Proceedings of ICRC 2001: 1780 © Copernicus Gesellschaft 2001

ICRC 2001

Explanation of the “knee” in the CR spectrum via interaction with massive neutrinos in the Halo

M. T. Dova[1], **L. Epele**[1], **and J. D. Swain**[2]

[1]Departamento de Física, Universidad Nacional de La Plata, C.C.67 - 1900 La Plata, Argentina
[2]Department of Physics, Northeastern University, Boston, MA 02115

Abstract. Despite efforts by many researchers, the interpretation of the “knee” in the cosmic ray spectrum at $E \approx 10^{15.5} eV$ remains controversial. We propose that this feature in the cosmic ray spectrum may be due to the interaction of cosmic rays with massive neutrinos in the halo. The required cross section is assumed to be larger than that predicted by the Standard Model and due to a neutrino magnetic dipole moment. The position of the knee is determined by the neutrino mass. The values for the neutrino parameters obtained from the analysis of existing experimental data can be compatible with present bounds, making this an attractive explanation of the knee which can be confronted with future experiments.

1 Introduction

The cosmic ray spectrum can be described by a power law of the form $E^{-\gamma}$ in a large energy range. There are three distinct ranges characterized by different values of the spectral index. Around $10^{15.5} eV$, in the so called “knee” region, the spectrum steepens and the spectral index changes from 2.75 to 3. Between $10^{17} eV$ and $10^{18} eV$ the energy spectrum steepens again, presenting a second “knee” where the spectral index increases from 3.0 to 3.3. At higher energies the “ankle” appears where the spectrum flattens and the spectral index decreases. However, this region extending to $3.0 \times 10^{20} eV$, γ is measured with very large errors due to poor statistics. The need for good quality data and enough statistics in the upper-end of the spectrum is evident. The first change in the slope, the “knee”, was first reported in 1959 (Kulikov and Khristiensen, 1959) and later by other experiments (Nagano, 1984; Danilova, 1993; EAS-TOP Coll., 1995; Amenomori, 1996; Chudakov, 1997; Glasstetter, 1997), and the origin of this feature is not yet understood despite the good statistical accuracies in this energy range. This fact has motivated new experiments with novel detection techniques in order to try to understand the origin and nature of these events (Pierre Auger Observatory Design Report, 1997).

There exist strong arguments based on the universality of spectral indices, isotropy and the total integrated energy supporting the widely accepted idea that below $3.0 \times 10^{18} eV$ the cosmic ray (CR) particles are accelerated in energetic galactic objects such as supernova explosions. The most straightforward interpretation of the spectrum features is then that they are due to contributions from different types of sources. The most popular models describe the knee as a change in the sources from Type I to Type II SN and/or to changes of the particle acceleration efficiency as a function of the electric charge (Lagage and Cesarsky, 1983; Druri et al., 1994; Peters, 1961). These models predict a transition of the composition from proton (or light-nuclei) to iron(or heavy-nuclei) dominated primaries.The observed isotropic arrival direction can be attributed to a diffusion process to the galactic magnetic field. There are other proposals that associate the changes of the spectral index to the reduction of the efficiency of the galactic magnetic fields to confine the CR’s (Syrovatsky, 1971; Wdowczyk and Wolfendale, 1984; Ptuskin et al., 1993). It has been also suggested that the “knee” represents a change in the characteristics of hadronic interactions since the available interaction models are not able to predict the measurements of all observables satisfactorily. However, observation of the “knee” in different EAS components do not seem to show the sorts of contradictions that might suggest new physics in these interactions. An alternative explanation of the “knee” is that of Erlykin and Wolfendale. They claim observational evidence for a complicated structure at the “knee” region which could be attributed to a recent nearby supernova (Erlykin and Wolfendale, 1997, 1999, 2000).

Alternatively, several models have been proposed for the origin of UHECR beyond the predicted GZK cut off. Among them the most conventional solution is the annihilation of UHE neutrinos with massive relic neutrinos clustered into large galactic halos where they constitute an important hot dark matter component (Weiler, 1982; Roulet, 1993; Fargion et al., 1999; Yoshida et al, 1998; Waxman, 1998). The sce-

---

Correspondence to: M. T. Dova (dova@fisica.unlp.edu.ar)

nario, however, is controversial as the number of neutrinos needed would be close to the total luminosity of the universe. It is clear that more theoretical studies as well as high statistics collected by new experiments are needed to provide convincing evidence of a dark neutrino halo, and to estimate neutrino masses using this kind of model.

