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Fluxes of γ rays, antiprotons and deuterons in cosmic rays

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Abstract. We present calculations on the fluxes of secondary particles with energies greater than 10 GeV arising from the collisions of primary cosmic rays with interstellar matter. The present calculations are based on the parametrization of the accelerator data on production cross sections of $\pi^{\pm}$, $\bar{p}$ and deuterons in proton–proton collisions up to 1500 GeV as a function of rapidity variable for different transverse momenta of the particle produced. The following results have been obtained for the fluxes at the top of the Earth's atmosphere: (i) the flux of γ rays with energies greater than 10 GeV in the direction of the galactic centre is nearly 10^{-4} of the primary proton flux; (ii) the ratio of antiproton to proton flux is $(2\text{–}3)\times10^{-4}$; and (iii) the deuteron flux from p–p collisions is negligible compared to that from the fragmentation of α particles and the latter can account for the experimental estimate of deuteron to proton flux.

1. Introduction

Measurements of the fluxes of γ rays, antiprotons and deuterons in cosmic rays are of astrophysical importance. These components of cosmic rays presumably arise predominantly as secondary radiation due to interaction or fragmentation of nuclear components (protons, α particles, etc) in the interstellar and intergalactic regions. Let us first summarize the various attempts that have been made to determine these fluxes. The integral flux of γ rays has been measured for energies greater than 100 MeV using satellites (Kraushaar *et al* 1972). Searches for antiprotons have been made (Fanselow *et al* 1968, Brooke and Wolfendale 1964, Bogomolov *et al* 1970, 1971) up to an energy of 5 GeV and an upper limit of 6×10^{-3} is obtained for the ratio of antiproton to proton flux. Searches for deuterons (Weber and Ormes 1963, Hasegawa *et al* 1963, Ganguli *et al* 1967, Appa Rao 1973) in the primary cosmic rays have also been made and probably they constitute about 2 to 5% of the proton flux at energies greater than 0·7 GeV. Recently, an indirect estimate of the deuteron flux has been made (Ganguli *et al* 1974) from the results of satellite experiments of Akimov *et al* (1970). It is concluded that the relative abundance of deuterons with respect to primary protons is $(-2\cdot0\pm2\cdot0)$% in the total energy range of 20 to 60 GeV, whereas it is (15 ± 4)% in the total energy range of 200 to 600 GeV. Thus there is some knowledge about these fluxes in the primary cosmic rays. There also exist several estimates for these components as secondary radiation, namely, the fluxes of γ rays and $\bar{p}$ from the interactions of primary protons with interstellar matter (Ginzburg and Syrovatskii 1964, Rosen 1967, Shen and Berkly 1968, Wayland and Bowen 1968, Stecker 1971, 1973, Gaisser and Maurer 1973) and deuterons from fragmentation of primary α particles (Meyer 1971). The methods adopted to estimate these fluxes are different for different components and excepting that of Gaisser and Maurer are based upon assumptions regarding the energy dependence of collision parameters like inelasticity, multiplicity, transverse momentum distribution etc. In this paper we present a model-independent method which can be used for calculating any type of secondary particle fluxes from proton–proton collisions.

The present calculation is based on the experimentally observed production cross section of $\pi^{\pm}$, $\bar{p}$ and to some extent $\bar{d}$ (and d) in proton–proton collisions up to 1500 GeV, as a function of rapidity of the particle produced. The advantage of the rapidity variable is twofold: (i) its additivity property regarding transformation from laboratory to centre of mass (CM) system and vice versa; and (ii) its approximate factorization property with respect to transverse momentum. The details of the calculation are described in § 2. The results of the calculation on fluxes are presented in § 3. Finally we present a summary in § 4.

2. Details of the calculation

The inclusive reaction for the production of particle C in collisions of primary cosmic ray protons with interstellar hydrogen can be written as:

$$\mathrm{p}+\mathrm{p}\rightarrow C+X \tag{1}$$

where X stands for 'anything' produced along with particle C. The particle C, in our present case, will be either π^0, $\bar{p}$ or d ($\bar{d}$). As the production cross sections are much better known for $\pi^{\pm}$ than for π^0, we shall derive information for π^0 from the average behaviour of π^+ and π^-.

