Massive relic neutrinos in the galactic halo and the knee in the cosmic ray spectrum

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Despite many efforts to find a reasonable explanation, the origin of the "knee" in the cosmic ray spectrum at $E \approx 10^{15.5} eV$ remains mysterious. In this letter we suggest that the "knee" may be due to a GZK-like effect of cosmic rays interacting with massive neutrinos in the galactic halo. Simple kinematics connects the location of the "knee" with the mass of the neutrinos, and, while the required interaction cross section is larger than that predicted by the Standard Model, it can be accommodated by a small neutrino magnetic dipole moment. The values for the neutrino parameters obtained from the analysis of existing experimental data are compatible with present laboratory bounds.

The cosmic ray (CR) spectrum is well-described by a power law of the $E^{-\gamma}$ form with a spectral index , which is nearly constant over rather wide ranges of energy E, but displays significant discontinuities. The most notable occurs in the region of the so-called "knee" [1–7], at about $10^{15.5}$ eV, where the spectral index changes from 2.75 to 3.

Several models have been proposed to explain this "knee", none of which has been particularly convincing. They include a change in CR sources from Type I to Type II supernovae and/or to changes of the particle acceleration efficiency as a function of the electric charge of the primary [8–10]. Other proposals associate changes of the spectral index with a reduction in the efficiency of the galactic magnetic field to confine the CR's [11,12], allowing those at higher energy to leak away. None of these models is able to reproduce the sharpness of the "knee". Another, rather controversial, explanation of this kink in the spectrum is to attribute it to a recent, strong single source [13].

In this Letter, we propose that the "knee" may be due to inelastic collisions between primary cosmic ray protons and the cosmic neutrino background. For light Standard Model neutrinos with mass (m_ν < 1MeV), Big Bang cosmology predicts a thermal neutrino background of temperature $T_\nu = 1.6 \times 10^{-4}$eV with an average number density of $n_\nu \approx 337\text{cm}^{-1}$, but which can rise dramatically in galaxies due to gravitational clustering provided that the neutrinos are sufficiently massive (non-relativistic).

The idea is a simple extension of the GZK mechanism [14,15] whereby protons above about 10^{19}eV rapidly lose energy via inelastic collisions with cosmic background radiation photons, but now considering the cosmic neutrino background instead. Even allowing for the possibility that neutrinos have mass and cluster significantly, it is easy to show that the Standard Model weak interaction cross sections are too small for these neutrinos to explain any structure as pronounced as the "knee". Fortunately, allowing for a nonzero neutrino mass also immediately opens up the possibility that neutrinos might carry magnetic dipole moments which could significantly increase the inelastic proton neutrino cross section. Effectively we propose a softer GZK-like effect where interaction with the cosmic microwave background radiation is replaced by interaction with virtual photons coupling to the magnetic dipole moment of massive neutrinos. Combined with the increase in relic neutrino density due to gravitational clustering, even rather modest values of magnetic dipole moment turn out to fit the experimental data of the KASCADE experiment [16] rather well.

The required neutrino mass is set by simple kinematics from the requirement that it be sufficiently large that the process $\nu + p \to \nu + \Delta, \quad \Delta \to p + \pi$, can take place. Including higher resonances is not expected to change the results significantly [21].

In order to calculate the inelastic proton-neutrino cross section in the relevant kinematics regime, we use the parameterization of the measured quasi-elastic (i.e. including, and dominated by the Δ) cross section from [17] and adapt it to the case of a neutrino with a magnetic moment. This necessitates replacing the usual electromagnetic coupling $-ie\gamma^\mu$ with the appropriate derivative coupling $\frac{\kappa}{2m_\nu}\sigma_{\mu\nu}q^\nu$ where κ is the magnetic moment. A reasonably straightforward calculation described in more detail elsewhere [22] then gives the required cross section as a function of both m_ν and κ. A (CP-violating) electric dipole moment would have the same effect, and would be modeled with the same sort of term with an additional factor of γ_5 .

Fixing the threshold energy for the pion production at $E_p = 3 \times 10^{15}$eV, one finds $m_\nu \approx 100$ eV. Laboratory experiments clearly rule out such a mass for the electron neutrino, although the muon and tau neutrinos are still viable candidates, as would be some other hypothetical neutrino-like dark matter particle. While neutrino oscillation experiments suggest the possibility of a lighter neutrino, and cosmological arguments also tend to favour lighter neutrinos, this rather large mass is by no means excluded. Of related interest is the "Z-burst model", which seeks to explain the origin of CR events with energies above the GZK cutoff by interaction of ultrahigh energy neutrinos with massive neutrinos in the galactic halo, producing bosons which then decay and give rise to the particles which we observe on earth (see the recent review [18] and references therein). This model favours a much lower neutrino mass, but both the Z-burst model and the explanation we propose here can peacefully coexist, assuming different neutrino species (of different masses) are responsible for the two effects.

