

Bounds on sterile neutrino using full kinematic reconstruction of radioactive decays

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New Instruments for Neutrino Relics and Mass
December 8, 2008 CERN

Outline

- 1 Implications for light sterile neutrino
- 2 Full kinematic reconstruction experiment
 - General consideration
 - Required precision and backgrounds
- 3 Existing experiments
 - ^{38m}K β decay
 - ^{37}Ar EC decay
- 4 Conclusions

Reading: [Behr, Gwinner, arXiv:0810.3942 \[nucl-ex\]](#)
[FB, Shaposhnikov, PRD,75,053005\(2007\)](#)

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Standard Model and neutrino masses

SM: gauge bosons: γ, W^\pm, Z, g ; Higgs boson H ;
 three matter generations: $L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, e_R; Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, d_R, u_R$

- Describes
 - ▶ all experiments dealing with electroweak and strong interactions
- Does not describe
 - ▶ Neutrino oscillations
 - ▶ Dark energy (Ω_Λ)
 - ▶ Dark matter (Ω_{DM})
 - ▶ Inflation
 - ▶ Baryon asymmetry
 - ▶ Gravity
- A lot can be explained by just adding three singlet neutrinos— ν MSM

Asaka, Shaposhnikov, 05

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Asaka, Shaposhnikov, 05

The scales for see-saw (ν MSSM)

The active neutrino masses m_ν are expressed from the Dirac masses m_D and singlet neutrino Majorana masses M by see-saw formula

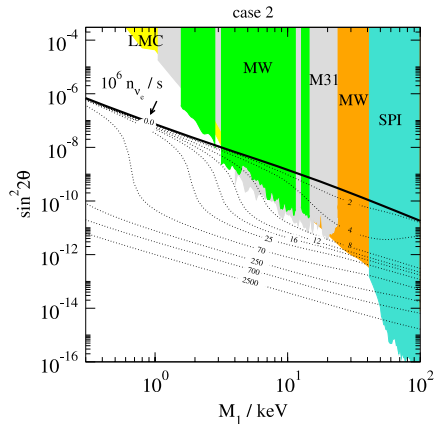
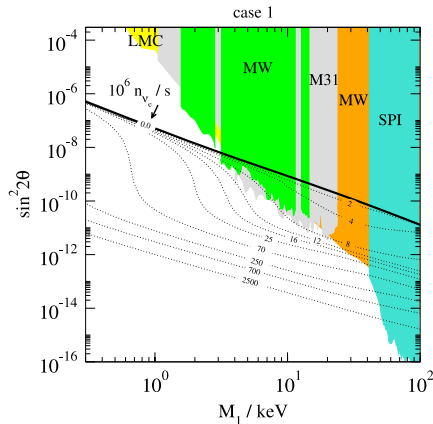
$$m_\nu = \frac{m_D}{M^2}$$

Two “natural” options:

- All the Yukawa couplings are of the same order.
Then the new energy scale is introduced for the singlet neutrinos,
 $M \sim 10^{10} - 10^{15}$ GeV.
- $M \sim$ SM scale, but the Yukawa couplings (or m_D) are very small

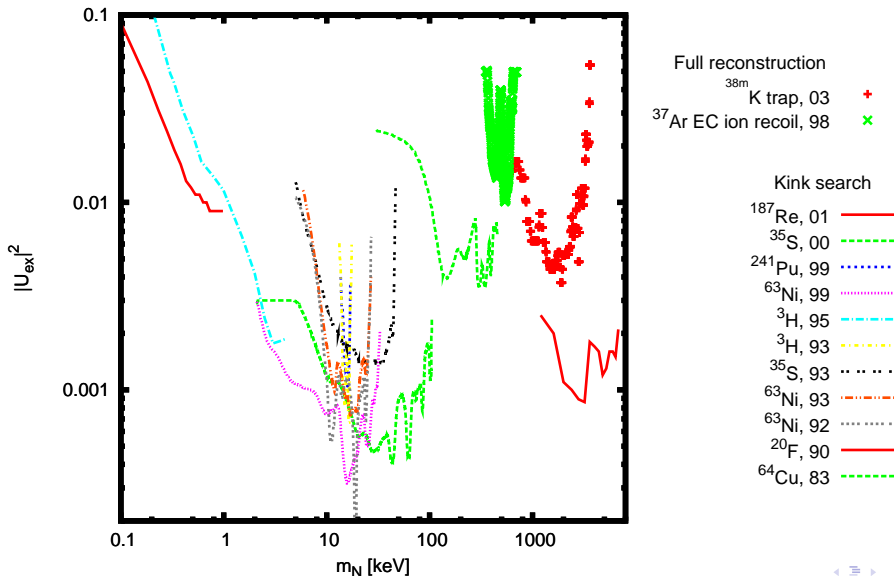
Sterile neutrino Dark Matter

2-50 keV sterile neutrino is a natural Warm Dark Matter candidate



Asaka, Shapohnikov 05; Laine, Shaposhnikov 08

Existing sterile ν bounds



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Possibilities of (light) sterile neutrino search

