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Bounds on dark matter from the ''atmospheric neutrino anomaly''

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Bounds are derived on the cross section, flux, and energy density of new particles that may be responsible for the atmospheric neutrino anomaly: $4.6\times10^{-45}\ \mathrm{cm}^2<\sigma<2.4\times10^{-34}\ \mathrm{cm}^2$. The decay of primordial homogeneous dark matter can be excluded. [S0556-2821(97)01819-5]

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The atmospheric neutrino anomaly [1–3] refers to indications that the ratio of muon neutrinos to electron neutrinos observed in underground detectors is significantly less than expected. Expectations are based on calculations of neutrino fluxes derived from pions produced by primary cosmic ray interactions in the upper atmosphere. Since Earth's atmosphere is not particularly dense the pions decay to produce muons and neutrinos and a good fraction of the muons also decay to produce neutrinos. Estimates based on detailed production models put the ratio of muon neutrino flux to electron neutrino flux close to 2 [4]. The overall normalization of these models is uncertain and so, it is the ratio for which one has the highest confidence.

The most popular explanation for the deficiency is that neutrino oscillations have converted some of the muon neutrinos to some other type so that the muon neutrino flux observed is much closer to the electron neutrino flux. The neutrino oscillation hypothesis has failed to be confirmed by a number of measurements [5,6] that use other, independent portions of the atmospheric neutrino spectrum. But these results themselves are at odds with the Kamioka multi GeV results [7]. While the oscillation alternative hypothesis can not be ruled out it is reasonable to seek alternative explanations for the observations.

These experiments are sensitive to extremely low energy densities, which have never been probed before. Since there is no way to tell whether the observed signal is actually attributable to neutrinos, nor if they are neutrinos if they are produced in the atmosphere, it is prudent to consider other possible alternatives. In particular, a flux of any particle that interacts in a way that does not produce the distinctive energetic muon in the final state might possibly contribute to an increase in the relative rates of observed ''electron''-like events to muon-neutrino-induced events.

This paper explores a number of constraints that can be placed on sources of nonmuon-type interactions in underground detectors.

These events are observed in deep underground detectors. This means that whatever is producing them must have penetrated the Earth (or have been present in the detector beforehand). There is no evidence for any directional dependence to the event rates so that the upwardgoing flux must be comparable to that from all other directions. The interaction length must be comparable to the Earth's diameter, or greater:

$$L=\frac{1}{\sigma\rho N_A}.$$

The interaction length depends on the cross section and density traversed. From the known density of the Earth we can get a bound that $\sigma<2.4\times10^{-34}\ \mathrm{cm}^2$. This is a conservative bound, in that we have used the average density of the Earth but the upwardgoing particles would have traversed the core which has considerably more mass. This cross section limit is well above the cross section for 1 GeV neutrinos which is about $0.7\times10^{-38}\ \mathrm{cm}^2$.

One might argue that while the observed events are isotropic this does not necessarily require an isotropic flux. Rather a reaction yielding an isotropic energy flow would do. But the majority of the observed events are classified as ''single prong'' implying that the observed energy and momentum are comparable. The momentum must be brought in with the interacting particle and so its flux is most likely isotropic. While this argument becomes more reliable as the energy increases the absence of anisotropy at any energy makes it the simplest interpretation.

If we attribute the anomalous observations to the presence of an excess of a nonmuon producing type of event we can get a bound on this new flux from the observed event rate and the cross section bound we have estimated. The observed muon flux is about 60% of its expected value relative to the nonmuon component. If the observed depression of the muon to electron ratio is interpreted as an enhancement in the ''electron,'' i.e., nonmuonic component, this enhancement must account for from 20% to 30% of all of the observed events. The event rate in a 3.3 kiloton water detector is about 1 event per day [8], which is about $R=5.8\times10^{-39}$ events/sec nucleon. This yields a flux limit of

$$F_{\mathrm{DM}}>PR/\sigma,$$

where P is the fraction of all events attributable to new physics and F_{DM} is the flux of new (dark) matter.

