User's Note:

Hadronic Interaction by Using DPMJET and Production Matrix

Part II: Leptons

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Abstract

The note summarizes the work on secondary lepton productions in hadronic interactions by the same method to determine the γ-ray production matrix for the cosmic-ray hadronic interactions as published earlier [1], namely applying the Monte-Carlo event generator, DPMJET-III.

For the detail reference, please refer to the author's articles on γ-ray production [1], on lepton production [2]. A work manual for the γ-ray production in cosmic-ray hadronic interactions is also available [3].

1 Hadronic Interaction by Using DPMJET-III

1.1 cosmic-ray particles

For the cosmic ray study, proton-generating and helium-generating interactions are simulated.

1.2 ISM Composition

The target is the interstellar medium (ISM) which is considered as a compound of 90% of proton, 10% of helium, 0.02% of carbon and 0.04% of oxgen.

1.3 generating energy for cosmic-ray particles

The total energy of generating CR particles (p or α) is given from π production threshold to 10^8 GeV that is described as

$$E_T = 1.24 \cdot (1 + 0.05)^i \quad \text{GeV/n}; \quad i = \begin{cases} 1, 2 \cdots 374 \text{ for } p \\ 1, 2 \cdots 374 \text{ for } \alpha \end{cases} \tag{1}$$

for consideration of energy resolution.

1.4 Parametric Model for Low Generating Energy and Resonance contribution

As discovered in our earlier work on γ-ray production [1], DPMJET is unreliable below a few GeV collision energy. This results from the resonance region for which the nuclear cascades are not very much investigated. At these energies, we therefore combine the simulation results with parametric models for $\pi^{\pm}$ and π^0 production [4,5] that include the production of the resonances $\Delta(1232)$ and $\Delta(1600)$ and their subsequent decays.

Note that the parametric models for pion and resonance production at low incident energies is for pp interactions only. We then use DPMJET to calculate the energy-dependent weight factors, which allow us to parametrically account for p+ISM and He+ISM collisions in the parametrization approach, even though it is derived for pp collisions only. The weight factors carry no strong dependence on the energy of the projectile particle.

2 Multiplicity Distribution and Spectra of Secondary Products

2.1 stable secondary particles

All secondary particles produced in simulated hadronic interactions are recorded while running the event generator DPMJET-III. Their decay contribution to each stable lepton is calculated respectively. The following decay modes show all the decay processes of secondary products with leptons as the final decay particles, that are taken into account. Stable leptons considered in this work are $e^{\pm}$, ν_e, $\bar{\nu}_e$, ν_μ, and $\bar{\nu}_\mu$.

Note that the lifetime of neutrons is about 886 s, much shorter than the propagation time scale of cosmic-ray particles in the Galaxy. Therefore, the neutrons are treated as having decayed entirely in this work.

2.2 energy sampling of secondary particles

The multiplicity distribution $N(E)$ and the energy spectra $\frac{dn}{dE}$ of the secondary products are calculated and allocated into a certain energy bin defined below. Choose the binning in kinetic energy $E_{k,min} = 10^{-2}$ GeV and $E_{k,max} = 1 \times 10^{8}$ GeV divided by the bin number NoEbin=201. If a particle has a kinetic energy E_k, this energy will be located in the i^{th} bin defined as

$$i = \frac{[\log(E_k) - \log(E_{k,min})]}{DB_{log}} + 1 \tag{2}$$

where

$$DB_{log} = \frac{\log(E_{k,max}) - \log(E_{k,min})}{\text{NoEbin}} \tag{3}$$

with the bin terminal values

$$\log(E_{LHS}) = \log(E_{min}) + (i-1) \cdot DB_{log} \tag{4}$$
$$\log(E_{RHS}) = \log(E_{min}) + i \cdot DB_{log} \tag{5}$$

This particle is therefore characterized by the mean energy

$$\bar{E} = \sqrt{E_{LHS} \cdot E_{RHS}} \tag{6}$$

3 Decay Channels

The decay channels considered in this work are shown as follows.

- baryonic decays:

$$n \to p + e^- + \bar{\nu}_e,$$
$$\bar{n} \to \bar{p} + e^+ + \nu_e,$$
$$\Lambda \to \begin{cases} p + \pi^-, \\ n + \pi^0, \end{cases}$$

$$\bar{\Lambda} \to \begin{cases} \bar{p} + \pi^+, \\ \bar{n} + \pi^0, \end{cases}$$
$$\Sigma^0 \to \Lambda + \gamma,$$
$$\Sigma^+ \to \begin{cases} p + \pi^0, \\ n + \pi^+, \end{cases}$$
$$\Sigma^- \to n + \pi^-.$$

