ASTROPHYSICAL SIGNIFICANCE OF THE OBSERVATIONS OF DEUTERONS AND ANTIPROTONS IN COSMIC RADIATION

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Abstract

A general survey of the different processes that lead to the production of deuterons and antiprotons in different regions of space and in cosmic rays is made. The avaiable observations on these particles are summarised and the information obtained from such studies are discussed. The importance of future investigation of these particles and the possible consequences of such observations are brought out.

INTRODUCTION

It is generally believed that cosmic rays are created and accelerated in explosive events occurring in the universe; the charge particle radiation observed in the neighbourhood of the Earth are produced and contained in the Galaxy. It is expected that the observed composition of cosmic rays should resemble the chemical composition of the matter at the source. However, after their production and acceleration in the sources, cosmic rays wander in interstellar space over a finite period of time resulting in a modification of their original composition. During this period of time, they interact with the interstellar gas and thereby the heavier nuclei spallate into nuclei of lower mass and charge; and charge mesons and nucleon-antinucleon pairs are also created in high energy interactions. Because of this reason, some of the nuclei and particles which are nearly absent in the source material could also be observed in considerable quantity in cosmic radiation. Deuterons (D) and antiprotons $(\bar{p})$ come under this category and their importance in the understanding of the propagation of cosmic rays has been realised during recent years. Apart from this, the recognition of the importance of these particles in astrophysics is a long standing one.

The observation of deuterons and antiprotons in cosmic radiation has many special merits compared to other particles which are of secondary nature as will be evident from the following reasonings. The propagation and distribution of cosmic rays in the Galaxy depend upon many factors, such as, the source distribution and strengths, physical conditions of the medium responsible for thier diffusion and the boundary conditions leading to their escape out of the Galaxy. One of the important parameters deduced from the study of cosmic rays is the amount of matter traversed by them (X), which reveals the physical conditions of the region where they reside. The simplest way to do this is to make observations on stable particles, created through the interactions of primary cosmic rays with interstellar gas. The abundance of secondary particles relative to their parents give, in principle, the product of value of X and the production cross-section. Such an estimate is found to be sensitive to the theoretical model used for the propagation of cosmic rays as the interaction mean free path of the particle becomes comparable to the value of X. The reason for this is that the information obtained from sampling particles close to the point of observation is extrapolated to the entire galactic volume through theoretical models. However, it can be easily shown that for D and $\bar{p}$ the information thus obtained is model independent, since their interaction mean free path at relativistic energies is very much larger than the mean amount of matter traversed by cosmic rays. Though these particles are similar in many respects, there are some important differences with regard to the propagation. Deuterons are produced at the same energy per nucleons as their parents, while antiprotons are created by parents of about 10 times their energy; the threshold for the production of D is in the region of tens of MeV/nucleon in contrast to about 10 GeV in the case of $\bar{p}$. The energy loss rate at low energies are also different. Beacause of these differences, a comparative study of their energy spectra from a few MeV to a few tens of GeV would shed light on the mode and regions of acceleration and propagation of cosmic rays, and on the solar modulation.

The basic nuclear processes by which D can be created require physical conditions, which are often more favourable for its destruction than creation. Therefore, a determination of the abundance of D in ambient matter gives a clue to the physical conditions under which nucleosynthesis of matter has taken place. Similarly, the detection of $\bar{p}$ in cosmic radiation in excess of those expected on the basis of cosmic ray interactions with interstellar gas, would lead to the discovery of antimatter in the galactic volume, which has a prime importance in the understanding of the evolution of the universe. In this review, the production mechanisms of deuterons are described in section 2, and the observational data along with its implications are given in section 3. In sections 4 and 5, the production of antiprotons and the available data are respectively presented. The important highlights of this paper are summarised in section 6 along with a brief discussion on some of the aspects, which are not covered in the main body of the text.

PRODUCTION OF DEUTERONS

Deuterons are created continuously in stellar interior by thermonuclear reactions. They can be created in the exploding objects like supernova and during the early phase of the origin of the universe. In the interstellar space, its production is through interactions of cosmic rays with the ambient matter. In this section a brief description of the important processes leading to the production as well as the destruction of D in different regions of space is given.