- *Creation* and *detection* in the lab
- Creation somewhere and *detection* in the lab
- *Creation* in the lab without subsequent detection

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Creation and detection

Suppressed by mixing angle θ^4

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X-ray experiments

Sterile N in the DM clouds decay by the channel $N \rightarrow \nu \gamma$ providing the X-ray line with $E_\gamma = M/2$.

Limit on θ^2 can be deduced as far as Ω_{DM} is known

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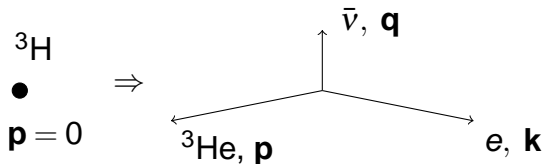
- ▶ Forbidden decays
- ▶ Decay kinematics

Partial kinematics kink search in electron beta decay spectrum.

- ★ Large statistics to see the effect (\sqrt{N} statistical error)
- ★ Excellent theoretical knowledge of the decay spectrum is needed (c.f. 17 keV neutrino “discovery”)

Full kinematics event-by-event mass measurement!

Beta decay kinematics



Neutrino mass is reconstructed from observed momenta

$$m_{\bar{\nu}}^2 = (Q - E_p^{\text{kin}} - E_e^{\text{kin}})^2 - (\mathbf{p} + \mathbf{k})^2$$

For ${}^3\text{H}$: $Q = 18.591 \text{ keV}$

- Typical ion energy $E_p^{\text{kin}} \sim 1 \text{ eV}$ or $|\mathbf{p}| \sim 100 \text{ keV}$
- Typical electron energy $E_e^{\text{kin}} \sim 10 \text{ keV}$

Possible experimental setup

- Cold and compact ^3H source
- Time of flight measurement of the recoil ^3He ion, using position sensitive detector for 3d momentum reconstruction
- Electron momentum measurement
 - ▶ Time of flight
 - ★ Needs decay moment trigger—Lyman photon from the excited ^3He ion ($\sim 25\%$ of the decays)?
 - ▶ Spectrometer for the electron energy measurement
 - ★ Electron itself can be used to determine the decay moment.

Required precision of momentum measurement

- To measure $m_\nu \sim \text{keV}$ one needs precision in momentum $\Delta\mathbf{p}, \Delta\mathbf{k} \sim \text{keV}$.
- For ${}^3\text{H}$ decay this means precision $\frac{\Delta p}{p} \sim 1\%$
- For other isotopes $\frac{\Delta p}{p} \sim \frac{\Delta p}{\sqrt{m_e Q}}$
Isotopes with higher energy release Q require better momentum measurement

Thermal noise

Nonzero thermal velocity $\langle \mathbf{v}^2 \rangle = 3T/M$ of the decaying atom imitates some nonzero neutrino mass in usual beta decays

$$m_{\nu}^{\text{eff}2} \simeq m_{\nu}^2 + M^2 \mathbf{v}^2 - 2M\mathbf{v}(\mathbf{p} + \mathbf{k})$$

Temperature constraint

$$T \lesssim \frac{0.7 \times 10^{-3}}{\log(1/\theta^2)} \left(\frac{m_s}{1 \text{ keV}} \right)^4 \left(\frac{6 \text{ GeV}}{M} \right) \left(\frac{18.6 \text{ keV}}{Q} \right)^2 (1 \text{ K})$$

“slow” neutrino cut $(\mathbf{p} + \mathbf{k})^2 \lesssim 3MT$ reduces the constraint

