DETERMINATION OF THE FLUX OF PRIMARY COSMIC RAY HYDROGEN AND HELIUM NUCLEI NEAR THE GEOMAGNETIC EQUATOR USING NUCLEAR EMULSIONS

III. The Flux of Deuterons on March 12, 1960, at Hyderabad

By S. N. Ganguli, N. K. Rao and M. S. Swami*

(Tata Institute of Fundamental Research, Bombay)

Received August 4, 1966

(Communicated by Dr. R. R. Daniel, F.A.SC.)

Abstract

Nuclear emulsions exposed to the cosmic radiation over Hyderabad, India, at an altitude of 31·3 km. for six hours, have been used to deremine primary cosmic ray deuteron flux. The flux of deuterons of rigidity $\geqslant 16 \cdot 9$ GV at the top of the atmosphere is found to be < 10 m.$^{-2}$ sec.$^{-1}$ sterad^{-1}; this may be compared with the proton flux of 83 ± 12 m.$^{-2}$ sec.$^{-1}$ sterad.$^{-1}$ in the same rigidity region over Hyderabad.

1. Introduction

Studies on the presence of low energy deuterons (energy $\leqslant 200$ MeV/*n* in the primary cosmic radiation have been made by Appa Rao and Lavakare (1962), Bryant *et al.* (1962), Hasegawa *et al.* (1963), Ormes and Webber (1963) and Badhwar (1964); but no such attempt has so far been made at high energies ($\geqslant 5$ GeV/n). The abundance of deuterons in the universe is known to be negligibly small (Suess and Urey, 1956) and, therefore, as in the case of Li, Be and B nuclei, the flux of deuterons in the cosmic radiation will yield information regarding the history of the radiation. The flux of relativistic deuterons in the primary cosmic radiation can be determined using nuclear emulsions, provided a method can be found for distinguishing deuteron induced stars from those induced by protons. The possibility of such a method has been suggested by Daniel *et al.* (1960 *a*). From a detailed study of the angular distribution of shower particles emitted from disintegrations

---

* Now at the Physics Department, Punjab University, Chandigarh, India, on deputation from the Tata Institute of Fundamental Research, Bombay.

induced by α-particles of energy $\geqslant 5$ GeV/n, it has been shown by Appa Rao *et al.* (1956) that 96% of the shower particles observed within an angle of 2×10^{-2} radian, with respect to the incident α-particle direction, are due to protons of the incident α-particle that did not participate in the collision process. From an analogy to this observation, Daniel *et al.* (1960 *a*) pointed out that in deuteron induced stars also (energy $\geqslant 5$ GeV/nucleon) if the proton did not participate in the collision process (the spectator proton), it will be emitted at a small angle ($\leqslant 2 \times 10^{-2}$ radian) with respect to the primary deuteron direction. This method could be adopted to distinguish deuteron induced stars [hereafter termed as (d, p) stars] from those induced by protons. In order to determine the deuteron flux from the production rate of (d, p) stars, the following parameters need to be known:

(*a*) $f(d, p)$, the ratio of the number of (d, p) stars to all deuteron induced stars; and

(*b*) the inelastic interaction mean free path (λ) for relativistic deuterons in nuclear emulsion.

The values of these parameters as determined by Daniel *et al.* (1960 *a*) have been used in this investigation; they are: $f(d, p) = 0 \cdot 4$ and $\lambda = 15 \cdot 8$ cm. The flux J (x) of deuterons at x g./cm.^{2} is then given by the relation:

$$\mathrm{J}(x) = \frac{\lambda n}{v \, \Omega \, t} \, m^{-2} \text{ sec.}^{-1} \text{ sterad.}^{-1} \tag{1}$$

where λ = interaction m.f.p. of deuterons in metres in emulsion, n = number of deuteron induced stars, V = volume in cubic metres of emulsion scanned, Ω = solid angle of acceptance of deuteron primaries and t=time of exposure in seconds.

2. EXPERIMENTAL RESULTS

A packet consisting of two G-5 emulsions, each of size $6'' \times 6'' \times 600\,\mu$m was exposed to the cosmic radiation at an altitude of 31·3 km. (8·1 g./cm.^{2} of air) for six hours. This exposure was made in a balloon flight made from Hyderabad, India (geomagnetic latitude 7·6° N), on March 12, 1960. These emulsion plates, as well as control plates (from the same batch of manufacture as the exposed plates) kept at sea-level, were area scanned for nuclear interactions with $\mathrm{N}_h \geqslant 3$, where N_h is the number of black and grey prongs associated with the disintegration. In this examination a total of 174 stars (with $\mathrm{N}_h \geqslant 3$) induced by singly charged particles arriving at zenith angles $\leqslant 60°$ were observed in an emulsion volume of 9·72 cm.^{3} Identification of tracks as due to primary particles producing the stars was made according to the procedure suggested by Waddington (1960). The detection efficiency for stars with $N_h \geqslant 3$ was found to be 96% while that for minimum ionising particles was found to be 100%. These observations were first used for the determination of the flux of primary protons which was found to be $83 \pm$ m.$^{-2}$ sec.$^{-1}$ sterad.$^{-1}$ (Ganguli *et al.*, 1963).