(a) Thermonuclear reactions in stellar interior:

The basic process through which deuterons are created in the stellar interior is the fusion of hydrogen atoms. The major reactions leading to the creation of D are $H(p,e^+\nu)\ D$ and $H(pe^-, \nu)\ D$. By virtue of the fact that the second reaction involves the capture of an electron, this reaction is inhibited by 5 orders of magnitude with respect to the first one. The rection rate $<\sigma v>$ in $cm^3\ s^{-1}$, which is the product of the cross-section and the velocity of the particle averaged over the Maxwellion distribution of velocities at a given temperature T is very sensitive to the temperature of the medium. In Fig. 1, the variation of the above reaction rate with temperature is shown by curve A as calculated using the relation given by Fowler *et al* (1967). From this one notices that the reaction rate for deuteron production is about $5 \times 10^{-40}\ cm^3\ s^{-1}$ at 10^9 °K decreasing to a value of $2 \times 10^{-44}\ cm^3\ s^{-1}$ at 10^7 °K, and below this temperature the reaction rate goes down rapidly. The destruction of D is more faster than its production in stellar interior. The most important destructive process is $D(p, \gamma)\ ^3He$, whose reaction rate is shown by curve B in Fig. 1. It can be seen that the reaction rate is about $6 \times 10^{-22}\ cm^3\ s^{-1}$ at 10^9 °K reduces to a value of 3×10^{-27} at 10^7 °K and decreasing more rapidly below this temperature than the deuteron creation rate.

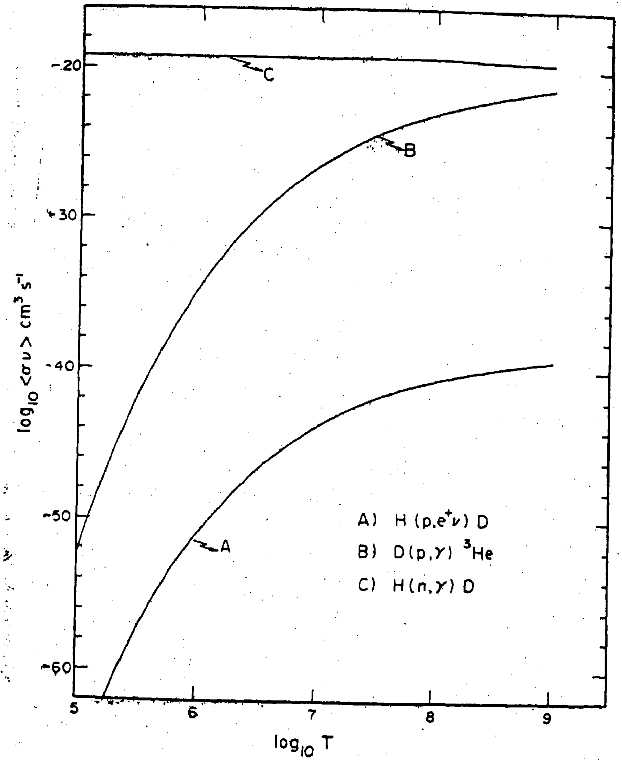

Fig. 1 : The reaction rate as a function of temperature

From the above one can infer that if deuteron production continues in stellar interiors, then for a typical case of a star (Stromgren 1965) of mass $1\ M_{\odot}$, the D/H atio at the end of 5 billion years would be $\sim 3 \times 10^{-3}$ (taking a mean value of $\rho = 22.4\ g\,cm^{-3}$ and $T = 8 \times 10^6$ °K corresponding to $M_r = 0.5$). However, if the destruction is taken into account, the equilibrium value of the D/H ratio reduces to $\sim 10^{-18}$. Therefore the stellar interiors, in which considerable amount of deuteron formation takes place, turns out to be more favourable for its destruction. As a result, over the life of the universe, nearly all D could be consumed inside stellar volumes or regions, where the temperature $T > 3.5 \times 10^5$ °K for a typical density of $1\ g\ cm^{-3}$ or $T > 10^6$ °K for $\rho \approx 10^{-6}\ g\ cm^{-3}$.

In the case of the Sun, while the temperature of the corona is sufficiently high enough, its density is too low to deplete D, and in the photosphere the temperature is too low to initiate the destructive reaction. From this one should expect that the presolar D should be preserved in the solar surface, except there exists sufficient mixing between the core and the surface.

(b) Deuteron production during the hot big-bang origin of the universe :

The advantage of the early phase of the universe for the production of deuterons over the stellar interior is the large amount of neutrons that should exist before decaying into protons and electrons. Consequently, creation of D through direct fusion of protons and neutrons takes place via $H(n, \gamma)\ D$. The reaction rate for this process is close to $10^{-19}\ cm^3\ s^{-1}$ nearly independent of the temperature of the medium (curve C in Fig. 1). Almost all the D created in this manner would survive as the destruction rate is comparatively small. The amount of D formed during the initial phase of the universe is a sensitive function of the mean baryon density. Since the temperature of the early universe in any model is fixed by the present day black body temperature of 2.7 °K, the deuteron fraction is determined by the present day baryon density of the universe. In the framework of the standard Friedmann cosmologies (Wagoner 1973) it is found that D/H ratio is about 3×10^{-3} for ρ_0 (present day baryon density) $= 2.3 \times 10^{-32}\ g\ cm^{-3}$ and about 4×10^{-7} at $\rho_0 = 2.3 \times 10^{-30}\ g\ cm^{-3}$ the ratio sharply decreases as ρ_0 increases (D/H $< 10^{-12}$ at $\rho_0 = 10^{-29}\ g\ cm^{-3}$). It is obvious from the above expectations that any desired amount of D can be obtained from cosmological considerations and conversely a precise determination of the deuteron abundance provides a nice handle to obtain some properties of the evolutionary model of the universe.

