

# Gamma Rays as Probe of Primary Hadronic Cosmic Rays

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The  $\gamma$ -ray energy spectrum from decays of neutral secondary particles ( $\pi^0$ 's,  $K^0$ 's and  $\Sigma^0$ 's) produced by CR protons interacting the ambient gas is calculated by the simulation tool DPMJET-III. The contribution of  $\gamma$ 's directly produced in hadronic collisions is also included and is found of importance for spectral component below 1 GeV. It is found that the  $\gamma$ -ray spectrum from neutral secondary decays has a strong representative of the generating proton spectrum thus is a good probe for the hadronic component in CRs. It is also found that  $\gamma$ -rays from these resources generated by CR protons, with or without an energy cutoff, can be interpreted by a similar function as protons, with an cutoff energy of about 0.13 of the proton cutoff energy.

## 1. Introduction

It is generally believed that the diffuse galactic  $\gamma$ -rays should be a better probe for the production sites and the acceleration sites of charged CRs in the Galactic disk than other charged particles themselves in CRs. Among the three distinguished regimes of diffuse Galactic  $\gamma$ -rays [1, 2, 3, 4], the  $\gamma$  component from the neural  $\pi^0$  decays is supposed to be more reliably determined than the bremsstrahlung and the Inverse Compton (IC) scattering processes between GeV and sub-TeV range, because, only the  $\gamma$ -ray component from  $\pi^0$  decays carries the information about the hadronic component in CRs.

In this article, the  $\gamma$ -ray component from  $\pi^0$  decays is carefully investigated by the simulation tool DPMJET-III [5]. The  $\gamma$ -ray energy spectra from the decays of secondary  $\pi^0$ 's produced by CR protons with ambient gas are then calculated with different proton spectra. For the consideration of more realistic physical processes, the  $\gamma$ -rays originating from the decays of  $K^0$ 's ( $K_L^0$ 's and  $K_S^0$ 's) and  $\Sigma^0$ 's are also considered. In addition, the inclusive  $\gamma$ -ray spectral component in  $p + p \rightarrow \gamma + X$  is investigated. Then the spectral characteristic of the  $\gamma$ -ray component from neutral secondary particle decays are investigated by introducing different CR proton spectra. The resultant  $\gamma$ -ray spectra are also calculated for the CR protons with an energy cutoff. A functional interpretation for  $\gamma$ -ray spectrum from these origins is finally introduced.

## 2. Neutral Secondaries ( $\pi^0$ , $K_L^0$ , $K_S^0$ , $\Sigma^0$ , $\gamma$ ) Produced in Nuclear Collisions

The  $\pi^0$  decays have contributed the most important component of CR-generated nucleonic  $\gamma$ -ray spectrum. Without worrying about the application limit discussed in the previous works [2, 6, 7, 8, 9, 10] for the isospin model [11], the scaling model [3] and the isobar model [2, 10, 12], the Monte Carlo event generator, DPMJET-III [5] is used to simulate the secondary particle production in nuclear collisions. It was reported [13] that this tool has reproduced agreeable atmospheric  $\gamma$ -ray spectra around 10 GeV at sea level and at balloon altitudes. In addition to  $\pi^0$  decays, the  $\gamma$ -rays from decays of secondary particles produced in different inclusive interaction channels are also considered:  $p + p \rightarrow (\pi^0, K_L^0/K_S^0, \Sigma^0) + X$ . The direct  $\gamma$ -rays produced in the hadronic collision  $p + p \rightarrow \gamma + X$  is also taken into account.

The simulation has reproduced the overall reliable distribution over the energy. Compared with the  $\pi^0$  data (see reference [3, 7, 14, 15] and reference therein), the simulated results for  $\pi^0$  production have shown an overall larger multiplicity. The excess is energy-dependent. For example, for energy around 100 GeV, the simulation shows about 1.3 times of data while at energy around TeV, the factor goes to about 1.4. This excess

in multiplicity also appears for antiprotons but in the case of antiprotons, the factor is very close to 1. This phenomenon could be viewed as the livetime and final produced particles considered in the simulation and the read-out of the angular distribution for the inclusive particles in accelerator experiments.

