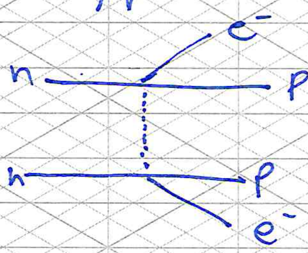
Direct measurement of the neutrino mass

In General

1) Cosmology : $\sum m_\nu < 1.0$ eV
(depending on included data)
~~from~~ [CMB data]

2) $0\nu\beta\beta$: Decay rate $\Gamma \propto \left|\sum U_{ei}^2 m_{\nu_i}\right|^2$
[coherent sum]



→ Majorana $\nu = \bar{\nu}$

3) Direct: – SN1987a TOF $m_\nu < 5.8$ eV (95% C.L.)
(model dependent)

– weak decay investigation

best limits (from direct measurements)

ν_e : from β-decay of T : $m(\nu_e) < 2.1$ eV (95% CL)
ν_μ : π^+-decay $m(\nu_\mu) < 170$ keV — " —
ν_τ : τ^- decay $m(\nu_\tau) < 15.5$ MeV — " —

better limits from $m(\nu_e)$ + Δm^2's

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β-decay ~~kinematics~~

$$\frac{dN}{dt\,dE} =$$

Fermi's Golden Rule : $\lambda_f = \frac{2\pi}{\hbar} |\mathcal{M}_{if}|^2 \rho_f$

density of final states, depends on electron energy E

→ β-spectrum for $m_\nu \neq 0$

$$\frac{dN}{dE} = \frac{g^2}{2\pi c^3 \hbar^7} |\mathcal{M}_{if}|^2 \cdot \underbrace{p_e \cdot (E + m_e) \sqrt{(E_0 - E)^2 - m_\nu^2}\,(E_0 - E)}_{\text{phase space factor [neglecting recoil]}} \cdot$$

$$\times F(Z, E)$$

Fermi function (electrostatic interaction)

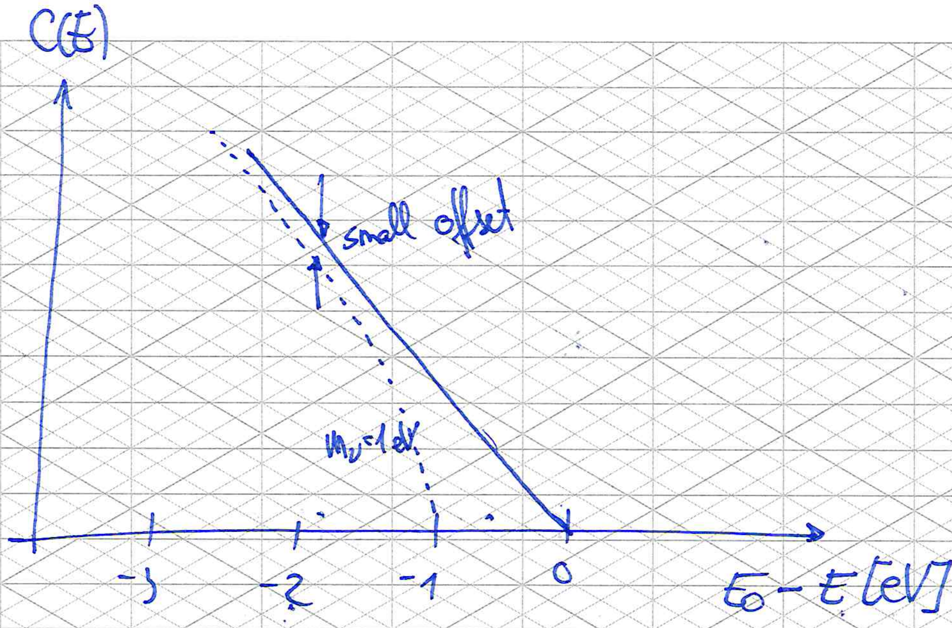
→ Curie plot $\quad C(E) = \sqrt{\frac{N(E)}{E^2 F(Z,E)}}$

$$\propto (E_0 - E) \cdot \sqrt[4]{1 - \left(\frac{m_\nu}{E_0 - E}\right)^2}$$

true for allowed decays

→ effect of m_ν visible for $E_0 - E \approx m_\nu$, i.e. close to the spectral end point.

→ changes spectral shape
↳ no exact knowledge of E_0 is needed!



