GALACTIC DEUTERIUM AND ITS ENERGY SPECTRUM ABOVE 20 MeV PER NUCLEON*

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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 g/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[1-3] 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 g/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,[5-7] 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 we recently reported.[4] The method of operation of the IMP-III detector system is similar to that of the IMP-I instrument and has been described elsewhere.[8] However, the IMP-I detector system could neither resolve the isotopes of helium, nor measure the differential proton spectrum. Therefore, we have modified the IMP-III instrument so as to achieve the resolution[4] required to separate He^3 from He^4 and H^1 from H^2. D_1 and D_2 are lithium-drifted detectors, each 900 μ thick with sensitive

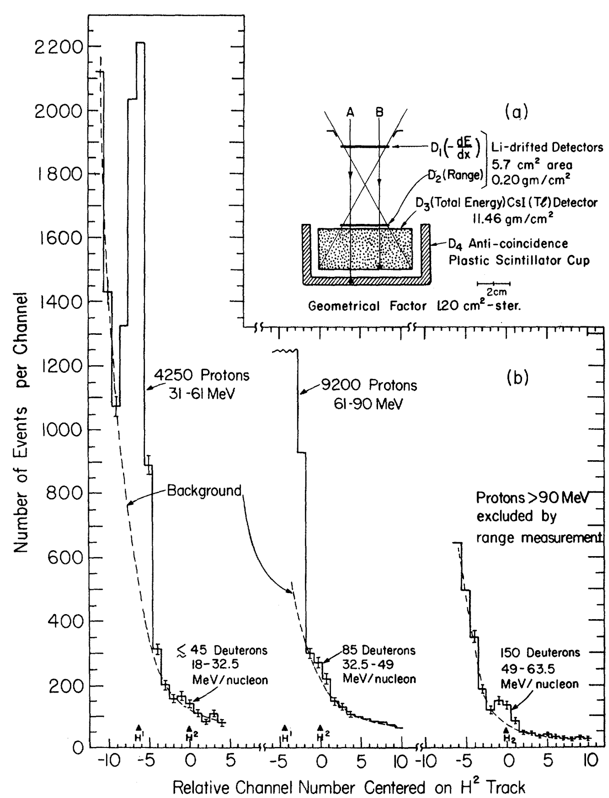

FIG. 1. (a) Cross section of the IMP-III cosmic-ray (charged-particle) telescope of the University of Chicago. (b) Mass distributions for protons and deuterons for three kinetic energy per nucleon intervals. Arrow heads indicate theoretically predicted positions of protons (left) and deuterons (right) for each histogram.

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; this corresponds to ~10% of the time 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 indicated intervals of kinetic energy per nucleon. These distributions were obtained by summing along the calculated H^2 track[9] in the two directional dE/dx-vs-E pulse-height distributions. Such a method of data analysis is typical for dE/dx-vs-E instruments and has been described in the literature.[3,4,7,8] We have shown[4] that the IMP-III instrument is able to resolve He^3 from He^4. The left histogram in Fig. 1(b) shows the resolution of this instrument for protons of energy 31-61 MeV. The full width at half-maximum is three channels in an energy region where the separation of the H^1 and H^2 tracks is 6.5 channels [arrow heads at bottom left of Fig. 1(b)].

The strongest evidence for the existence of deuterium comes from the mass histogram labeled "deuterons 49-63.5 MeV/nucleon" (or 98-127 MeV total kinetic energy). It is not possible for protons to contribute to this distribution since the maximum energy loss or pulse height in the D_3 detector produced by protons of any energy cannot exceed 87 MeV. Therefore, aside from background, only H^2 events can contribute to this histogram. At the calculated position of the H^2 track (arrow head labeled H^2) we see a peak with a width of 3 channels. Since this peak has the same width as the proton peak and since it is located at the calculated position for the deuterium track, we conclude that this peak represents deuterium detected by the instrument. The principal error in determining the deuterium flux is due to the systematic error inherent in subtraction of background. The analysis of background in regions of the dE/dx-vs-E pulse-height distributions where no particle events are expected has shown that the frequency distribution of background is a smooth function of the channel number, has a characteristic shape, and increases logarithmically with decreasing channel number. These properties of the background have been used when we fitted the dashed curve to portions of the mass histogram which did not contain the deuterium peak. The number of deuteron events shown in Fig. 1(b) has been corrected for background,[10] represented by the dashed curve below the peak. The standard deviations are shown by vertical error bars for each channel number. It is seen that the dashed background curve falls well below the error bars for the three channel numbers producing the peak. In fact, no reasonable shift of the background curve is consistent with the identification of the entire peak as background.

