

A NOTE ON THE NEUTRINO DECAY LINE AND
THE POSSIBILITIES OF ITS DETECTION

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When talking about spectral line shapes and intensities, one usually envisages some plasma similar to those produced in a laboratory, or existing in a natural environment. It is more than often completely disregarded that spectral lines can occur in a seemingly non-plasmatic part of physics – elementary particle physics.

The purpose of this contribution is to propose and discuss some mathematically simple but physically important results concerning the neutrino line and the possibilities of its detection. The cosmological importance of neutrinos stems from the fact that massive neutrinos may be the solution to the dark matter problem in the Universe (discussed in Frampton and Vogel, 1982; Sciama, 1993; Gelmini and Roulet, 1994, and numerous other publications). Outside cosmology, neutrinos are useful as probes of solar and stellar internal structure (for example, Hirata *et al.*, 1987; Burrows, 1990; Bahcall, 1994; Petcov, 1995) and stellar evolution (Castellani and Degl'Innocenti, 1993). Various kinds of interactions in which neutrinos participate can give rise to different spectral lines. The predicted wavelengths depend on the supposed neutrino masses.

The modern particle physics theory allows that neutrinos could have rest masses different from zero (Zeldovich and Hlopov, 1981). There are three neutrino types : ν_e , ν_μ and ν_τ , i.e. the number of types is equal to : $N_\nu = 3.00 \pm 0.04$ (Ting, 1993). The upper limit for their masses based upon earth based experiments are :

$$m_{\nu_e} < o(10 \text{ eV}),$$

$$m_{\nu_\mu} < 160 \text{ KeV}$$

and

$$m_{\nu_\tau} < 31 \text{ MeV.}$$

(Gelmini and Roulet, 1994).

The hot big-bang cosmology sets the upper limit to the total neutrino mass (Klinkhamer and Norman, 1981) :

$$\sum_i m_{\nu_i} < 100 \text{ eV}.$$

Neutrino mass plays the central role in the Sciama's (1993) decaying dark matter (DDM) model as well as in cold + hot dark matter ($C\nu^2\text{DM}$) model created by Primack, Holtzman, Klypin and Caldwell (1995).

Neutrinos were relativistic at the decoupling and their present density for each neutrino type is :

$$n_{\nu} = 112 \text{ cm}^{-3}$$

(Sciama, 1993).

The value of the neutrino mass for the type x , where $x = \nu, \mu, \tau$ can be expressed in the following form (see for example Schaeffer, 1994 and Samurović, 1995) :

$$m_{\nu_x} \sim 94h^2 \Omega_{\nu_x} \text{ eV} \quad (1)$$

where Ω_{ν_x} is the density parameter for the universe, and the estimations for its value are different in the different models. Hubble parameter, $h \equiv \frac{H_0}{100 \frac{\text{km/s}}{\text{Mpc}}}$ varies between 0.5 and 1, but it is possible that it is close to 0.5 in order not to get too small a value of the age of the universe.

Thus DDM model predicts $\Omega_{\nu_x} \sim 1$ and

$$m_{\nu_x} \sim 30 \text{ eV}$$

(Sciama, 1993). Here ν_x denotes most probably tau neutrino, ν_{τ} . Sciama (1993) found a lower limit for m_{ν} for the Milky Way :

$$m_{\nu} = 27.6 \pm 1 \text{ eV}.$$

Because of the fact that different neutrino types have different rest masses it is possible that the heavier neutrino decays into a lighter one. This process is followed by the emission of photons which produces observable ionization effects. Neutrino decay can be represented in the following form :

$$\nu_1 \rightarrow \nu_2 + \gamma.$$

We shall take that the more massive tau neutrino, ν_{τ} , decays into a photon and a muonic neutrino, ν_{μ} , where $m_{\nu_{\tau}} \gg m_{\nu_{\mu}}$:

$$\nu_{\tau} \rightarrow \nu_{\mu} + \gamma, \quad E_{\gamma} = \frac{1}{2}E_{\nu_{\tau}} = \frac{1}{2}m_{\nu_{\tau}}. \quad (2)$$

DDM theory (Sciama, 1993) gives the following value of this ratio $\frac{m_{\nu_{\mu}}}{m_{\nu_{\tau}}} \lesssim 0.2$. If we take that $E_{\nu_{\tau}} = 28 \text{ eV}$ we shall get the flux of 14 eV photons - this value exceeds a little the Lyman limit of 13.6 eV for the hydrogen ionizing energy. However, these emitted photons will be redshifted by cosmological expansion and, therefore, will be

able to ionize hydrogen near their point of origin. Also, self-absorption of the decay photons by the neutrinos can be ignored, because their energy will be below the one needed to initiate "the reverse action" of the type $\nu_\mu + \gamma \rightarrow \nu_\tau$ (OWB).

Due to the similarity of their ionization potentials, wherever hydrogen is ionized, nitrogen is also ionized. It can be shown (Sciama, 1993a) that :

$$14.53 < E_\gamma < 14.68 \text{ eV.}$$

The upper limit for the value of the decaying photon energy follows from the requirement that these photons are the solution of the C^0/CO ratio problem.

Thus one obtains that

$$E_\gamma = 14.605 \pm 0.075 \text{ eV}$$

(Sciama, 1993a). This would give, according to equation (2) the following value for the tau neutrino mass :

$$m_{\nu_\tau} = 29.21 \pm 0.15 \text{ eV}$$

(Sciama, 1993a).