2.1. Rapidity variable

Rapidity variable is defined in a given Lorentz frame as:

$$Y=\tfrac{1}{2}\ln[(E+p_{\mathrm{L}})/(E-p_{\mathrm{L}})] \tag{2}$$

where Y is the rapidity of the particle under consideration, namely C of reaction (1), E and p_{L} are the total energy and longitudinal momentum of the particle C in the given Lorentz frame. Transformation of the rapidity from one Lorentz frame to another, namely laboratory to CM system is simply given by:

$$Y_{\mathrm{lab}}=Y_{\mathrm{CM}}+\ln[\bar{\gamma}(1+\bar{\beta})] \tag{3}$$

where Y_{lab} and Y_{CM} are the rapidities of particle C in the laboratory and CM system respectively, $\bar{\gamma}$ is the Lorentz factor of the CM system and $\ln[\bar{\gamma}(1+\bar{\beta})]$ is the rapidity of the incident particle in the CM system. This is the additivity property of rapidity.

The invariant cross section for the production of particle C, reaction (1), is a function of three variables which can be taken as s, Y and p_{T}:

$$E\frac{\mathrm{d}^3\sigma}{\mathrm{d}^3p}=f(s, Y, p_{\mathrm{T}}) \tag{4}$$

where E, Y and p_{T} are total energy, rapidity and transverse momentum of the particle C and s is the square of the total CM energy, $s=2m_{\mathrm{p}}(m_{\mathrm{p}}+E_{\mathrm{lab}})$, where m_{p} is the rest mass and E_{lab} is the total energy of the incident proton.

2.2. Fragments of target and projectile

In the CM system, fragments of the target move in the backward hemisphere (values of Y_{CM} are all negative) whereas the fragments of the projectile lie in the forward hemisphere (values of Y_{CM} are all positive). Since we are dealing with p–p collisions, there is a symmetry in the CM system. This symmetry is also reflected in the rapidity distribution. If Y_{inc} is the rapidity of the incident proton in the laboratory system, $Y_{inc}=2\ln[\bar{\gamma}(1+\bar{\beta})]$ where $\bar{\gamma}$ and $\bar{\beta}$ are the Lorentz factor and velocity of the CM system, the produced particle C will have symmetry in the rapidity distribution (i) in the CM system around zero rapidity; and (ii) in the laboratory system around $\frac{1}{2}Y_{inc}$, see equation (3) and figure 1. This property is very useful because it means that we need to parametrize only the Y distribution from the target fragmentation.

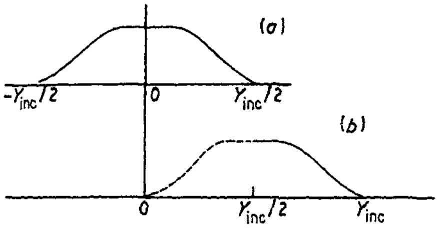

Figure 1. Sketch of a rapidity distribution of a produced particle in proton–proton collisions: (*a*) in the CM system; (*b*) in the laboratory system.

2.3. Factorization

The invariant cross section defined by equation (4) can be written as a product of two functions $g(Y)$ and $h(p_T)$; the dependence on s is taken care of through the parametrization of $g(Y)$. Thus we write

$$f(Y, p_T) = g(Y)h(p_T) \tag{5}$$

where $h(p_T)=\exp(-bp_T)$. This factorized form holds good (Rossi *et al* 1975) for $Y_{lab}\gtrsim 2$, whereas for $Y_{lab}<2$ it is approximately true. Nevertheless, this factorized form provides good results because for $Y_{lab}<2$ the cross section decreases rapidly.

In equation (5) the slopes of the p_T distribution are related to average value of p_T, $\langle p_T\rangle$, by:

$$b=2/\langle p_T\rangle \tag{6}$$

and the values for b are (Rossi *et al* 1975, Alper *et al* 1973a):

$$\begin{aligned} b_{\pi^+}&=6{\cdot}5\ (\mathrm{GeV}/c)^{-1}\\ b_{\pi^-}&=7{\cdot}0\ (\mathrm{GeV}/c)^{-1}\\ b_{p}=b_{\bar{p}}&=4{\cdot}0\ (\mathrm{GeV}/c)^{-1}\\ b_{d}\simeq b_{\bar{d}}&=2{\cdot}7\ (\mathrm{GeV}/c)^{-1}. \end{aligned} \tag{7}$$

2.4. Parametrization of laboratory distribution of $\pi^{\pm}$ and $\bar{p}$

The laboratory rapidity distributions of $\pi^{\pm}$ and $\bar{p}$ from p–p collisions are known for various p_T in the energy range 24 to 1500 GeV (Capiluppi *et al* 1974, Albrow *et al*

1973, Alper *et al* 1973b, Banner *et al* 1972, Allaby *et al* 1972, Blobel *et al* 1973). We show in figure 2 the $Y_{\rm lab}$ distribution for $\pi^{\pm}$ at $p_{\rm T} = 0{\cdot}4$ GeV/c; it is seen that the scaling is reasonably good up to 1500 GeV. On the other hand the $Y_{\rm lab}$ distribution of $\bar{\rm p}$, shown in figure 2, for $E_{\rm inc} = 24$ GeV is a little lower than the $Y_{\rm lab}$ distribution for $E_{\rm inc} > 200$ GeV, i.e. the scaling is not very good for $\bar{\rm p}$ production. Therefore, for the $\bar{\rm p}$ production we shall make two parametrizations of the rapidity distribution, one for energies below 50 GeV and another for energies above 50 GeV; for the former we shall use the measurements at 24 GeV whereas for the latter we shall use the data for $E_{\rm inc} > 200$ GeV.

