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Signal of dark matter in beta decay experiment

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Warm dark matter:
keV scale right-handed neutrino(or sterile neutrino)

mixing with active neutrinos very small

Is it possible to detect this dark matter with small mixing?
Check more carefully the density of dark matter

Content

Content:

- keV scale ν_{R1} in low energy see-saw model
- keV scale ν_{R1} as dark matter candidate
- Local density of ν_{R1}
- ν_{R1} capture by radioactive nuclei
- Summary

keV scale ν_{R1} in low energy see-saw model

The see-saw mechanism

$$m_\nu = y^T M_R^{-1} y v^2$$

mixing:

$$\nu_{La} = \nu'_{La} + R_{a\alpha}\ \nu'^{c}_{R\alpha}$$
$$R = y^\dagger v (M_R^*)^{-1}$$

R: the mixing matrix

We usually assume R very small
if M_R very heavy ($\gtrsim 10^{13}$ GeV), yv of electro-weak scale
if M_R of electro-weak scale, $y \sim 10^{-7}$

keV scale ν_{R1} in low energy see-saw model

In general

$$\begin{aligned} yv &= M_R^{1/2} O m_\nu^{1/2} \\ (yv)^T M_R^{-1} yv &= (m_\nu^{1/2})^T O^T (M_R^{1/2})^T M_R^{-1} M_R^{1/2} O m_\nu^{1/2} \\ &= (m_\nu^{1/2})^T O^T O m_\nu^{1/2} = m_\nu \end{aligned}$$

O, a complex rotation matrix: $O^T O = O O^T = 1$.

$$R = (m_\nu^\dagger)^{1/2} O^\dagger (M_R^*)^{-1/2}$$

Mixing R can be enhanced by large elements of O
Fine tuning unavoidable

keV scale ν_{R1} in low energy see-saw model

A low energy see-saw model(keV scale ν_{R1} and GeV scale $\nu_{R2,3}$) (Asaka, Blanchet and Shaposhnikov, 2005)

Decay of ν_{R1} mainly through $\nu_{R1} \rightarrow \nu + 2\bar{\nu}, 2\nu + \bar{\nu}$:

$$\tau_{\nu_{R1}} = 5. \times 10^{26} s \left(\frac{1\mathrm{keV}}{M_{R1}} \right)^5 \frac{10^{-8}}{\Theta^2}$$

$\Theta^2 = |R_{e1}|^2 + |R_{\mu 1}|^2 + |R_{\tau 1}|^2$.
$\tau_{\nu_{R1}}$ much larger than the age of the universe $\sim 10^{17}$s

ν_{R1} can be a dark matter candidate

keV scale ν_{R1} as dark matter

ν_{R1} dark matter can be produced in the early universe

- either through mixing with active neutrinos
  with resonance when enough lepton asymmetry is present
- or through the decay of a singlet S: $S \rightarrow \nu_{R1}\nu_{R1}$
  (Shaposhnikov and Tkachev, 2006; Kusenko, 2006)

$$\Delta L = \frac{f_\alpha}{2} S \bar{\nu}_{R\alpha} \nu^c_{R\alpha} + h.c. + V(S, H)$$

$< S >$ gives mass to ν_R
S in thermal equilibrium but ν_{R1} is not

keV scale ν_{R1} as dark matter

Major constraints on this model of dark matter comes from

- Production of $\rho_{\nu_{R1}}$ in the right range of Ω_{dm}
- Satellite X-ray observation on the decay line of $\nu_{R1} \rightarrow \nu + \gamma$
- Lyman-α forest constraints

Recent analysis show(Boyarskya et.al., 2009):
keV scale ν_{R1} with $|R_{a1}|^2 \lesssim 10^{-7} - 10^{-8}$ passes these constraints

Local density of ν_{R1}

One may wonder detection of background ν_{R1} is very difficult because of the very small mixing R_{a1}.

Note that
the number density of ν_{R1} is enhanced by its small mass

Taking the estimate of the galactic value of ρ_{dm} in the solar system

$$\nu_{\nu_{R1}} = 10^5 \ \mathrm{cm}^{-3} \frac{\rho_{dm}}{0.3\mathrm{GeV} \ \mathrm{cm}^{-3}} \frac{3\mathrm{keV}}{M_{R1}}$$

Local density of ν_{R1}

In simulation of structure formation

- there are sub-structures in galactic halo;
- sub-halos (even satellite galaxies, in contradiction to observation) predicted in some simulations of ΛCDM model;
- warm dark matter has larger velocity dispersion than cold dark matter at the time of matter-radiation equality and leads to less sub-structures in simulation(Colin et al., APJ, 2000);
- we might stay in a sub-halo of dark matter in which local dark matter density can be much larger than the galactic average value.

Local density of ν_{R1}

$n_{\nu_{R1}}$ much larger if the solar system in a sub-halo of dark matter

A dark matter distribution in the solar system can modify the universal Kepler's third law of planetary motion

$$\frac{T^2}{a^3} = \frac{(2\pi)^2}{GM}$$

Astronomical constraint (J.-M. Frere et.al., 2008):

$$\rho_{dm} \lesssim 10^5 \ \mathrm{GeV\ cm}^{-3}$$

It means $n_{\nu_{R1}} \lesssim 10^{11}$ cm^{-3} for keV scale ν_{R1}

ν_{R1} capture by radioactive nuclei

Capture of ν_{R1} on radioactive nuclei produce mono-energetic electron well beyond the end point of beta decay spectrum

$$E_e = Q_\beta + m_{\nu_{R1}}$$

Signal is clear, easy to discriminate

Although the cross section suppressed by $|R_{e1}|^2$
event rate enhanced by the large $n_{\nu_{R1}}$ and hence the flux of ν_{R1}.
On Tritium

$$N \approx 7.1\ \mathrm{year}^{-1} \times \frac{n_{\nu_{R1}}}{10^8 cm^{-3}} \frac{|R_{e1}|^2}{10^{-8}} \frac{{}^3\mathrm{H}}{10\ \mathrm{kg}}$$

ν_{R1} capture by radioactive nuclei

On ^{106}Ru target the capture rate is

$$N \approx 1.6 \text{ year}^{-1} \times \frac{n_{\nu_{R1}}}{10^8 cm^{-3}} \frac{|R_{e1}|^2}{10^{-8}} \frac{^{106}\mathrm{Ru}}{100 \text{ kg}}$$

Background caused by solar pp neutrinos with energy $\lesssim$ 10keV:

$$\sim 4.0 \times 10^{-3} \text{year}^{-1} \quad \text{for 10 kg } ^3\mathrm{H}$$
$$\sim 8.5 \times 10^{-4} \text{year}^{-1} \quad \text{for 100 kg } ^{106}\mathrm{Ru}$$

solar neutrino background can be neglected.

Summary

Possible to detect of keV scale ν_{R1} dark matter in β decay experiment

- Number density of keV scale ν_{R1} can be large if we live in a sub-halo of dark matter
- The suppression in cross section caused by small mixing is compensated by the large number density of ν_{R1}.
- Capture of ν_{R1} give mono-energetic electron well beyond the end point of the beta decay spectrum; signal very clear
- Event rate of capture can reach a few events per year for 10kg Tritium or 100kg ^{106}Ru if we live in a sub-halo