The knee of the cosmic ray (CR) spectrum was discovered more than 50 yr ago (Kulikov & Kristiansen 1958). However, its underlying physical causes are still under debate (Hörandel 2004). The most popular scenario is the so-called poly-gonato model, in which each composition of CRs has its own knee and the superposition of all compositions form the observed knee structure of the CR spectra (Hörandel 2003). Phenomenologically the knee of each composition could be charge dependent due to, e.g., the acceleration limit or propagation leakage (Lagage & Cesarsky 1983; Voelk & Biermann 1988; Ptuskin et al. 1993; Berezhko 1996; Wiebel-Sooth et al. 1998), mass dependent due to the interactions (Karakula & Tkaczyk 1993; Kazanas & Nicolaidis 2001; Candia et al. 2002; Hu et al. 2009; Wang et al. 2010; Guo et al. 2013) or even constant (Hörandel 2003). The three types of phenomenological models can all fit the all-particle spectrum; however, the spectrum of each composition shows distinctive behaviors (Hörandel 2003). A precise measurement of the spectrum of individual composition in PeV energies will be essential for the understanding of the knee puzzle.

Apart from the direct measurement of the spectra of individual nuclei, diffuse γ-ray and neutrino spectra carry exact information on CR spectrum in energy-per-nucleon and thus are important in testing the composition models. The diffuse γ-ray emission with energy from multi-MeV to sub-TeV has been well studied by EGRET (Hunter et al. 1997) and Fermi-LAT (Ackermann et al. 2012) experiments. Although the electron processes contribute a proper fraction of the observed flux, it has been well established that the diffuse γ-ray emission in the Galactic plane is dominated by the hadronic nuclei–nuclei collisions (Strong et al. 2000, 2004). Extending this scenario to the knee energy region, we expect a guaranteed source of the diffuse sub-PeV γ-rays and neutrinos from the collision of the CRs and the interstellar medium (ISM) in the Galactic plane. Given the fact that electrons suffer strong energy losses at PeV energies, the diffuse γ-rays and neutrinos should be dominantly related with the hadronic process.

1. INTRODUCTION

The origin of the knee in the cosmic ray spectrum remains to be an unsolved fundamental problem. There are various kinds of models that predict different break positions and the compositions of the knee. In this work, we suggest the use of diffuse γ-rays and neutrinos as probes to test these models. Based on several typical types of composition models, the diffuse γ-ray and neutrino spectra are calculated and show distinctive cutoff behaviors at energies from tens of TeV to multi-PeV. The expected flux will be observable by the newly upgraded Tibet-ASγ+MD (muon detector) experiment as well as more sensitive future projects, such as LHAASO and HiSCORE. By comparing the neutrino spectrum with the recent observations by the IceCube experiment, we find that the diffuse neutrinos from interactions between the cosmic rays and the interstellar medium may not be responsible to the majority of the IceCube events. Future measurements of the neutrinos may be able to identify the Galactic diffuse component and shed further light on the problem of the knee of cosmic rays.

**Key words:** cosmic rays – neutrinos – X-rays: ISM

**Online-only material:** color figures

**ABSTRACT**

The origin of the knee in the cosmic ray spectrum remains to be an unsolved fundamental problem. There are various kinds of models that predict different break positions and the compositions of the knee. In this work, we suggest the use of diffuse γ-rays and neutrinos as probes to test these models. Based on several typical types of composition models, the diffuse γ-ray and neutrino spectra are calculated and show distinctive cutoff behaviors at energies from tens of TeV to multi-PeV. The expected flux will be observable by the newly upgraded Tibet-ASγ+MD (muon detector) experiment as well as more sensitive future projects, such as LHAASO and HiSCORE. By comparing the neutrino spectrum with the recent observations by the IceCube experiment, we find that the diffuse neutrinos from interactions between the cosmic rays and the interstellar medium may not be responsible to the majority of the IceCube events. Future measurements of the neutrinos may be able to identify the Galactic diffuse component and shed further light on the problem of the knee of cosmic rays.