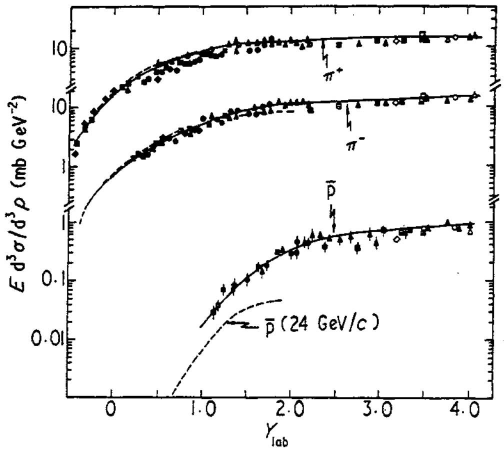

Figure 2. The invariant production cross sections of $\pi^{\pm}$ and antiprotons against laboratory rapidity are shown at $p_{\rm T} = 0{\cdot}4$ GeV/c. The full curves refer to the parametrization as described in the text. The data points are: ◆, ⊕ and ◇ for $\sqrt{s} = 23$ GeV; ■, ⊠, ⊡ and □ for $\sqrt{s} = 31$ GeV; ● and ○ for $\sqrt{s} = 45$ GeV; ▲, △ and △ for $\sqrt{s} = 53$ GeV; the broken lines refer to low energy data with $\sqrt{s} = 6{\cdot}8$ GeV. The fitted curve to the low energy data of $\bar{\rm p}$ is not shown because it overlaps with the broken curve.

The parametrization of the function $g(Y)$ (equation (5)) of the target fragmentation region is made as follows (in units of mb GeV^{-2})

$$g(Y) = A_1 \exp[-A_2/(z+Y)^{\alpha}] + A_3, \tag{8}$$

where z is a constant taken as 2 for $\pi^{\pm}$ and 0 for $\bar{\rm p}$ distributions. For large Y values this function reaches a plateau region as is also seen from the trend of the experimental data, see figure 2. We have made χ-squared fits to the data of $\pi^{\pm}$ and $\bar{\rm p}$ for $p_{\rm T}$ values in the range 0·2 to 0·8 GeV/c. The fitted values of the parameters are given in table 1; the value of χ^2/data point is approximately 4. The fitted curves to the invariant cross section at $p_{\rm T} = 0{\cdot}4$ are also shown in figure 2.

It should be mentioned that the uncertainty in the parametrization leads to 10 to 20% uncertainty in the pion flux and 20 to 30% uncertainty in the antiproton flux as determined in § 3.

2.5. *Laboratory rapidity distributions of* $\bar{\rm d}$(d)

The data on $\bar{\rm d}$ and d production in p–p collisions are extremely poor (Binon *et al* 1969.

Table 1. Values of the fitted parameter to the rapidity distributions of $\pi^{\pm}$ and $\bar{p}$.

Produced particles	A_1 (mb GeV^{-2})	A_2	A_3 (mb GeV^{-2})	α	Remark
π^-	252·5	74·9	0·03	3·90	—
π^+	183·8	197·9	4·3	5·32	—
$\bar{p}$	6·8	5·2	0·0	1·6	Energy > 200 GeV
$\bar{p}$	3·3	4·7	0·0	1·1	Energy = 24 GeV

Appel *et al* 1974, Alper *et al* 1973a). We know only $R(\bar{d})/R(\pi^-)$, $R(\bar{d})/R(\bar{p})$ and $R(d)/R(\bar{d})$ where $R = d^2\sigma/dp\, d\Omega$, for a fixed p_T value. From ISR measurements with CM energy as 53 GeV we know the above ratios only at $p_T = 0{\cdot}7$ GeV, whereas the Serpukhov data are basically for p–Al collisions.

