The Decay of Dark-Matter Inflatons Can Produce Very Energetic Cosmic Rays

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Abstract

We have shown that inflatons with a mass which is calculated to be of the order of $10^{10}$ GeV can constitute a dominant part of dark matter. They can decay uniquely into a neutrino ($\nu_\tau$) and antineutrino with a lifetime calculated to be greater than the present age of the universe. We show here that these neutrinos can give rise to a localized bump in the primary energy spectrum of extensive air showers. The structure would appear above the sharply-falling spectrum at the expected Greisen-Zatsepin-Kuzmin cut-off energy for primary protons $\sim 5 \times 10^{19}$ eV. The flux which is necessary to compensate for the small cross section is, in principle, attainable, with distant structures also as possible significant sources, and such events might be observable in coming experiments.

1 Introduction

It is possible that dark matter is predominantly in the form of inflatons. These have a mass which is calculated to be of the order of $10^{10}$ GeV, and have a lifetime which is calculated to be of the order of $10^3 t_0$ or greater, where $t_0 \approx 4 \times 10^{17}$ sec is the present age of the universe. We have calculated explicit potentials which exhibit features characteristic of an inflationary period in the early universe. These potentials have a calculated maximum and calculated minimum. This structure is the result of radiative corrections to the tree-level potential. The radiative corrections are calculated using the renormalization-group equations in a (chiral-like) dynamical model involving only the scalar inflaton field, a pseudoscalar field, and a neutral lepton. The inflaton decays uniquely into a neutrino ($\nu_\tau$) and an antineutrino, with energies of the order of $10^{10}$ GeV. In this paper, we show that these neutrinos can give rise to a localized bump in the primary energy spectrum of extensive air showers. The structure would appear above the sharply-falling spectrum at the expected Greisen-Zatsepin-Kuzmin cut-off energy for primary nucleons, $\sim 5 \times 10^{19}$ eV. The essential idea was put forward in the paper. Here we give numerical examples of a localized “bump” structure. We estimate the matter of
whether a sufficiently large flux of tau neutrinos is, in principle, attainable, in order to compensate for the small neutrino-air interaction probability. We remark upon zenith-angle dependence of air-shower events.

2 Representation of the data

In Fig. 1, new data from the AGASA experiment is reproduced [8]. For a qualitative comparison, we have calculated the curves from the following phenomenological representation, which involves adding a local structure to the falling spectrum near to the GZK cut-off energy \( \sim 5 \times 10^{19} \) eV.

\[
E^3 I \approx \begin{cases} 
(10^{24.6}) \left( \frac{10^{18}}{E} \right)^{0.2} + (E^3 10^{-14.6}) e^{-\frac{(E-E_0)^2}{2\sigma^2}} \sqrt{2\pi \sigma} 
& \text{for } 10^{18} \leq E \leq 10^{20.5}, \\
& \text{in eq. (1), } E \text{ is the primary energy in eV and } I \text{ represents a flux in } \text{(m}^2 - \text{sec} - \text{sterad} - \text{eV})^{-1}, \text{times a (total) interaction probability for a primary neutrino traversing the (full) atmosphere (i.e. the fraction of the flux which interacts to produce an extensive air shower). The first term is an approximate representation of the data in Fig. 1 in the interval } 10^{18} \leq E \leq 10^{19}. \text{ For this part of the spectrum presumably due to protons with interaction probability in the atmosphere of about unity, the flux (times } E) \text{ at } E \approx 10^{18} \text{ is normalized to about } 4 \times 10^{-12} (\text{m}^2 - \text{sec} - \text{sterad})^{-1}. \text{ The second term represents the hypothetical localized structure. The neutrino energy is } E_0 \text{ and to illustrate the possible effect, we have assumed a Gaussian distribution of apparent values of } E, \text{ characterized by a spread } \pm \sigma \text{ about } E_0. \text{ For this part of the spectrum, the flux (times } E) \text{ times interaction probability is normalized to about } 4 \times 10^{-12} (\text{m}^2 - \text{sec} - \text{sterad})^{-1}. \text{ The mean-free path } l_0 \text{, is then of the order of } 1.2 \times 10^{13} \text{ cm. The fraction of neutrinos which interact in a characteristic}
\end{cases}
\]

