GALACTIC DEUTERIUM AND ITS ENERGY SPECTRUM

ABOVE 20 MeV PER NUCLEON*

C. Y. Fan, George Gloeckler and J. A. Simpson+
Enrico Fermi Institute for Nuclear Studies
The University of Chicago
Chicago, Illinois 60637

Laboratory for Astrophysics and Space Research
Preprint No. EFINS 66-58

* This research was supported in part by the National Aeronautics and Space Administration under Grant NASA NsG 179-61 and by the Air Force Office of Scientific Research under Grant AF 49 (638) 1642.

+ and Department of Physics.

GALACTIC DEUTERIUM AND ITS ENERGY SPECTRUM

ABOVE 20 MeV PER NUCLEON*

C. Y. Fan, George Gloeckler and J. A. Simpson+
Enrico Fermi Institute for Nuclear Studies
The University of Chicago
Chicago, Illinois 60637

Abstract

The fluxes and energy spectra of deuterium, protons and helium were measured on the IMP-III satellite at a time near minimum solar activity. The deuterium differential energy spectrum in the range 17 - 63 MeV/nucleon is $\propto E^{+2}$ and, at 60 MeV/nucleon, the relative abundance ratios are $H^2/He^4 = 0.15$ and $H^2/H^1 = 0.05$. If present values of experimental cross-sections for the production of H^2 from nucleon interactions with He^4 are used, the observed deuterium abundance may be accounted for by the traversal of He^4 through 4 to 6 gm/cm^2 of matter in cosmic ray sources and the interstellar medium.

Measurements of He^3 in the primary cosmic rays both above 100 MeV per nucleon[1,2,3] and more recently at lower energies[4] are consistent with the hypothesis that He^3 is produced principally through the spallation reaction of He^4 on protons in the traversal of approximately 3 - 5 gm/cm^2 of hydrogen in cosmic ray sources and in the interstellar medium. Consequently, we expect a small amount of deuterium to be present in the galactic cosmic radiation, also produced by spallation of He^4. Although a number of attempts have been made to measure H^2 in the primary cosmic rays in different energy ranges,[5,6,7] either a clear identification of primary H^2 could not be obtained or it was possible only to place upper limits of approximately 0.08 for the H^2/H^1 ratio. In this Letter we report the detection of deuterium from the galaxy and the measurement of its differential energy spectrum in the energy range 17 to 63 MeV per nucleon. Since the observations were made in interplanetary space on the IMP-III satellite (apogee 260,000 km) with no obstructions within the cone angle of acceptance for the incoming particles, there were no corrections required for matter above the detector, or for geomagnetic effects.

The cross-section of the detector assembly is shown in Fig. 1(a). This instrument was used for the direct measurement of He^3 which was recently reported,[4] and is similar to the IMP-I detector system which has been described elsewhere.[8] D_1 and D_2 are lithium-drifted detectors, each 900 μ thick with sensitive areas of 5.7 cm^2. D_3 is a CsI (Tℓ) scintillation crystal with two light-sensitive photodiodes (not shown in the figure) mounted on the sides of the crystal. To identify a charged particle and to determine its energy, simultaneous pulse height analysis is made of the energy loss in D_1 (-dE/dx) and the total residual energy (E) in D_3 for particles which are completely stopped in the CsI (Tl) crystal. (Trajectory "B" in Fig. 1(a)). The anticoincidence cup D_4 eliminates most of the background from nuclear interactions and prevents analysis of penetrating particles. (Trajectory "A" in Fig. 1 (a)) To obtain measurable fluxes of primary deuterium, we have analyzed data obtained continuously over a period of almost seven months from 29 May 1965 (launch date) to 25 December 1965. Approximately 10% of these data have been excluded from analysis, representing times when the satellite was inside the Earth's magnetosphere or when low energy particles from a solar flare event were present.