We make a reasonable assumption that the shape of the Y_{lab} distribution of $\bar{d}$ is the same as that of $\bar{p}$ distributions. The constant A_1 of equation (8) for $\bar{d}$ is then calculated by using the ratios $R(\bar{d})/R(\pi^-)$ and $R(\bar{d})/R(\bar{p})$ of ISR data. For this purpose we first express the ratios in terms of invariant cross sections, namely

$$\frac{IR(\bar{d})}{IR(\pi^-)} = \left(\frac{E_d}{p_d^2}R(\bar{d})\right)\left(\frac{E_\pi}{p_\pi^2}R(\pi^-)\right)^{-1} \tag{9}$$

and a similar expression for $IR(\bar{d})/IR(\bar{p})$; here $IR = E\, d^3\sigma/d^3p$. The values of $IR(\pi^-)$ and $IR(\bar{p})$ are obtained from equations (5) to (8) and table 1. For $IR(\bar{d})$ we treat the values of A_1 as unknown. From two data points of ISR we have determined the value of A_1 (in mb GeV^{-2}) as:

$$A_1 = 2{\cdot}3 \times 10^{-3}. \tag{10}$$

For $\bar{d}$ with $E_{inc} \simeq 30$ GeV, we reduce the value of A_1 by 33/68 as seen for $\bar{p}$ (see table 1).

2.6. *Differential energy spectrum of particle C from* $p + p \rightarrow C + X$

Charged particle products of p–p collisions in interstellar space are expected to be isotropic at the top of the Earth's atmosphere because of their confinement due to the interstellar magnetic field. On the other hand, neutral particle products, namely γ rays (from decay of π^0), are expected to be directionally dependent. For the latter only the matter along the line of sight of the telescope is important. Therefore for the cosmic γ ray, produced in p–p collisions, we shall be discussing the production rate and the differential energy spectrum per hydrogen atom. We describe below the details of calculating the production spectrum of charged particles and in § 2.6.4 that of neutral particles.

2.6.1. *Differential rapidity spectrum of charged particle C.* For a given primary energy E_{inc} (or Y_{inc} in terms of rapidity) of protons, the Y distribution of C in the laboratory system can be written as:

$$E\, d^3\sigma/d^3p = f(Y, p_T)$$

or,

$$(1/\pi)(d^2\sigma/dY\,dp_T^2) = g(Y)\,e^{-bp_T}$$

or,

$$d\sigma/dY = (2\pi/b^2)g(Y), \tag{11}$$

where $d\sigma/dY$ is in units of millibarns.

As discussed in § 2.4, we have parametrized only the target fragmentation region (the broken curve of figure 1(*b*)) and let us denote it by:

$$(d\sigma/dY)_{tar} = (2\pi/b^2)g(Y). \tag{11a}$$

Because of symmetry in the Y distribution around $\frac{1}{2}Y_{inc}$, the Y distribution from the projectile fragmentation region can be obtained simply by replacing the argument of the function g by $(Y_{inc} - Y)$:

$$(d\sigma/dY)_{proj} = (2\pi/b^2)g(Y_{inc} - Y). \tag{11b}$$

Equations (11*a*) and (11*b*) together represent the production cross section of particle C per proton collision.

Let us now define the differential rapidity spectrum for particle C as dN/dY, which represents the number of particle C having rapidity in the range Y and $Y+dY$ produced per proton interaction with the interstellar hydrogen matter:

$$\frac{dN}{dY} = \left(\frac{N_0}{A}\rho L\right)K\frac{d\sigma}{dY} \tag{12}$$

where N_0 is Avogadro's number, A is the atomic weight of hydrogen (in g), L is the length of the medium (in cm), ρ is the density (in g cm^{-3}) and $K = 10^{-27}$ (which is the conversion factor from mb into cm^2). As the average path length traversed by the primary proton ($\sim$5 g cm^{-2}) is much less compared to its interaction mean free path ($\sim$50 g cm^{-2} in hydrogen), we assume that the primary proton makes at the most one interaction with the interstellar medium and we also neglect any further interactions of the particles produced with the medium. For simplicity, we have assumed here that all the collisions are those of high energy cosmic ray protons with hydrogen nuclei in the interstellar matter. The contributions from p–α, α–p and α–α collisions are taken care of in the final result, § 3.

Now the differential spectrum of the primary cosmic ray protons is to be folded in equation (12). We shall do this by assuming a single power-law spectrum of protons, which we write as:

$$\frac{dI}{dE_{inc}} = \eta E_{inc}^{-(\gamma+1)}, \qquad (\text{in } (\text{cm}^2\,\text{s sr GeV})^{-1}) \tag{13}$$

where η and γ are constants and E_{inc} is the total energy of the proton (in GeV). In terms of rapidity this spectrum can be written as:

$$\frac{dI}{dY_{inc}} = \eta(m_p/2)^{-\gamma}\exp(-\gamma Y_{inc}), \qquad (\text{in } (\text{cm}^2\,\text{s sr})^{-1}) \tag{13a}$$

where m_p is the mass of the proton in (GeV/c^2).

