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## MONOCHROMATIC COSMIC RAY DEUTERON SOURCE

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The reaction $pp \rightarrow \pi^+ d$ resulting from the high energy cosmic rays incident on the interstellar hydrogen gas gives rise to secondary deuterons. Since the total cross section for this reaction is appreciable only at proton kinetic energies of 600 MeV, the deuterons have a very small spread in energy. It is estimated that the flux of deuterons from this mechanism should be easily discernible from deuterons produced by other reactions and copious enough to be detected at the earth. The narrow deuteron energy distribution could provide an energy calibration for the study of the existence of a postinjection acceleration.

As the high energy cosmic ray protons interact with the interstellar hydrogen gas, a variety of proton-proton interactions occur. In this letter we would like to examine one interaction, $pp \rightarrow \pi d$, particularly with regard to the deuteron energy spectrum. This excitation function for this reaction has a threshold at an incident proton kinetic energy of $T_p = 290$ MeV, rises swiftly to a maximum value of 3 mb at 660 MeV, and falls equally swiftly to a value of less than 250 μb at 1.3 GeV.[1] The cross section remains very small at proton energies beyond 3 GeV (Fig. 1). To appreciate the magnitude of the 3-mb

bump, one can notice that the total proton-proton inelastic cross section is constant with energy and equal to about 30 mb.[3] Thus in the narrow region of proton energies the deuteron production rises to quite an appreciable value and then quickly becomes negligibly small. Since the deuterons are produced over such a small range in proton energies, the deuteron energy spread is correspondingly small, and, as a direct result of the extensive accelerator study of this reaction, the deuteron energy spectrum is easily calculable. To rephrase this, what we are suggesting is that in all regions of the galaxy containing hydrogen and energetic cosmic ray protons an essentially monoenergetic deuteron "signal" is being emitted. A more quantitative examination of this signal, some estimates of the signal-to-noise ratio, and possible uses of the signal are discussed in the following portions of this letter.

The energy spectrum of the deuterons from the $pp \rightarrow \pi d$ reaction is calculated from

$$Q(T_d) = 4\pi \int_{290}^{\infty} \frac{d\sigma}{dT_d}(T_d, T_p)\, n_H J(T_p) dT_p, \tag{1}$$

where $Q(T_d)$ is the number of deuterons produced per $cm^3$ sec GeV of deuteron laboratory-system energy, $\frac{d\sigma}{dT_d}(T_d, T_p)$ is the differential cross section for deuterons of energy $T_d$ produced by incident protons of energy $T_p$, $n_H$ is the density of the interstellar hydrogen gas in the galaxy, including the halo, $J(T_p)$ is the incident cosmic ray proton flux in particles per $cm^2$ sec sr GeV.

The differential cross section $\frac{d\sigma}{d\Omega}$ for $pp \rightarrow \pi^+ d$ has been measured by a number of different experimenters. Because of the symmetry in the proton-proton interaction the expansion of this cross section into a power series in $\cos\theta$, the center-of-mass scattering angle, contains only even powers of $\cos\theta$. At these energies only a few partial waves are present and $\frac{d\sigma}{d\Omega} = A + C\cos^2\theta$

is an adequate parameterization of the data. The coefficients from various experiments are given in Table I. In order to perform the integral over $T_p$ expressed in Eq. (1), we must convert this angular distribution to a distribution in $T_d$. The necessary kinematic transformation is given by

$$\frac{d\sigma}{dT_d} = 2\pi \frac{d\sigma}{d\Omega} \frac{d(\cos\theta)}{dT_d} = \frac{2\pi}{\bar{\eta}p} \left[ A(T_p) + C(T_p) \left( \frac{T_d + m_d - \bar{\gamma} w_d}{\bar{\eta}p} \right)^2 \right] ,$$

where $m_d$ is the deuteron mass, $w_d$ is the energy of the deuteron in the center-of-mass system, p is the c.m. momentum, and $\bar{\gamma}$ and $\bar{\eta}$ are the usual c.m. transformation parameters. All these quantities except $m_d$ are functions of $T_p$.