Here any possible nuclear shadowing has been neglected. It is assumed that all of the target nucleons available for neutrino interactions are available for this new interaction too. While one might argue that the lack of a significant observed atmospheric neutrino anomaly in iron detectors [9] might imply some shadowing in the heavier iron nucleus the upper bound we have found for the cross section, in the Earth, makes this unlikely.

The limit on flux obtained from these arguments is $F_{\mathrm{DM}} > P \times 2.4\times 10^{-5}$ particles/cm^2 sec. With $P = 0.25$ this is $F_{\mathrm{DM}} > 6\times 10^{-6}$ particles/cm^2 sec.

Recall that the flux is inversely proportional to the cross section. These additional particles could be electron neutrinos that are not of atmospheric origin. Using an average neutrino cross section of $\sigma_{\nu_e} = 3.4\times 10^{-39}$ cm^2, $\langle E_\nu\rangle = 500$ MeV the excess flux would be $F_{\nu_e} = 0.4$ neutrinos/cm^2 sec.

Only a lower bound on the flux of new particles can be obtained from this argument since, if it is a new interaction of a new particle, the cross section is not known.

A continuous flux of new particles would indicate the presence of an energy density. The energy density can be estimated from

$$\epsilon = F_{\mathrm{DM}} \langle E\rangle / v,$$

where $\langle E\rangle$ is the mean energy and v is the velocity of the flux. The mean energy can be estimated from the energy deposition by the interaction. But the visible energy found in the detector is usually a fraction of the energy of the incident particle. For ν_e interactions the visible energy is equal to the energy of the electromagnetic shower produced but on average this is only 1/2 of the neutrino energy. The observed visible energy distribution of the excess events seems to be flat below about 600 MeV [10]. We will take $\langle E\rangle = (300/x)$ MeV, where x is the fraction of particle energy found in the detector. It is assumed that the velocity is of the order the speed of light, that is the particles are relativistic. This yields $\epsilon > 2.4\times 10^{-13}(P/x)$ MeV/cm^3. This is about $4\times 10^{-19}(P/x)$ ergs/cm^3, which should be compared with the cosmic matter density of one nucleon per cubic meter. $\epsilon_{\mathrm{cosmic}} = 1.5\times 10^{-9}$ ergs/cm^3.

If the events are assumed to be ν_e induced so that σ, x, and P are known one gets $\epsilon_{\nu_e} = 8.6\times 10^{-9}$ MeV/cm^3 or $\epsilon_{\nu_e} = 1.4\times 10^{-14}$ ergs/cm^3 which is well below the cosmic baryon energy density.

The choice of $\langle E\rangle = (300/x)$ MeV is conservative. It is possible that the anomaly does not extend to higher energies. Even if the evidence presented in [7] is correct the mean energy of the flux will only be higher. Higher mean energies for this ‘‘dark matter’’ would lead to tighter bounds than those presented here. It is possible that if the new matter responsible for the anomaly has a cross section that drops rapidly with energy there could be considerably more of it present than as sampled by the observed effect. Using a, possibly low, energy estimate based on observations makes the limits obtained conservative.

Given a bound on the energy density of the universe we can get a lower limit on the cross section if this energy density is manifesting itself via these excess underground events. The relationship between energy density and cross section can be summarized by $\epsilon = (PR/\sigma)/(\langle E\rangle/v)$ where R is the number of events observed per nucleon per second, P is the fraction of events attributable to the new particle, σ is the interaction cross section, $\langle E\rangle$ is the mean energy of the interacting particles, and v is the velocity of these particles.

One can expect an upper bound on the energy density to be enough to close the universe, $\epsilon_{\mathrm{closure}}$. Under these conditions one finds $\sigma_{\min} > (PR/\epsilon_{\mathrm{closure}})(\langle E\rangle/v)$ With $\epsilon_{\mathrm{closure}} = 10^{-8}$ ergs/cm^3 [11,12] this yields $\sigma_{\min} > 4.6\times 10^{-45}$ cm^2 nucleon for $P = 0.25$, $\langle E\rangle = 600$ MeV, and $v = c$.