Ideal Experiment

- high ~~res~~ energy resolution at endpoint
- large statistics : large source strength & acceptance
- low background in endpoint region
  → no pile up of low-E events

Candidate Isotopes

- Low endpoint → large ratio of decays in endpoint
  → better absolute energy resolution

$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$ $\quad E_0 = 18.6$ keV $\quad T_{1/2} = 12.3$ y $\quad$ super-allowed

source ≠ spectrometer

$^{187}Re \rightarrow {}^{187}Os + e^- + \bar{\nu}_e$ $\quad E_0 = 2.47$ keV $\quad T_{1/2} = 4.3 \cdot 10^{10}$ y

unique forbidden

source = spectrometer

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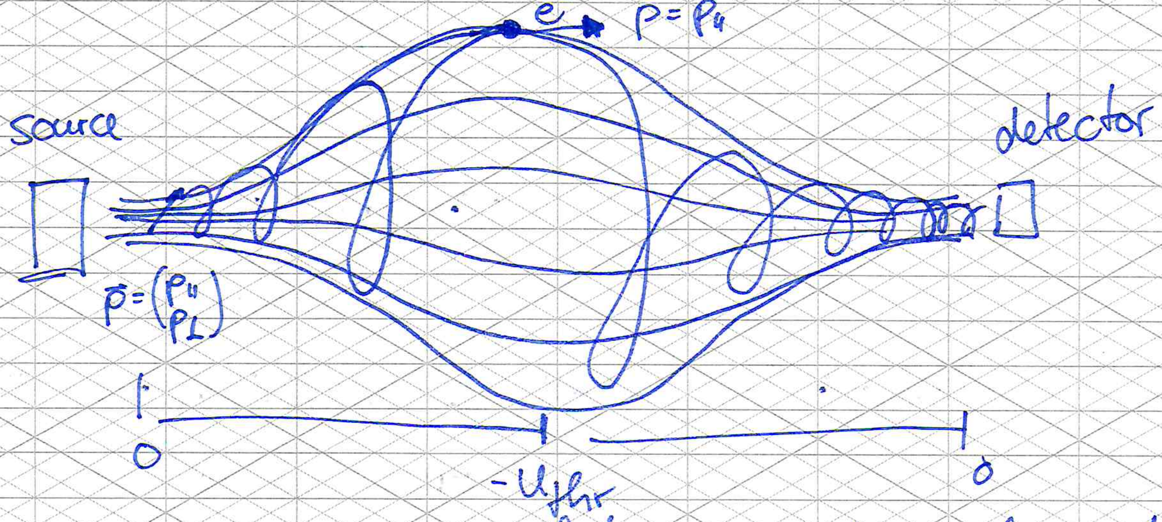
Tritium decay experiments : source + detector

· Source: ~~gaseous~~ T_2

- main concern : energy loss inside the source
  - → molecular T_2 gas in windowless source (Troitzk, KATRIN)
  - → thin cryogenic film (Mainz)
- $({}^3HeT)^+$ recoil : not an issue, since constant in endpoint region ~1.7 eV
- 1st electronic excitation > 35 eV → not dangerous
- rotational / vibrational excitations :
  width of 0.4 eV, partially compensated by recoil

· Spectrometer : MAC-E Filter

Magnetic Adiabatic Collimation with Electrostatic Filter



+ ~~superior~~ in high E resolution + luminosity
+ high angular acceptance — Penning traps

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- B-field converts all initial transverse momentum $p_\perp$ of electronics into parallel momentum $p_\parallel$
- E-field acts as high-pass filter for electrons of $E > e \cdot U_{thr}$
- by variation of U_{thr} → incremental measurement of spectrum → detector purely counting
- sharpness of filter depends of variation of B-field

$$\frac{\Delta E}{E} = \frac{B_{min}}{B_{max}} \longrightarrow \text{size does matter}$$

Current best limits on m_ν from Mainz + Troitzk (2.2 eV) 95% CL

KATRIN goal $m_\nu < 0.2$ eV

<u>Future</u> Project 8

- source: gaseous T_2. held by B-field
- electron energy measurement via cyclotron radiation

$$B = 1T,\ E_0 = 186\ \text{keV} \longrightarrow f_0 = \frac{q \cdot B}{2\pi(m_0 + E)} \approx 27\ \text{GHz}$$