The results of performing the integration over the incident proton energy spectrum is shown in Fig. 2. We assume $n_H$ to be 0.03 proton per $cm^3$ and take $J(T_p) = 1.05\ (T_p + M_p)^{-2.5}$ particle/$cm^2$ sec sr GeV.[4,5] The deuteron laboratory-system energy spectrum rises sharply from 130 MeV to a peak at 200 MeV. There is a pronounced shoulder at 450 MeV, and by 600 MeV the production has essentially vanished. The deuteron production can be characterized, then, by a peaked distribution with a high-energy tail and a full width at half maximum of about 150 MeV. The total rate of deuteron production in this distribution, $I = \int Q(T_d) dT_d$, is $I = 1.7 \times 10^{-28}/cm^3$ sec. This forms a source for injection into the galaxy, with a spatial distribution which is determined by the amount of overlap between the cosmic-ray proton beam and the interstellar gas. If the protons are assumed to permeate the galaxy uniformly the dependence on $Q(T_d, \underset{\sim}{r})$ is given by the $\underset{\sim}{r}$ dependence on $n_H$.

The question of deuterons produced by other mechanisms in sufficient numbers at this energy to provide enough background to mask the effect is not

completely answered, due to the sparse data on the two types of production reactions which would seem to be important. However, the estimates that can be made are quite encouraging. Proton-on-helium or alpha particle-on-hydrogen reactions would logically be the leading candidate for producing deuterons, since the abundance of He is fairly large, $\approx 0.1\ n_H$. The only experiment which seems to have appropriate data is that of Riddiford and Williams[6] for 970-MeV protons. Of their 564 inelastic events we estimate an upper limit of 200 events which contained deuterons, leading to our estimate of 33 mb of deuteron production via this mechanism. This of course neglects the energy spread, and so should be an upper limit in the region of interest. When we take the helium abundance into account, we arrive at an estimate of 3.3 mb of deuteron production spread over a wide range of energies.

The proton interaction with the $0.01\ n_H$ abundance of heavy nuclei has an appreciable probability of producing deuterons. For 190-MeV protons bombarding Ni, Ag, and Au, Hyde[7] gives approximately 10 mb-sr in the forward hemisphere and approximately 5 mb/sr in the backward hemisphere, yielding roughly 96 mb total cross section, or about a 30% background. This background is again spread over a wide energy range. Thus, taking both production on He and production on heavy nuclei into account, we might expect at worst a one-to-one or one-to-two signal-to-noise ratio in the energy region of interest. Of course, the question of backgrounds can be answered experimentally by observing the deuteron abundance at slightly below $T_d = 125$ MeV and at slightly above 600 MeV.

The equilibrium distribution of cosmic rays has received considerable attention recently, primarily because of interest in the high energy electron spectrum and in the secondary antiproton spectrum. Jokiipi and Meyer have

pointed out that one must solve the diffusion equations carefully and that the resulting equilibrium concentrations are dependent upon the boundary conditions placed upon the solution.[8] It is not our purpose in this letter to make a careful calculation of the equilibrium distribution of the deuterons, but we discuss a few of the considerations involved.

The only loss mechanism applicable is the loss from the galactic confinement.[9] The electromagnetic loss mechanisms are negligible due to the large mass of the deuteron; nuclear collisions in the usually assumed path length of 3 $g/cm^2$ of interstellar material are unimportant because of the long deuteron interaction length of 60 $g/cm^2$.[10] The possibility of acceleration of the deuterons after injection is particularly intriguing, since the source spectrum does not follow a power law. If a power-law distribution were observed in the energy of the deuteron it would constitute good evidence for a postinjection acceleration. If, however, we assume no subsequent acceleration it is easy to get an approximation for the number of deuterons in the equilibrium distribution.