**Key words:** cosmic rays – neutrinos – X-rays: ISM

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Very-high-energy diffuse γ-rays have been extensively explored by ground-based extensive air shower (EAS) array experiments. In the PeV energy region, an upper limit on γ-ray flux was reported by CASAMIA (Chantell et al. 1997; Borione et al. 1998), KASCADE (Schatz et al. 2003), EAS-TOP (Aglietta et al. 1992), UMC (Matthews et al. 1991) and IC40 (Aartsen et al. 2013c). In the muti-TeV region, HEGRA (Karle et al. 1995), Tibet-ASγ (Amenomori et al. 2002) reported a flux upper limit, while MILAGRO (Abdo et al. 2008) and ARGO-YBJ (Ma 2011) gave measurements in limited sky regions of the Galactic plane.

Recently, the very-high-energy neutrino observation has made great progress thanks to the IceCube experiment. The IceCube collaboration reported the detections of two PeV neutrino events and 26 other neutrino events from 20 to 400 TeV (Aartsen et al. 2013a; IceCube Collaboration 2013). The number of events exceeds the standard atmospheric background estimate by 2.8σ and 3.3σ respectively, and may imply an astrophysical origin (IceCube Collaboration 2013). Several works have discussed the Galactic contribution to these neutrino events, such as the TeV γ-ray sources (Fox et al. 2013; Neronov et al. 2014), the Galactic center and Fermi bubbles (Razzaque 2013; Ahlers & Murase 2014; Su et al. 2010), and the diffuse component due to CR interaction with the ISM (Gupta 2013; Joshi et al. 2014). For a recent review, please see Anchordoqui et al. (2014a). A general conclusion is that a hard neutrino spectrum $E_{\nu}^{-2.0}$ with a cutoff at a few PeV, or a slightly softer one $E_{\nu}^{-2.3}$ for the single power-law assumption (Anchordoqui et al. 2014b) was inevitable in order to explain the PeV observation.

In this work, we investigate the effect of the composition models on the diffuse γ-ray and neutrino spectra. Through comparing the calculated fluxes with expected sensitivity curves of existing or future experiments, the possibility to test the composition models by diffuse γ-ray and neutrino measurements is discussed. In the next section, we briefly describe the phenomenological poly-gonato model (Hörandel 2003) used in the following calculation. In Section 3, we present the calculated γ-ray and neutrino spectra. Finally, Section 4 is the conclusion.
2. COMPOSITION MODELS IN THE KNEE REGION

Although all particle spectrum has been well-measured in the energy region around the knee, precise measurements for individual species are not yet available. Limited by small effective area, space and balloon borne experiments can measure the CR spectra with energies less than a few hundred TeV. On the other hand, ground-based EAS experiments have large enough effective area but bear rather large systematics to distinguish different nuclei species. Therefore, the model to describe the knee is basically based on the extrapolation of low-energy measurements, some physical considerations as well as the fit to the all particle spectrum. (Hörandel 2003) summarized the measurements, some physical considerations as well as the fit to the all particle spectrum. (Hörandel 2003) summarized the typical three types of models of the knee. We briefly describe them here.

The first type of the model is motivated by the diffusive shock acceleration (DSA) or propagation process. According to the DSA theory, CRs will have a power-law spectrum with a maximum energy cutoff. The cutoff energy depends on the source properties. For supernova remnants, the cutoff energy is estimated to be about PeV (Lagage & Cesarsky 1983). Simply because the acceleration energy is proportional to the charge of the accelerated particle, the cutoff energy for different species should be Z-dependent (Lagage & Cesarsky 1983). From the point of view of CR propagation, the knee structure might be a consequence of the leakage of CRs from the Galaxy (Ptuskin et al. 1993). As the gyromagnetic radius of a particle is proportional to the rigidity, the knee structure of the individual nuclei should also be Z-dependent.