(c) Deuteron production from exploding objects :

It has been suggested (Colgate 1974; Hoyle and Fowler 1973) that during the progression of a shockwave into the outer layers of an exploding object, velocities corresponding to several MeV/nucleon will be reached, and as a result, atoms in the medium undergo extensive spallation reaction. Helium will be broken into one or more deuterons and free nucleons. If the densities are not too low ($> 10^{-8}$ g cm^{-3}) and the post-shock temperature not too high (kT $<$ 2 keV) the remaining neutrons recombine with protons to form D and the deuterons will not be destroyed by further capture of a proton. From an estimate of the deuteron production through supernova explosions, Reeves (1974) came to a conclusion that the interstellar abundnce from this mechanism should be much less than 10^{-6}. One severe problem with such models is the over production of other light elements (Epstein *et al.* 1976a).

Deuterons can be formed if matter is brought to high temperatures where heavy nuclei decompose into free nucleons (T$>$ 10^9 – 10^{10} K, depending on the density) and then rapidly expanded and cooled (Epstein *et al.* 1976b). Two possible sequences by which deuteron formation could be effective are when : (i) the expansion is rapid enough to inhibit recombination of at least some of the nucleons until the freeze out temperature of kT $\lesssim$ 2 keV is reached, and (ii) the formation of D takes place while the gas is still hot and is ejected during expansion without being destroyed. In either case, it is found that the estimated mass of the exploding region to satisfy the required amount of expansion rate has to be 10^{-7}M$_\odot$, which is much too small compared to any reasonable astronomical event. Apart from this mechanism, the production of D by the ejection of free neutrons from disrupted neutron stars has also been speculated (Epstein *et al.* 1976b), but no quantitiative estimate has been made so far on this basis.

(d) **Deuteron production through cosmic ray interactions :**

An important process by which deuterons are continuously created in space is the interaction of cosmic ray protons and helium nuclei with interstellar gas. The modes of interaction of cosmic ray protons with hydrogen and helium atoms in the ambient gas are (i) p (p, π^+) D; (ii) p[α, p(π)] 2D; p [α, n 2p(π)] D and (iii) p (α, ^{3}He(π))D. The alpha interactions with ambient hydrogen atoms are identical to (ii) and (iii) when the energy of the interacting particle is expressed in energy per nucleon. The first reaction has a threshold around 260 MeV, attains a maximum cross-section of a few millibarnes at about 600 MeV and then decreases rapidly at high energies. The 2nd reaction has a threshold around 30 MeV; the cross-section rises rapidly to about 30 mb around 100 MeV and has a constant value of about 60 mb at relativistic energies. The 3rd reaction has a threshold close to 20 MeV ; the cross-section rises sharply to a value of about 45 mb and then decreases rapidly beyond about 50 MeV. The deuterons having energies less than $\simeq$70 MeV lose their energy through collision and become part of the interstellar gas. An estimate (Mitler 1972) made of the total amount of D thus produced over the life of our galaxy, by assuming time dependent cosmic ray density gives a value of 10^{8} for D/H ratio.

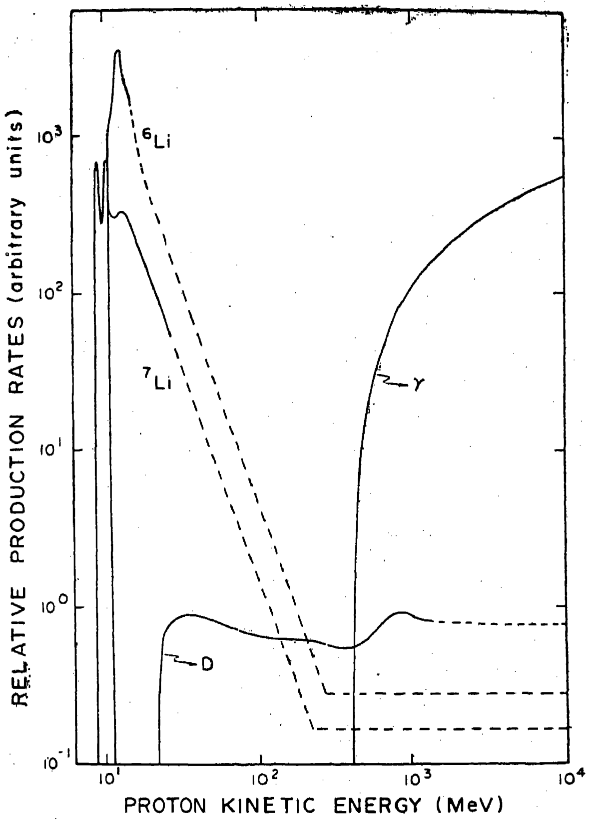

Fig. 2 : Production rate of nuclei through spallation reaction of cosmic rays is shown as a function of incident energy. In the case of gamma rays the integral flux $>$ 70 MeV is given as the ratio of the expected to the observed.