For the  $K_L^0/K_S^0$  and  $\Sigma^0$  production, the result shows that the energy spectra are very small relative to the  $\pi^0$  spectrum, with a factor less than 10% even at their maximum strength; below the particle energy of 1 GeV, the  $\pi^0$  energy spectrum is extremely larger than the others. This implies that, almost all low energy  $\gamma$ -rays must come from  $\pi^0$  decays. It is noted that  $\Sigma^0$ 's show a comparable energy spectrum with that of  $\pi^0$ 's around the maximum possible production energy. This implies that  $\Sigma^0$ 's will have comparable contribution to the tail of  $\gamma$ -ray spectrum from the decay process with  $\pi^0$ 's.

The inclusive  $\gamma$ -rays in process  $p + p \rightarrow \gamma + X$  have shown an overall larger energy spectrum than  $K_S^0$ 's,  $K_L^0$ 's and  $\Sigma^0$ 's; below the energy around 1 GeV, these  $\gamma$ 's show a factor of about 20% of the  $\pi^0$  energy spectrum. This implies that, for the resultant  $\gamma$ -ray spectrum, one cannot neglect this component at  $\gamma_E < 1$  GeV.

### 3. Gamma-Ray Spectrum from Neutral Secondary Particle Decays

The  $\gamma$ -ray spectrum from different decay channels of CR-generated products  $\pi^0$ ,  $K_S^0/K_L^0$  and  $\Sigma^0$  is calculated as the same approach for  $\pi^0$ 's [6] and the other decay modes [16]. The spectrum presents the same characteristics discussed previously [3, 6, 9, 12]. The calculated  $\gamma$ -ray spectrum corresponding to the median proton flux [4] shows agreeable results as the calculation [4] or by the delta function approximation [1] and by scaling model [3]. It shows no great deviation from the result from merely  $\pi^0$  decays calculated in previous work [6]. Thus, it suggests that, the  $\gamma$ -ray spectrum from  $\pi^0$  decay is an agreeable approximation for this issue.

For the recent interest in the diffusive shock acceleration of charged particles due to the cutoff region dependence on particle acceleration, energy dissipations and diffusion coefficients [17, 18, 19], the resultant  $\gamma$ -ray spectra from the pileup-like and sharp nail-like CR proton spectra are investigated. Fig. 1 Left shows some examples of the CR proton spectra: Curve 1 as the simple normalized power-law spectrum with the spectral index  $\alpha = 2.0$ ; Curve 2 as the spectrum with an exponential decrease with an energy cutoff  $E_p = 1$  TeV, i.e.,  $\frac{dN}{dE_p} \propto E_p^{-\alpha} \exp(-E_p/E_0)$ , with  $E_0 = 1$  TeV; Curves 3 and 4 as the power-law spectra but with sharp drops at some energies, i.e.,

$$\frac{dN}{dE_p} \propto \begin{cases} E_p^{-\alpha} & E_p \leq 1 \text{ TeV (Curve 3)}; 50 \text{ GeV} \leq E_p \leq 1 \text{ TeV (Curve 4)} \\ 0 & \text{else} \end{cases} \quad (1)$$

The pileup-like proton energy spectrum is written in form of

$$\frac{dN}{dE_p} \propto E_p^{-\alpha} \left[ 1 + \left( \frac{E_p}{E'} \right)^\delta \right] \exp \left[ - \left( \frac{E_p}{E_0} \right)^\Gamma \right] \quad (2)$$

with parameters  $\delta = 4.0$ , the cutoff energy  $E_0 = 1$  TeV,  $E' = 500$  GeV and  $\Gamma = 5$  as to get a sharp pileup spectrum. In this Figure, the CR proton spectra except the one with a simple power-law energy distribution are not normalized by the same CR energy density  $\rho_E \approx 1$  eV/cm<sup>3</sup> but amplified by the same leading factor and with  $\alpha = 2.0$ . Fig. 1 Right shows the resultant  $\gamma$ -ray spectra corresponding to each curve in Fig. 1 Left respectively. The result calculated for a power-law CR proton spectrum with  $\alpha = 2.5$  is shown for comparison.