To estimate the effects of gravitational clustering, we use the well accepted galactic halo mass distribution model from [19] where the halo is described by the spheroidal density distribution. This assumes a uniform distribution of neutrinos in a core of 10 kpc, and for $m_\nu = 100$ eV yields $n_\nu = 1.4 \times 10^8 \mathrm{cm}^{-3}$, compatible with bounds due to the Pauli exclusion principle and the Tremaine-Gunn phase-space density constraints [20].

Following earlier work [21] on energy loss of cosmic rays in the cosmic microwave background, we find an energy loss rate of

$$dE/dt = \frac{c}{\gamma} \int_0^{w_m} dw_o \, K(w_o) \, \sigma(w_o) \, n \tag{1}$$

where w stands for the neutrino final energy in the proton rest frame, n is neutrino density, σ the proton-neutrino cross section calculated above, and K is the average energy loss of the nucleon in the collision.

This equation is solved numerically, with the neutrino mass, magnetic dipole moment and propagation time as parameters. Conservation of the number of nucleons is enforced by a balance equation

$$\frac{\partial N}{\partial t} = \frac{\partial [b \, N]}{\partial E} + D \; \nabla^2 N + Q \tag{2}$$

Here $b(E)$ is the mean rate at which particles lose energy. The diffusion effect due to galactic magnetic field, modeled by the $D \; \nabla^2 N$ is approximated here from the galactic residence time for CR's, calculated from a diffusion model with a containment volume which extends out 10 kpc from the core. The range of values we consider here is limited from above by the age of the galaxy (10^{10} years) and from below by 10^8 years from the expected residence time derived from spallation [23]. The third term corresponds to the particle injection rate which is assumed to have a power law behavior, so that $Q = K \, E^{-\gamma}$. The solution of this equation can be obtained in the same manner as in reference [21].

Figure 1 shows the total cosmic ray differential flux as measured by KASCADE together with the modified total energy spectrum which is obtained from a sum of a proton component (abundance $\approx 60\%$) plus an iron component, both with spectral index $\gamma = 2.8$ and a curve for the fitted value of $\kappa = (5.4 \pm 0.6) \times 10^{-6} \mu_B$, where μ_B is the Bohr magneton assuming a residence time of 3×10^8 years. Different values of κ and t fit equally well provided that $\kappa^2 t$ is held constant. We use a simple superposition model to estimate the energy losses suffered by iron nuclei due to interactions with neutrinos in the halo so that any effect in the iron spectrum should also be present at higher energies scaling with A .

Interestingly, the corresponding soft GZK-like cutoff for the heavy component is expected above 10^{17}eV, consistent with a possible "second knee" [24]. The KASCADE collaboration has shown [25] that the "knee" is dominated by the light component (≈ 70 %) of the CR with an energy dependent mass composition favouring a decrease of light elements above the "knee". They have also shown that the light and heavy mass groups have comparable slopes up to the "knee" region, but beyond this energy the light component follows a steeper curve.

The heavy mass composition shows no significant "knee" with a constant index γ . The calculated spectrum successfully reproduces the KASCADE data in the region of the sharp "knee", with abundances matching well with those estimated by the collaboration. The differences between the predicted and observed fluxes over 10^{16}eV may be attributable to the fact that in a more rigorous calculation the leakage of cosmic rays from the galaxy cannot be completely neglected, while we assume here, as a first approximation, that the residence time is independent of energy. In any case, the sharpness of the "knee" in the spectrum cannot be explained by smooth analytic effects of a transition between a regime dominated by diffusive propagation in the galactic magnetic field and ones in which the escape of cosmic rays from the galaxy are suppressed (galactic modulation models).