The second type of model is motivated by the interaction processes. In these models, either threshold interactions or new physics at a certain energy scale can lead to a change in the measured flux or energy (Karakula & Tkaczyk 1993; Kazanas & Nicolaidis 2001; Candida et al. 2002; Hu et al. 2009). As the threshold energy is related to the Lorentz factor of the CR particle, the break energy is expected to be A-dependent. The third type of break is constant for all species. It is not well physically motivated, but it might be a simple possibility.

We note that the problem of the knee was still open until now. There is no consensus about the origin of the knee, mainly due to the limited knowledge about the individual spectrum of each composition. Therefore, our discussion is based on three typical kinds of phenomenological approaches to the knee, i.e., the poly-gonato model with A or Z dependent or constant break energies (Hörandel 2003). It is possible that the problem may be even more complicated, and the results in the specific model may be different from these phenomenological approaches. We expect that these three approaches can be typical representatives of various kinds of physical models. As an example, we adopt the model incorporating photon–nuclei pair production (Hu et al. 2009; Wang et al. 2010) to show the result of a physically based model. In this model, the knee of each composition is approximately A-dependent. However, the energy spectrum after the interactions is not simply a broken power law or a power law with cutoff. Due to the detailed interaction energy losses, there is both a pile-up effect and a high-energy tail of the particle spectrum (Hu et al. 2009; Wang et al. 2010). It is worth noting that the KASCADE experiment recently reported a discovery of ankle-like spectrum for light elements at about 10 PeV (Antoni et al. 2005).

Following (Hörandel 2003), the CR spectrum of each composition is parameterized as

\[
\frac{d\Phi_i}{dE}(E) = \Phi_i^0 E^{-\gamma_i} \left[ 1 + \left( \frac{E}{\hat{E}_i} \right)^{\epsilon_i} \right]^{\frac{\epsilon_i}{\gamma_i}}
\]

(1)

where \( \Phi_i^0 \) and \( \gamma_i \) are the normalization and spectrum index before the break of the \( i \)th species, \( E \) is the total energy of the particle, \( \Delta\gamma \) and \( \epsilon \) characterize the change in the spectrum at the break energy \( \hat{E}_i \). The break energy \( \hat{E}_i \) is expressed as

\[
\hat{E}_i = \begin{cases} 
\hat{E}_p \cdot Z, & \text{charge-dependent} \\
\hat{E}_p \cdot A, & \text{mass-dependent} \\
\hat{E}_p, & \text{constant}
\end{cases}
\]

(2)

where \( \hat{E}_p \) is the break energy of protons. The values of the key parameters of the poly-gonato model are listed in Table 1 (Hörandel 2003).

As for the physically based interaction model, the flux of individual nuclei depends on the energy loss rate and cannot be analytically parameterized. We adopt the numerical results presented in Wang et al. (2010) in the calculation.

The flux of the all of the particle spectrum can be obtained by summing over all CR species

\[
\frac{d\Phi}{dE}(E) = \sum_i \frac{d\Phi_i}{dE}(E).
\]

(3)

The all particle spectra are shown by solid lines in Figure 1. Note that an extra component might be necessary to explain the sub-EeV data for Z- or A-dependent scenarios (Hillas 2005).

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Table 1

| Model                      | \( \hat{E}_p \) (PeV) | \( \Delta\gamma \) | \( \epsilon \) |
|----------------------------|------------------------|---------------------|----------------|
| Z-dependent break          | 4.49                   | 2.1                 | 1.9            |
| A-dependent break          | 3.81                   | 5.7                 | 2.34           |
| Constant break             | 3.68                   | 0.44                | 1.84           |

Note that an extra component might be necessary to explain the sub-EeV data for Z-dependent (red), constant break (black), and the physical interaction model (blue), respectively. The all particle spectrum of the A-dependent break model gives essentially the same result with the Z-dependent break model, and is not shown. Dashed lines show the corresponding nuclear spectra. References of the data are Antoni et al. (2005), Knurenko et al. (2001), Nagano et al. (1992), Amenomori et al. (2008), Hörandel (2003). (A color version of this figure is available in the online journal.)