In Fig. 1(b), we show mass histograms for the three kinetic energy per nucleon intervals as indicated for each distribution. To optimize the resolution of the deuterium peak we summed along the calculated H^2 track[9] in the two-dimensional dE/dx vs. E pulse height distributions.[8] For deuterium energies below 49 Mev/nucleon, both H^1 and H^2 are observed at their predicted positions indicated by the respective arrows. Protons above 90 MeV will trigger the anticoincidence detector D_4 and will not be analyzed. Therefore, only H^2 should be present in the 49 - 63.5 Mev/nucleon energy interval, which is, indeed, confirmed by the data. Since protons which reach D_4 (> 90 Mev) will deposit a smaller energy loss in D_3 than protons of $\sim$ 90 MeV, even an inefficiency of the D_4 anticoincidence cannot result in the registration of such protons as spurious H^2 "events." The number of background events has been obtained by interpolation of the measured background levels below the proton peak and above the H^2 peak. The actual number of deuterium events shown has been corrected for background,[10] as indicated by the dashed curves. The statistical uncertainties are given by the vertical error bars in Fig. 1(b) for each channel number.

The deuterium differential energy spectrum is shown in Fig. 2. For comparison we give the differential energy spectra of He^4 and protons over approximately the same energy intervals for the same time period. The proton spectrum and fluxes were obtained from the same data used to derive the H^2 spectrum, and the same background corrections were used. The fact that this spectrum agrees with independent measurements by another instrument[11] provides additional evidence that our treatment of the background is correct.

We conclude that the observed deuterium is of galactic origin because, a) the data are taken at times when there were no solar particle events, and b) the deuterium spectrum falls off with decreasing energy in a manner similar to those portions of the He^4 and H^1 spectra which have been shown to be of galactic origin over the past few years.[11,12]

Since deuterium is believed to be rare in astrophysical bodies[13] and since other evidence indicates that the cosmic ray He^4 has passed through approximately 3 to 5 grams/cm^2 of material in traveling between the source and Earth,[14] we first attempt to explain the observed deuterium by assuming that 1) it is a daughter product of the primary cosmic rays produced through spallation within cosmic ray sources and in interstellar hydrogen, and b) that the largest contribution to the production of H^2 under these circumstances would be from the observed spallation reaction of He^4 on protons. Therefore, it is instructive to consider the abundance ratio $\frac{H^2}{He^4}$ [$\equiv \Gamma (H^2/He^4)$] as a function of energy per nucleon (or velocity) over the energy range covered by our measurements. The ratios derived from the spectra of Fig. 2 are shown in Fig. 3 for three energy intervals. It is seen that as a function of energy per nucleon, $\Gamma (H^2/He^4)$ is energy dependent, having a value of ≤ 0.06 near 25 MeV per nucleon, and rising to approximately 0.15 at 60 MeV per nucleon. For comparison, the observed abundance ratio H^2/H^1 at 60 Mev per nucleon is 0.05 ± 0.01 (or in units of magnetic rigidity the abundance ratio $H^2/H^1 = 0.005 \pm 0.001$ at 0.7 Gv.)

Solar modulation will not introduce any energy dependence in $\Gamma (H^2/He^4)$ since both H^2 and He^4 have the same charge-to-mass ratios and all reasonable models of solar modulation depend upon some combination of magnetic rigidity and velocity of the particle. Consequently, the values of $\Gamma (H^2/He^4)$, as a function of velocity, at the orbit of Earth and in the nearby interstellar medium are expected to be identical.

We now examine the factors which influence the magnitude and energy dependence $\Gamma (H^2/He^4)$. Since we know of no direct measurements of the production cross-section for H^2 from the (He^4, p) reactions we have assumed that such cross-sections are not substantially different from those of (He^4, n) interactions, which have been measured to be 45 mb at 90 MeV[15] and 34 mb at 300 MeV[16] neutron energy. Using a value of 40 mb we have calculated the abundance ratio $\Gamma (H^2/He^4)$ for penetration depths of 3 and 6 gm/cm^2 and show the results as the dashed lines in Fig. 3. If we neglect ionization loss effects and the production of deuterium from cosmic ray protons interacting with helium in the interstellar medium we find that 6 gm/cm^2 can explain the experimental value for Γ at

60 MeV per nucleon. The observed decrease of Γ with decreasing energy could be due to an energy dependence of the production cross-section which must approach zero for threshold energies.

