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The Present Status of the Decaying Neutrino Theory [and Discussion]

D. W. Sciama and A. W. Wolfendale

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The present status of the decaying neutrino theory

By D. W. Sciama

International School for Advanced Studies (SISSA), and International Centre for Theoretical Physics, Strada Costiera 11, 34014 Trieste, Italy

The present status of the decaying neutrino theory is reviewed. Three recent developments are highlighted: (*a*) the proposal that the dark matter in rich clusters of galaxies is mainly baryonic; (*b*) the implications of the hypothesis that decay photons are the solution of the C^0/CO ratio problem; (*c*) the strong supporting evidence from recent observations with the Hubble space telescope.

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1. The decaying neutrino theory

If neutrinos have non-zero rest mass one would expect a more massive neutrino type ν_1 to decay into a photon and a less massive neutrino type ν_2:

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

Conservation of energy and momentum in the decay tells us that the energy E_γ of the photon in the rest frame of ν_1 is given by

$$E_\gamma = \tfrac{1}{2}m_1(1 - m_2^2/m_1^2).$$

It is very likely that $m_2^2/m_1^2 \ll 1$. In that case we would have the result

$$E_\gamma = \tfrac{1}{2}m_1.$$

Cowsik (1977) pointed out that even if the lifetime for this decay is much longer than the age of the universe, the photon flux from the cosmological distribution of neutrinos pair created in the hot Big Bang might be appreciable, simply because of the great length of the line of sight through the universe. This point has led to a considerable literature which I will not go into here. As I write this article I am completing a book which gives a detailed discussion of this question and is entitled *Modern cosmology and the dark matter problem.*

The point of departure for this article was my suggestion (Sciama 1990*a*) that decay photons from dark matter neutrinos in our galaxy might be responsible for the otherwise puzzling widespread ionization of hydrogen in the interstellar medium. The key point here is that the ionization potential of hydrogen is 13.6 eV, so we require $E_\gamma > 13.6$ eV and therefore $m_1 > 27.2$ eV. This gives us the first of the many coincidences in this subject because (*a*) the Tremaine–Gunn phase space constraint for neutrinos to be bound in the galaxy leads to essentially the same lower limit (*b*) the cosmological density ρ_{ν_1} of ν_1 neutrinos is such that

$$m_1 = 93\Omega_{\nu_1} h^2 \,\text{eV},$$

where as usual $\Omega_{\nu_1} = \rho_{\nu_1}/\rho_{\text{crit}}$ and h is the Hubble parameter given by

$$H_0 = 100h \text{ km}^{-1}\,\text{s}^{-1}\,\text{Mpc}^{-1} \quad (\tfrac{1}{2} < h < 1).$$

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If $\Omega_{\nu_1} \approx 1$ and $h \approx \frac{1}{2}$ (which would be compatible with the observed age of the universe) we would have $m_1 \approx 23$ eV. Thus if h is only slightly greater than $\frac{1}{2}$ we would again have $m_1 > 27.2$ eV, and the decay photon would be able to ionize hydrogen.

Encouraged by these coincidences I evaluated the decay lifetime τ needed to account for the observed electron density in the interstellar medium ($n_e \approx 0.03\ \mathrm{cm}^{-3}$) and obtained $\tau \approx 2 \times 10^{23}$ s.

This choice of lifetime leads to another coincidence. Let us evaluate the intergalactic ionizing flux F of decay photons from the cosmological distribution of neutrinos of density n_{ν_1}. A naive estimate would be

$$F \sim (n_{\nu_1}/\tau)\,(c/H_0).$$

With $n_{\nu_1} \approx 100\ \mathrm{cm}^{-3}$, $\tau \approx 2 \times 10^{23}$ s and $c/H_0 \approx 2 \times 10^{28}$ cm we would obtain

$$F \approx 10^7\ \text{photons cm}^{-2}\,\text{s}^{-1}.$$

At first sight this result is a disaster because there is an observational upper limit on F, namely

$$F \lesssim 10^6\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}.$$

We can try to solve this problem by using the fact that the decay photons will be red shifted as they propagate, and once their energy is reduced below 13.6 eV they will no longer contribute to the ionizing flux. This effect is simple to include. If one writes

$$E_\gamma = (13.6 + \epsilon)\ \mathrm{eV},$$

one has

$$F = \frac{n_{\nu_1}}{\tau}\frac{c}{H_0}\frac{\epsilon}{13.6}.$$

We can therefore solve our problem if $\epsilon \lesssim 1$, so that $E_\gamma \lesssim 14.6$ eV. Hence $E_\gamma = 14.1 \pm 0.5$ eV, and $m_1 = 28.2 + 1$ eV. This gives us a new coincidence since this value of m_1 leads to $\Omega_\nu \approx 1$ for a low value of h. Also the resulting value of F would account for the otherwise puzzling ionization of the intergalactic medium and Lyman α clouds.