The differential rapidity spectrum of particle C, after folding the primary proton spectrum, becomes:

$$\frac{dN}{dY}=\left(\frac{N_0}{A}\rho L\right)K_\eta(m_p/2)^{-\gamma}\int\left(\frac{d\sigma}{dY}\right)\exp(-\gamma Y_{inc})\,dY_{inc} \tag{12a}$$

(in units of $(cm^2\,s\,sr)^{-1}$). Rewriting $(d\sigma/dY)$ in terms of target and projectile fragmentation as given by equations (11*a*) and (11*b*) and with proper integration limits we get:

$$\frac{dN}{dY}=\left(\frac{N_0}{A}\rho L\right)K\eta(m_p/2)^{-\gamma}\left[\int_{Y_{inc}=Y_{min}}^{2Y}\left(\frac{d\sigma}{dY}\right)_{proj}\exp(-\gamma Y_{inc})\,dY_{inc}\right.$$
$$\left.+\int_{Y_{inc}=2Y}^{\infty}\left(\frac{d\sigma}{dY}\right)_{tar}\exp(-\gamma Y_{inc})\,dY_{inc}\right] \tag{12b}$$

or,

$$\frac{dN}{dY}=\left(\frac{N_0}{A}\rho L\right)K\eta(m_p/2)^{-\gamma}\left(\frac{2\pi}{b^2}\right)$$
$$\times\left(\frac{g(Y)}{\gamma}\exp(-2\gamma Y)+\int_{Y_{inc}=Y_{min}}^{2Y}g(Y_{inc}-Y)\exp(-\gamma Y_{inc})\,dY_{inc}\right). \tag{12c}$$

The upper limit of $2Y$ on the projectile fragmentation follows from the fact that the particle in this limit is produced with zero rapidity in the CM system and then using equation (3) we get the upper limit. In the above equations Y_{min} represents the minimum (or threshold) value of Y_{inc} needed to produce particle C with rapidity Y.

2.6.2. Differential energy spectrum of C. The expression for rapidity (equation (2)) can also be written as:

$$Y=\ln\left(\frac{E+(E^2-W^2)^{1/2}}{W}\right) \tag{2a}$$

where $W^2=p_T^2+m_C^2$, E is the laboratory energy of particle C (in GeV) and m_C is its mass (in GeV/c^2).

Because of the experimentally observed sharp decrease of the transverse momentum distribution, we replace p_T by $\langle p_T\rangle$, i.e. $2/b$, in equation (2*a*). The expression for E in terms of rapidity is thus given by:

$$E=\tfrac{1}{2}W(e^{Y}+e^{-Y}).$$

The differential energy spectrum of C can now be written as:

$$\frac{dN}{dE}=\frac{2}{W(e^{Y}-e^{-Y})}\frac{dN}{dY}, \qquad \text{(in } (cm^2\,s\,sr\,GeV)^{-1}) \tag{14}$$

where dN/dY is given by equation (12*c*).

2.6.3. Ratio N_C/N_p at a given energy E. The differential energy spectra of primary protons and the produced charged particle C are given by equations (13) and (14) respectively. The ratio N_C/N_p, i.e. the ratio of the flux of the produced particle C and the incident proton flux at the same total energy E is just given by

$$\frac{N_C}{N_p}=\frac{(dN/dE)_C}{dI/dE}. \tag{15}$$

2.6.4. Production spectrum of neutral particle C from $p+p\to C+X$. For neutral particles, as mentioned at the beginning of § 2.6, the flux is directionally dependent, see also Ginzburg and Syrovatskii (1964), it is therefore more useful to give the flux per collision in units of (s sr GeV)$^{-1}$. We define it by dQ/dE,

$$\frac{dQ}{dE}=\left(\frac{dN}{dE}\right)\left(\frac{N_0}{A}\rho L\right)^{-1}, \qquad (\text{in (s sr GeV)}^{-1}). \tag{16}$$

3. Results and discussions

We now present the results of the numerical calculation regarding the fluxes of γ rays, antiprotons and deuterons $(d+\bar{d})$ with energies above 10 GeV at the top of the Earth's atmosphere from collisions of primary cosmic ray protons with interstellar matter. As mentioned in § 2.6.1, we have described the procedure for calculating the fluxes of secondary particles only from p–p collisions; the other collisions of astrophysical significance are the p–α, α–p and α–α collisions. For the case of γ rays we shall take care of the latter effect by increasing the calculated fluxes by 70% (see Stecker 1971) and for the case of deuterons we shall use the estimation based on fragmentation of α particles by Meyer (1971). For the case of antiprotons the above effect is not known and hence we shall present its flux from p–p collisions.

