Nuclear enhancement factor in calculation of Galactic diffuse gamma-rays: A new estimate with DPMJET-3

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Abstract
A new calculation of nuclear enhancement factor, used in estimation of Galactic diffuse gamma-ray flux from proton-proton interaction in order to take account of heavy nuclei included in cosmic-rays and interstellar matter, is presented by use of a Monte Carlo simulator, DPMJET-3. A new value of 1.8–2.0 in the energy range of 6–1000 GeV/nucleon, slightly increasing with kinetic energy of projectile cosmic rays, is about 20% larger than previous estimates.

Key words: gamma-rays; cosmic-rays; interstellar matter

1. Introduction

Majority of cosmic gamma-rays observed by EGRET onboard the Compton gamma-ray observatory concentrate around the Galactic plane, and they are known as Galactic diffuse gamma-rays \[1\]. Gamma-ray point sources near the Galactic plane are observed above this diffuse ‘background’ gamma-rays, and the diffuse emission model based on high-energy particle interaction with interstellar matter/field is extremely important for the analysis of gamma-ray emitting objects in the Universe.

The dominant component of Galactic diffuse gamma-rays above 100 MeV is well explained by decay gamma-rays from neutral pions generated in nuclear interaction of high-energy cosmic-rays and interstellar matter \[2,3\].

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In calculation of this process, most authors have computed gamma-ray flux generated by neutral pion decay which is produced in high-energy proton interaction on proton target (see Kamae et al. [4] for the most recent calculation). Actually, there are heavy nuclei both in cosmic-rays and target matter. This fact is taken into account by introducing a nuclear enhancement factor, $\epsilon_M$, to be multiplied to the result of gamma-ray yield assuming cosmic-ray protons on proton target only. Previous estimates are as follows: $\sim 2.0$ by Stecker [5], 1.5 by Cavallo and Gould [6], 1.6 ± 0.1 by Stephens and Badhwar [7], 1.45 by Dermer [8], $1.52 + \max(1, (T_p/100 \text{ GeV})^{0.12})$ by Mori [9], where $T_p$ stands for kinetic energy of cosmic-ray proton. Mori [9] used the low-energy value of 1.52 given by Gaisser and Shaefer [10] derived for calculation of cosmic antiproton flux without a factor related only to propagation, and took the spectral difference of heavier nuclei into account.

Later, Simon, Molner and Roesler [12] calculated interstellar secondary antiproton flux with a Monte Carlo model, DTUNUC, to study contributions to the antiproton flux from $p$-nucleus, nucleus-$p$ and nucleus-nucleus collisions. They gave the energy dependence on the nuclear enhancement factor (which they call ‘nuclear scaling factor’ in their paper) which differs significantly in low-energy region ($T_p < 10 \text{ GeV}$) from a constant value as given by Gaisser and Shaefer [10]. The situation is similar to the case of Galactic diffuse gamma-rays, and we need detailed calculation of nuclear effect taking account of energy dependence for the new era of gamma-ray astronomy with a launch of Fermi (formerly called GLAST) gamma-ray space telescope in June 2008 [11].

Here we use a Monte Carlo model, DPMJET-3 [13], which is an updated version of DTUNUC, to calculate a nuclear enhancement factor for the Galactic diffuse gamma-ray flux.

2. Calculation

We calculated gamma-ray yield from $p$-nucleus, nucleus-$p$ and nucleus-nucleus collisions using DPMJET-3. It is a Monte Carlo model capable of simulating hadron-hadron, hadron-nucleus, nucleus-nucleus, from a few GeV

\(^1\)Recently, Huang et al. calculated gamma-ray yield from $(p, \alpha)$+(interstellar matter) interactions using the same Monte Carlo model [14], but their results are given as final spectra and the nuclear effect on the gamma-ray production was not explicitly discussed in their paper.
Table 1: Multiplication factor at $T=10$ GeV/nucleon. G&S is quoted from ref.[10].

| Nuclei     | $m_{ip}$  | $m_{i\alpha}$ |
|------------|-----------|----------------|
| H ($A=1$)  | (1)       | 3.81           |
| He ($A=4$) | 3.68      | 14.2           |
| CNO ($A=14$) | 11.7     | 42.5           |
| Mg-Si ($A=25$) | 20.3     | 73.2           |
| Fe ($A=56$) | 38.8      | 142            |

up to the highest cosmic-ray energies, and has been successfully applied to the description of hadron production in high-energy collisions [13]. To check our calculation with this model, “multiplication factor”, $m_{ip}$ and $m_{i\alpha}$ for proton and Helium target, respectively, given in Gaisser and Schaefer [10], was recalculated for $T = 10$ GeV where $T$ is a kinetic energy per nucleon. This is a relative yield of gamma-rays from nucleus-$p$ and nucleus-Helium collisions compared with that from $p$-$p$ collisions, and is defined as $m_{ip} \equiv (\sigma_{ip}/\sigma_{pp})(\langle n_{\gamma,ip}\rangle/\langle n_{\gamma,pp}\rangle)$ and similarly for $m_{i\alpha}$, where $\sigma_{ip}$ ($\sigma_{pp}$) and $\langle n_{\gamma,ip}\rangle$ ($\langle n_{\gamma,pp}\rangle$) are a production cross section and an average number of gamma-rays produced in nucleus-$p$ ($p$-$p$) collision, respectively. The results are given in Table 1. For each entry, 20,000 collisions were generated. Reasonable agreement is seen, and in fact, using the flux values at 10 GeV/nucleon, nuclear enhancement factor can be calculated as

$$\epsilon_M = 1 + \sum_i m_{ip} \frac{\phi_i(T)}{\phi_p(T)} + \sum_i m_{i\alpha} \frac{\phi_i(T)}{\phi_p(T)} \times \frac{r}{1-r} = 1.52$$

and is close to 1.52, the value given by Gaisser and Schaefer [10], assuming the interstellar matter abundance and cosmic-ray composition given by ref.[10] (with the fraction of Helium in interstellar matter $r = 0.07$). Thus the low-energy value of the nuclear enhancement factor changes little by use of modern nuclear interaction model.