The other factors which may influence the magnitude and energy dependence of Γ and must eventually be considered are, a) energy loss by ionization, b) the kinematics of the (He^4, p) interaction, c) production of deuterium by cosmic ray protons interacting with helium in the interstellar medium, and d) production by other elements interacting with interstellar hydrogen. Since for a given velocity H^2 will lose less energy by ionization than He^4, this effect will introduce an increase in Γ as observed at Earth, which will become larger with decreasing energy. Compensating this energy dependent increase is a kinematic effect due to H^2 nuclei emerging from (He^4, p) interactions having a lower velocity than the incoming particles. The magnitude of these two effects at any given energy will depend on the shape of the spectrum of He^4 at the time of the interactions, but in this Letter we do not examine the consequences for various assumed source spectra. Cosmic ray protons interacting with helium in the interstellar medium may account for ~ 30 percent of the observed deuterium. This is based on the assumption that the abundance ratio of protons to helium in the interstellar medium is 10:1, and the fact that the proton flux at the energies of interest (~ 50 - 200 MeV) is about 4 to 6 times the helium flux in the equivalent energy per nucleon range. For the production from elements other than He^4 and protons, we note that although C^{12}, O^{16}, etc. have large cross-sections, compared with He^4, their fluxes are so low[17] that the additional production of H^2 would constitute a second-order correction. The reaction $p + p \longrightarrow H^2 + \pi^+$ has cross sections of < 1 mb at the energies of interest[18] and will not produce much additional deuterium.

If our assumptions are correct - especially regarding the magnitude of the (He^4, p) cross-section - the present measurements point to a value of ~ 6 gm/cm^2 for the traversal of cosmic rays in interstellar matter and cosmic ray sources. However this value could be reduced by as much as 50 percent if one takes account of the production of deuterium by cosmic ray protons interacting with interstellar helium. It is likely that the H^2 and He^3 results may be consistent with a common interstellar penetration depth, once a quantitative treatment of cosmic ray propagation in the interstellar medium and source material is considered, taking into account the various effects which we have outlined. In particular, measurements of production cross-sections are needed at low energies. Furthermore, a better understanding of solar modulation is required to determine the abundance ratio $He^3 / (He^3 + He^4)$ observed near Earth relative to its value in the interplanetary medium.[4]

Cosmic ray deuterium detected here represents the third direct observation of H^2 in nature, and the first one from the galaxy. The other two are terrestrial deuterium[13] and meteoritic deuterium (from carbonaceous chondrites)[19] whose abundance is similar to the terrestrial value.

We wish to thank the staff of the Laboratory for Astrophysics and Space Research in our Institute, especially R. Jacquet for the engineering, S. Tado for the checkout of our instrument before launch, A. Tuzzolino and J. Kristoff for development of the new Li-drifted solid state detectors. For the data reduction program and for the preparation of the data we thank L. Littleton, W. Dietrich and K. Hsieh. For the integration of our experiment into the IMP-III satellite and its launching, we are grateful to the Goddard Space Flight Center staff, particularly P. Butler and F. McDonald. We thank Prof. A. Turkevich for an interesting discussion of the cross-sections and K. Fenton for pointing out the additional production of deuterium from helium in the interstellar medium.

---

* This research was supported in part by the National Aeronautics and Space Administration under Grant NASA NsG 179-61 and by the Air Force Office of Scientific Research under Grant AF 49 (638) 1642.

+ and Department of Physics.

1. S. Biswas, P. J. Lavakare, S. Ramadurai, and N. Sreenivasan, in Proceedings of the Ninth International Conference on Cosmic Rays, London, 1965, The Physical Society (in press).

2. F. W. O'Dell, M. M. Shapiro, R. Silberberg, and B. Stiller, in Proceedings of the Ninth International Conference on Cosmic Rays, London, 1965, The Physical Society (in press).