There is a considerable discrepancy (Sreekantan 1972) regarding the value of the slope and the absolute intensities of the primary proton spectrum. We shall therefore consider here two different shapes of the primary proton spectrum for energies above 10 GeV, and they are summarized below.

Case 1. Single power-law spectrum for all energies:

$$dI/dE=2{\cdot}35E^{-2{\cdot}67}, \qquad (\text{in (cm}^2\text{ s sr GeV)}^{-1}). \tag{17}$$

Case 2. Four different power-law spectra:

$$dI/dE=0{\cdot}89E^{-2{\cdot}5} \qquad 10\leqslant E<10^2\text{ GeV} \tag{18a}$$

$$dI/dE=2{\cdot}24E^{-2{\cdot}7}, \qquad 10^2\leqslant E<10^6\text{ GeV} \tag{18b}$$

$$dI/dE=2{\cdot}24\times10^3E^{-3{\cdot}2}, \qquad 10^6\leqslant E<3{\cdot}16\times10^8\text{ GeV} \tag{18c}$$

$$dI/dE=1{\cdot}78\times10^{-2}E^{-2{\cdot}6}, \qquad 3{\cdot}16\times10^8\leqslant E<10^{11}\text{ GeV} \tag{18d}$$

in units of (cm^2 s sr GeV)$^{-1}$.

3.1. Production rate of γ rays

The production spectra, $dQ^{\pm}/dE$, of $\pi^{\pm}$ from p–p collisions have been obtained by numerical integration of equation (16) using equations (14) and (12*c*) with two different types of primary proton spectrum. The energy spectrum of π^0, dQ^0/dE, is then obtained by taking the average of π^+ and π^- fluxes. The expression for the production spectrum of γ rays from decay of π^0, assuming isotropic emission of γ rays in the rest frame of π^0, is given by

$$\frac{dQ^\gamma}{dE}=2\int_{E_{min}}^{\infty}\frac{1}{(E'^2-m_\pi^2)^{1/2}}\frac{dQ^0}{dE'}dE' \tag{19}$$

where the factor 2 takes care of the production of two γ rays from a π^0 decay, m_π is the mass of π^0 in (GeV/c^2) and $E_{min}=(E+m_\pi^2/4E)$ is the minimum energy of π^0 needed to produce a γ ray of energy E.

We have shown in figure 3 the production rate of γ rays per collision in units of (s sr GeV)$^{-1}$ for the two different shapes of primary proton spectrum. The effect of α–p, p–α and α–α interactions is taken into account by multiplying the fluxes by a factor of 1·7 as estimated by Stecker (1971). Since the composition of primary cosmic rays is not well known beyond 10^5 GeV, the factor 1·7 mentioned above may be in doubt. We have therefore presented the γ-ray flux beyond 10^4 GeV by broken lines in figure 3. The curves A and B show the final result for the two primary spectra as given by equations (17) and (18) respectively. For the conventional primary proton spectrum, equation (17), the production rate of γ rays can be written as:

$$\frac{dQ^\gamma}{dE}=2{\cdot}64\times10^{-27}E^{-2{\cdot}67}, \qquad (\text{s sr GeV})^{-1}. \tag{20}$$

For the sake of comparison we have also shown the result of Stecker (1971) as curve C in figure 3 which was calculated by using the primary proton spectrum as given by equation (18). His calculation was based on an isobar-pionization model of particle production in p–p collisions where there are many unknown parameters. Comparing curves B and C we find that the values of the fluxes are nearly the same at $E=10$ GeV, whereas beyond 100 GeV, curve C is lower by a factor of about 10 to 40. We believe

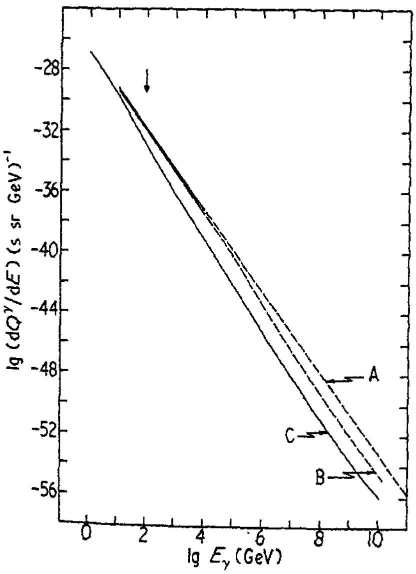

Figure 3. The production rate of γ rays per effective target atom, dQ^γ/dE, is plotted against energy of γ rays. Curves A and B refer to the two different shapes of the primary proton spectrum. Curve C is taken from the calculation of Stecker.