For the case of no postinjection acceleration and galactic escape as the only loss term, the solution for the diffusion equation becomes

$$\frac{\rho(T_d)}{\tau_L} - Q(T_d) = 0,$$

where $\rho(T_d)$ is the equilibrium density and $\tau_L$ is the leakage lifetime. Assuming $\tau_L = 1.5 \times 10^{15}$ sec (this is consistent with our choice of $n_H = 0.03$ and 3 $g/cm^2$ of interstellar path length), we get $\rho = 2.5 \times 10^{-13}/cm^3$ for deuterons with kinetic energies between 130 and 600 MeV. This would correspond to an observed intensity of $j_d = \frac{c}{4\pi} \rho = 6.1/M^2$ sec sr.

An intensity of this magnitude should not be difficult to observe experimentally. Some preliminary observations of the deuteron flux have already been made, yielding results of integral fluxes which are consistent with our suggestion.[11] Unfortunately, there is no sufficiently detailed energy spectrum available. The peak energy of 200 MeV is low enough so that solar modulation effects will be important, and may alter the observations; alternatively, the deuteron flux might provide a method of studying the modulation.

I am especially grateful to Afzaal Hussain for his assistance with the numerical calculations. I have enjoyed a number of informative and stimulating conversations with Frank S. Crawford. The continued guidance, support, and encouragement of Luis W. Alvarez is appreciated, as are a number of his suggestions concerning the deuteron-loss mechanisms.

## FOOTNOTES AND REFERENCES

*Work done under auspices of the U. S. Atomic Energy Commission.

1. Frank S. Crawford Jr., and M. Lynn Stevenson, Phys. Rev. 91, 468 (1953); T. H. Fields, J. G. Fox, J. A. Kane, R. A. Stallwood, and R. B. Surton, Phys. Rev. 92, 638 (1964); M. G. Mescherjakov, N. P. Bogacer, and B. S. Neganov, Nuovo Cimento Supp. 3, 119 (1956); B. Baldoni, S. Focardi, H. Hromadnik, L. Monari, F. Saporetti, S. Fermino, F. Mezzanares, E. Bertolini, and G. Gialanella, Nuovo Cimento 26, 1376 (1962); D. V. Bugg, A. J. Oxley, J. A. Zoll, J. G. Rushbrooke, V. E. Barnes, J. B. Kinson, W. P. Dodd, G. A. Ioran, and L. Riddiford, Phys. Rev. 133B, B1017 (1964); O. E. Overseth, R. M. Heinz, L. W. Jones, M. J. Longo, D. E. Pellett, M. L. Perl, and F. Martin, Phys. Rev. Letters 13, 59 (1964).

We have not included any data obtained by the principle of detailed balance on the inverse reaction $\pi^+ D \rightarrow pp$.

2. S. Mandelstam, Proc. Roy. Soc. (London) A244, 491 (1958).
3. G. Alexander, O. Benary, and U. Maor, Nucl. Phys. B5, 1 (1968).
4. R. Ramaty and R. E. Lingenfelter, J. Geophys. Res. 71, 3687 (1966).
5. J. F. Ormes and W. R. Webber, in Proceedings of the International Conference on Cosmic Rays, London, 1965, 349.
6. L. Riddiford and A. W. Williams, Proc. Roy. Soc. (London) A257, 316 (1960).
7. Earl K. Hyde, The Nuclear Properties of the Heavy Elements, Vol. 3 (Prentice Hall; Englewood, New Jersey, 1964).
8. J. R. Jokiipi and Peter Meyer, Phys. Rev. Letters 20, 752 (1968).
9. Ignoring a correction for the ionization loss in the 3 g/cm$^2$ of interstellar hydrogen. This reduces the deuteron energy about 15% at $T_d = 250$ MeV. Photo disintegration of the deuteron should occur as a result of the interaction with the 3° K photons; however, we calculate this threshold to be $T_d = 3000$ GeV.
10. R. R. Daniel, P. J. Lavakare, and P. K. Aditya, Nuovo Cimento 17, 837 (1960), have determined the interaction mean free path for deuterons in emulsion to be 15.8 cm. Using an emulsion density of 3.8, we estimate an interaction path of 60 g/cm$^2$.
11. S. N. Ganguli, N. Kameswara Rao, and M. S. Swami, in Proceedings of the International Conference on Cosmic Rays, Jaipur Vol. 3, (1963) 65; W. R. Webber and J. Ormes, ibid., 69; H. Hasegawa, S. Nakagawa, and E. Tamai, ibid., 86.