Figure 1. Energy spectra of CRs. The solid lines are all particle spectra for Z-dependent break (red), constant break (black), and the physical interaction model (blue), respectively. The all particle spectrum of the A-dependent break model gives essentially the same result with the Z-dependent break model, and is not shown. Dashed lines show the corresponding nuclear spectra. References of the data are Antoni et al. (2005), Knurenko et al. (2001), Nagano et al. (1992), Amenomori et al. (2008), Hörandel (2003). (A color version of this figure is available in the online journal.)
The inelastic hadronic interactions are characterized by the nucleons in the particles. For the discussion of the $\gamma$-ray and neutrino production, we convert the previous particle spectrum to nucleon spectrum

$$\frac{d\Phi_n}{dE_n} = A \cdot \frac{d\Phi}{d(E/A)}$$

$$= A^{-\gamma + 2} \Phi_n^{-\gamma} \left[ 1 + \left( \frac{E_n}{E/A} \right)^{\tau_f - 3/2} \right]$$

where $E_n = E/A$ is the energy per nucleon. We find that the nucleon spectrum will be suppressed by a factor of $A^{-\gamma + 2}$ compared with the all particle spectrum, and the break energy is also different. As an example, for iron nucleus, the suppression factor is $56^{-2.59+2} = 0.09$. The expected nucleon spectra of different models are also shown in Figure 1 by dashed lines. A very interesting feature of the spectrum is the existence of a "dip" structure for either charge-Z- or mass-A-dependent models.

3. GAMMA-RAYS AND NEUTRINOS FROM CR INTERACTION WITH THE ISM

As we discussed earlier, the dominant contribution of the diffuse $\gamma$-rays and neutrinos with energy higher than 10 TeV should be the CR interaction with ISM. The spectrum of $\gamma$-ray production is calculated using a formalism by Dermer (Dermer 1986)

$$F(\epsilon) = \int_{e^{1/2}}^{\epsilon} dE_\gamma \frac{f(E_\gamma)}{E_\gamma^{1/2}}.$$  \hspace{1cm} (5)

Here, $E_\gamma$ is the total energy of the neutral pion and $m_\pi$ is its mass, $f(E_\gamma)$ is the spectrum of neutral pions, which is

$$f(p) = 4\pi n_{gas} \int dp \frac{d\sigma(p, p')}{dp} n(p'),$$  \hspace{1cm} (6)

where $n_{gas}$ is the gas density, $d\sigma(p, p')/dp$ is the production cross section, $n(p')$ is the nucleon density, $p$ and $p'$ are the momenta of the pions and incident nucleons. The key points are the density distribution of CRs and the ISM distribution in the Galaxy.

We extend the propagation scenario of the Galactic CRs described by GALPROP (Strong & Moskalenko 1998) to the knee region. The spatial and energy distribution of CRs is described by the solution of the propagation equation

$$\frac{\partial \psi(r, p, t)}{\partial t} = q(r, p, t) + \nabla \cdot (D_{xx} \psi - V_c \psi)$$

$$+ \frac{\partial}{\partial p} \frac{p^2}{2} D_{pp} \frac{\partial}{\partial p} \frac{1}{2} p^2 \psi - \frac{\partial}{\partial p} \left[ p \psi - \frac{p}{3} (\nabla \cdot V_c) \psi \right]$$

$$- \frac{\psi}{\tau_f} - \frac{\psi}{\tau_r},$$  \hspace{1cm} (7)