that our present calculation is a reliable one because it is based simply on the shape of the rapidity distribution of the pions from p–p collisions which is known up to 1500 GeV and this shape as seen from figure 2 is a very smooth one approaching the plateau region beyond $Y_{lab} \geq 2$. It is also to be noted that up to the energy 200 GeV of pions (or antiprotons) from p–p collisions we do not need an extrapolation much beyond ISR energies, because the contribution to the flux of π (or $\bar{p}$) of energy 200 GeV is a maximum from primary protons of energy about 10^3 GeV and the contribution becomes 10% of the maximum at 10^4 GeV due to the steepness of the primary proton spectrum. Essentially this means that γ-ray fluxes calculated up to about 100 GeV are quite reliable as they do not need an extrapolation of accelerator data much beyond ISR energies. The arrow marked in figure 3 shows the 100 GeV limit.

The intensity of γ rays as mentioned earlier is directionally dependent. For the sake of illustration we calculate this intensity in the direction of the galactic centre with the following assumptions: the extent of the region is nearly 20 kpc with a mean hydrogen concentration as 1 atom cm^{-3} (i.e. $N_0 \rho L/A = 6 \times 10^{22}$ cm^{-2}). This leads to an integral intensity of γ rays with $E \geq 10$ GeV from equation (20), with single power primary proton spectrum, as:

$$I_\gamma(E \geq 10\ \mathrm{GeV}) = 2 \times 10^{-6}\ \gamma\ \mathrm{rays}\ (\mathrm{cm}^2\ \mathrm{s\ sr})^{-1}. \tag{21}$$

The corresponding intensity of the proton flux, equation (17), is:

$$I_p(E \geq 10\ \mathrm{GeV}) = 3 \times 10^{-2}\ \mathrm{protons}\ (\mathrm{cm}^2\ \mathrm{s\ sr})^{-1} \tag{22}$$

therefore

$$I_\gamma/I_p = 7 \times 10^{-5} \qquad \text{for } E > 10\ \mathrm{GeV}. \tag{23}$$

It is to be noted that there is some indication of the presence of molecular hydrogen (Solomon and Stecker 1974); the above ratio of I_γ/I_p will have to be appropriately modified when the concentration of molecular hydrogen is known.

3.2. Ratio of antiproton flux to proton flux

The differential energy spectrum of antiprotons is obtained by numerical integration of equation (14). We have assumed the total matter traversed by primary protons as $\langle \rho L \rangle = 5$ g cm^{-2}. We have also assumed that $\bar{n}$ production is equal to $\bar{p}$ production and since all $\bar{n}$ eventually will decay into $\bar{p}$, the production spectrum of $\bar{p}$ as obtained from equation (14) is multiplied by a factor of 2. The ratio of antiproton to proton flux, $N_{\bar{p}}/N_p$, is then obtained by using equation (15). The results as obtained by using two different primary proton spectra are as follows.

Case 1, equation (17). Up to about 10 GeV the ratio $N_{\bar{p}}/N_p$ rises and beyond 10 GeV it becomes *a constant*; the latter value is

$$N_{\bar{p}}/N_p = 2{\cdot}2 \times 10^{-4}, \qquad E_{\bar{p}} > 10\ \mathrm{GeV}. \tag{24}$$

Case 2, equation (18). Up to about 10 GeV the ratio $N_{\bar{p}}/N_p$ rises and beyond 10 GeV it decreases slowly due to the variation in the exponent of the energy spectrum. It is to be noted that the increase in the exponent decreases the ratio $N_{\bar{p}}/N_p$ which can be seen from equation (12*c*) and also from the values quoted in table 2. The last column of table 2 gives an indication of the energy range from the quoted exponent of the primary protons effective in producing antiprotons of a given energy quoted in column 1 of table 2.

Table 2. The ratio $N_{\bar{p}}/N_p$ obtained by using primary proton spectrum given by equation (18).

Enery of antiproton (GeV)	$N_{\bar{p}}/N_p$	Exponent of energy spectrum in effective use
20	$2{\cdot}8\times10^{-4}$	1·5 and 1·7
80	$2{\cdot}2\times10^{-4}$	1·5 and 1·7
$10^2 \leqslant E_{\bar{p}} \leqslant 1{\cdot}5\times10^4$	$2{\cdot}1\times10^{-4}$	1·7
10^5	$1{\cdot}9\times10^{-4}$	1·7 and 2·2
$10^6 \leqslant E_{\bar{p}} < 10^7$	$7{\cdot}6\times10^{-5}$	2·2
$E_{\bar{p}} > 3\times10^8$	$2{\cdot}6\times10^{-4}$	1·6