## FIGURE CAPTIONS

Fig. 1. The total cross section for the reaction $pp \rightarrow \pi^+ d$ as a function of incident proton kinetic energy. The dashed curve is from S. Mandelstam (Ref. 2).

Fig. 2. The production energy spectrum of deuterons from the reaction $pp \rightarrow \pi^+ d$. We have assumed $n_H = 0.03$ particle/cm$^3$ and $J_p = 1.05 E_{tot}^{-2.5}$ particles/cm$^2$ sr sec GeV. The total flux of deuterons in the peak is $I = \int Q(T_d)\, dT_d = 1.7 \times 10^{-28}$ particle/cm$^3$ sec.

Table I. Total cross section and c. m. angular distribution for $pp \rightarrow \pi^+ d$.

| $T_p$ (GeV) | A (mb) | C (mb) | $\sigma_{tot}$ (mb) | Reference |
|---|---|---|---|---|
| 0.327 | 0.0076 | 0.02 | 0.1793±.03 | Crawford & Stevenson PR 91, 468, 1953. |
| 0.340 | 0.0099 | 0.03 | 0.2501±.03 | Crawford & Stevenson PR 91, 468, 1953. |
| 0.437 | 0.0402 | 0.2012 | 1.35 ±.13 | Fields et al. PR 95, 638. |
| 0.460 | 0.051 | 0.213 | 1.54 ±.16 | Mescherjakov et al. N. C. Supp. 3, 199, 1956. |
| 0.560 | 0.131 | 0.264 | 2.75 ±.29 | Baldoni et al. N. C. 26, 1376, 1962. |
| 0.657 | 0.099 | 0.435 | 3.1 ±.20 | Mescherjakov et al. N. C. Supp. 3, 119, 1956. |
| 0.970 | 0.01247 | 0.0772 | 0.48 ±.08 | Bugg et al. PR 133B B1017, 1964. |
| 1.3 | 0.01122 | 0.0188 | 0.22 ±.03 | Overseth et al. PRL 13, 59, 1964. |
| 1.5 | 0.00558 | 0.128 | 0.124 ±.019 | Overseth et al. PRL 13, 59, 1964. |
| 1.7 | 0.001 | 0.0173 | 0.085 ±.013 | Overseth et al. PRL 13, 59, 1964. |
| 2.0 | 0.00065 | 0.01117 | 0.055 ±.018 | Overseth et al. PRL 13, 59, 1964. |
| 2.5 | 0.00024 | 0.00716 | 0.033 ±.005 | Overseth et al. PRL 13, 59, 1964. |
| 2.8 | 0.0002 | 0.00679 | 0.031 ±.005 | Overseth et al. PRL 13, 59, 1964. |

Angular distribution over the above energy range taken to be

$$\frac{d\sigma}{d\Omega} = A + C\cos^2\theta; \quad \sigma_{tot} = \int \left(\frac{d\sigma}{d\Omega}\right) d\Omega = 4\pi\,(A + 1/3C).$$

