Possibilities for terrestrial detection of kev-mass ‘sterile’ neutrinos

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Brief review of

Direct detection of sterile $\nu$ dark matter
  • Inverse beta decay
  • electron scattering

Detecting rare sterile $\nu$ events in beta decay
  • End point of Tritium beta spectrum
  • $\nu$ mass reconstruction in K-capture events
Galactic dark matter may be keV-mass sterile neutrinos

(1) Existing neutrino family looks incomplete

text book list of weak couplings to Z boson show missing RH ν current (and LH $\overline{ν}$)

leptons

$$g_L^\nu \overline{ν}_e γ_μ (1 - γ_5) ν_e$$

$$g_L^e \overline{e}_μ γ_μ (1 - γ_5) e + g_R^e \overline{e}_μ γ_μ (1 + γ_5) e$$

quarks

$$g_L^u \overline{u}_μ γ_μ (1 - γ_5) u + g_R^u \overline{u}_μ γ_μ (1 + γ_5) u$$

$$g_L^d \overline{d}_μ γ_μ (1 - γ_5) d + g_R^d \overline{d}_μ γ_μ (1 + γ_5) d$$

(2) Theoretical studies for > 20 years show keV-mass $ν_s$ is a convincing DM candidate

1994: Dodelson & Widrow, propose $\sim 30 – 300$ eV sterile ν as dark matter

1999: Shi & Fuller propose $0.1 – 10$ keV sterile ν as dark matter

2000 – 2010: > 40 papers & reviews confirming that a keV-mass sterile ν matches DM requirements

(3) Possible galactic 3.5 X-ray signal could be decaying 7 keV $ν_s$

2014 Boyarsky et al, Bulbul et al

$sin^2 2θ \sim 10^{-10}$ if 100% DM

$sin^2 2θ \sim 10^{-9}$ if 10% DM
Direct detection of dark matter sterile neutrinos by inverse beta decay?

Example:
normal $\beta$ decay $^3\text{H} \rightarrow ^3\text{He}^+ + e^- + \nu$
implies inverse $\bar{\nu_s} + ^3\text{H} \rightarrow ^3\text{He} + e^-$

Would give events beyond the $\beta$ decay end point separated by an energy $m_{\nu_s}$

Proposed 30 years ago to detect relic neutrino background, but needed large tritium target (now aim of PTOLEMY)
Same principle would detect sterile $\nu$ dark matter

For 7 keV, Li & Xing PLB2011 find 10 events/year
for 10 kg $^3\text{H}$ ($t_{1/2} = 12\text{y}$)
or 1 ton $^{106}\text{Ru}$ ($t_{1/2} = 1\text{y}$) needs replenishment!

Must be in the form of gas or surface layers to detect the electrons. Not feasible in near future.

Li & Xing: “may not be hopeless in the long run”
Direct detection of dark matter sterile neutrinos by electron scattering?

\[ \nu_s \]

Sufficient energy transfer to produce ionization

But for \( m_s \sim 7 \text{ keV} \), coupling \( \sim 10^{-9} \)

Rate \( \sim 1 \text{ event/year/kiloton} \) (inc \( Z^2 \) coherence)

Also \( \nu_s \) decay to X-ray

In an enclosure

Rate \( \sim 1 \text{ event/year/km}^3 \)
Distortion of beta spectrum by sterile neutrino admixture

Basis of attempts over 30 years to measure $\nu$ mass* by its effect on the end point of a beta spectrum.

(*nowadays $\nu_e \equiv \text{sum over three mass eigenstates} \)
Possible future limits from KATRIN

KATRIN high resolution spectrometer 70m x 10m
Aims to measure sub-eV $\nu$ mass from end-point

KATRIN also analyzing spectrum for admixture of sterile $\nu$ events.

(a) 3-year mixing limit $10^{-7}$-$10^{-8}$ for design T source.
(b) Future limit $10^{-9}$ (3y) achievable with 10x source.
(c) Thus $10^{-10}$ (3y) achievable with 100x source.
Detection of sterile $\nu$ in beta decay by total energy-momentum reconstruction

Beta decay with electron emission

$$m_\nu^2 = [Q - E_e - E_\gamma - E_N]^2 - \left[ p_\gamma + p_e + p_N \right]^2$$

Beta decay by K-capture

$$m_\nu^2 = [Q - E_a - E_\gamma - E_N]^2 - \left[ p_\gamma + p_{ea} + p_N \right]^2$$

Recent studies show this may now be feasible.
Not a new idea - suggested for over 20 years.
but reaching masses < 100 keV and < $10^{-4}$ mixing is very difficult (‘challenging’)