where $\psi(r, p, t)$ is density of CR particles per unit momentum $p$ at position $r$, $q(r, p, t)$ is the source term, $D_{xx}$ is the spatial diffusion coefficient, $V_c$ is the convection velocity, $D_{pp}$ is the diffusion coefficient in momentum space and used to describe the reacceleration process, $p \equiv dp/\partial t$ is momentum loss rate, $\tau_f$ and $\tau_r$ are timescales for fragmentation and radioactive decay, respectively. The spatial diffusion coefficient is assumed to be space-independent and has a power-law form $D_{xx} = \beta D_0 (\rho/\rho_0)^{\delta}$ of the rigidity $\rho$, where $\delta$ reflects the property of the ISM turbulence. The reacceleration can be described by the diffusion in momentum space and the momentum diffusion coefficient $D_{pp}$ is coupled with the spatial diffusion coefficient $D_{xx}$ as (Seo & Ptuskin 1994)

$$D_{pp} D_{xx} = \frac{4 p^2 v_A^2}{3 \delta (4 - \delta^2) (4 - \delta w)}$$  \hspace{1cm} (8)

here $v_A$ is the Alfvén speed, $w$ is the ratio of magnetohydrodynamic wave energy density to the magnetic field energy density, which can be fixed to one. The CRs propagate in an extended halo with a characteristic height $z_h$, beyond which free escape of CRs is assumed.

In this work, we adopt the nominal propagation parameters of the diffusion reacceleration scenario, which are adjusted to reproduce the CR data such as B/C, $^{10}$Be/$^{9}$Be, the local proton and electron spectra (Zhang et al. 2010). The major parameter values are $D_0 = 5.5 \times 10^{22}$ cm$^2$ s$^{-1}$, $\delta = 0.54$, $v_A = 32$ km s$^{-1}$, $z_h = 4$ kpc.

The ISM is composed of about 10%–15% of the total mass of the Galactic disk and its chemical composition is dominated by hydrogen and helium. The helium fraction of the gas is taken as 0.11 by number. The hydrogen gas density $n_H$ includes three main components: molecular ($H_2$), atomic (H$^+$), and ionized (H$^+$). We use the gas distribution in GALPROP, which is based on the survey results and related modeling (Bronfman et al. 1988; Gordon & Burton 1976; Cordes et al. 1991).

3.1. Diffuse $\gamma$-ray Emission

The spectrum of diffuse $\gamma$-ray emission can be calculated based on the calculated CR distribution in the Milky Way. In our calculation, the spectral index of CRs after propagation is $\sim -2.7$ and the corresponding spectral index of $\gamma$-ray is $\sim 2.6$. Because the majority of the EAS experiments are located in the northern hemisphere, we choose an inner Galactic plane region $(20^\circ \leq l < 55^\circ$ and $|b| < 2^\circ)$ and an outer Galactic plane region $(140^\circ < l < 225^\circ$ and $|b| < 2^\circ)$ to display the results.

The Galaxy is not transparent to very-high-energy $\gamma$-rays. The main three processes resulting in energy losses of photons are photoelectric effect, Compton scattering, and pair production. The photoelectric effect is negligible for the very-high-energy $\gamma$-ray photons discussed here, whose energies are higher than tens of TeV. As for the comparison between Compton scattering ($\gamma\gamma$) and pair production ($\gamma\gamma$), we can compare the electron density with the ISRF target photon number density. The typical value of the interstellar gas density in the Galactic plane is $\sim 1$ cm$^{-3}$. It means that the electron density is about $1$ cm$^{-3}$, which is much less than that of the infrared and microwave background photons (Strong et al. 2000; Porter & Strong 2005). Therefore, the Compton scattering losses of the $\gamma$-rays can also be neglected. The dominant contribution to the attenuation of the very-high-energy $\gamma$-rays comes from the pair production. The optical depth as a function of photon energy and direction, $\tau(E, \psi)$, can be calculated as (Zhang et al. 2006; Moskalenko et al. 2006)