The 174 stars were carefully scrutinised for tracks of shower particles under high magnification (1500 × oil); the space angles of all the detected secondary shower particles with respect to the primary direction were measured. Stars with at least one shower particle making an angle $\leqslant 10°$ with respect to the primary direction were chosen for further analysis. In this selection only 29 stars containing a total of 79 shower particles were found. From this sample the very high energy stars ($E \geqslant 50$ GeV/n) have to be first removed since these have a high probability of having secondary shower particles within 1° and can therefore be wrongly attributed as due to (*d*, *p*) stars. The energies of all stars with 6 or more shower particles were determined from the angular distribution of the shower particles; from this, nine stars were found to be induced by primaries of energy $\geqslant 50$ Gev/n. The remaining 20 stars were examined further. Since in (*d*, *p*) stars the " spectator" proton is emitted within one degree with respect to the primary direction, the angles of all shower particles having projected angles $\leqslant 5°$ with respect to the primary direction were remeasured in the following way: the track of the primary particle of each star was aligned parallel to the stage motion of a Koristka scattering microscope; the projected and dip angles of the shower particles were then measured at different places along their trajectories. By this procedure the projected angles were measured accurate to about $\frac{1}{2}°$ and the dip angles, to about 1°. It is to be remembered here that these large errors arise because of the fact that events with relativistic singly charged primary particles having zenith angles $\leqslant 60°$ have been included in this analysis. In view of these large errors of measurement it will be more meaningful at present to set only a reliable upper limit on the flux of deuterons. In order to do this, we adopted the following criteria:

(*a*) the projected angle of a shower particle with respect to its primary direction should be $\leqslant 2°$;

(*b*) the dip angle of the shower particle with respect to the primary particle should be $\leqslant 3°$.

With the above criteria, we found 6 stars that could be classified as (*d*, *p*) stars. Correction was then made by the method described by Appa

Rao *et al.* (1956) for events in which there is a shower particle other than the " spectator proton " within the small angle; the corrected number of (d, p) stars is found to be 5·7. We then made use of the value of $f(d, p) = 0{\cdot}4$ and estimated the total number of deuteron induced stars with $N_h \geqslant 3$ as 14·5.

This number has to be corrected for the loss of stars with $N_h < 3$. The star size distribution for α-particle and proton induced interactions (of energy > 5 GeV/n) has been found to be the same; the ratio R of the number of stars with $N_h \geqslant 0$ to the number with $N_h \geqslant 3$ is 1·5 (Daniel *et al.*, 1960 *b*). The same value of $R = 1{\cdot}5$ was assumed for the deuteron induced stars because of the absence of information regarding their N_h distribution. After correcting for the loss of deuteron induced stars with $N_h < 3$ the total number with $N_h \geqslant 0$ has been estimated to be 21·4. [However, it is possible that the low N_h stars are richer in (d, p) type of stars. If so, the estimated total number of (d, p) stars will be correspondingly underestimated]. This leads to a value of the flux of deuterons at a depth $x = 11{\cdot}5$ g./cm.^{2} as $J(x) = 5$ m.$^{-2}$ sec.$^{-1}$ sterad.$^{-1}$ The value of $x = 11{\cdot}5$ g./cm.^{2} used here represents the mean amount of overlying matter (equivalent amount of air and packing material) present at the ceiling altitude.

In order to extrapolate the flux to the top of the atmosphere the following corrections were made:

(*a*) atmospheric absorption of primary deuterons; and

(*d*) the production of deuterons from interactions of nuclei of $Z \geqslant 2$ of the cosmic radiation above the detector level.

It is estimated that 14% of the primary deuterons will interact before reaching the level of observation (*i.e.*, 11·5 g./cm.^{2}) and that the flux of fragment deuterons due to interaction of heavy primaries $(Z \geqslant 2)$ is 1–2 m.$^{-2}$ sec.$^{-1}$ sterad.$^{-1}$ By taking the above two factors into consideration the flux at the top of the atmosphere is found to be ≈ 5 m.$^{-2}$ sec.$^{-1}$ sterad.$^{-1}$ This value may be compared with the primary proton flux of 83 ± 12 m.$^{-2}$ sec.$^{-1}$ sterad.$^{-1}$ obtained with emulsions from the same flight, by Ganguli *et al.* (1963).