3 The flux of neutrinos from the decay of dark-matter inflatons

The qualitative comparison to present data provided by the curves in Figs. 1,2 suggests a flux times interaction probability somewhat less than of \( 10^{-15} (\text{m}^2 - \text{sec} - \text{sterad})^{-1} \). Consider a very energetic neutrino, \( E \sim 10^{10} \text{ GeV} \). The neutrino-air cross section can be greater than \( 10^{-32} \text{ cm}^2 \). The mean-free path \( l_0 \), is then of the order of \( \frac{1}{2} \times 10^{13} \text{ cm} \). The fraction of neutrinos which interact in a characteristic
atmospheric length $l_{\text{atm}}$ of roughly 25 km is (conservatively) about \( \frac{l_{\text{atm}}}{2 l_0} \) $\cong 2.5 \times 10^{-7}$. We write the flux as approximately (for $\tau \gg t_0$, and $E_{\nu} \lesssim \frac{\mu}{2}$)

$$I_{\nu} \cong \frac{1}{4\pi} \frac{\rho_{\text{CDM}}}{m} \frac{L}{\tau}$$

In eq. (2), $\rho_{\text{CDM}}$ is the energy density of cold dark matter from inflatons of mass $m$, which have a lifetime $\tau$. We have calculated\[1\] the following estimates: $\rho_{\text{CDM}} \cong 2 \times 10^{-47}$ GeV$^4$, $m \cong (6 \times 10^9 - 5 \times 10^{10})$ GeV, $\tau \sim 10^{21} - 10^{23}$ sec. Using $L \sim 10^{28}$ cm for the inclusion of distant structures as possible diffuse sources\[7\], and $m \cong 5 \times 10^{19}$ eV (for which $\tau \sim 10^{23}$ sec\[1\]), eq. (2) gives

$$I_{\nu} \sim 0.4 \times 10^{-8} (m^2 \text{sec}^{-1} \text{sterad})^{-1}$$

This suggests that a sizeable flux is, in principle, attainable (also with smaller effective $L$ compensated by larger effective $\rho_{\text{CDM}}$). There is a small diminution of neutrino energy here due to red-shift $z < 1$. Diminished inflaton decay at very early times tends to reduce contributions (a lower energies here) from very large $z$.

It is instructive to compare our results with those in a recent paper\[9\] which invokes strongly-interacting energetic decay products of a hypothetical tiny component of very long-lived cold dark matter as the origin of the highest energy air showers. First, the statement\[9\] is made that the highest energy primaries are predominantly $\gamma$-rays. Second, a broad spectrum of primary energies extends to far above $10^{20}$ eV, where there are no events (at present). Third, the required flux for $E > 10^{19}$ eV is obtained from a formula like eq. (2) with the following changes:

(a) $\rho_{\text{CDM}}$ is taken to be $\cong 0.3$ GeV/cm$^3$ (a “dark-matter halo” density in our galaxy), times an a priori very small number $\epsilon_X$\[9\]. Without the factor $\epsilon_X$, this is $\sim 10^5$ larger than our $\rho_{\text{CDM}}$.

(b) This is partly compensated by the ad hoc choice of $m = (10^{13} - 10^{14})$ GeV.