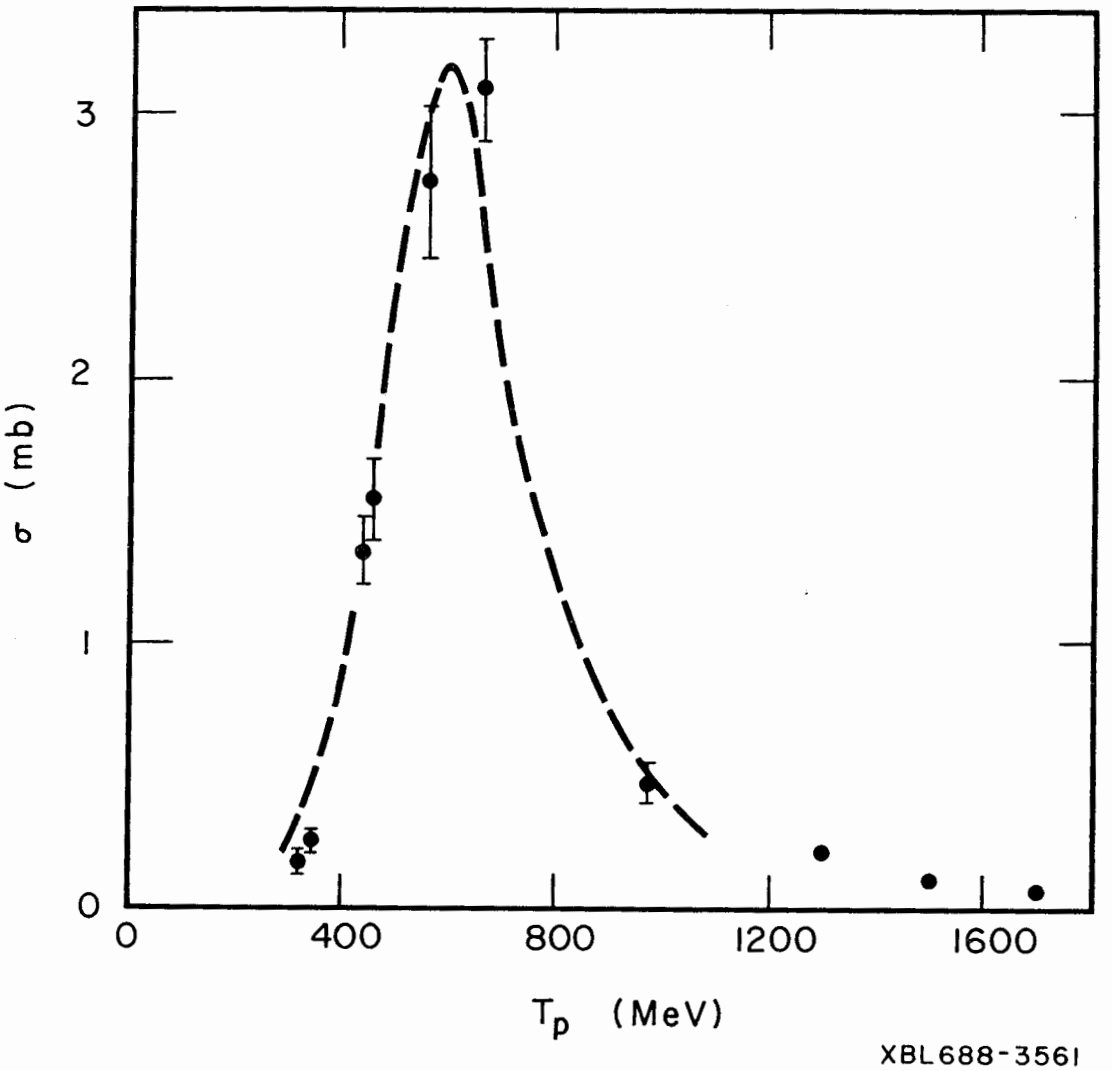


Fig. 1

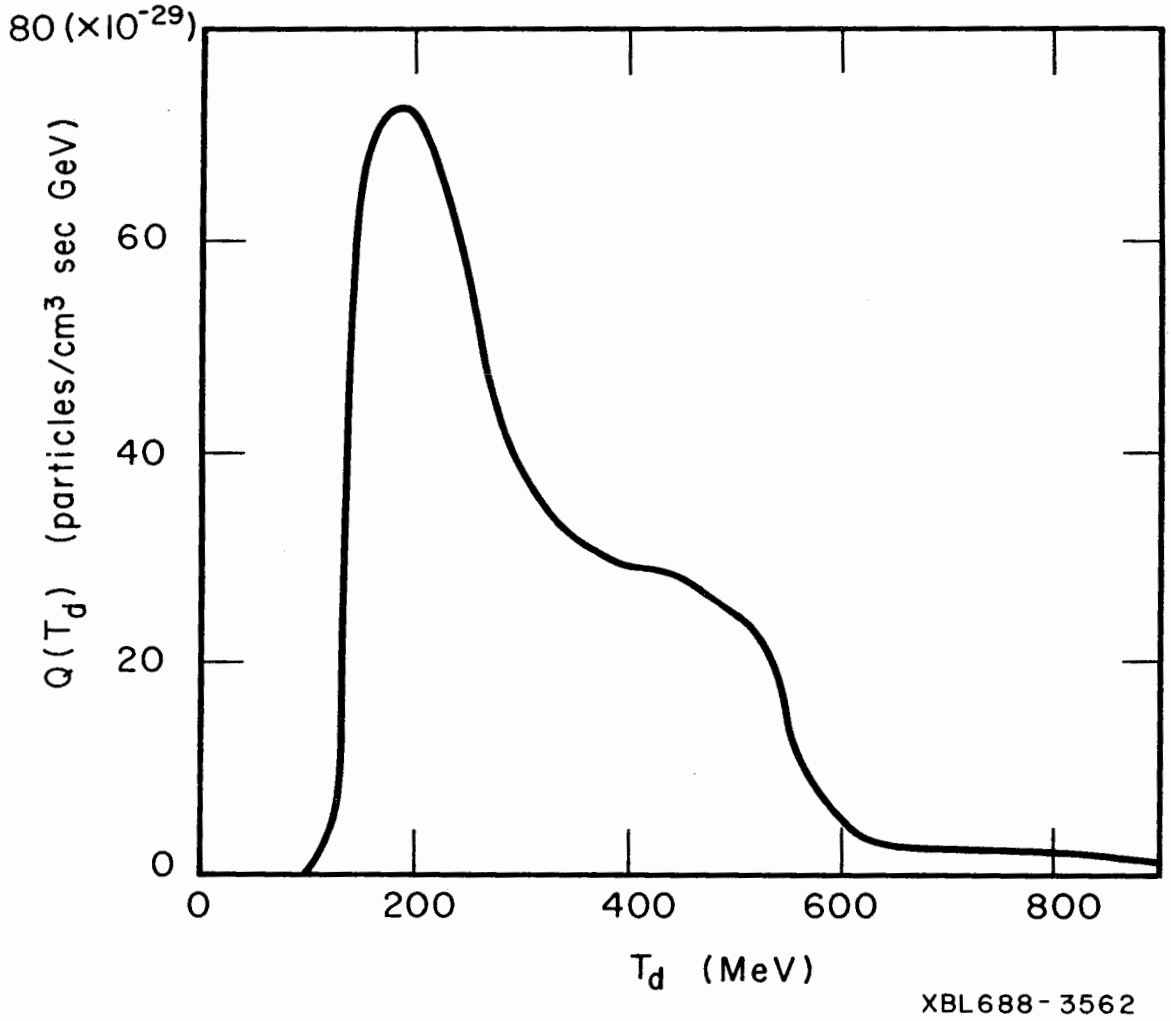
80 (×10^-29)
60
40
20
0
Q(T_d) (particles/cm^3 sec GeV)
0
200
400
600
800
T_d (MeV)
XBL688-3562

Fig. 2

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