3. D. J. Hofmann and J. R. Winckler, Phys. Rev. Letters, 16, 109 (1966).

4. C. Y. Fan, G. Gloeckler, K. C. Hsieh, and J. A. Simpson, Phys. Rev. Letters 16, 813 (1966).

5. H. Hasegawa, S. Nakagawa and E. Tamai, Nuovo Cim. 36, 18 (1965).

6. M. V. K. Appa Rao and P. J. Lavakare, Nuovo Cim. 26, 740 (1962).

7. G. H. Ludwig and F. B. McDonald, Phys. Rev. Letters, 13, 783 (1964).

8. C. Y. Fan, G. Gloeckler, and J. A. Simpson, J. Geophys. Res. 70, 3515 (1965).

9. To calculate the H^2 track, we applied range-energy relations to each absorber in the telescope and used in-flight calibrations for the conversion from energy to channel number. Similar calculations for the H^1 and He^4 were found to agree well with the well-defined proton and He^4 tracks in the data.

10. The systematic error introduced by the subtraction of background does not exceed 25% in the 49 - 63 MeV/nucleon energy interval.

11. V. K. Balasubrahmanyan, D. E. Hagge, G. H. Ludwig, and F. B. McDonald, Goddard Space Flight Center Report No. X-611-65-480, 1965 (unpublished).

12. C. Y. Fan, G. Gloeckler, and J. A. Simpson, in Proceedings of the Ninth International Conference on Cosmic Rays, Session Accel.-3, London, 1965, The Physical Society (in press).

13. L.H. Aller, The Abundance of the Elements, Interscience, New York (1961).

14. We pointed out in Reference 4 that the ratio $He^3 / (He^3 + He^4)$ extrapolated to the nearby interstellar medium and, hence, a calculation of the amount of matter traversed depends upon the charge-to-mass and velocity dependence of solar modulation. Therefore, the range of possible values for the traversed material is from 2.5 to 5 gm/cm^2.

15. P. E. Tannenwald, Phys. Rev. 89, 508 (1953).

16. W. H. Innes, Report UCRL-8040 (1957) unpublished.

17. G. M. Comstock, C. Y. Fan, and J. A. Simpson, Ap. J. (to be published), and preprint EFINS 66-09 (1966).

18. A. M. Sachs, H. Winick, and B. A. Wooten, Phys. Rev. 109, 1733 (1958).

19. G. Boata, Geochim. et Cosmochim. Acta, 6, 209 (1954).

Figure Captions

Fig. 1. (a) Cross-section of the charged particle telescope.

(b) Mass distributions for protons and deuterons for three kinetic energy per nucleon intervals. Arrow heads indicate theoretically predicted positions of protons (left) and deuterons (right) for each histogram.

Fig. 2. Observed primary differential energy spectra for protons, deuterons and helium nuclei, obtained over the same time period near the minimum of the present solar activity cycle. The deuterium spectrum can be represented by $dJ/dE \propto E^{+2}$. Errors shown for the proton, helium and deuterium data are due to both statistics and uncertainties in the energy calibration. For the lower energy deuterium data systematic errors due to subtraction of background may be large. The upturn of the helium spectrum was already reported in reference 12.

Fig. 3. Energy dependence of the abundance ratio of H^2/He^4, Γ (H^2/He^4) computed from the data of Fig. 2. Production cross-sections for H^2 from He^4 interacting with protons in cosmic ray sources and interstellar matter are deduced from experimental measurements by Tannenwald (reference 15) using 90 Mev neutron and Innes (ref. 16) using 300 Mev neutrons.