A crude flux bound can be obtained from some of these ideas. It is dependent only on the observed energy and the closure bound on energy density:

$$F_{\mathrm{DM}} < \epsilon_{\mathrm{closure}} v / \langle E\rangle.$$

To be conservative we take $v = c$ and $\langle E\rangle > 300$ MeV, which yields $F_{\mathrm{DM}} < 6.2\times 10^5$ particles/cm^2 sec.

It is possible that the excess events observed as the anomaly come from the decay of particles in the detector rather than interactions with an ambient flux. This hypothesis is attractive since the anomaly is not confirmed by dense detectors but only by the relatively low density water detectors. Neutrino interactions (and proton decay) should depend on the fiducial mass of the device. But if one is observing the decay of an ambient dark matter flux the rate should depend on the *volume* of the detector and not its mass. The low density water detectors observe a significantly large volume, by a factor of 3–4 relative to the mass viewed. So the anomalous fraction of decay events found in dense detectors should be greatly suppressed relative to neutrino interactions.

The observed decay rate should be $R_u = \rho_N V/\tau$ where V is the volume of the detector, ρ_N is the number density of the decaying particle, and τ is the particle lifetime. For water detectors the excess event rate per unit volume $R_u/V = P\times 3.5\times 10^{-15}$ events/second cm^3. P is the fraction of total events attributable to dark matter decay, about 25%.

For a bound on this hypothesis we can rewrite it in terms of the energy density ϵ and the particle lifetime τ:

$$\frac{\rho_N}{\tau} = \frac{\epsilon}{\langle E\rangle \tau} = \frac{R_u}{V},$$

$$\frac{\epsilon}{\tau} = \frac{R_u \langle E\rangle}{V}.$$

Here $\langle E\rangle$ is the mean energy associated with each particle at the present time. Such particles might be very massive but we can bound $\langle E\rangle$ by the average energy observed in the detector for each decay $\langle E\rangle > 300$ MeV. This implies

$$\left(\frac{\epsilon}{\tau}\right)_{\mathrm{obs}} > 8.4\times 10^{-19}\ \text{ergs/cm}^3\,\text{sec.}$$

One expects an upper bound on ϵ to be $\epsilon_{\mathrm{closure}}$ and a lower bound on τ to be comparable to the age of the universe. This yields

$$\frac{\epsilon}{\tau} < \frac{\epsilon_{\mathrm{closure}}}{\tau_{\mathrm{universe}}} = 3.2\times 10^{-26}\ \text{ergs/cm}^3\,\text{sec.}$$

Comparing this with the observational result above we can conclude that the hypothesis of the decay of ambient dark matter can be ruled out. This bound could be circumvented if there is a reason why the dark matter should cluster at well above the cosmic density limit in the vicinity of the detector.

Since the origin of the ‘‘atmospheric neutrino anomaly’’ is still uncertain we have attempted to place a number of bounds on the possible source. While the bounds include the conventional explanation of muon neutrino oscillations, our more general approach gives a range of alternatives and may provide motivation for additional theoretical and experimental work on the subject.

The dark matter we have set limits on refers to an ambient, weakly interacting form of matter. It is clear from the work on energy density that at the low density limits permitted by this work, there would be negligible gravitational effects on galactic dynamics. On the other hand, we have used closure of the universe as other analyses have [13] to get an upper bound on the energy density where gravitational effects would certainly be noticed.

The decay of a primordial homogeneous component can be ruled out. The absence of any apparent point sources, in terrestrial or celestial coordinates, in the data implies either a diffuse local source, or a cosmological one. It is difficult to understand how natural processes could populate the several hundred MeV energy region with electron neutrinos or other penetrating particles.

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