Gamma-Ray Energy Spectra through Decays of Neutral Pions Produced in Proton-Proton Interactions

Ching-Yuan Huang
Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg, Germany

Abstract

The accuracy of different parameterisations of neutral pion production in proton-proton collisions is investigated based on analyses of accelerator measurements of differential and integrated total cross sections. The energy spectra of gamma-rays from the decay of secondary particles produced by interactions of cosmic-ray protons with ambient gas is calculated over wide energy range for different primary spectra of protons. It is found that a proton flux with a spectral index $\alpha = 2.4 \sim 2.6$ is appropriate to reproduce the GeV bump in the diffuse γ-ray flux.

1. Introduction

The γ-rays are a good probe for the information about the production sites and also the propagation of accelerated charged particles in the Galactic plane. The diffuse γ-ray emission of the galactic plane provides the information about Galactic cosmic rays (CRs), the interstellar medium, and also the interactions between them (see references in [1-3]).

Three regimes of diffuse Galactic γ-rays are distinguished [4-7]. However, the relative contributions of the other two processes (the bremsstrahlung and the inverse Compton (IC) scattering) with respect to the decays of neutral pions, produced in collisions of CR protons/nuclei with the ambient gas, is uncertain [6]. With the reasonable assumption on uniform and continuous distribution of CR sources in the Galaxy [2], the γ-ray spectrum can be more reliably determined from π^0 decay between GeV and sub-TeV range, because, unlike the other two processes involving with electrons in CRs, the γ-rays from π^0 decays carry the information about the hadronic component in cosmic rays.

2. Neutral Pion Meson Production Cross Section

To calculate the γ-ray spectrum, one requires the knowledge of π^0 production in nuclear collisions. In this work, a new parametrisation of inclusive cross section of π^0 production in pp collisions is applied [8]. This parametrisation has

pp. 2297–2300

well reproduced the invariant differential cross section at energies from $P_p = 50$ GeV/c to the CM energy $\sqrt{s} = 63$ GeV over a wide scattering angle range [8-10]. As to investigate the accuracy of the π^0 production parametrisations from different models and other works [5-6, 11-14], both invariant differential and total cross section are calculated. The present work has shown an overall good agreement with data, from threshold to a few TeV. Although at $E_p > 100$ GeV, the calculations have underestimated the values by a factor of 20-30%, such deviation is still within the experimental uncertainties and the generating CR protons with energies up to this value is found to contribute about 98% of the π^0 population.

3. Gamma-Ray Spectrum from Neutral Pion Decays

The spectrum of γ-rays produced from CR-generated π^0 decays $pp \rightarrow \pi^0 \rightarrow 2\gamma$ is calculated as

$$q_\gamma(E_\gamma) = 2 \int_{E_\pi^{min}(E_\gamma)}^{\infty} dE_\pi \frac{q_\pi(E_\pi)}{\sqrt{E_\pi^2 - m_\pi^2}} \tag{1}$$

where $q_\pi(E_\pi)$ is the π^0 spectrum produced in CR-generating collisions:

$$q_\pi(E_\pi) = 4\pi n_H \eta \int_{E_p^{min}(E_\pi)}^{\infty} dE_p J_p(E_p) \frac{d\sigma_\pi(E_\pi, E_p)}{dE_\pi} \tag{2}$$

with energies in GeV, $E_p^{min}(E_\pi)$ the minimum energy determined by kinematics, $J_p(E_p)$ the CR proton flux, n_H the number density of the ambient gas, being taken as $n_H = 1$ H/cm^3, η the factor by considering the π^0 production from channels involving heavier nuclei in CRs and the ambient gas, being assumed 1.6, $d\sigma_\pi(E_\pi, E_p)/dE_\pi$ the differential cross section for a CR proton of energy E_p to produce a π^0 with an energy E_π, and $E_\pi^{min}(E_\gamma)$ the minimum energy for a π^0 decaying to create photons with energy E_γ, being derived by kinematics as $E_\pi^{min}(E_\gamma) = E_\gamma + m_\pi^2/4E_\gamma$.

The generating CR spectrum is assumed as a simple power-law. Different modulated CR spectra show no strong influence on the shape nor the peak of the π^0 spectrum. At energy above a few GeV, the π^0 spectrum tends to attain a power-law asymptotically. Fig. 1. shows the γ-ray emissivities from π^0 decays calculated in different works, corresponding to the median proton flux [7]. The current work shows no great deviation from the previous work [6], although these two works have reproduced different π^0 multiplicities below a few GeV. The same calculation but for the local CR proton flux $J_p(E_p) = 2.2\ E_p^{-2.75}$ cm^{-2}s^{-1}sr^{-1}GeV^{-1} [15] is also shown in the figure, from which, one can conclude that the more accurate π^0 cross section below 2 GeV doesn't evidently change the γ-ray flux even low energy neutral pions could produce a broad γ-ray energy distribution. By investigating the π^0 and γ populations due to proton energy contribution, the overall γ flux is