In this letter we propose a new explanation: that the "knee" might be due to high energy cosmic rays losing energy due to interaction with massive neutrinos in the galactic halo. The usual weak interaction cross sections are too small to produce the observed structures, but once the possibility of a nonzero rest mass is included, a magnetic dipole moment can also be present, and can, in principle, dramatically increase the inelastic neutrino-nucleon cross section.

2 The $p - \nu$ cross section

In order to calculate the inelastic neutrino-proton cross section in the relevant kinematic regime, we use the parametrization of the measured quasielastic (*i.e.* including, and dominated by the Δ) cross section from (Mo and Tsai, 1969) 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 m_{ν} is the mass of the neutrino and κ its magnetic moment. A reasonably straightforward calculation described in more detail elsewhere then gives the required cross section as a function of both n_{ν} and κ.

3 Effects of Massive Neutrinos with Magnetic Moments on Cosmic Rays

To determine the effect of the energy loss due to proton-neutrino interaction on the CR spectrum we must first obtain the mass of the neutrinos. We assume that the sharp feature of the "knee" in the spectrum gives the threshold energy for the proton-neutrino process - a sort of weaker, lower energy version of the GZK effect. m_{ν} is then obtained from the kinematics of the $p\nu$ interaction, considering single pion production from a nucleon N:

$$\nu + N \rightarrow \nu + \Delta, \quad \Delta \rightarrow N + \pi \tag{1}$$

Fixing the threshold energy for the pion production at $E_p = 3 \times 10^{15}$eV and analysing the point at which the interaction begins to be relevant, one finds $m_{\nu} = 100$ eV. Such a mass is clearly ruled out for the electron neutrino, but still open for the muon or tau neutrinos, or some heavier neutrino or neutrino-like particle. Required values for the magnetic moment will further constrain the candidate neutrino species as discussed later in this paper. More sophisticated fits are in preparation and will be presented elsewhere.

Relatively low mass neutrinos are expected to cluster into large galactic halos and this has led to the possibility of their playing an important role as hot dark matter. In fact, the gravitational clustering of relic cosmic neutrinos in the HDM halo is more efficient for heavier ν_{τ} or ν_{μ} (Zel'dovich et al., 1980). The uncertainties in the parameters that describe the dark halo, core radius, local density, spatial extent and shape, are large because observations do not tightly constrain it. In order to estimate the neutrino number density in the galactic halo we used the favoured halo mass distribution model from (Dehnen and Binney, to appear) where the halo is described by the spheroidal density distribution

$$\rho = \rho_0 \,(\frac{m}{r_0})^{-\gamma}\,(1 - \frac{m}{r_0})^{\gamma-\beta}\,exp(\frac{-m}{r_t^2}) \tag{2}$$

with,

$$m = (R^2 \, + \, q^{-2}\, z^2)^{\frac{1}{2}} \tag{3}$$

where the parameters were fitted to observational data with q fixed to 0.8. This distribution allows us to determine the neutrino number density n_{ν} assuming a uniform distribution of neutrinos in a core of 10 kpc, which results $n_{\nu} = 1.5 \times 10^8 cm^{-3}$ for the calculated value of $m_{\nu} = 100$ eV. This value for the number density is compatible with the bounds of neutrino clusters in the galactic halo due to the Pauli exclusion principle and the Tremaine-Gunn phase-space density constraint (Tremaine and Gunn, 1979), which implies that if neutrinos constitute all dark matter in galaxies then their masses should be larger than 100 eV.