In order to increase the deuteron concentration in the ambient matter through cosmic ray spallation reactions, high intensity of pregalactic or cosmological cosmic rays was speculated (Epstein 1977; Montmerle, 1977). However, interaction of cosmic rays also produces other light elements and gamma rays. In Figure 2, the relative production rate of ^{6}Li and ^{7}Li are shown along with that of D as a function of incident proton energy (Epstein 1977). Also shown in this figure is the ratio of gamma ray production rate to the observed integral number of background gamma rays of energy $>$ 70 MeV. From this figure, it is evident that cosmic rays with energies $<$ 300 MeV/n generate large Li/D ratios and for energies $>$ 500 MeV/n high γ/D ratios are obtained. Therefore, models of cosmic ray spallation origin of D in interstellar space require either low energy cosmic rays with a mechanism to destroy preferentially the lithium, or high energy cosmic rays with some means of absorbing gamma rays, or mono-energetic cosmic rays around 400 MeV during the pregalactic era (Epstein *et al.* 1976b). It appears that none of the above conditions can be realised in a very convincing manner.

Inspite of the fact that spallation reactions by cosmic rays do not produce appreciable amount of D to have any remarkable effect on the interstellar abundance, it is still important in cosmic ray studies because the amount of D produced through spallation of cosmic ray nuclei constitute about 1.5% of the protons in cosmic radiation. In Table 1, the observed abudances for a

TABLE 1

Observed Particle Abundances of Cosmic Rays

Particle	Abundance	Particle	Abundance
H	10^6		
He	$4.5x10^4$		
		^2H	$1.5x10^{4*}$
e^-	$5x10^3$		
C;O	10^3		
e+	$5x10^2$		
		$\bar{p}$	$3x10^{2*}$
Mg; Ne; Si	$2x10^2$		
Fe	60		
$Z \geqslant 35$	10^{-2}		
$Z \geqslant 90$	10^{-4}		

* expected values

TABLE 2*

Observations of Deuteron

Observations	Technique	Value D/H
D in interstellar matter	Lyman lines	$1.4x10^{-5}$
DCN in Orion nebula	emission at 72 and 145 MHz	upto $6x10^{-3}$ in HCN
HD in Jupiter	Absorption of molecular line at 7468 A°	$2x10^{-5}$
D in protosolar nebula	Analysis of water formation	$1.6x10^{-4}$
D in solar surface	Photospheric, Coronal lines: solar wind	$<4x10^{-6}$

* Taken from Reeves (1974)

typical set of cosmic ray components are given with respect to a million protons at relativistic energies in descending order of their relative abundances. The expected abundances of D and p are also shown. This table gives an impression that inspite of the large abundance of D compared to heavy nuclei (10^8 times that of ultra heavy nuclei of charge $\geqslant 90$), not many attempts have been made so far to detect them. It may be pertinent to remark here that for heavy nuclei the detection and identification are straight forward due to the signature of their charge and thus requiring only a large collecting power for an experiment, while for D and $\bar{p}$ one requires an efficient discrimination against the vast background of protons.

OBSERVATIONAL RESULTS ON DEUTERSON

(a) Cosmic abundance of deuterons :

In Table 2 we present a typical set of deuteron measurements as compiled by Reeves (1974). It can be seen that the D/H ratio in interstellar space is about 1.5×10^{-5}, which is also confirmed by a recent measurement of Vidal-Madjar *et al.* (1977). This abundance of D in interstellar space can represent the equilibrium value in the ambient matter at present in the Galaxy. Since D/H ratio during the birth of the Sun (a few billion years back) as determined from the Jupiter (Table 2) is the same as that in the interstellar space, one may infer that the deuteron abundance is unchanged during the last billion years. Therefore, the processes, which we have discussed earlier, other than those during the pregalactic period, may not contribute much to the ambient D in the Galaxy. Such large abundance of D could be easily realised through thermonuclear processes during the initial phase of the big-bang origin of the universe. If this value is representative of the universal abundance, one can set a limit of $\lesssim 6x10^{-31}$ g cm $^{-3}$ for ρ_0 in the universe (Epstein *et al.* 1976b) which is much less than the Einstein-de Sitter critical baryon density of $3H_0^2/8\pi G$ $= 4.5 \times 10^{-30} (H_0/50)^2$ g cm^{-3} for the closure of the universe; here H_0 is the Hubble's constant and G is the gravitational cotstant. In the framework of Friedmann cosmologies with cosmological canstant $\Lambda = 0$ this would mean that the universe is forever expanding.