$$\tau(E, \psi) = \int_{l, a, \theta} dL \int d\cos(\theta) \int \frac{dn(\epsilon, R, z)}{d\epsilon} \times \sigma_{\gamma\gamma}(E, \epsilon, \cos(\theta)) \frac{1 - \cos \theta}{2} d\epsilon,$$  \hspace{1cm} (9)

where $\epsilon$ is the energy of the ISRF photon, $dn(\epsilon, R, z)/d\epsilon$ is the differential number density of ISRF, which depends on the
spatial location in the Galaxy, $\sigma_{\gamma\gamma}$ is the pair production cross section. The integral of $dL$ is along the line of sight (l.o.s.) of the incoming $\gamma$-ray photon. In our calculation, we adopt the ISRF model developed in Porter & Strong (2005), which is based on the new modeling of star and dust distributions, the scattering, absorption and re-emission of the stellar light by the dust.

The calculated diffuse $\gamma$-ray spectra are shown in Figure 2. The left panel is for the inner Galactic plane region and the right panel is for the outer Galactic plane region. Different colors show the results of three different composition models of the knee: $Z$-dependent break (red), constant break (black), and the physical interaction model (blue). The result of the $A$-dependent break model is similar to the $Z$-dependent one and is not shown here. The dashed lines represent the unattenuated spectra and the solid lines are attenuated ones. It is shown that the $\gamma$-ray spectrum up to several hundred TeV, the $Z$-dependent one and the knee-like structure. However, it may still have difficulty discriminating different models, because the largest difference comes out in PeV energies. The new generation high-energy $\gamma$-ray projects such as LHAASO (Cao 2010) and HiSCORE (Tluczykont et al. 2012) will have better capabilities to measure the $\gamma$-ray shape precisely and to distinguish different models.

Figure 2. Calculated $\gamma$-ray spectrum for inner ($20^\circ < l < 55^\circ$, $|b| < 2^\circ$, left) and outer ($140^\circ < l < 225^\circ$, $|b| < 2^\circ$, right) Galactic plane regions. The dashed lines are the unattenuated spectra and the solid lines are the attenuated ones. Different colors show results for three models to describe the knee. See the text for details.

(A color version of this figure is available in the online journal.)

To roughly investigate the detectability of such kinds of structures, we compare the sensitivity of the Tibet-AS$\gamma$+MD experiment with muon detectors (Tibet-AS$\gamma$+MD) (Sako et al. 2009). The sensitivity of the Tibet-AS$\gamma$ experiment is defined as a $5\sigma$ observation of $\gamma$-ray excess over the survived CR background after muon detector rejection in one year of operation. Below 1 PeV, the CR background is rejected partly and the significance can be simply defined as $N_{\gamma}/\sqrt{N_{\text{CR}}}$. Above 1 PeV, the number of CR background is fully suppressed down to less than one event per year and the sensitivity is defined as 10 $\gamma$-ray events. Figure 3 shows the integral flux and a comparison with the sensitivity of the Tibet-AS$\gamma$ experiment. The line labels are similar to Figure 2. With a few years of observations, Tibet-AS$\gamma$+MD may detect the diffuse $\gamma$-ray component up to several hundred TeV, and the knee-like structure. However, it may still have difficulty discriminating different models, because the largest difference comes out in PeV energies. The new generation high-energy $\gamma$-ray projects such as LHAASO (Cao 2010) and HiSCORE (Tluczykont et al. 2012) will have better capabilities to measure the $\gamma$-ray shape precisely and to distinguish different models.

Figure 3. Same as Figure 2, but for integral spectrum, compared with the sensitivity of Tibet-AS$\gamma$+MD.

(A color version of this figure is available in the online journal.)
et al. 2013b) and the recent IceCube results of possible astrophysical neutrinos are the atmospheric muon neutrino background observed by IceCube (Aartsen et al. 2013; Liu et al. 2014).

