User's Note:

Hadronic Interaction by Using DPMJET and Production Matrix

Part I: Gamma-Rays

C. Y. Huang

Department of Physics and Astronomy, Iowa State University, Ames IA 50011
Tel: (515)294-5062; Fax: (515)294-3747; Email: huangc@iastate.edu

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Abstract

The note summarizes the work on hadronic interactions by using the simulation tool DPMJET-III (DPMJET3.04 [1]) and secondary production as well as the decay products which are used in the cosmic ray propagation.

1 Hadronic Interaction by using DPMJET-III

(1) For the cosmic ray study, proton-generating and helium-generating interactions are simulated.
(2) 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.
(3) The generating energy of CR particles (p or α) is given by

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

for consideration of energy resolution.

[1] DPMJET-III has two different versions. DPMJET3.04 is older in which, the immediate decays to γ from produced secondaries are not considered while DPMJET3.04c, a revised version, has taken into account the immediate γ-decays from, for example, π^0, Σ^0 etc., in the intranuclear cascades.

2 Multiplicity Distribution and Spectra of Secondary Products

(1) The following secondary products in hadronic interactions are recorded while running DPMJET:
baryon - $p,\ \bar{p},\ n,\ \bar{n},\ \Lambda,\ \bar{\Lambda},\ \Sigma^{\pm},\ \Sigma^{0}$
meson - $\pi^{\pm},\ \pi^{0},\ K^{\pm},\ K_S^0,\ K_L^0$
lepton - $e^{\pm},\ \nu_e,\ \bar{\nu_e},\ \mu^{\pm}$
photon - γ

(2) 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 $E_{k,min} = 0.01$ 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) High Energy event generators are not likely to provide reliable results at low energies. This corresponds to the resonance region for which the nuclear cascades are not very much investigated. Based on the multiplicity distributions for secondary products generated by DPMJET-III, it is discovered that below 4 GeV, DPMJET cannot provide reliable structures. Thus, the parametrization approach [1] is applied to evaluate the spectra of π^0 and $\pi^{\pm}$ for $p+p$ collisions at low energies. At energies between 2 and 4 GeV, the transition between the parametrization and DPMJET is applied. A scaling approach is applied to the spectra evaluated by parametrization for $p+p$ collisions to $p+ISM$ collisions, by investigating the correspondence between the production cross section and the incident energy.

3 Particle Decay

(1) Decay processes are considered for those particles whose lifetime is comparatively shorter than the time scale in cosmic ray propagation.
(2) Decay channels are taken into account by isobar theory [2], Dalitz distribution [3] and Particle Data Group [4].
(3) After considering the decay modes shown in Section 4, only 9 stable particles finally survive from the decays and propagation. These particles are $p,\ \bar{p},\ e^{\pm},\ \nu_e,\ \bar{\nu}_e, \nu_\mu,\ \bar{\nu}_\mu$ and γ.
(4) For each stable particle, a matrix showing its energy spectrum is created by including all generating energies.

4 Decay Channels

This work has considered the resonance production near pion production threshold.

The decay modes and decay fractions for resonances are considered as follows based on the Particle Data Group [4].

$\Delta(1232) \rightarrow p + \pi^0$;
$\Delta(1600) \rightarrow p + \pi^0$;
$\Delta(1600) \rightarrow \Delta(1232) + \pi^0$;
$\Delta(1600) \rightarrow \mathrm{N}(1440) + \pi^0$;
$\mathrm{N}(1440) \rightarrow p + \pi^0$;
$\mathrm{N}(1440) \rightarrow \Delta(1232) + \pi^0$;
$\mathrm{N}(1440) \rightarrow p + 2\pi^0$.

The π^0 contribution from resonances is then added to the non-resonant π^0 production.

For the other secondary products, the following decay modes are considered in this work.

(1) baryonic decays:

$$\begin{cases} n \rightarrow p + e^- + \bar{\nu}_e \\ \bar{n} \rightarrow \bar{p} + e^+ + \nu_e \end{cases} \tag{7}$$

$$\begin{cases} \Lambda \rightarrow p + \pi^- \\ \Lambda \rightarrow n + \pi^0 \end{cases} \tag{8}$$

$$\begin{cases} \bar{\Lambda} \to \bar{p} + \pi^+ \\ \bar{\Lambda} \to \bar{n} + \pi^0 \end{cases} \tag{9}$$

$$\Sigma^0 \to \Lambda + \gamma \tag{10}$$

$$\begin{cases} \Sigma^+ \to p + \pi^0 \\ \Sigma^+ \to n + \pi^+ \end{cases} \tag{11}$$

$$\Sigma^- \to n + \pi^- \tag{12}$$

(2) mesonic decays:

$$\begin{cases} \pi^+ \to \mu^+ + \nu_\mu \\ \pi^- \to \mu^- + \bar{\nu}_\mu \end{cases} \tag{13}$$

$$\begin{cases} \pi^0 \to 2\gamma \\ \pi^0 \to e^- + e^+ + \gamma \end{cases} \tag{14}$$

$$\begin{cases} K^+ \to \mu^+ + \nu_\mu \\ K^+ \to \pi^+ + \pi^0 \end{cases} \tag{15}$$

$$\begin{cases} K^- \to \mu^- + \bar{\nu}_\mu \\ K^- \to \pi^- + \pi^0 \end{cases} \tag{16}$$

$$\begin{cases} K^0_S \to 2\pi^0 \\ K^0_S \to \pi^+ + \pi^- \end{cases} \tag{17}$$

$$
\begin{cases}
K_L^0 \rightarrow 3\pi^0 \\
K_L^0 \rightarrow \pi^+ + \pi^- + \pi^0 \\
K_L^0 \rightarrow \begin{cases} \pi^+ + e^- + \bar{\nu}_e \\ \pi^- + e^+ + \nu_e \end{cases} \\
K_L^0 \rightarrow \begin{cases} \pi^+ + \mu^- + \bar{\nu}_\mu \\ \pi^- + \mu^+ + \nu_\mu \end{cases}
\end{cases} \tag{18}
$$

