# Weakly Unstable Dark Matter

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## ABSTRACT

The ranges of allowed masses and coupling strengths for massive dark matter particles falls within a limited range of a two dimensional parameter space. In particular, their mass may not exceed several Tev if their lifetime exceeds the Hubble time. Here we discuss whether such particles, if weakly unstable, could manifest themselves astrophysically via their decay. In particular, we show that decay of particles of several Tev due to symmetry breaking at the grand unification scale could account for the anomalous positrons in the galactic cosmic radiation at E>10 Gev. The viability of the right-handed neutrino as weakly unstable dark matter is also discussed.

## Introduction

There are currently some motivations for considering unstable particles that decay over a cosmological timescale. Particle decay has been widely invoked in the literature to provide revisionist scenarios for big bang nucleosynthesis, to account for the reported Wein excess in the microwave background, and to remove most of the closure density from superclusters . For several years, the anomalous positron excess in the cosmic radiation at E>10 Gev has aroused the curiosity of this author since "conventional" astrophysical explanations for it , though not inconceivable, are neither easy to come by. We considered[1] whether they could result from the annihilation of massive Dirac neutrinos with a mass of ~20 Gev and found that this supplied a plausible explanation. At about the same time however, Avignone, Drukier and co-workers [2] announced that they could rule out such particles in the galactic halo, and we had to accept that this result invalidated our hypothesis.

The motivations for hypothesizing non-baryonic dark matter have been long aired and have been discussed at length at this conference. An attractive choice of parameters for the dark matter particles are such that $\Omega = 1$, i.e. that the total density of the universe, most of which is dark matter, is the closure density, as predicted from inflationary models of the early universe with vanishing cosmological constant. However this is not insisted upon by most cosmologists.

Dark matter and unstable particles are related topics in that they both invite the theorist to invent unknown candidate.particles. Dark matter, of course, need not be unstable, and unstable matter, if its half life is small compared to the Hubble time, cannot currently be dark matter. But if dark matter lasts for a Hubble time and is nevertheless weakly unstable, perhaps we could detect it via its decay products. Most massive particles may be unstable at the grand unification (GUT) scale, so weakly unstable dark matter may not be much more radical a notion than the stable variety.

If the reported Wein excess is to be attributed to Comptonization via plasma that has undergone decay heating, several constraints must be obeyed.[3] To live for cosmological timescales, the particle must be able to escape from a collapsing star if produced thermally at the core. If it eventually decays into gamma rays, the decay products due to supernovae greatly exceed the observational limits on the gamma ray background. So either the particle is not thermally produced in collapsing cores or its rest mass is sufficiently small that the high Lorentz factor at Mev energies stabilizes it over a Hubble time. In the latter case however, the decay photons of big bang relics would heat the cosmic plasma very inefficiently. Typically, the constraint that the particle not be thermally produced in collapsing stellar cores constrains the mass to be above 100 Mev.

In addition, a) the total energy density of the decay products should not exceed about 10% of the blackbody background, b) the decay must take place late enough to allow the Comptonization distortions to survive rethermalization ($z<10^6$) . If the particles annihilate in the big bang according to conventional particle physics, constraints a) and b) typically require the particle mass to be above a Gev or so. In this case, radiative decay scenarios via weak interactions yield too short a lifetime to obey b). Thus, if weakly unstable massive particles are to account for the reported Wein excess, they must be protected against rapid decay by some new consideration.

Having reviewed the general motivations above, this paper discusses a couple of specific examples of a weakly unstable massive particle. As emphasized in the discussion, assumptions are introduced (e.g. a low energy symmetry) to protect the particle against rapid decay.

## Tev Particles

The annihilation cross section that leaves $\Omega = 1$ is given by [4,5] $<\sigma v> = 4 \times 10^{-27}\ h^{-2}\, cm^2\, s^{-1}$, where h is the Hubble constant in units of 100 km $s^{-1}$ $Mpc^{-1}$. Now if the mass M of the mediating particle that governs the annihilation is lower than the mass of the dark matter particle m, the annihilation cross section will not depend significantly on M, and, in fact, is comparable to the electromagnetic annihilation cross section. The "electron-positron" cross section, scaled appropriately to the mass of the dark matter particle, is given by $<\sigma v> = \pi\alpha^2 m^{-2}$. If there are j species of lighter particles that couple to the same mediating boson, the annihilation cross section is raised above the electron - positron annihilation cross-section by a factor of $(2j + 1)$ because the decay can process via a virtual boson[5]. It follows that the dark matter gives an $\Omega$ of unity if $m=0.7h(2j+1)$ Tev.

This mass estimate is otherwise quite general in that it doesn't assume a particular value for M, only that $M<m$.

The usual strong assumption one must make is that the dark matter particle is protected by an extremely good quantum number. We shall now assume that this quantum number is good up to the GUT energy scale, and that at this scale there are interactions that can cause the dark matter particle to decay. The lifetime of the particle is then given by

$$\tau = 3 \times 10^{16}\ \mathrm{yr}\ (\tau_p/10^{33}\mathrm{yr.})(\sin\theta)^{-4}(2\ \mathrm{Tev}/m)^5,$$

where $\tau_p$ is the proton lifetime and $\theta$ is a mixing angle. Though the decay time is much longer than the Hubble time, allowing the particle to currently exist as dark matter, the decay products are cosmic rays and could be detectable even if only a very small fraction of the dark matter has decayed.