From Table 2 one also infers that the deuteron abundance in the solar surface is $< 4 \times 10^{-6}$. As pointed out in section 2a that the physical conditions in the corona and photosphere are not good enough to deplete presolar deuterons. Therefore, the observed small values indicate possible mixing of solar material continously or during the early phase of the evolution of the Sun. In this regard, one may refer to the observation of a possible variation (Geiss 1973) of the solar wind composition of $^3He/^4He$ which can only be understood in terms of a slow and continuous mixing of solar-material (Stephens and Balasubrahmanyan 1975). The amount of D in water, however, is about an order of magnitude larger than the presolar abundance. It is important to note here that the quoted values of D/H here corresponds to the ratio n(HDO)/[n(HDO) + 2n (H_2O)] and not the true value of D/H that exists in the chemical state of this phase. This leads to an explanation of the apparent enhancement of the D in water as due to effect of molecular exchange reaction of the type $HDO + H_2 \rightleftharpoons HD + H_2O$, in which n(HDO)/ n($H_2O$) increases as the temperature decreases. An enrichment of a factor of 10 is reached at T = 180 to 200° K. However, this value of the temperature is well below the temperature of 350°K required for the accretion of volatiles in meteorites (Reeves 1974). In a similar manner, the enhancement of D in the Orion Nebula is attributed to the chemical equilibruium state of the HCN phase through the exchange reaction

$$HD + HCN \rightleftharpoons DCN + H_2.$$

The impression one gathers from Table 2 without explanation and interpretations is that the deuteron

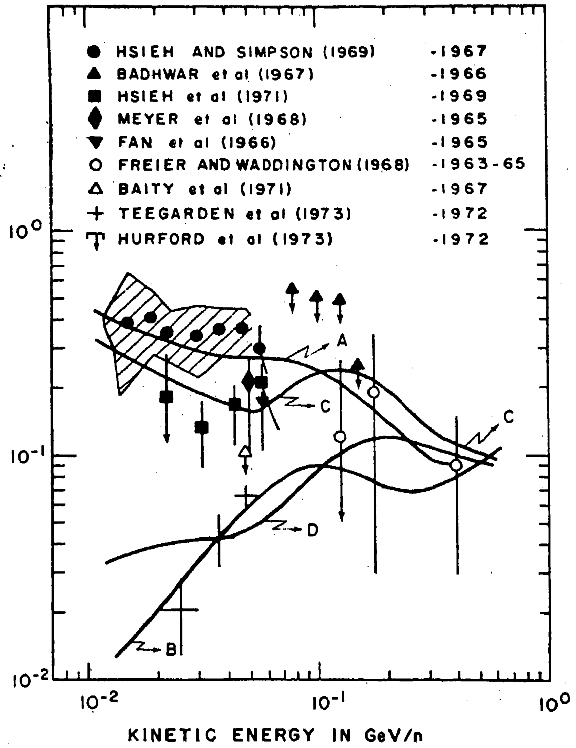

Fig. 3 : The ratio of the flux of deuterons to that of helium nuclei as a function of kinetic energy per nucleon as compiled by Daniel and Stephens (1975). Theoretical estimates of this ratio in interstellar space by solid curves are for different injection spectra.

abundance varies from region to region in space. It may not be too wrong to take the point of view that existence of deuterons in quantities comparable or even larger than that expected in cosmic rays through spallation reaction alone, cannot be ruled out in specialised region in space which are not accessible to direct observation. It is therefore essential from this point of view to measure accurately the abundance of deuterons in cosmic rays.

(b) **Cosmic ray abundance of deuterons** :

It is a practice in cosmic ray studies to present the observational data on deuterons as a fraction of the observed helium nuclei because the production of D, except at very low energies, is mostly through the spallation of cosmic ray helium nuclei. As the rigidity of D is the same as ^{4}He for a given energy per nucleon and the effect of solar modulation is identical for both these nuclei, the above comparison can directly reveal their abundances in interstellar space, except at low energies, where adiabatic deceleration against the solar wind is important. A compilation of such a data (Daniel and Stephens 1975) is shown in Figure 3. One infers from this figure that finite values of D/He ratio are available only at energies below a few hundred MeV/nucleon and that too with large discrepancies between measurements. The different curves shown in this figure are the estimated ratio, using a model for the propagation of cosmic rays with homogeneous distribution of sources and a mean matter traversal of about 7 g cm^{-2} of hydrogen, for different assumed spectra for helium. Curves B,C, and D correspond to simple power law energy spectra for helium nnclei respectively in knietic energy per nucleon, total energy per nucleon and rigidity. The observed discrepancy between 1972 data and the rest could be explained on the basis that the enhanced low energy flux of helium nuclei during 1972 could have had an origin closer to the solar system. Inspite of this, the adiabatic deceleration of cosmic rays, during their traversal against the continuous flow of solar wind, which amounts to about 200 MeV/nucleon would prevent one to draw meaningful conclusions on the propagation of cosmic rays using the data shown in this figure.