The experimental searches (Fanselow *et al* 1968, Brooke and Wolfendale 1964, Bogomolov *et al* 1970, 1971) for antiproton flux in the primary cosmic radiation have been made up to 5 GeV and *the upper limit* on $N_{\bar{p}}/N_p$ is given as 6×10^{-3} by Bogomolov *et al* (1971). This result is to be compared with our present calculation of $N_{\bar{p}}/N_p$ as $(2\text{-}3)\times10^{-4}$. A similar calculation has also been made by Gaisser and Maurer (1973) who have obtained the upper limit as $4{\cdot}6\times10^{-4}$. Several other theoretical estimates (Rosen 1967, Shen and Berkly 1968, Wayland and Bowen 1968) have been made in the past but their results were limited mainly because of the lack of data on $\bar{p}$ production in high energy p–p collisions. Results on $\bar{p}$ production from ISR have now led to a reliable estimate of $N_{\bar{p}}/N_p$ and thus there is a need to make more precision measurements on $N_{\bar{p}}/N_p$ in cosmic radiation to infer whether the observation of $\bar{p}$ in cosmic rays could be understood from primary proton collisions or whether there is a need for antimatter sources.

3.3. *Ratio of deuteron flux to proton flux*

The differential energy spectrum of deuterons from p–p collisions is obtained in the same way as that of antiproton flux described in § 3.2. It is found that the ratio N_d/N_p, for the same total energy of d and p, increases rapidly up to about 30 GeV and beyond 30 GeV it becomes a constant (we have used the primary proton spectrum as given by equation (17)). The latter value is

$$N_d/N_p = 1{\cdot}4\times10^{-6}, \qquad E_d > 30\ \text{GeV}. \tag{25}$$

There is another mechanism by which deuterons can be produced and it is from the fragmentation of cosmic ray ^{4}He in collisions with interstellar matter. This production mechanism has been studied in detail by Meyer (1971) and he finds that:

$$N_d/N_{^4\text{He}} \simeq 0{\cdot}3, \qquad \text{above 10 GeV/nucleon}. \tag{26}$$

Now, since $N_p/N_{^4\text{He}}$ in primary cosmic radiation is about 10 above a few GeV/nucleon, we therefore obtain:

$$N_d/N_p \simeq 0{\cdot}03, \qquad \text{above 10 GeV/nucleon}. \tag{27}$$

In terms of the same total energy of deuteron and proton, the ratio becomes:

$$N_d/N_p \simeq 0{\cdot}18, \qquad \text{for total energy} > 20\ \text{GeV}. \tag{28}$$

From equations (25) and (28) we find that the production of deuterons is mainly due to fragmentation of ^{4}He. This result should be compared with the experimental estimate of $(0{\cdot}15 \pm 0{\cdot}04)$ made by Ganguli *et al* (1974) in the energy range 200 to 600 GeV; the experimental estimate and the calculation from fragmentation of ^{4}He are in good agreement.

4. Summary

We have presented a simple method of calculating fluxes of γ rays, antiprotons and deuterons from collisions of protons with hydrogen in interstellar space. For γ rays and deuterons we have included the contribution from fragmentation of primary ^{4}He. The present calculation is based on experimental production cross sections of $\pi^{\pm}$ and $\bar{p}$ as a function of rapidity from collisions of protons with protons up to 1500 GeV. A smooth extrapolation is made beyond this energy on the assumption of slow flattening of the rapidity distribution as exhibited by the experimental data up to 1500 GeV. It is also to be mentioned that the contribution to the secondary fluxes up to 200 GeV does not need extrapolation much beyond 1500 GeV due to the steepening of the primary proton spectrum. The following conclusions are drawn from this analysis.

(i) The production rate of γ rays per collision for a single power-law proton spectrum is $(2{\cdot}64 \times 10^{-27} E^{-2{\cdot}67})$ in units of $(\mathrm{s\ sr\ GeV})^{-1}$; the exponent comes out to be the same as that of the primary proton spectrum. For a more complicated spectrum we have presented the result in figure 3.

(ii) The intensity of γ rays with energies of 10 GeV or above in the direction of the galactic centre is nearly 10^{-4} of the total primary proton flux with energies of 10 GeV or more, with the assumption that the mean hydrogen concentration is 1 atom cm^{-3}.

(iii) The ratio of antiproton to proton flux with energies above 10 GeV at the top of the Earth's atmosphere is found to be $(2\text{–}3) \times 10^{-4}$. This result assumes that on the average primary protons pass through 5 g cm^{-2} of matter between their injection and observation at the top of the Earth's atmosphere.

(iv) The deuteron flux from p–p collisions is found to be negligible compared to that from the fragmentation of primary α particles. It is found that the experimental estimate of the ratio of deuteron to proton flux as $(0{\cdot}15 \pm 0{\cdot}04)$ is consistent with the expectation of fragmentation of α particles for high energies.

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