3. SOME REMARKS ABOUT THE METHOD

The result obtained above is based on the assumption that the following parameters used are correct:

(*a*) the interaction mean free path of relativistic deuterons in emulsions, $\lambda = 15{\cdot}8$ cm.

(*b*) ratio $f(d,p)$ of (d,p) stars to all deuteron induced stars is 0·4.

(*c*) the ratio $n\,(N_h \geqslant 0)/n\,(N_h \geqslant 3) = 1 \cdot 5$ is true for the N_h distribution of deuteron induced stars.

The parameters (*a*) and (*b*) mentioned above were determined from data of poor statistical weight. The parameter (*a*) has also been determined by Appa Rao and Lavakare (1962) from a study of 275 MeV deuteron induced interactions in nuclear emulsions; the value obtained by them is $\lambda = 16 \cdot 6 \pm 1 \cdot 8$ cm. This value of λ is consistent with that obtained by Daniel *et al.* (1960 *a*) at energies $\geqslant$ 5 GeV/nucleon. However in the absence of information regarding the energy dependence of these parameters, we have used the values determined by Daniel *et al.*, though these have large statistical errors associated with them. The ratio $n\,(N_h \geqslant 0)/n\,(N_h \geqslant 3)$ could be as large as 2, for it seems probable that the low N_h stars are richer in (*d, p*) type of stars.

Considering the errors in parameters (*a*), (*b*) and (*c*) it would be safe to say at present that the flux of primary deuterons of rigidity $\geqslant 16 \cdot 9$ GV is < 10 m.$^{-2}$ sec.$^{-1}$ sterad.$^{-1}$ The abundance of deuterons (in the energy range 72–175 MeV/nucleon) in the primary cosmic radiation has been investigated by Appa Rao *et al.* (1962) and Badhwar (1964) and their results are consistent with the absence of deuterons in primary cosmic radiation. On the other hand Hasegawa *et al.* (1963) obtained a flux of $2 \cdot 5 \pm 1$ m.$^{-2}$ sec.$^{-1}$ sterad.$^{-1}$ for deuterons in the energy interval 56–200 MeV/n; this may be compared with the proton flux of 51 ± 3 m.$^{-2}$ sec.$^{-1}$ sterad.$^{-1}$ in the energy interval 82–305 MeV. In view of the large errors associated with the last measurement and the negative results from the earlier two attempts it may be concluded that at low energies also the ratio of deuteron to proton flux is not more than a few per cent. The present results for energies $>$ 5 GeV/n show that this ratio is $< 10\%$ and probably not more than a few per cent.

ACKNOWLEDGEMENTS

We are indebted to the Plastic Balloon Section (TIFR) for exposing the nuclear emulsions and to Prof. R. R. Daniel for valuable discussions.

REFERENCES

1. Suess, H. E. and Urey, H. C.	*Rev. Mod. Phys.*, 1956, **28**, 53.
2. Appa Rao, M. V. K., Daniel, R. R. and Neelakantan, K. A.	*Proc. Ind. Acad. Sci.*, 1956, **43 A**, 181.

3. Daniel, R. R., Lavakare, P. J. and Aditya, P. K. *Nuovo Cimento*, 1960 *a*, **16**, 1.
4. ——, Kameswara Rao, N., Malhotra, P. K. and Tsuzuki, Y. *Ibid.*, 1960 *b*, **16**, 1.
5. Waddington, C. J. .. *Phil. Mag.*, 1960, **5**, 1105.
6. Appa Rao, M. V. K. and Lavakare, P. J. *Nuovo Cimento*, 1962, **26**, 740.
7. Bryant, D. A., Ludwig, G. H. and McDonald, F. W. *V Interamerican Seminar on Cosmic Rays*, 1962, **12**, 1.
8. Hasegawa, H., Nakagawa, S. and Tamai, E. *Proc. Int. Conf. on Cosmic Rays, Jaipur, India*, 1963, **3**, 86.
9. Ormes, J. and Webber, W. R. *Ibid.*, 1963, **3**, 69.
10. Ganguli, S. N., Kameswara Rao, N. and Swami, M. S. *Nuovo Cimento*, 1963, **30**, 33.
11. Appa Rao, M. V. K. and Lavakare, P. J. *Ibid.*, 1963, **39**, 321.
12. Badhwar, G. D. .. *Jour. Geophys. Res.*, 1964, **69**, 4435.