We can do even better than this if we use recent observational data to argue that the decay photons must also be able to ionize nitrogen (Sciama 1992). This requires that $E_\gamma > 14.53$ eV. Remarkably, this is just compatible with our upper limit and would lead to $E_\gamma = 14.565 \pm 0.035$ eV, and $m_1 = 29.13 \pm 0.07$ eV. Thus the mass of the decaying neutrino (?ν_τ) would be pinned down to better than 1%. Also if we assume that $\Omega = 1$ when the baryon density is included then we obtain (Sciama 1990*b*)

$$H_0 = 56 \pm 0.5\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

so that the Hubble constant would be pinned down to 1%.

With this background we are now ready to consider three recent developments in these ideas.

2. The nature of the dark matter in clusters of galaxies

This decaying neutrino theory is widely regarded as having been disproved by the failure of Davidsen *et al.* (1991) to observe a decay line from dark matter neutrinos in the rich cluster of galaxies A665. However, since then Hughes & Tanaka (1992) have published detailed observations of the X-ray emission from the hot gas in this cluster and have derived model distributions for the density of the galaxies, the gas and the dark matter. From this, one can show (Sciama *et al.* 1992, 1993) that the dark matter is more concentrated to the centre of the cluster than are either the galaxies or the gas. A similar concentration is found in other clusters both from the X-ray data and the gravitational lens data. I find it rather pleasing that general relativity can be used to help demonstrate this excess concentration of the dark matter.

It seems unlikely that neutrinos would be more concentrated than baryons in clusters, since the neutrinos are non-dissipative. It is more likely that most of the dark matter in this case is baryonic. One possibility is that a cooling flow in the hot gas ends up as faint low mass stars (Thomas & Fabian 1990). The absence of an observable decay line would then be explained.

By contrast the dark matter in our galaxy has a more extended distribution than the visible matter. This would fit in well with the hypothesis that this dark matter is in the form of neutrinos, but does not demand it. In any case I believe that these considerations make clear that the decaying neutrino theory is still viable.

3. Ultraviolet radiation in dense molecular clouds

It has been known for a long time that the abundance ratio of atomic carbon to carbon monoxide in the interiors of dense molecular clouds in the galaxy is typically 10^5 times greater than would be expected from simple equilibrium models. This is referred to as the C^0/CO ratio problem. In these models the flux of ultraviolet radiation in the interiors of the clouds is very low because of their great opacity, and so the dissociation rate of CO is also very low. One class of proposed solutions to this problem involves mechanisms for increasing the ultraviolet flux in the interiors. These proposals have recently been reviewed by Sorrell (1992). They involve complicated mechanisms which are difficult to assess.

By contrast, decaying neutrinos situated in the clouds would provide a straightforward mechanism, as was pointed out by Tarafdar (1991). This proposal has recently been updated by Sciama (1993*a*). A crucial role in Tarafdar's analysis is played by the opacity of the clouds to the decay photons, since this controls the resulting flux of these photons. The clouds typically have particle densities in the range 10^3–$10^5\ \mathrm{cm}^{-3}$, and the vast majority of these particles is in the form of H_2 molecules. The flux of decay photons would only be sufficient to solve the C^0/CO ratio problem if these photons are unable to dissociate the H_2 molecules, so that the opacity of the clouds would be relatively small. Here enters a new coincidence. The photodissociation continuum of H_2 has a threshold of 14.68 eV. Hence we require that $E_\gamma < 14.68$ eV. This constraint is essentially the same as our previous one, which followed from considering the intergalactic ionizing flux ($E_\gamma \lesssim 14.6$ eV). The new constraint is more stringent in the sense that the threshold involved has been accurately measured, whereas the previous constraint involved more uncertain quantities (the decay lifetime and the observational limit on the intergalactic flux). If our nitrogen and C^0/CO assumptions are both correct we would then have the essentially exact constraints $14.53 < E_\gamma < 14.68$ eV, and (if $m_2 \ll m_1$) $29.06 < m_1 < 29.36$ eV. The consequences for the value of the Hubble constant would then be essentially the same as before.