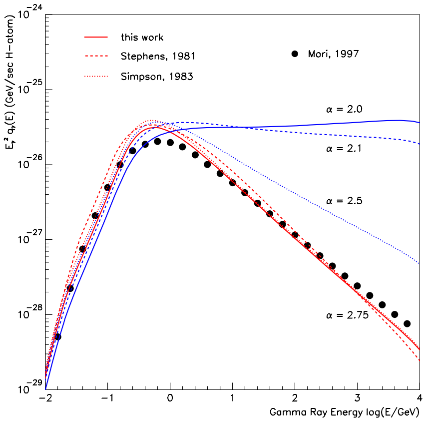

Fig. 1. *The emissivities of π^0-decay γ-rays calculated by using different π^0 production cross sections [6, 10] corresponding to the median proton flux [7], as compared with the calculations by Mori [7], whose data are shown as full dots. The γ-ray emissivities corresponding a simple power-law proton flux with indices, from top to bottom, $\alpha = 2.0,\ 2.1,\ 2.5$ and 2.75, are also calculated as indicated in the figure. See the text for discussions.*

contributed by protons with energies above few GeV. Fig. 1. also shows different γ-ray flux generated by CR proton spectra of a simple power-law $\propto E_p^{-\alpha}$, with $\alpha = 2.0,\ 2.1$ and 2.5 for comparison. The CR proton energy spectra have been normalised to the same CR energy density $\rho_E \approx 1$ eV/cm^3. The γ-ray spectrum from π^0 decays is seen to attain a power-law above few GeV.

The γ-ray flux from π^0 decays is also calculated in comparison with the observed bump of diffuse γ-ray radiation at GeV range:

$$J_\gamma(E_\gamma) = \int \frac{q_\gamma(\boldsymbol{r}, E_\gamma)}{4\pi} dl_d \approx \frac{\overline{q_\gamma}(E_\gamma)}{4\pi} l_d \tag{3}$$

where l_d is the characteristic line-of-sight depth of the emission region and is taken as the typical Galactic radius, $l_d \simeq 15$ kpc. Fig. 2. shows the γ-ray flux from π^0 decays generated by simple power-law proton energy spectra with indices $\alpha = 2.4,\ 2.5$ and 2.6, and with CR-gas coefficient $\rho_E N_H = \rho_E n_H l_d \simeq 3.4 \times 10^{-22}$ eV/cm^5, for which, N_H stands for the gas column density. It is seen that a proton energy spectrum softer than $\alpha = 2.6$ fails to explain the observed diffuse γ-ray flux from the inner Galaxy at energies above 1 GeV, nor one harder than $\alpha = 2.4$. Based on the current calculation, a proton energy spectrum with a power-law spectral index $\alpha = 2.4 \sim 2.6$ could explain the spectral shape of the observed GeV bump in the diffuse γ-ray radiation.

4. Conclusions

A parametrised π^0 production cross section in *pp* collisions is verified with detail analysis. The observed γ-ray flux above sub-GeV is well reproduced. The proton flux with a spectral index $\alpha = 2.4 \sim 2.6$ is found appropriate for the explanation of the observed GeV bump in the diffuse γ-ray radiation.

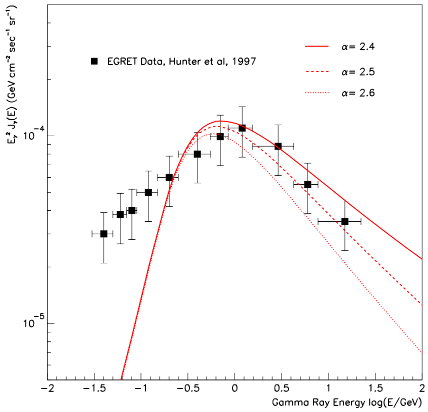

Fig. 2. *The γ-ray flux from π^0 decays calculated for CR proton energy spectrum corresponding to a simple power-law distribution with indices $\alpha = 2.4$, 2.5 and 2.6, compared with the EGRET data [16].*

Acknowledgements. The author would like to gratefully acknowledge F. A. Aharonian for his important comments and D. Horns for the useful discussions.

References

[1] Nishmura, J. et. al. 1980, ApJ 238, 394

[2] Aharonian, F. A., Atoyan, A. M., Völk, H. J. 1995, A&A 294, L41

[3] Erlykin, A. D., Lipski, M., Wolfendale, A. W. 1998, Astropart. Phys. 8, 283

[4] Aharonian, F. A., Atoyan, A. M. 2000, A&A 362, 937

[5] Dermer, C. D. 1986, ApJ 307, 47

[6] Stephens, S. A., Badhwar, G. D. 1981, Astrophys. Space. Sci. 76, 213

[7] Mori, M. 1997, ApJ 478, 225

[8] Blattnig, S. R. et al, 2000, Phys. Rev. D 62, 094030

[9] Jaeger, K. et al. 1975, Phys. Rev. D 11, 1756

[10] Büsser, F. W. et al. 1976. Nucl. Phys. B106, 1

[11] Lipkin, H. J., Peshkin, M. 1972, Phys. Rev. Lett. 28, 862

[12] Stecker, F. W. 1970, Astrophys. Space Sci. 6, 377

[13] Dermer, C. D. 1986, A&A 157, 223

[14] Gaisser, T. K., Shaefer, R. K. 1992, ApJ 394, 174

[15] Simspon, J. A. 1983, Ann. Rev. Nucl. part. Phys. 33, 323

[16] Hunter, S. D. et. al. 1997, ApJ 481, 205