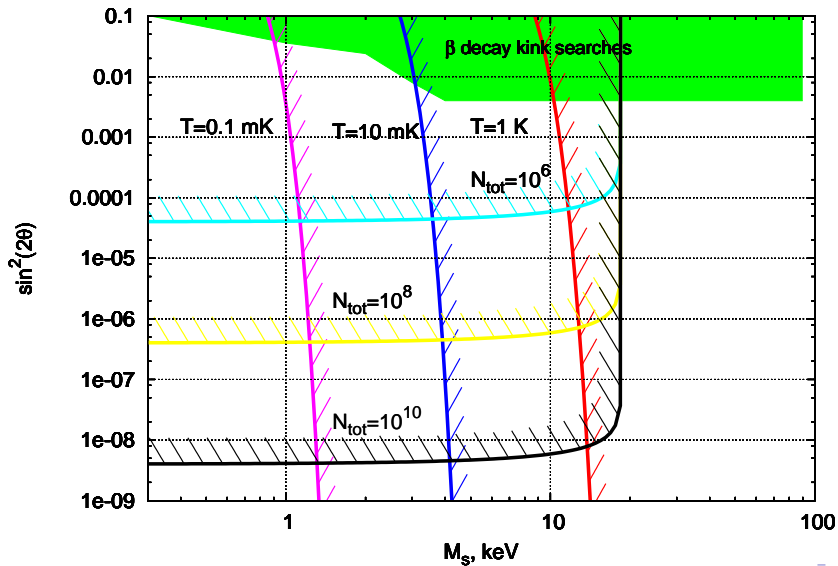
$$T \lesssim \frac{1}{\log(1/\theta^2)} \left(\frac{m_s}{1 \text{ keV}} \right)^2 \left(\frac{6 \text{ GeV}}{M} \right) (1 \text{ K})$$

and luminosity... $T \sim 1 \text{ K}$ $Br(\mathbf{p} + \mathbf{k} < 1 \text{ keV}) \sim 3 \times 10^{-4}$
 $T \sim 0.01 \text{ K}$ $Br(\mathbf{p} + \mathbf{k} < 0.1 \text{ keV}) \sim 3 \times 10^{-7}$

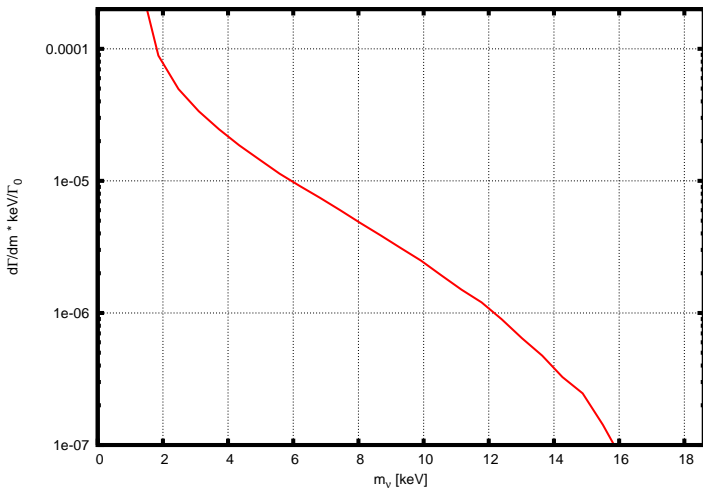
Existing cooling techniques

- Supersonic jets
 - ▶ $T \sim 0.1$ K, density $10^{11} - 10^{12} \text{ cm}^{-3}$ (10^{15} cm^{-3} ?)
- Magnetic trapping of decelerated supersonic jet of H atoms,
 $T \sim 0.1$ K
Hogan et al., PRL101,143001(2008)
- Single-photon atomic cooling
Price et al., PRL100,093004(2008)
 1.5×10^5 of ^{87}Rb atoms in an optical trap
 $100 \mu\text{m} \times 100 \mu\text{m} \times 130 \mu\text{m}$ at $7 \mu\text{K}$
Cooling of H is promised

Optimistic prospects (zero background)



Background from radiative decay ${}^3\text{H} \rightarrow {}^3\text{He} + e + \bar{\nu}_e + \gamma$



$$N(E_\gamma > 1 \text{ keV})/N_{total} \sim 4 \times 10^{-5}$$

Other backgrounds

- Tritium molecule dissociation
 - ▶ Should not be a major problem—very large momentum distortion
- Scattering in the source

Possible variations of the experimental setup:

- Other isotopes
 - ▶ Easier to capture, shorter lifetime
- Electron capture instead of beta decay
 - ▶ 2-body kinematics