4. Recent HST observations of the electron density in the interstellar medium

Strong support for the neutrino decay theory can be derived (Sciama 1993*b*) from the analysis by Spitzer & Fitzpatrick (1993) of their observations of a galactic halo star HD93521 using the Hubble space telescope. They observed the ultraviolet absorption spectrum of several regions along the line of sight to this star. One of the absorbing species was singly ionized carbon in an excited state, CII*. The excitation is probably due to electron collisions and so leads to the value of the electron density n_e in each absorbing region.

In their analysis Spitzer & Fitzpatrick also used the 21 cm emission observations of Danley *et al.* (1992) which showed that the atomic hydrogen column density makes each region opaque to Lyman continuum photons. They concluded that the ionized and neutral gas are intimately mixed up together, in contrast to the standard view that these two components of the interstellar medium are located in separate regions (the warm ionized medium (WIM) and the warm neutral medium or (WNM)).

If this is correct we face the same type of problem as we did in the previous section with the molecular clouds. In this case we are dealing with an excess of hydrogen-ionizing photons in an opaque region rather than an excess of CO dissociating photons. Again decaying neutrinos come to the rescue. In fact it was related opacity problems which led to the decaying neutrino theory in the first place, but we have here the first clear observational evidence that the free electrons (which were previously known to exist from Hα and pulsar dispersion data) are located in opaque regions.

Further support for the theory comes from the values of n_e derived by Spitzer & Fitzpatrick. They found for the slowly moving absorbing regions (which would be unaffected by shock waves) that n_e is the same in each region to their observing precision of 10%. This is just what would be expected for opaque regions in the decaying neutrino theory, and it was predicted in the original paper (Sciama 1990*a*). The reason is simple. Since every decay photon produces an ionization locally, to be followed by a recombination, one has the ionization equilibrium equation

$$n_\nu/\tau = \alpha n_e^2,$$

where α is the appropriate recombination coefficient. In limited regions of the galaxy n_ν will be nearly constant, and n_e will depend on the gas temperature T (via $\alpha(T)$) only as $T^{0.37}$. Moreover in warm regions, such as those observed by Spitzer & Fitzpatrick, the temperature is fairly constant. Hence n_e should be nearly constant, as is observed.

Moreover, if one assumes that carbon is undepleted in these regions (for which there is some evidence (Sciama 1993*b*)), one finds for the four slowly moving regions $n_e = 0.055\ \mathrm{cm}^{-3}$. This is just the same as the values found for three other regions from an analysis of the pulsar dispersion measures of three pulsars with accurately known (parallactic) distances (Reynolds 1990; Sciama 1990*c*). One would not expect such constancy for other ionization mechanisms. Future HST measurements should provide a stringent test of these ideas.

5. Conclusions

I conclude from this discussion that the evidence in favour of the decaying neutrino theory is rather strong. One should therefore take seriously its other implications. These include the early reionization of the universe and the resulting suppression of anisotropies in the cosmic microwave background on small angular scales (Scott *et al.* 1991), and attempts to derive the required decay lifetime from elementary particle physics (Roulet & Tommasini 1991; Gabbiani *et al.* 1991).

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Discussion

A. W. Wolfendale (*University of Durham, U.K.*). Is it not possible that cosmic rays contribute significantly to the ionization of the ISM, particularly away from the galactic plane? Even in the plane they are invoked to explain the modest heating that occurs in the depth of dense molecular clouds.

The cosmic ray injection rate is *ca.* 10^{40} erg s^{-1} for the Galaxy and about 10% of this is lost within the Galaxy. The ionization produced would amount to about $0.3\,f$ ion pairs per cm^3, where f is the fraction of the ionization deposited over a period of 10^{10} years, which 'remains' at any one time.

In fact Chi and I have claimed that there is a strong flux of sub-MeV electrons in the Galaxy; these, too, will produce considerable ionization.

D. W. Sciama. It was shown many years ago, from the observed ionization rate in interstellar clouds, that cosmic rays are an important ionizing agency.