4 Propagation effects

In a previous paper, we studied the effect of the universal radiation field on UHECR. We use now a similar approach to calculate the implications of the interaction of galactic CR's with an assumed density of massive neutrinos in the galactic halo. In spite of the fact that the neutrino-proton cross section at $E \approx 10^{15} eV$ is rather small, the energy loss rate is enhanced if the massive neutrinos cluster in the galaxy. Although the photo-pion cross section is large, this process is highly suppressed due to the low density of starlight photons. The energy loss due to interactions with massive neutrinos in the halo is determined by the integral of the nucleon energy loss per collision multiplied by the probability per unit time for a nucleon collision moving through the neutrino background.

$$dE/dt = \frac{c}{\gamma}\int_0^{w_m} dw_o\, K(w_o)\,\sigma(w_o)\,n \tag{4}$$

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

The numerical integration of equation (4) is finally performed where the neutrino mass, the corresponding magnetic dipole moment and the propagation time are the parameters appearing in the interaction. In order to study the modification of the CR spectrum we use the balance equation which

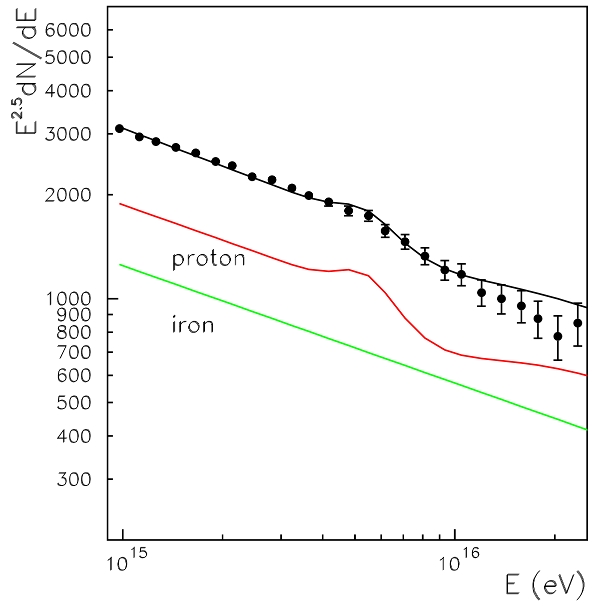

Fig. 1. Fit to the cosmic ray flux spectrum derived by KASCADE with a proton and an iron component.

takes into account the conservation of the total number of nucleons in the spectrum.

$$\frac{\partial N}{\partial t} = \frac{\partial [b\,N]}{\partial E} + D\;\nabla^2 N + Q \qquad (5)$$

where $b(E)$ is the mean rate at which particles lose energy. The diffusion effect due to galactic magnetic field is usually included in the balance equation by a term of the form $D\;\nabla^2 N$. In the present paper we take into account the diffusion in the galaxy by calculating the galactic residence time for CR's. It is worth noting here that there exist bounds on residence time values for CR particles in this energy region. The third term corresponds to the particle injection rate into the volume which is considered to have a power law $Q = K\,E^{-\gamma}$. The solution of this equation can be obtained in the same manner than in reference [Anchordoqui et al. (1997)]. The parametrization of $b(E)$ does not allow for a complete analytical solution. However, using the change of variables

$$\tilde{t} = \int_E^{E_g} \frac{d\tilde{E}}{b(\tilde{E})}, \qquad (6)$$

with $E_g = f(E, \tilde{t})$ and $d\tilde{t} = dE_g/b(E_g)$ we obtain,

$$N(E,t) = \frac{\kappa}{b(E)} E_g^{-\gamma} b(E_g) \qquad (7)$$

5 Results and Discussion

The energy loss mechanism proposed here is controlled by 3 parameters: the neutrino mass, the neutrino magnetic moment, and the residence time in the volume under consideration, which includes the galactic disk and halo. The mass of the neutrino is determined from simple kinematics by the position of the "knee". The residence time is calculated from a diffusion model with a containment volume which extends out $\sim$ 10kpc from the core. A simple calculation considering diffusion from the galactic plane and the same diffusion coefficient in the whole volume yields a residence time $t = 3 \times 10^8$y. That leaves one free parameter - the magnetic moment k, which controls the steepening of the spectrum at the "knee".

In the present work we use the high statistics KASCADE data as presented in [(KASCADE COLL., 2001) in order to estimate the magnetic moment of the neutrinos in the halo. Fig. 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 value of $k = 5 \times 10^{-6}\mu_B$, where μ_B is the Bohr magneton. We consider a simple superposition model to estimate the energy losses suffered by iron nuclei in their interaction with the neutrinos in the halo. It is evident, in this case, that any effect in the iron spectrum should be present at higher energies scaling with A. It is interesting to note that the corresponding cutoff for the heavy component is expected above 10^{17}eV in agreement with the observed "second knee" observed in the data (Nagano et al., 1992).