(c) $L$ is taken as a halo length scale of $3 \times 10^{23}$ cm. For $\tau \sim 3 \times 10^{21}$ sec, these changed factors compensate to yield $\sim \epsilon_X (l_{\text{atm}}/2 l_0)$ relative to our result for $I_{\nu} \times$ (interaction probability). The ad hoc parameter $\epsilon_X < 2.5 \times 10^{-7}$ is thus essentially taking the role of the known small probability for neutrino interaction\[2\]. (Clearly, we can have the galactic halo contributing in eqs. (2,3), with a larger effective $\rho_{\text{CDM}}$ at a smaller $L$. One can even imagine MACHOs.)

\[F^1\] Another recent paper\[10\] has considered the possible connection between the strongly-interacting decay products of hypothetical, very long-lived cold dark matter and the highest energy cosmic-ray events. In general, the primaries are affected by the GZK cut-off, for distant sources.

\[F^2\] A recent article\[11\] concerning, in particular, the few cosmic-ray events which appear to have primary energies greater than $10^{20}$ eV, has proposed that these are due to neutrinos which acquire strong interactions at c. m. collision energies above about $10^{14}$ eV. The argument given\[11\] for assuming a neutrino-air cross section of a few hundred millibarns involves the hypothesis of strong, long-range interaction of a neutrino coherently with the quarks in a nucleon. However, this type of coherent interaction results in diffraction dissociation\[12\]: the cross section for diffraction dissociation must tend to zero as the target continually blackens at very high c. m. collision energies\[13\]\[14\]. This cross section is empirically a near-constant, small part (some millibarns) of the increasing total $p\pi^0$ cross section at Tevatron energies and above\[13\]. See also\[14\].
4 Conclusion

It is possible that neutrinos from decay of cold dark matter can give rise to an observable localized “bump” structure in the primary energy spectrum of extensive air showers. This would appear above the sharply-falling spectrum at the expected (for distant sources) GZK cut-off energy for primary protons, \( \sim 5 \times 10^{19} \) eV. With finite energy resolution, this structure would ensure that there is a smooth transition near to the GZK cut-off energy to energies just above.

Given the stated presence of attenuation with zenith angle in the handful of the highest-energy events, it seems unlikely that these could be all initiated by (weakly-interacting) tau neutrinos. It is essential to take into account that there are some protons near to \( 10^{20} \) eV (as a tail of the GZK cut-off, at least). Only for the (presently relatively few) events in the highest-energy bins would one expect a diminished presence of zenith-angle dependence, if (weakly interacting\(^{\text{F3}}\)) \( \nu_\tau \) are initiating events. If the mass of the \( \nu_\tau \) is only \( \sim 0.05 \) eV (instead of \( \sim 1.8 \) eV as used in \([1]\)) then the lifetime is lengthened by \( \sim 10^3 \), and the flux in eq. (3) is reduced to \( \sim 4 \times 10^{-16} \) (cm\(^2\) sec \(-\) sterad\(^{-1}\)). A sizeable flux of \( \nu_\tau \) should be observable at the larger detection systems for very high-energy air showers which are being constructed, and in the detectors which are constructed specifically for neutrinos (with due account taken of the hadronic shower that could be an observable aspect of the decay of produced, lower-energy \( \tau \)).

It is possible that compact, very massive quasi-stellar and galactic-core entities involve inflatons of mass \( \sim 10^{10} \) GeV, i.e. of the order of \( 10^{10} \) times the nucleon mass. The decay produces very large amounts of energy in radiation associated with such entities. This could provide a new approach to the development of these energetic objects with very strong gravitational fields. (It is noteworthy that this decay provides a nonequilibrium microscopic process for the direction of time on the scale of the universe).

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Figures

Figure 1: The new data from the AGASA experiment in the interval $10^{18}$ eV $\leq E \leq 10^{20.5}$ eV. The curves are from eq. (1), with $E_0$ and $\sigma$ as stated in the text at the end of section 2. (For illustration, we have used a generous spread $\sigma$ in order to simulate a number of possible uncertainties. Possible rapid motions of decaying inflatons would also contribute to broadening.)
Figure 2: The dashed-dotted curve from Fig. 1, but with the first term in eq. (1) removed at $E \approx 10^{19.7}$ eV, so as to roughly simulate the GZK cut-off at this point. An expected slight “pile-up” of events just before the GZK cut-off is not included in our simple parametrization in eq. (1), because our concern here is with the idea of a possible “bump” structure for the highest-energy events.