Under the assumption that the dark halo of the Galaxy consists mainly of massive neutrinos, Melott and Sciama (1981) and Sciama (1993) found that the neutrino decay will give the following limit for the neutrino lifetime :

$$\tau \geq 10^{23} \left(\frac{T}{10^4} \right)^{\frac{3}{2}} \left(\frac{0.6 \text{ cm}^{-3}}{n_e} \right)^2 \left(\frac{1 \text{ kpc}}{d} \right) \left(\frac{0.05 \text{ rad}}{\varphi} \right) \left(\frac{30 \text{ eV}}{m_\nu} \right) N$$

where τ is expressed in seconds. T is the cloud temperature, n_e its electron density, d its distance, φ its angular radius and N is the average number of ionizations caused by a given photon. From this equation one can see that lifetime τ ranges from 10^{23} to 10^{24} s.

One can establish an equation that connects the lifetime τ and transition magnetic moment μ_{12} under the assumption $\frac{m_{\nu\mu}}{m_{\nu\tau}} \ll 1$ (Sciama, 1993) :

$$\tau = 10^{23} \left(\frac{30 \text{ eV}}{m_1} \right)^3 \left(\frac{10^{-14} \mu_B}{\mu_{12}} \right)^2 \text{ s}$$

where the Bohr magneton $\mu_B = \frac{eh}{2m_e c}$. For $m_1 = m_{\nu_\tau} \sim 30 \text{ eV}$ and $\mu_{12} \sim 10^{-14} \mu_B$ one would obtain the lifetime $\tau \sim 10^{23}$ s. Castellani and Degl'Innocenti (1993) considered the effect of a nonvanishing neutrino magnetic moment on the stellar evolution and obtained the upper limit $\mu_{12} < 10^{-12} \mu_B$ which points out that the estimated value for the neutrino lifetime τ is possible.

Although Hopkins Ultraviolet Telescope during its observations of the cluster A655 did not detect the line of the decay photon with energy E_γ that ranges between 14.5 and 15 eV (Sciama, 1993) it is quite possible that the dark matter in the center of this cluster is partly baryonic (Ashman, 1992). In this case the strength of the neutrino decay line is less than the one predicted by the fact that *all* the dark matter in the cluster is made of decaying neutrinos (Ashman, 1992). In this cluster there could be significant amounts of neutrinos (Sciama, 1993).

However, Reimers and Vogel (1993) detected HeI resonance lines in four high-redshift Lyman limit systems of the QSO HS 1700+6416 ($z=2.72$). They found neutral hydrogen to neutral helium column density ratios $\frac{N_{\text{HI}}}{N_{\text{HeI}}} \approx 30$. According to their analysis HeI column densities are ~ 5 times greater than column densities obtained by their model calculations. The fact that effective hydrogen ionizing flux is ~ 8 times greater than helium ionizing flux may be the consequence of the feature of the DDM theory, according to which decay photons can ionize hydrogen but not helium (Sciama, 1994).

According to $C\nu^2$ DM theory proposed by Primack, Holtzman, Klypin and Caldwell (1995) that uses cold + hot dark matter (CHDM) requirement that a total neutrino mass ~ 5 eV, suggests that masses of mu and tau neutrinos are approximately equal i.e. $m_{\nu_\mu} \approx m_{\nu_\tau} \approx 2.4$ eV. It is worth noting that this value is obtained from equation (1), but the density parameter is taken to be $\Omega_\nu \sim 0.3$ and the Hubble parameter is again $h \sim 0.5$.

We discuss the simple case of the radiative decay of these light neutrinos. The obvious relation :

$$m_\nu c^2 = h \frac{c}{\lambda}$$

gives

$$\lambda = \frac{h}{m_\nu c}$$

for the wavelength of the spectral line emitted in the process. When we insert the appropriate numerical values, we obtain :

$$\lambda_{\text{nm}} = \frac{1239.85}{m_\nu[\text{eV}]}$$

For $m_\nu = 2.4$ eV, we obtain $\lambda = 516.6$ nm.

Another spectroscopically interesting question is the shape of this line. As cross sections for neutrino interactions with matter are very low, it can safely be assumed that the line is very nearly monochromatic, i.e., that it only has the natural width. Its value can be simply estimated from the uncertainty principle as :

$$\Delta\lambda = \frac{\lambda^2}{2\pi c\tau}$$

which tends to 0 due to huge values of τ .

The order of magnitude estimates of the neutrino decay line wavelength and its natural width are presented in the Table 1.

Table 1

Neutrino type	m_ν	λ [nm]
e	10 eV	123.985
μ	150 KeV	0.0083
τ	30 MeV	4.1×10^{-5}

It can be concluded that the line is monochromatic. As for the wavelengths, the only one which could be experimentally detected is the line originating in the radiative decay of ν_e . The precise value of the wavelength depends (obviously) on the mass; if $m_\nu \approx 2.4$ eV, as in the $C\nu^2DM$ theory, $\lambda = 516.6$ nm. The line intensity is a function of the concentration of the decaying neutrinos; the precise form of this dependence remains a problem for further study. It has very recently been shown (Vassilevskaya, Gvozdev and Mikheev, 1995) that the probability of a radiative decay of a massive neutrino can greatly increase in strong electromagnetic fields. Under certain conditions, the increase can be as large as 10^{33} times! This renders the detection of the neutrino decay line much easier in the case of astronomical objects in whose vicinity exist strong electromagnetic fields.

A word about cosmological neutrinos. A neutrino decaying in an astronomical object having redshift z would give a line with

$$\lambda = \frac{h}{m_\nu c}(1+z)$$

which could be important in case of QSOs, for example.

1. CONCLUSION

The object of this note is the spectral line due to the radiative decay of a massive neutrino. We have calculated the wavelength and the natural width of the line as a function of the mass and lifetime of the neutrino having $m_\nu \lesssim 10$ eV. Several observational consequences of this process were discussed. The newly discovered enhancement of the decay rate in strong electromagnetic fields renders the analysis of the neutrino decay line important even for observational astronomers.

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