It should be mentioned at this point, that the analysis performed by the KASCADE collaboration shows that the "knee" is dominated by the light component (70 %) of the CR. Besides an energy dependent mass composition was obtained favouring a decrease of light elements above the "knee". It was also shown that the light and heavy mass groups have comparable slopes up to the "knee" region, but beyond this energy the light component increases the slope. Actually, the heavy mass composition shows no significant "knee" with a constant index γ. It can be seen from Fig. 1, that the obtained modified spectrum successfully reproduces the KASCADE data in the region of the sharp "knee" and that the abundances correspond with those estimated by the collaboration. The differences between the predicted and observed fluxes over 10^{16}eV may be attributed 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 constant at all energies. It should be emphasized that, as mentioned in (Erlykin and Wolfendale, 2001), 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 then, 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 limits set at accelerators ($5 \times 10^{-7} \mu_B$), making future prospects very interesting indeed!

Acknowledgements. We would like to thank Lucas Taylor for useful discussions in the early stages of this work.

References

Amenomori, M., et al., Ap.J., 461, 408, 1996.

Anchordoqui,L.A., Dova, M.T.,Epele L.N. and Swain, J. Phys. Rev. D55, 7356, 1997

Chudakov, A.E. et al.,Proc. 25th ICRC, 6, 177, 1997.

Danilova T.V., et al., J.Phys.G, 19, 429, 1993

Dehnen, W. and Binne, astro-ph/9612059 to be published in Mon. Not. R. Astron.

Druri, L.C. et al. Astron. Astrophys. 287, 959, 1994

EAS-TOP Coll., Proc. 24th ICRC, 2, 732, 1995

Erlykin, A.D. and Wolfendale, A.W., Astropart. Phys. 7, 203, 1997.

Erlykin, A.D. and Wolfendale, A.W., Astropart. Phys. 10, 69, 1999.

Erlykin, A.D. and Wolfendale, A.W., J. Phys. G26, 203, 2000.

Erlykin, A.D. and Wolfendale, A.W., astro-ph/0103477

Fargion, D., Mele. B, Salis, A., Astrophys. J. 517, 725(1999)

Glasstetter, R. (KASCADE Coll.), Proc.25th ICRC, 6, 157, 1997

Horangel et al, Proc. 26th. ICRC

KASCADE Collaboration (K.H. Kampert et al.) Proc. of the 30th International Symposium on Multiparticle Dynamics, astro-ph/0102266

Kulikov, G.U. and Khristiensen G.B, Sov. Phys. JETP, 35, 44, 1959.,

Lagage, P. O. and Cesarsky, C. J., Astron. Astrophys. 118, 223 (1983) and Astron. Astrophys. 125, 249 (1983)

Mo, L. and Tsai, Y. S., Rev. Mod. Phys. 41, 212, 1969.

Nagano, M. et al., J. Phys. G18, 423, 1992.

Nagano M. et al., J. Phys. G10, 1295, 1984.

Peters B., Nuovo Cimento 22, 800, 1961.

Pierre Auger Project Design Report, 1997, Auger Coll., Fermi National Accelerator Laboratory. (www.auger.org/admin)

Ptuskin, V.S. et al., Astron. Astrophys. 268, 726, 1993.

Roulet, E., Phys. Rev. D47, 12, 5247, 1993.

Syrovatsky, S.I., Comm. Astrophys. Space Phys. 3, 155, 1971

Tremaine, S. and Gunn, J.E., Phys. Rev. Lett 42, 407, 1979.

Waxman, E., astro-ph/9804023

Weiler, T.J, Phys. Rev. Lett. 49, 234, 1982

Wdowczyk, J. and Wolfendale, A. W.,J. Phys. G10, 1453, 1984.

Yoshida, S., Sigl, G. and Lee, S., Phys. Rev. Lett. 81, 5505, 1998

Zel’dovich, Y. et al, Sov. J. Nucl. Phys 31, 664, 1980.