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Figure 4. Calculated diffuse neutrino spectrum from the collision of the CRs with the ISM in the inner \((-30° < l < 30°, |b| < 5°\), upper solid) and outer \((90° < l < 270°, |b| < 5°\), lower dashed) Galactic plane regions. Also shown are the atmospheric muon neutrino background observed by IceCube (Aartsen et al. 2013b) and the recent IceCube results of possible astrophysical neutrinos (Aartsen et al. 2013a; IceCube Collaboration 2013), adopted from (Murase et al. 2013; Liu et al. 2014).

(A color version of this figure is available in the online journal.)

discriminate the different line curve, such as five years with more than 50 γ-ray event observations. Furthermore, the possible systematics will make the case less optimistic, which depends on detailed simulation of the detectors (Cui et al. 2014).

3.2. Diffuse Neutrino Emission

The charged pion decay will produce neutrinos accompanied with the γ-rays. Different from γ-rays, neutrinos will propagate freely in the space without absorption, which may carry the information of the primary CRs more directly.

On average, the \( pp \) collision produce one/third neutral pions and two-thirds charged pions. Each neutral pion decays into a pair of γ-rays, and each charged pion decays into two muon neutrinos and one electron neutrino (we do not distinguish neutrinos and anti-neutrinos). The initial neutrino flux ratio is approximately \( \nu_e : \nu_{\mu} = 1 : 2 : 0 \) from charged pion decay. The flavor ratio will be close to \( \nu_e : \nu_{\mu} = 1 : 1 : 1 \) at the Earth after vacuum oscillation with traversal of astrophysical distance. The typical energy of the neutrinos resulting from these decays is half of the γ-ray photons. Therefore, the resulting neutrino spectrum is shifted relative to the source γ-ray spectrum. The typical spectrum of the muon neutrinos (\( \nu^+ + \nu^- \)) is then \( 2^{1/2} \) times of the γ-ray spectrum, with \( \Gamma \) the spectrum index of the photon spectrum (Kistler & Beacom 2006).

The calculated neutrino spectrum is shown in Figure 4 for the inner Galactic plane \((-30° < l < 30°, |b| < 5°\) and outer Galactic plane \((90° < l < 270°, |b| < 5°\)). Also shown is the estimated neutrino flux of recent IceCube observations (Aartsen et al. 2013a; IceCube Collaboration 2013), adopted from (Murase et al. 2013; Liu et al. 2014). In the inner region, the Galactic diffuse neutrinos are consistent with the IceCube observation in the \( \sim 100 \) TeV energy region, but it is not enough to account for the high-energy (up to PeV) events. Therefore, it is possible that the Galactic neutrinos from interactions between CRs and the ISM may contribute a proper fraction to the low-energy events by IceCube (Razzaque 2013; Ahlers & Murase 2014; Gupta 2013; Joshi et al. 2014; Wang et al. 2014), while the rest events may require another origin with harder spectrum (He et al. 2013). More and better measurements of the neutrino events are necessary to clearly identify the Galactic component and distinguish different models of the knee.

4. CONCLUSION

In this work, we propose an alternative method to pinpoint the CR compositions around the knee region with diffuse γ-rays and neutrinos. It is shown that both γ-rays and neutrinos from the interactions between the CRs and the ISM will experience a knee-like structure at hundreds of TeV. Different models of the knee will predict different behaviors of the generated γ-ray and neutrino spectra due to the different compositions around PeV energies. Precise measurement of the diffuse γ-ray and neutrino spectra may be used to test different models to explain the knee. The newly upgraded Tibet-ASγ+MD experiment will have the potential to detect the knee of the diffuse γ-rays. However, to test different models of the knee, we need future, more sensitive experiments, such as LHAASO and HiSCORE. As a guaranteed source of neutrinos, we show that the diffuse Galactic neutrinos may contribute to a proper fraction of the recently reported neutrino events by IceCube at low energies (Aartsen et al. 2013a; IceCube Collaboration 2013). The high-energy events, however, require another origin with harder spectrum.

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