In this figure, the  $\gamma$  spectrum still keeps the characteristic of the generating proton spectrum. For the power-law CR protons with a spectral index  $\alpha > 2.0$ , the emissivity  $E_\gamma^2 q_\gamma(E_\gamma)$  for each power-law proton spectrum has a maximum at  $E_\gamma \approx 1$  GeV; for  $\alpha = 2.0$ , the emissivity becomes quite flat above 1 GeV, but with a gradual

and exiguous increase with energy, resulting from the fact that the secondary product multiplicity in nuclear collisions increases with the incident proton energy. By observing the  $\gamma$ -ray spectra produced by CR protons with spectra described in (1), it is found that the most  $\gamma$  rays above 10 GeV are produced by CR protons with energies above 50 GeV while even higher energy protons don't show any drastic contribution to the  $\gamma$  rays with energies below 1 GeV, even for protons with a strong pileup in spectrum. It is also found that, a bump in  $\gamma$ -ray spectrum is seen for the calculation by a proton energy spectrum except the soft flat spectrum calculated from the power-law proton spectrum with  $\alpha = 2.0$ , even for those CR protons with stronger energy cutoffs. This might suggest that the bump in  $\gamma$ -rays comes from the most likely the incident proton spectral effect.

#### 4. Gamma-Ray Spectra Generated by Cosmic-Ray Protons with Energy Cutoffs

A strong spectral correlation is found between the secondary decay component in  $\gamma$ -rays and the generating CR protons. Since this component is more reliably determined than the bremsstrahlung and the IC component, one may propose to verify the CR proton spectrum by the  $\gamma$ -ray measurements in the current and future  $\gamma$ -ray experiments. Suppose the CR protons have a simple power-law energy distribution with an energy cutoff  $E_{cutoff}$ , then by the discussion in Section 3, one can also suppose the resultant  $\gamma$ -rays with an apparent energy cutoff. By the correlation discussed in Fig. 1, the  $\gamma$ -ray spectrum can therefore be interpreted by a similar form as

$$J_{\gamma}(E_{\gamma}) = \frac{dN_{\gamma}}{dE_{\gamma}} = AE_{\gamma}^{-(\alpha+\delta)} \exp \left[ - \left( \frac{E_{\gamma}}{E'_{\gamma}} \right)^{\Gamma} \right] \quad (\text{GeV sec sr cm}^2)^{-1} \quad (3)$$

where  $A$ ,  $\delta$ ,  $\Gamma$  and  $E'_{\gamma}$  are constants to be determined and  $E'_{\gamma}$  is the cutoff energy in  $\gamma$ -ray spectrum. Assume the generating protons with spectral indices  $\alpha = 2.0, 2.2, 2.4, 2.5$  and  $2.6$  and with an energy cutoff  $E_{cutoff} = 100$  TeV, then the constants in Eq. (3) are determined as  $(A, \delta, E'_{\gamma}) = (1.38 \times 10^{-4}, -0.009, 13000)$ , by setting  $\Gamma = 1$ . As expected, a softer  $\gamma$ -ray spectrum appears because of the energy increasing multiplicity of secondary particles. If one fits separately the values with the  $\gamma$ -ray spectrum in form (3) relative to each  $\alpha$ , the leading constant  $A$  can vary in the range between  $1.3 \times 10^{-4}$  and  $1.5 \times 10^{-4}$ . Nevertheless, it is possible to leave  $\Gamma$  in Eq. (3) as a free parameter. However, with a cutoff energy power  $\Gamma$  different from that in proton spectrum, there is no group of fixed constants, for which, the  $\gamma$ -ray spectrum expressed in (3) can individually fit well all values calculated by different  $\alpha$ . By considering CR proton spectra with different cutoff energies, the monomial form (3) can thus fit the calculated values, i.e.,

$$J_{\gamma}(E_{\gamma}) = \frac{dN_{\gamma}}{dE_{\gamma}} = (1.38^{+0.12}_{-0.08}) \times 10^{-4} E_{\gamma}^{-(\alpha-0.009)} \exp \left[ - \left( \frac{E_{\gamma}}{E'_{\gamma}} \right) \right] \quad (\text{GeV sec sr cm}^2)^{-1} \quad (4)$$