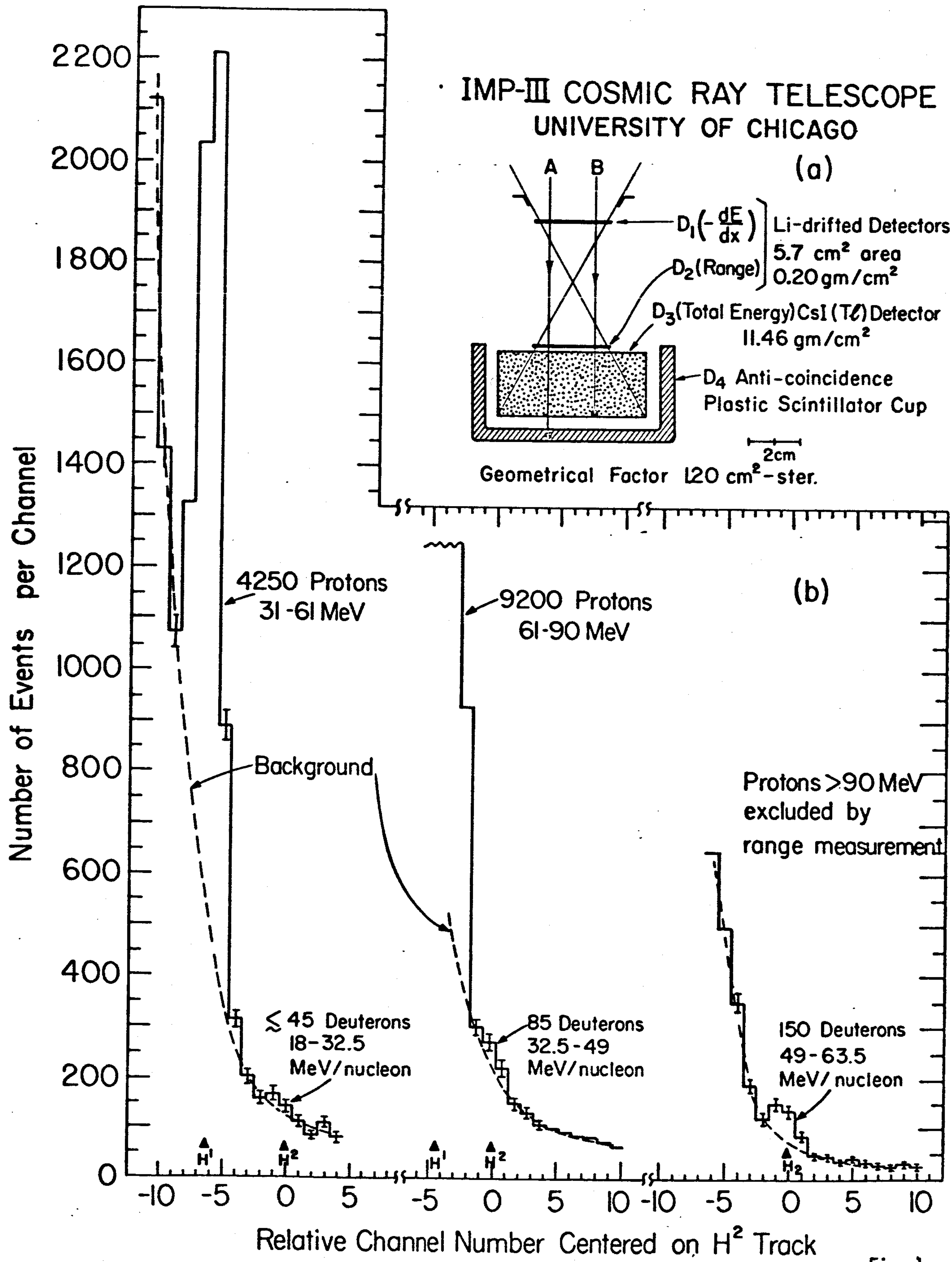
IMP-III COSMIC RAY TELESCOPE
UNIVERSITY OF CHICAGO
(a)
A
B
$D_1(-\frac{dE}{dx})$
D_2(Range)
Li-drifted Detectors
5.7 cm² area
0.20 gm/cm²
D_3(Total Energy) CsI (Tl) Detector
11.46 gm/cm²
D_4 Anti-coincidence
Plastic Scintillator Cup
2cm
Geometrical Factor 1.20 cm²-ster.
(b)
4250 Protons
31-61 MeV
9200 Protons
61-90 MeV
Background
Protons >90 MeV
excluded by
range measurement
≲45 Deuterons
18-32.5
MeV/nucleon
85 Deuterons
32.5-49
MeV/nucleon
150 Deuterons
49-63.5
MeV/nucleon
H¹
H²
Number of Events per Channel
Relative Channel Number Centered on H² Track