Other backgrounds

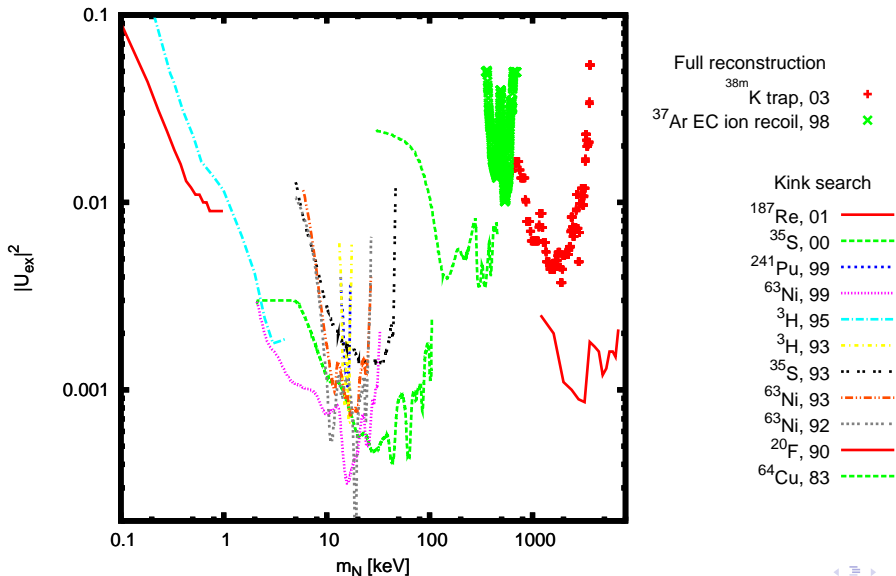
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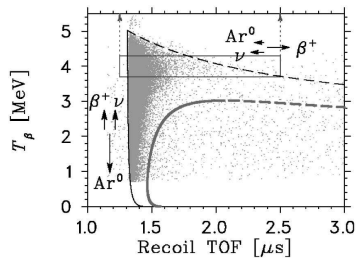
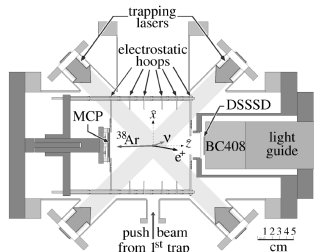
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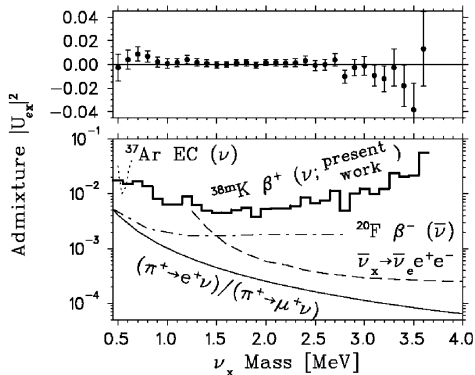
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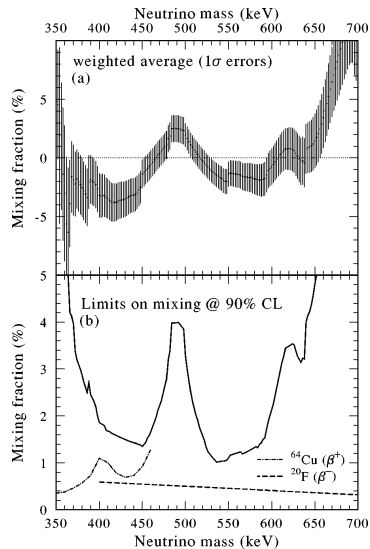
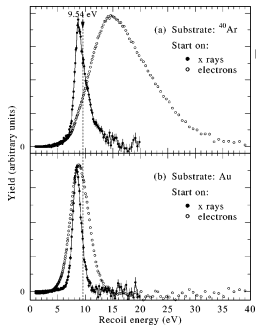
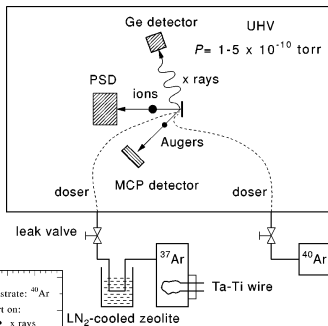


TRIUMF, Canada



Trinczek et al., PRL90(2003)012501

^{37}Ar EC decay



Hindi et al., PRC58(1998)2512

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- For light sterile neutrino isotopes with small decay energy and small mass are good — 3H
- Detailed study of these type of experiments is needed!
- Excellent experimental techniques exist and are constantly improving!

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