- mesonic decays:

$$\pi^+ \to \mu^+ + \nu_\mu,$$
$$\pi^- \to \mu^- + \bar{\nu}_\mu,$$
$$\pi^0 \to e^+ + e^- + \gamma,$$
$$K^+ \to \begin{cases} \mu^+ + \nu_\mu, \\ \pi^+ + \pi^0, \end{cases}$$
$$K^- \to \begin{cases} \mu^- + \bar{\nu}_\mu, \\ \pi^- + \pi^0, \end{cases}$$
$$K_S^0 \to \begin{cases} 2\pi^0, \\ \pi^- + \pi^+, \end{cases}$$
$$K_L^0 \to \begin{cases} 3\pi^0, \\ \pi^- + \pi^+ + \pi^0, \\ \pi^+ + e^- + \bar{\nu}_e, \\ \pi^- + e^+ + \nu_e, \\ \pi^+ + \mu^- + \bar{\nu}_\mu, \\ \pi^- + \mu^+ + \nu_\mu. \end{cases}$$

- leptonic decays:

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu,$$
$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu,$$
$$\tau^+ \to \begin{cases} \mu^+ + \nu_\mu + \bar{\nu}_\tau, \\ e^+ + \nu_e + \bar{\nu}_\tau, \end{cases}$$
$$\tau^- \to \begin{cases} \mu^- + \bar{\nu}_\mu + \nu_\tau, \\ e^- + \bar{\nu}_e + \nu_\tau, \end{cases}$$

Note some other decay channels of above decay parents are also possible. In this work they are neglected due to their relatively extremely small contributions.

For the two-body decay processes, the decay spectra are evaluated by particle kinematics; for the electrons/positrons from muon decays, the decay spectra are calculated by Lorentz transformation of the particle distribution in the center-of-mass system of the muon, which also includes the effect of the μ polarization [6]; for kaon decays and heavy nucleon decays, the Dalitz-plot distribution is applied. The values published in Particle Data Group are employed for the fraction of each individual decay process.

Note that contributions to e^-/e^+, $\nu_e/\bar{\nu}_e$, $\nu_\mu/\bar{\nu}_\mu$ and γ from resonance decays obtained from parametric models are finally added to the results simulated by DPMJET.

4 Particle Production Matrix

The differential production rate of a final secondary particle is given by

$$Q_{\rm 2nd}(E) = \frac{dn}{dt \cdot dE \cdot dV} = n_{ISM} \int_{E_{CR}} dE_{CR}\, N_{CR}(E_{CR})\, c\beta_{CR} \left(\sigma \frac{dn}{dE}\right) \quad (7)$$

with $N_{CR}(E_{CR}) = \frac{dn_{CR}}{dE_{CR} \cdot dV}$ (GeV cm^3)$^{-1}$ as the differential density of CR particles (p or α). The differential cross section of a secondary particle produced in (p,α)-ISM collisions is

$$\frac{d\sigma}{dE}(E_{CR}, E) = \sigma_{prod} \frac{dn}{dE} \quad (8)$$

where σ_{prod} is the inelastic production cross section, i.e., the sum of diffraction, non-diffraction and resonance components whose values are calculated by DPMJET and the parametric model; $\frac{dn}{dE}$ is the multiplicity spectrum of the secondary particle in question.

The final spectrum of the stable secondaries γ-rays, $e^\pm$, ν_e, $\bar{\nu}_e$, ν_μ and $\bar{\nu}_\mu$ as

$$Q_{\rm 2nd}(E_i) = \sum_k n_{ISM} \int_{E_{CR}} dE_{CR}\; N_{CR}(E_{CR})\, c\beta_{CR}\, \sigma(E_{CR})\, \frac{dn_{k,i}}{dE_i}(E_i, E_{CR}) \quad (9)$$

where $\frac{dn_{k,i}}{dE_i}$ is the multiplicity spectrum of stable particle species i resulting from production channel k, either an unstable secondary or direct production. For binned particle spectra, the production integral can be re-written as

$$Q_{\rm 2nd}(E_i) = \sum_j n_{ISM}\, \Delta E_j\; N_{CR}(E_j)\, c\beta_j\, \sigma(E_j)\; \sum_k \frac{dn_{k,i}}{dE_i}(E_i, E_j) \tag{10}$$

$$= \sum_j n_{ISM}\, \Delta E_j\, N_{CR}(E_j)\, c\beta_j\, \sigma_j\, \mathbb{M}_{ij} \tag{11}$$

for the secondary particle of interest. The production matrix $\mathbb{M}_{ij}$ that describes the production spectrum of the stable secondary particles, one for each, for arbitrary cosmic-ray spectra, separately for protons and Helium nuclei.

The production matrix for each stable secondary particle is available for download on the website *http://cherenkov.physics.iastate.edu/lepton-prod/*.

References

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