(3) leptonic decays:

$$
\begin{cases}
\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \\
\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu
\end{cases} \tag{19}
$$

(4) No η meson is shown in DPMJET read-out table. However, η should exist if looking into the intranuclear cascades during the DPMJET simulation. Nevertheless, these η-mesons are with very short lifetime: with full width $\Gamma \approx 1.18$ keV, i.e., mean life $\tau \approx 5.58 \times 10^{-19}$ sec.[2] With such short lifetime, η-mesons are supposed to decay quickly to other particles principally via the decay modes:

$$
\begin{aligned}
&\eta \rightarrow 2\gamma \\
&\eta \rightarrow 3\pi^0 \\
&\eta \rightarrow \pi^+ + \pi^- + \pi^0 \\
&\eta \rightarrow \pi^+ + \pi^- + \gamma
\end{aligned}
$$

There is also a very small contribution to electron/positron pair from η-decay via

$$
\eta \rightarrow e^- + e^+ + \gamma
$$

with a fraction $\Gamma_i/\Gamma = 4.9 \times 10^{-3}$. Combining the secondary η-spectrum calculated with SIBYLL [5] and the η decay modes, it coincides the read-out e^-/e^+ pair in DPMJET simulation at different energies. That is to say, the η-mesons produces in the hadronics collisions are considered to decay quickly in DPMJET simulation thus are not shown in the read-out tables. Conclusively, it is strongly believed that the read-out e^-, e^+, γ , π^+, π^-, π^0 are actually composed of contribution of η-decays.

(5) No τ lepton is reported in DPMJET-III. τ has the mean life $\tau \approx 290 \times 10^{-15}$ sec. Once τ leptons are produced in DPMJET simulation, they can decay very quickly to μ and e leptons and neutrinos. If τ leptons exist in DPMJET simulation and the decays take place immediately after

[2] For π^0, $\tau \approx 8.4 \times 10^{-17}$ sec.

their production, there should also exist some ν_τ and $\bar{\nu}_\tau$. However, in the DPMJET read-out tables, no τ-neutrinos are found.

5 Particle Production Matrix

(1) The differential cross section of a secondary particle produced in the $(p, \alpha) + ISM$ collision is described as

$$\frac{d\sigma}{dE}(E_{CR}, E) = \sigma_{inel}\frac{dn}{dE} \tag{20}$$

where σ_{inel} is in unit of mb and is represented in a matrix $\sigma_{prod}(E_{CR}, p/\alpha + ISM)$, in title of 'prodxsection.matrix.data'.

(2) In this work, $\frac{dn}{dE}$ is calculated as the resultant of the direct production in hadronic collisions and also the component contributed in the decays from its parent particles.

(3) All energy is defined in GeV. Thus, the energy spectrum is in unit of 1/GeV.

(4) Thus, after considering the hadronic collisions and the decays, the spectrum of a final secondary particle can be described as

$$Q_{2nd}(E) = \frac{dn}{dt \cdot dE \cdot dV} = n_{ISM}\int dE_{CR}N_{CR}(E_{CR})c\beta_{CR}\left(\sigma\frac{dn}{dE}\right) \tag{21}$$

where $N_{CR}(E_{CR}) = \frac{dn_{CR}}{dE_{CR} \cdot dV}$ (GeV cm^3)$^{-1}$ defined as the differential density of CR particles (p or α).

(5) Eq. (21) can be changed to

$$Q_{2nd}(E) = n_{ISM}\sum_{E_{CR}} \Delta E_{CR} \cdot N_{CR}(E_{CR}) \cdot c\beta_{CR} \cdot \sigma(E_{CR}) \cdot \frac{dn}{dE} \tag{22}$$

where E_{CR} is given by Eq. (1); σ and $\frac{dn}{dE}$ are given in matrix forms.

(6) The element of the energy spectrum matrix, $\mathbf{M}_{ij}$, with $i = 1, 2 \cdots 201$ for the particle energy in the defined energy bin (see formula (6)), $j = 1, 2 \cdots$ for the generating CR energy defined in formula (1), shows the value of the resultant particle energy spectrum $\frac{dn}{dE}|_{E=E_i, E_{CR}=E_j}$.

(7) Matrices for multiplicity distribution in function of particle energy corresponding to the generating energy is also available.

(8) Each matrix appears in arrangement as spectrum (or multiplicity), particle type, decay, generating particle, matrix, and data.

(9) file 'espectra_gamma.decay.p.matrix.pion0.data' means the matrix of the γ-ray energy spectrum contributed by decays of π^0 in p-generating interactions;

(10) file 'espectra_gamma.direct.p.matrix.data' menas matrix for the directly produced γ-rays in p-generating interactions;

(11) file 'espectra_gamma.p.matrix.data' menas matrix for the matrox of total γ-ray energy spectrum in p-generating interactions;
(12) The matrices are stored in ragnar:/home/data/hadronproduction/CRpHe.

For detailed discussion, please refer to the article: *Gamma-Rays Produced in Cosmic-Ray Interactions and the TeV-band Spectrum of RX J1713-3946*, by C.-Y. Huang, S.-E. Park, M. Pohl and C. D. Daniels [6].

References

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