Fig. 1

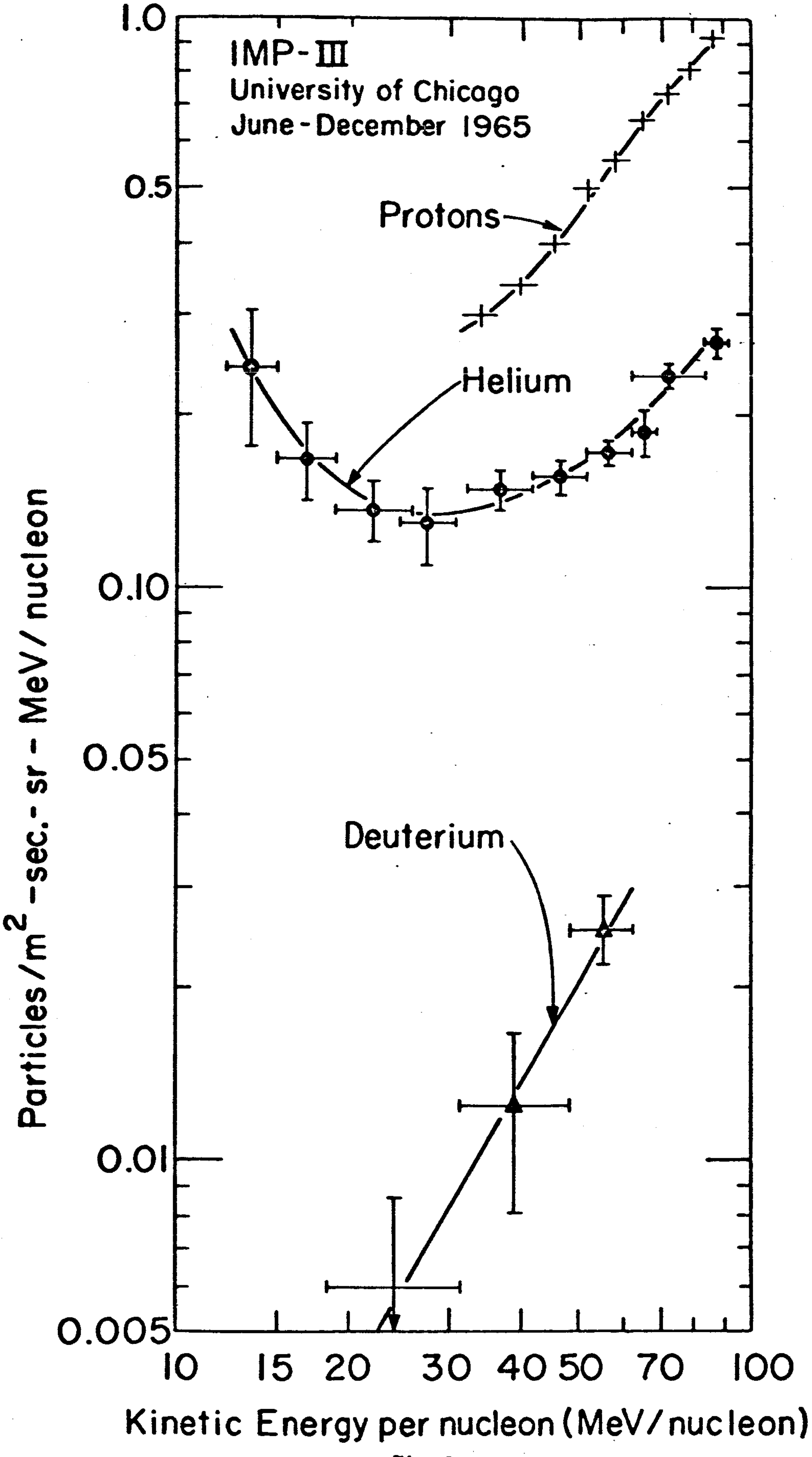
IMP-III
University of Chicago
June-December 1965
Protons
Helium
Deuterium
1.0
0.5
0.10
0.05
0.01
0.005
10
15
20
30
40
50
70
100
Particles/m2-sec.-sr-MeV/nucleon
Kinetic Energy per nucleon (MeV/nucleon)