At relativistic energies, the expected value of D/H is about 1.5 x 10^{-2} due to the spallation of helium nuclei. The existing upper limit in this energy region (Apparao 1973) is consistent with this value. It has been recently found that in cosmic rays the relative abundance of secondary nuclei to their primiaries decrease with increasing energy. A summary of the abundance of Li, Be, B and N nuclei with respect to C and O nuclei as a function of energy (Daniel and Stephens 1975) showed that the relative abundance around 100 GeV/n is about a factor of about 3 smaller than that in the few GeV region. Such a decrease can be expected from propagation effects if there is energy dependent confinement of particles either in the Galaxy or in specialised regions where most of the matter is traversed. This trend holds good for deuterons also and therefore the D/H ratio in cosmic rays is expected to decrease from a value of 1.5 x 10^{-2} at 1 GeV/nucleon to about 5 x 10^{-3} at 100 GeV/nucleon. An upper limit to the deuteron flux deduced (Ganguli *et al.* 1974) from the inelastic collision-mean-free path observed for cosmic ray singly charged particles with carbon in the energy region 10-30 GeV/n is consistent with this hypothesis.

In the energy region above 100 GeV/nucleon there has been some appeal from a few for a large fraction of deuteron to exist in cosmic rays. The observed positive to negative ratio of muons at sea-leavel is about 1.3, almost independent of energy from about 10 GeV to a few hundred GeV. The charge ratios of pions and kaons at production in proton-proton collisions are about 1.7 and 2.7 respectively when the energy spectrum of cosmic rays is folded into the calculation (Badhwar, Stephens and Golden 1977). If there is no proper dilution of these charge ratios at production in proton-nucleus collisions in the atmosphere, one requires a large fraction of neutrons to be present in cosmic rays in the form of composite nuclei. It is thus estimated that when allowance is given to the normal composition of cosmic rays, as observed at low energies, the required (Adair 1974) D/H ratio is about 0.3. Of course, this is only a point of view and it has been shown that the normal composition is sufficient to explain the observed $\mu+/\mu^-$ ratio using the interaction characteristics consistent with the observed proton-nucleus collisions (for details see Badhwar *et al.* 1977, and references quoted therein). However, from a recent accelerator experiment designed to simulate atmospheric conditions for the decay of pions, it has been pointed out (Adair *et al.* 1977) that indeed the fraction of bound neutrons in cosmic rasy should be as large as speculated earlier, this conclusion is questioned on the basis that this experiment does not simulate the kaon decay in the atmosphere (Ramanamurthy 1977). It is also found that at energies > 100 GeV/nucleon, the observed inelastic cross-section for cosmic ray singly charged particles with carbon is 13 per cent larger than that expected from Glauber theory and such an increase could be explained (Ganguly *et al.* 1974) if D/H ratio in cosmic rays is about 5×10^{-2}. Table 3 summarises all these values. The uncertainties in all these speculated values make it very important at this stage to determine the abundance of deuterons in cosmic rays through direct observations at all energies.

TABLE 3

Deuteron Abndance in Cosmic Rays

Energy	Expected abundance D/H	Remark
<GeV/n	1.5×10^{-2}	expected from the break-up
7.5GeV/n	.13	experimental value
10-30GeV/n	1.5×10^{-2}	From p-e inelastic interaction.
100 GeV/n	.3(?)	From μ^{+}/μ^{-} at sea-level
”	5×10^{-2}	From p-e inelastic inter-action

Production of Antiprotons

Antiprotons ($\bar{p}$) are not expected to exist in space as part of the ambient gas because it would be annihilated. The only manner it could exist in space is when antimatter is well separated from the matter. During the birth of the universe, if baryon symmetry is observed, equal amount of matter and antimatter are expected to be in equilibrium with photons. If separation between matter and antimatter takes place at an early phase, say at a time $t > 10^{5}$ sec from the birth of the universe when $T > 4 \times 10^{12}$°K, they would survive destruction (Steigman 1976). A small mixing of these would give rise to the production of neutral pions, which decay at rest into two gamma rays of energy 67.5 MeV each. The resultant spectrum of background gamma rays would have a strong peak at this energy. Since the annihilation rate is expected to be high during the early epoch when the density is very large, the peak in the background spectrum of gamma rays would be shifted to lower energies. Beyond this epoch (red shift $z > 70$) absorption through pair production and Compton scattering become important and as a result contribution from earlier epochs reduces. It is found that (Stecker *et al.* 1971) most of the gamma rays originate during the epoch corresponding to $z = 10$ to 70 and the gamma-ray spectrum would exhibit a peak in the region of 1 to 10 MeV. In Fig.4 is shown the expected gamma ray background through annihilation process and one could see a peak in the region of about 1-10 MeV. The early gamma ray observation did indicate, as summarised by Stecker (1974) in Figure 4, a deviation from a power law around this energy region. It may be pointed out here that such an enhancement is also expected from the interaction of large burst cosmic rays at similar early epoch (Stecker 1974). However, an observed upper limit to the flux well below the expectation (Daniel *et al.* 1972) in this energy region, the consequent revision of some of the experimental data and the later observations (see proceedings of the 14th International Cosmic Rays, Volume 1) do not at present support the possibility of a symmetric universe and the existence of $\bar{p}$ in space.