An example of dark matter that is unstable at the GUT scale might be the lightest of a fourth generation of leptons. If fourth generation lepton number is a good quantum number up to the GUT energy scale, then decay to less massive leptons must proceed through the hadronic sector. This will in fact happen if there is Cabibbo mixing between the fourth generation quarks and lighter ones.

The dark matter mass density in the halo is about 0.3 proton masses per $cm^3$.[6] In the present scenario, this implies a positron emissivity Z in the galactic halo of about

$$Z = 1.5 \times 10^{-27}(\#/10)(\sin\theta)^4(m/2\ \mathrm{Tev})^4\ (10^{33}\mathrm{yr.}/\tau_p)\ e^+/cm^3\ s,$$

where # is the positron multiplicity per decay. If the decay involves a quark jet, # could easily be of the order of 10.

The positron emissivity required to sustain a galactic excess above 10 Gev at the reported level, i.e.the number density divided by the escape time, is $10^{-29}$ $cm^{-3}$ $s^{-1}$. Details are given in references 1 and 7. This is in good agreement with the emissivity estimated above from GUT decay dark matter particles if # = 10, $\tau_p=10^{33}$yr., and $m\sin\theta$ = 0.6 Tev.

The idea that weakly unstable dark matter gives rise to the positron anomaly at E>10 Gev in the galactic cosmic rays, if crazy, is at least testable in several ways. First, dark matter particles with masses of several Gev can be detected in laboratory experiments. If they have spin-independent interactions, they are close to being detected with current technology.[2] Secondly, the positrons should have a characteristic inverse-Compton loss spectrum, as calculated by Tylka and Eichler .[1] This spectrum will be measurable with great accuracy with the superconducting magnet facility on the space station. Thirdly, the flux of gamma rays accompanying the positrons from any quark jet, and also the inverse-Compton gamma rays from prompt Tev lighter leptons should be easily detectable with the EGRET experiment on the Gamma Ray Observatory [7]. Fourthly, since the dark matter particles are in the several Tev range, the physics is well within the range of the planned superconducting supercollider.

## Right-Handed Neutrinos

Right-handed neutrinos are required in many particle physics scenarios. Left - right (L- R) symmetric scenarios require them, and L - R symmetry breaking enables the $\nu_R$ to be much heavier than $\nu_L$. If the Dirac $\nu$ mass is of order the electron mass, as in standard "see-saw" models, the $\nu_R$ decays rapidly into $\nu_L$, e+, and e-. However, if the Dirac $\nu$ mass happens to vanish then the $\nu_R$ can be stable. It is possible, however, that a tiny but finite Dirac mass can be acquired through higher order loop corrections. In this case, cosmologically interesting lifetimes can in principle result even though the $\nu_R$ is very massive.

An illustrative model has been sketched by Babu, Eichler, and Mohapatra,[8] in which the right-handed neutrino decays via a virtual $W_R$ that is mixed with the $W_L$ . (Note that the "right-handed" $W_R$ is the weak gauge boson that couples to $\nu_R$; here the subscript R does not refer to the helicity of the W.) This mixing is accomplished by loops of very massive particles that appear as radiative corrections to the W propagator, that , by virtue of their Dirac mass, mix the left and right handed sectors. (Note that by definition, a Dirac mass term mixes left and right components.) Electrons and quarks (e,u,d) are assumed to acquire a Dirac mass only via their coupling to these massive fermions (E,U,D), as in "universal see-saw" models,[9] i.e. the mixing between the left and right sectors is accomplished only by these heavy partners. The neutrino fails to pick up a Dirac mass simply because (by assumption) it has no massive partner . It turns out that mixing at the one (quark) loop level can cause too fast a decay, so in this particular model a discrete symmetry is invoked to prevent one of the heavy quark partners (say the D) from directly mixing the left and right sectors. The mixing $d_R$ and $d_L$ is accomplished by yet another coupling,this time between the d and u quarks via a charged scalar particle, and the L-R mixing takes place through the U. The mass of this scalar particle and its coupling strength to the quarks determine the decay rate of the right-handed neutrino. There are many free parameters in the theory. Babu, Eichler and Mohapatra [8] choose a $\nu_R$ mass of 30 Gev, and with other mass scales suitably chosen, the $\nu_R$ lives for about $10^{25}$ s. With these parameters, the $\nu_R$ can comprise the closure density as well as account for the high energy positron anomaly . If we readjust the mass of the $\nu_R$ to be 100 Gev, and readjust the strength of the coupling between left- and right-handed sectors, we can arrange for the $\nu_R$ to comprise an $\Omega$ of about $0.1h^{-2}$ (until it decays, of course) and for the lifetime to be merely $\sim 10^{10}$ s, corresponding to a decay redshift of $\sim 10^5$ in an Einstein - de Sitter universe. This would then account for the reported Wein distortion, for, at a redshift of $10^5$, the rest energy density of the $\nu_R$'s would be about 0.05 of that in the blackbody background.

For completeness, we note that although the lightest supersymmetric partner is usually taken to be completely stable, its protecting quantum number, R-parity, may not be exactly conserved. If so, then the lightest supersymmetric partners could be weakly unstable. However, we refrain here from quantitative speculation.

To summarize, weakly unstable massive particles (m>Gev) that have a cosmologically interesting decay rate are possible, if not probable, given the current understanding of particle physics. If they are still around and still decaying, they could be highly conspicuous through their decay products.

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