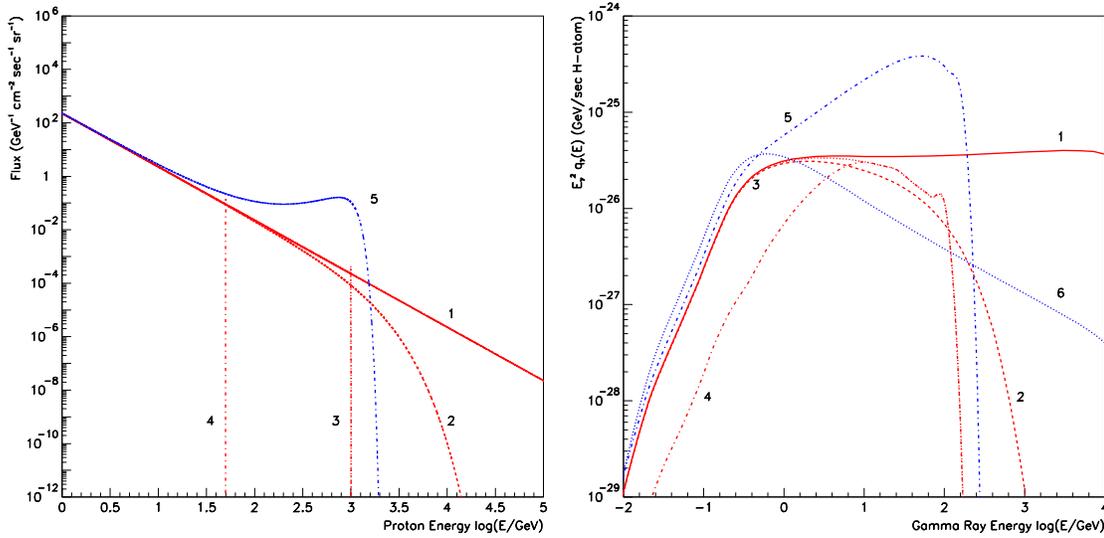
with the cutoff energy of  $\gamma$ -ray spectrum

$$E_{cutoff}(\gamma) = E'_{\gamma} \simeq 0.13 E_{cutoff}(p) \quad (5)$$

Thus, by the  $\gamma$ -ray spectrum in Eq. (4) and cutoff energy relation in Eq. (5), one can easily probe the CR proton spectrum by the  $\gamma$ -ray observations.

#### 5. Conclusions

The  $\gamma$ -ray spectrum from secondary particle decays is calculated by the simulation code DPMJET-III for the secondary particle production in nuclear collisions. A strong correlation between  $\gamma$ -ray spectrum contributed by decays of secondary particles and the generated CR proton spectrum is found. A functional expression for such  $\gamma$ -ray spectrum and the relation for their cutoff energies are suggested for the observations.



**Figure 1.** Left: Different CR proton spectra. Curve 1 shows the normalized power-law proton spectrum with  $\alpha = 2.0$ ; Curve 2 shows the power-law spectrum as Curve 1 but with an energy cutoff at  $E_p = 1$  TeV; Curve 3 shows the spectrum as Curve 1 but with a sharp spectrum drop at  $E_p = 1$  TeV respectively; Curve 4 shows the spectrum with two drops at  $E_p = 50$  GeV and at  $E_p = 1$  TeV respectively; Curve 5 shows the pileup-like spectrum described in form (2). Right: The emissivities of  $\gamma$ -rays from neutral secondary decays calculated by different CR proton spectra, corresponding to each curve shown in the left figure. The result from  $\alpha = 2.5$  is also shown in this figure (Curve 6) for comparison. See the text for discussion.

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