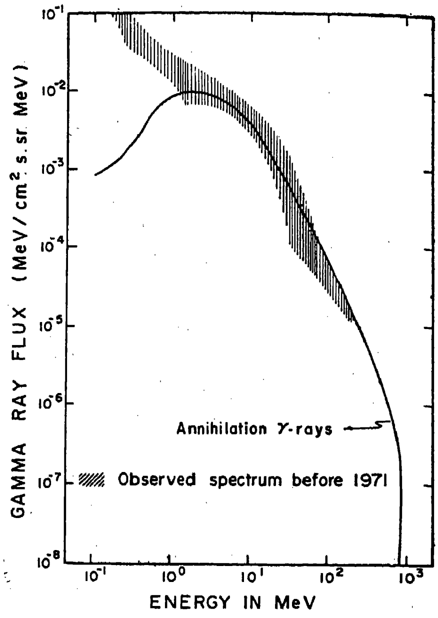

Fig. 4 : The differential background gamma ray spectrum. The observed spectrum shown is from the compilation of the data before 1971.

The important process by which antiprotons are continuously created is the interaction of cosmic rays with ambient gas. The antiprotons thus form the secondary component of cosmic rays. The threshold for the production of nucleon-antinucleon pair in p-p collision is about 7 GeV. One can make use of the available experimental cross sections from accelerator experiments to calculate the expected energy spectrum of secondary $\bar{p}$ in cosmic rays; the antineutrons created in such collisions to form $\bar{p}$. In Figure 5 the expected spectrum of $\bar{p}$ is shown by curve A in interstellar space for 5 g cm^{-2} of interstellar hydrogen traversed from the work of Gaisser and Levy (1974). One can notice that this spectrum peaks around 2 GeV, which corresponds closely to the energy of $\bar{p}$ produced near the threshold for production. The dotted curve in this figure corresponds to the expected $\bar{p}$ spectrum near the earth. For comparison is shown the observed spectrum of protons (curve C) during the minimum solar activity. From this one infers that the $\bar{p}$/p ratio is about (3-4) x 10^{-4} above 5 GeV, which decreases to a value less than 10^{-6} at energies below 200 MeV. If one takes into account the energy dependent propagation (EDP) effect in the general confinement volume, then the ratio is expected to decrease to a value

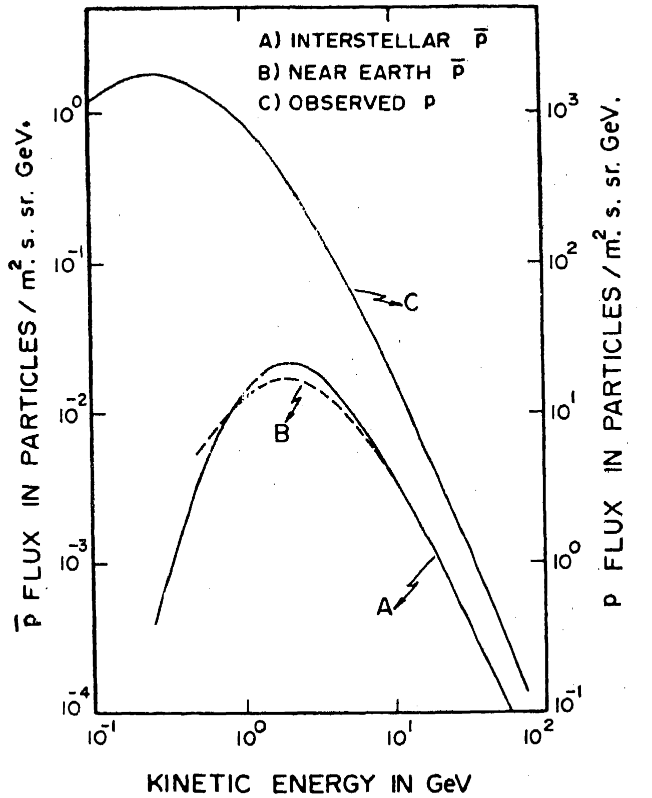

Fig. 5 : The calculated differential energy spectrum of secondary antiprotons in cosmic rays. For comparison the observed proton spectrum is also shown.

of less than 10 around 100 GeV. In the case of EDP in specialised regions of space, $\bar{p}/p$ ratio becomes $\approx 2\times10^{-4}$ even at 5 GeV, because in this case the effect of EDP on the parent particle (10 times $\bar{p}$ energy) is important. Thus antiproton spectrum would give an indication of the region where the EDP is taking place. From the observational point of view it is clear from Fig. 5 that the best region to look for antiprotons is at energies greater than a few GeV. However, since the expected flux of $\bar{p}$ is small at low energies, the energy region below 100 MeV is best suited to look for $\bar{p}$ of primary origin.