In summary, we have considered the effect of CR particles interacting with massive neutrinos in the halo as an explanation of the "knee" in the cosmic ray spectrum. We have developed a novel approach which allows us to obtain information about the properties of relic neutrinos in the galactic halo, as well as about their masses and magnetic dipole moments. We are able to reproduce the KASCADE data around the "knee" with a mixed composition of protons and iron nuclei, with a sharp cutoff in the light component which is compatible with experimental data. Results of detailed fits will be presented elsewhere, together with discussions of the possibilities for earth-based accelerator experiments to study such neutrinos (or perhaps other massive candidate particles). So far, the best fit results are not far from the present direct limits [26] set at accelerators ($5 \times 10^{-7} \mu_B$), making future prospects very interesting indeed!

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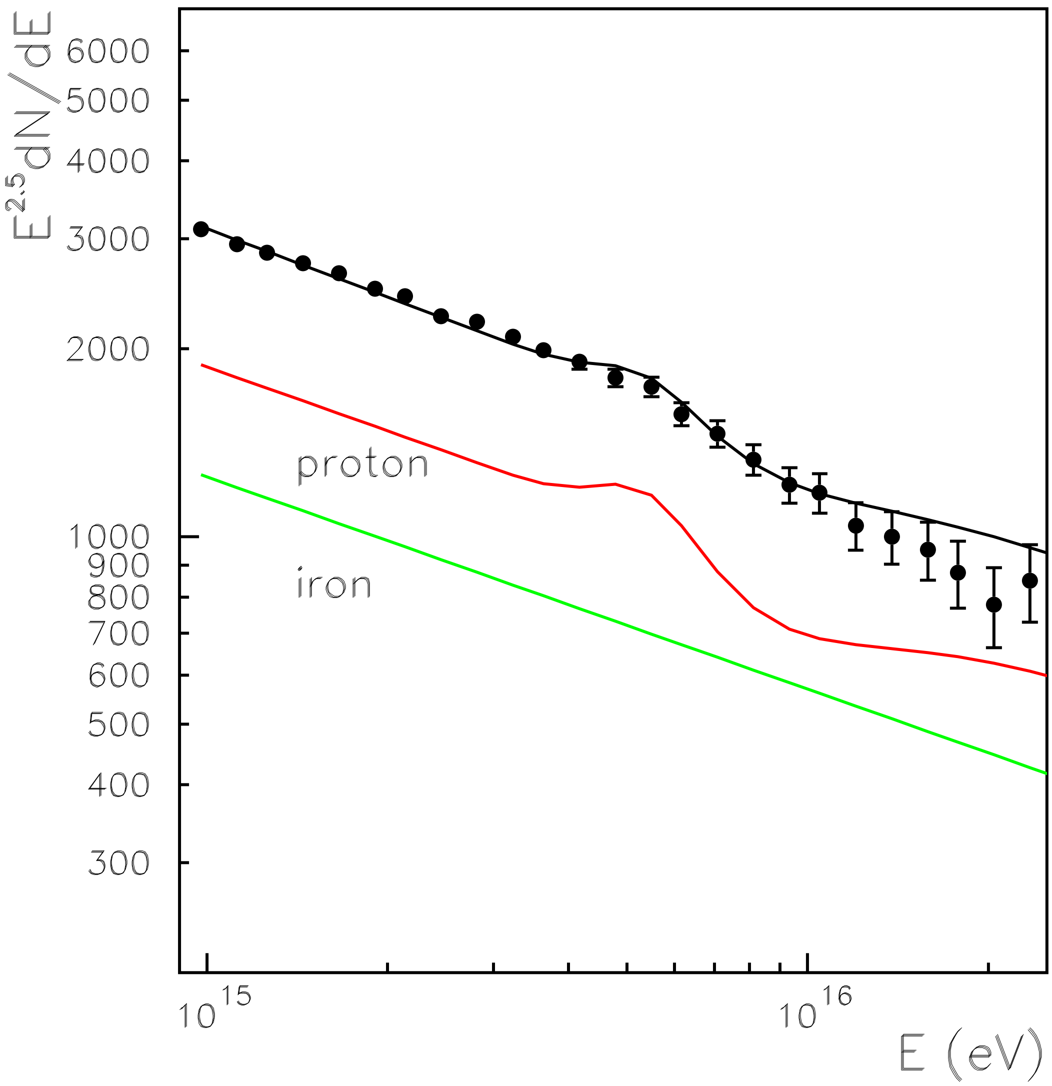
Figure Caption

Figure 1: Differential cosmic ray spectrum as observed bt KASCADE. Solid line shows the result of the fit with a mixed proton-iron component.



$E^{2.5}dN/dE$
6000
5000
4000
3000
2000
1000
900
800
700
600
500
400
300
proton
iron
10^{15}
10^{16}
E (eV)