Fig. 2

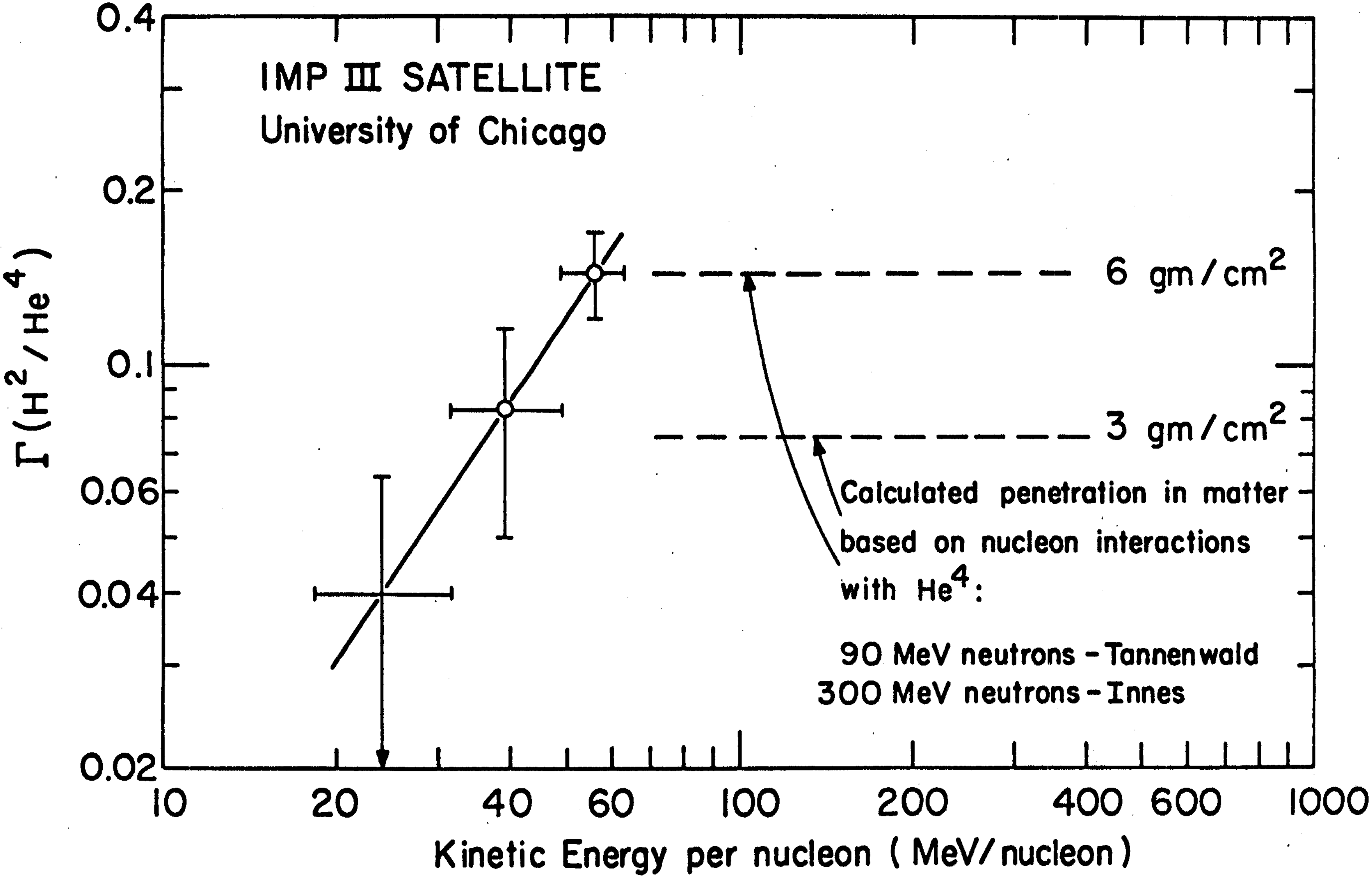
IMP III SATELLITE
University of Chicago
6 gm/cm²
3 gm/cm²
Calculated penetration in matter
based on nucleon interactions
with He⁴:
90 MeV neutrons - Tannenwald
300 MeV neutrons - Innes
0.4
0.2
0.1
0.06
0.04
0.02
Γ(H²/He⁴)
10
20
40
60
100
200
400
600
1000
Kinetic Energy per nucleon (MeV/nucleon)

Fig. 3