OBSERVATIONS OF ANTIPROTONS

A compilation (Steigman 1976) of the available experimental results is given in Table 4. It is very clear from this table that so far antiprotons are not detected in cosmic rays. The upper limits on the flux of $\bar{p}$ are at least two orders of magnitude larger than the expected values. Recently, an upper limit of 6.6×10^{-4} has been obtained for the $\bar{p}/p$ ratio with 95 per cent confidence level using a magnetic spectrometer (Badhwar *et al.* 1977) in the energy region between 4-12 GeV. This value is close to the expected ratio of about 4×10^{-4} in cosmic radiation and can thus rule out any model for the cosmic ray propagation involving a total confinement of cosmic rays. Detection of a finite flux of $\bar{p}$ may not be difficult task at present and it will not be a surprise if none is seen at all!

TABLE 4*

Antiproton Observations with 95% Confidence Level Limits

Energy	$\bar{p}/p$	Remark
100-150 MeV	9×10^{-4}	expected $\lesssim 10^{-6}$
200-800 MeV	3×10^{-3}	expected $\lesssim 10^{-5}$
2-5 GeV	10^{-2}	expected $\approx 2\times10^{-4}$
$\geqslant$ 16 GeV	0.13	indirect estimate
$\geqslant$1000 GeV	5×10^{-2}	indirect estimate

* Taken from Steigman (1976)

It may be interesting at this stage to discuss the possibilities which lead to a little or no antiprotons in cosmic radiation in contrast to that anticipated from cosmic ray interactions. The effective threshold for the production of $\bar{p}$ by taking into account the cosmic ray spectrum is about 10 GeV. It has been pointed out by Badhwar *et al.* (1975) that if cosmic rays traverse most of the matter during the acceleration phase before they acquire an energy about 10 GeV, one would expect only a few antiprotons even though other secondary particles from spallation reactions like deuterons would be seen as expected. The second possibility is that if CPT is violated then $\bar{p}$ would have a finite life time and hence would not be seen in cosmic rays provided its decay time is less than the cosmic ray life time in the Galaxy (Badhwar *et al.* 1977). Such a possibility if it exists could save the symmetric cosmology as this explains the present universe without antimatter.

6. SUMMARY

The following are the important highlights of the present discussion on the study of deuterons and antiprotons relating to their observations.

(a) We have shown that the deuteron production processes in the general astrophysical environment cannot account for the observed abundance of D in the interstellar space. The only convincing manner to explain, at present, these observations is the nucleosynthesis process during the initial phase of the big-bang origin of the universe. Since the observations are limited to regions in the vicinity of the solar system, it may not be fully justified to attribute these results to the universal abundance to draw conclusion on the present baryon density of the universe. Therefore, it is important to extend such observations to various parts of the Galaxy and to external galaxies.

(b) Observations of deuterons in cosmic rays help in the understanding of the cosmic ray propagation in the Galaxy, more directly than from other secondary components, and therefore reliable measurements of deuterons are needed at relativistic energies. Very accurate measurements of D are essential to look for any possible excess of D flux over that expected from cosmic ray spallation reactions, in order to explore new possibilities of producing them.

(c) A simultaneous observation of D and ^{3}He at low energies, where solar modulation is effective would give definitive information on the dynamics of solar modulation because they have different rigidities for the same energy per nucleon and their parent nuclei are the same.

(d) Direct observation of D at high energies is important to remove some of the uncertainties that prevail at present, while drawing useful inferences from the sea level muon observations and the propagation hadronic components of the cosmic rays in the atmosphere.

(e) It has been emphasized that since the energy of the parent particles for D and $\bar{p}$ are widely different, the energy dependent propagation effect would be felt by these particles in a different manner. In the case of EDP operative in the general confinement volume, it is expected that such dependence would terminate at some high energy region. This effect would be felt by the $\bar{p}$ component at an energy 10 times smaller than D. Similarly, in the case of EDP operative in specialised regions of space where most of the matter is traversed, the effective grammage determined from $\bar{p}$ at 5 GeV would be a factor 2 smaller than that from D. Thus a comparative study of these two components can differentiate between these two models.

(f) It has been shown that if reasonable amount of matter is traversed during the acceleration phase of the cosmic rays, the $\bar{p}$ flux will be suppressed in comparison with D. Therefore a direct comparison of their spectra would give information on the physical conditions in the accelerating regions which cannot be deducted from other means.

(g) Measurement of $\bar{p}$ flux in cosmic rays can also possibly provide information on the decay life time of $\bar{p}$ on a time scale very difficult to envisage in the laboratory and hence a test for CPT violation.

(h) $\bar{p}$ measurements can also be utilised for the study of antimatter in the universe upto a level of one part in a million at energies less than 100 MeV.

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