**1992**

Proposed $^3$H decay reconstruction for 17 keV neutrino with mixing $\sim 10^{-2}$

**1998**

Used $^{37}$Ar K-capture reconstruction to set limit $\sim 10^{-2}$ at 300-600 keV

**2003**

Used $^{38m}$K decay reconstruction to set limit $\sim 10^{-2}$ at 0.7-3.5 MeV

**2007**

Discussion of $^3$H decay reconstruction for keV masses & mixing $< 10^{-6}$
COLTRIMS – COLd Target Recoil Ion Mass Spectroscopy

Used extensively for 20 years for 3-D studies of atom-atom and photon atom collisions

- time of flight precision 200 ps
- spatial precision (MCP) 40 µm

(supplied by Roentdek, Germany)

MOT - Magneto-Optical Trap

Developed for over 20 years for Cooling and suspension of neutral atoms

- No of trapped atoms: $10^8 - 10^{12}$
- effective temperature: 10 - 100 µK

(supplied by Roentdek, Germany)
Trapped atoms

Laser beam

MCP array for recoil ion

Position sensitive X-ray & Auger detector arrays

Trigger X-ray

MCP array for recoil ion

Trapped atoms

Laser beam 3

Mu metal magnetic screen

3m

Basic geometry for 3-D time-of-flight measurements
Some backgrounds

- Cosmic ray muons
- Residual gas scatters
- Radioactivity & untrapped atoms

Reject by real time tests - most self-vetoing:
- Signals not in correct time window
- Signal pulses wrong size or shape
- X-Ray triggers not followed by Augers in 200ns
- Mass reconstruction $m_{\nu}^2 = [Q - E_e - E_\gamma - E_N]^2 - [p_\gamma + p_e + p_N]^2$ negative or wrong magnitude

Backgrounds found tolerable in published MOT atomic experiments
Requirements to reach mass and coupling levels of the X-ray signal?

- need > 6 sigma separation of signal from zero mass peak
- kinematic simulations show possible with ± 0.2 ns timing and ± 0.1 degrees X-ray direction

feasible in principle

- needs $10^{11}$ reconstructed decays/y for 5-10 events/y
- analysis of 3000 events/s – achieved in COLTRIMS expts
- fast decaying isotope: eg Cs131 ($t_{1/2}=10$ days) good for MOT
$^{131}$Cs K-capture has $Q = 352$ keV - allows sterile mass range $5 - 350$ keV
Event timelines – no overlapping

- find trigger with matching Auger and ion signals
- wait for completion of event before searching for next matching set

Decays
- 1.5\(\mu\)s average decay interval

X-ray trigger
- 15\(\mu\)s average trigger interval
- 0.2\(\mu\)s

Auger electrons
- 200\(\mu\)s

Recoil ion
- average 300\(\mu\)s

(shown timescales not linear)
Faster processing with overlapping events

- search for overlapping events by matching corresponding Auger and ion signals
- BUT majority of events are incomplete (Auger and/or ion signals missing)
- thus overlap allows more analyzed events/year, but software analysis complex

Decays

X-ray trigger

0.2μs

Auger electrons

200μs

Recoil ion

(shown timescales not linear)
Proposal submitted based on Cs131:

CACHE (Cesium Atomic-electron Capture with Heavy neutrino Emission)

C J Martoff, J Napolitano (Temple) E R Hudson, H Wang, P F Smith (UCLA)
A Renshaw (Houston), G M Fuller (UCSD, theory), E Grohs (Michigan, theory)

Smaller-scale phase 1 experiment
confirming mass reconstruction & background rejection

Initial objectives
• 100 processed events/h
• coupling sensitivity $\sim 10^{-6}$ in 400d running
• mass sensitivity $\sim 30$-300 keV

Could be upgraded to a fully instrumented phase 2
reaching sensitivity $< 10^{-10}$ and 7 keV mass
K-capture provides example of wave packet collapse and ‘EPR paradox’

$$\nu_e = c_{11}\nu_1 + c_{12}\nu_2 + c_{13}\nu_3 + c_{14}\nu_s + ?$$

different masses $\rightarrow$ different momenta and speed

Detection of recoil collapses combined wave function

Wave function collapse to sterile $\nu$
Summary

- keV mass sterile neutrinos are a strong dark matter candidate
- Detecting keV sterile neutrinos in the laboratory will be feasible
Auger electrons

- X-ray leaves another vacancy, producing a cascade of electron transitions, including Auger electron emission.

- Choice of N-shell X-ray as trigger gives only 1 or 2 Augers of 60-120 eV, whose momentum and direction must be measured.