Figure 1 shows the energy dependence of multiplication factor. Due to limitations of the DPMJET-3 model, calculations below about 5 GeV/nucleon produce errors and we stop calculations there. Table 2 shows multiplication factors for heavy target nuclei calculated using DPMJET-3. Note the approximate symmetry between projectile and target nuclei (ex. $p$-Fe vs. Fe-$p$).
Figure 1: Energy dependence of multiplication factor for various combination of projectile-target nuclei.

Table 2: Multiplication factor at $T=10$ GeV/nucleon for heavy nuclei target.

| Projectile nuclei | Target nuclei |
|-------------------|---------------|
|                   | CNO     | MgSi    | Fe     |
| H ($A=1$)         | 11.6    | 20.1    | 38.9   |
| He ($A=4$)        | 42.3    | 73.4    | 143.1  |
| CNO ($A=14$)      | 120.6   | 204.2   | 386.3  |
| Mg-Si ($A=25$)    | 204.2   | 343.1   | 628.8  |
| Fe ($A=56$)       | 384.4   | 634.0   | 1067   |
Next, we explore other elements of nuclear enhancement factor: cosmic-ray spectra and composition of interstellar matter.

The primary cosmic-ray spectra, \( \phi_i(T) \), are summarized in empirical formulas by Honda, Kajita, Kasahara and Midorikawa (2004) \cite{15}:

\[
\phi_i(T) = K(T + b \exp(-c\sqrt{T}))^{-\alpha} \quad [\text{m}^{-2}\text{s}^{-1}\text{sr}^{-1}]
\]

with parameters \( \alpha, K, b \) and \( c \) tabulated in Table 3, where cosmic-ray nuclei are divided into five groups. If we use these spectra, the nuclear enhancement factor is calculated to be 1.66 at 10 GeV/nucleon, about 10% larger than that by Ref.\cite{10}.

As for the composition of interstellar medium, Meyer summarizes elemental abundances in local Galactic interstellar media in detail \cite{16}. In his Table 2 the He/H ratio is 0.096\footnote{This ratio is also consistent with the average of abundance in interstellar gas in various objects tabulated in Table 21.9 of Ref.\cite{17}, 0.096 \pm 0.07 (omitting 30 Dor and Crab which shows extra values).} which is significantly larger than 0.07/0.93 = 0.075 assumed in Gaisser and Shaefer \cite{10}. This fact leads to a further larger value of \( \epsilon_M \). Numerically, if we use relative abundance of H:He:CNO:NeMgSiS:Fe= 1 : 0.096 : 1.38 \times 10^{-3} : 2.11 \times 10^{-4} : 3.25 \times 10^{-5} following the compilation by Meyer \cite{16}. Then we obtain the nuclear enhance factor at 10 GeV/nucleon:

\[
\epsilon_M = 1 + \epsilon(H) + \epsilon(\text{He}) + \epsilon(\text{CNO}) + \epsilon(\text{NeMgSiS}) + \epsilon(\text{Fe}) = 1.84
\]
difference resides in abundance of Helium in cosmic-ray flux and interstellar medium. Table 4 shows the contribution of each component to the nuclear enhancement factor.

Fig. 2 shows the energy dependence of the nuclear enhancement factor including contributions from each ISM abundance. The total factor is also tabulated in Table 5. Although it is nearly constant above about 10 GeV/nucleon, it decreases gradually toward lower energies. However, the calculation is limited above above 5 GeV/nucleon, again due to the limitation of DPMJET-3.

3. Conclusion

Nuclear enhancement factor used in models of the Galactic diffuse gamma-rays from cosmic-ray and interstellar matter interaction has been calculated by use of a Monte Carlo simulator, DPMJET-3. A new value of 1.8–2.0,
Table 4: Nuclear enhancement factor decomposed to each component at 10 GeV/nucleon.

| Target | H    | He   | CNO  | NeMgSi | Fe   | Sum  |
|--------|------|------|------|--------|------|------|
| Projectile |      |      |      |        |      |      |
| H      | 1    | 0.405| 0.0177| 0.0047 | 0.0006| 1.288|
| He     | 0.203| 0.083| 0.0036| 0.0035 | 0.0004| 0.520|
| CNO    | 0.038| 0.015| 0.0006| 0.0018 | 0.0002| 0.023|
| MgSi   | 0.033| 0.013| 0.0005| 0.0026 | 0.0003| 0.0147|
| Fe     | 0.014| 0.006| 0.0002| 0.0021 | 0.0002| 0.0017|
| Sum    | 1.288| 0.520| 0.023 | 0.0147 | 0.0017| 1.845|

Table 5: Energy dependence of nuclear enhancement factor.

| Kinetic energy (GeV/nucleon) | 6.31 | 7.94 | 10.0 | 100 | 1000 |
|------------------------------|------|------|------|-----|------|
| Nuclear enhancement factor   | 1.75 | 1.84 | 1.84 | 1.89| 2.00 |

slightly increasing with kinetic energy of projectile cosmic rays in the range 6–1000 GeV/nucleon, is about 20% larger than previous estimates. This factor could have a larger energy dependence below 5 GeV/nucleon where DPMJET-3 is not applicable (see Simon et al. [12] for the case of antiproton production), but we do not have a proper tool to treat that energy region.

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