→ Detection by radio antennae

$\cancel{\frac{mv^2}{2}} = q \cdot v \cdot B$

$v = \omega r$

$\frac{m \cdot v^2}{r} = m\omega^2 r = q \cdot B \cdot \omega \cdot r$

$\omega = \frac{q \cdot B}{m}$

for $\Delta E = 1$ eV

$\Delta f / f \approx \frac{\Delta E}{m} \approx 2 \cdot 10^{-6}$

Nyquist theorem: $t_{min} = \frac{2}{\Delta f} \approx 38\,\mu s$

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mean free path: $t_{min} \cdot \beta c = 3000\,m$

$\rightarrow$ max T_2 density $\rho_{max} \sim 10^{12}\,cm^{-3}$
to avoid inelastic scattering

Advantages: · different systematics
· good scalability

Rhenium decay experiments

- source: metallic Rhenium or ^{187}Re alloys,
e.g. $AgReO_4$

· source = detector:
advantage: calorimetric measurement of total (non-ν) energy released (cf. T source effects)

natural abundance of ^{187}Re: 63%
$\rightarrow$ no enrichment required

· ~~crystals of~~ detector type: Cryo-bolometers
$\rightarrow$ ~~electron~~ deposited energy heats up the bolometer $\Delta T = \frac{\Delta W}{C}$ ← heat capacity, should be small!

Debye model: $C \propto \underset{\uparrow \atop \#\,atoms}{N} k_B \cdot \Big(\frac{T}{\underset{\uparrow \atop \text{Debye-}T}{\Theta_D}}\Big)^3$

$\rightarrow$ small detectors @ ~~small~~ & low T provide best sensitivity

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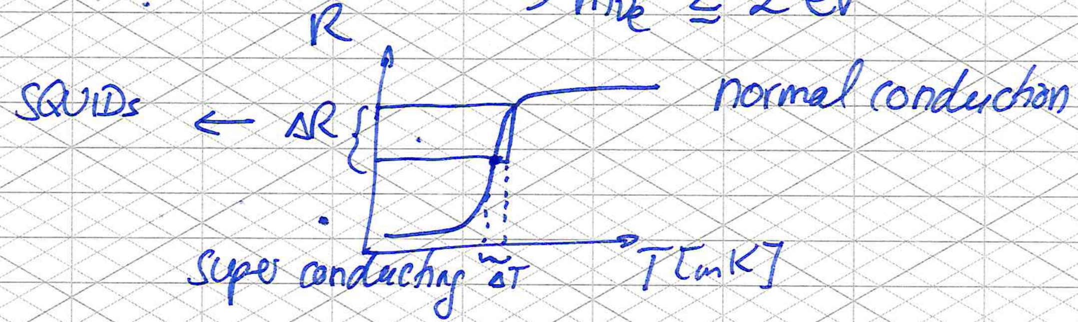
<u>problems</u> · low half-life → much ^{187}Re needed
· all low-E events included
· slow detectors → pile up
(O(100 μs) rise time)
→ array of small crystals / detectors

<u>Experiments</u>

neutron transmutation doped

· MANU (Genua): 1.6 mg metallic Re + NTD germanium detector
$m_{\nu_e} < 26$ eV (95% CL)
· MiBeta (Mailand): Array of 0.25–0.30 mg $AgReO_4$ absorbers
thermistor readout
$m_{\nu_e} < 15$ eV (90% CL)

· future MARE: few grams of Re, TES readout
→ $m_{\nu_e} \leq 2$ eV



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^{163}Ho EC experiments

$$^{163}Ho + e^- \to {}^{163}Dy_i^* + \nu_e \to {}^{163}Dy + E_i + \nu_e$$

(mostly x-rays) $Q \sim (2.3-2.8)$ keV

$$\dot{N}(E_C) = \frac{G_F^2 \cdot \cos^2\theta_C}{4\pi}(Q-E_C)\sqrt{(Q-E_C)^2 - m_\nu^2} \cdot \sum_i n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi} \cdot \frac{1}{(E_C-E_i)^2 + \Gamma_i^2/4}$$

Atomic levels: Breit-Wigner resonances, peak at E_i, width Γ_i

→ detection of X-rays : $m_\nu < 420$ eV

→ source = detector : calorimetric measurement of all energy released → ECHo

Advantages: – low $Q_i = 2.3-2.8$ keV

– short $T_{1/2} \sim 4570$ y

→ small sources directly coupled to detectors

Paper ref Drexlin, Hannen, Mertens, Weinheimer

arXiv 1307.0101