The amount of deuterium was estimated in two additional energy regions using the method of background correction described. In the 18- to 32.5-MeV/nucleon energy window we can only obtain an upper limit for the flux of deuterium. In the 32.5- to 49-MeV/nucleon interval the flux value is subject to a large systematic error due to background subtraction.

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 over the past few years to be of galactic origin.[11,12]

Since deuterium is believed to be rare in astrophysical bodies[13] and since other evidence

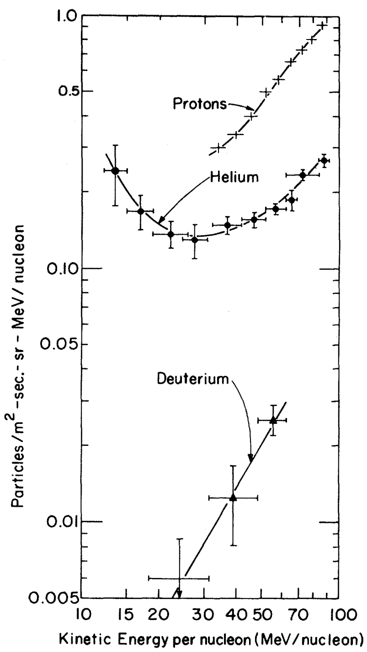

FIG. 2. Observed primary differential energy spectra for protons, deuterons, and helium nuclei, obtained over the same time period, from June to December 1965, near the minimum of the present solar activity cycle. The deuterium spectrum can be represented by $dJ/dE \propto E^{+2}$. Errors shown for the 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 Ref. 12.

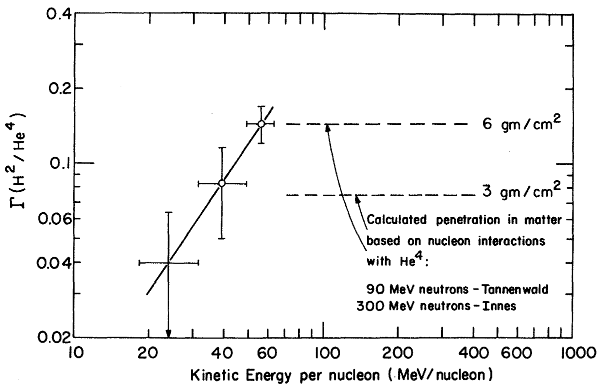

FIG. 3. Energy dependence of the abundance ratio of H^2/H^4, $\Gamma(H^2/H^4)$, computed from the data of Fig. 2. Production cross sections for H^2 from He^4 interacting with protons in cosmic-ray sources and interstellar matter are deduced from experimental measurements by Tannenwald (Ref. 15) using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

indicates that the cosmic-ray He^4 has passed through approximately 3 to 5 g/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 (2) that the largest contribution to the product 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 $H^2/He^4 \equiv \Gamma(H^2/He^4)$ 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 to 60 MeV per nucleon.

For comparison, the observed abundance ratio $\Gamma(H^2/H^1)$ at 60 MeV per nucleon is 0.05 ± 0.01 [or in units of magnetic rigidity the abundance ratio $\Gamma(H^2/H^1) = 0.005 \pm 0.001$ 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 of $\Gamma(H^2/He^4)$. 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 g/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 g/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% 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 range of energy per nucleon. 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 $p+p\rightarrow H^2+\pi^+$ 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 g/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% 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.

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

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ALMOST EXACT SUM RULES FOR NUCLEON MOMENTS FROM AN INFINITE-DIMENSIONAL ALGEBRA*

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Recently there has been a great surge of interest in almost exact sum rules for the magnetic moments of nucleons.[1-4] (By almost exact we mean exact to all orders in the strong couplings but only to the lowest order in electromagnetic and weak couplings.) Besides providing a means for calculation of the magnetic moments on the same level as the calculation of G_A/G_V by Adler[5] and Weisberger,[6] these sum rules, taken together with the Adler-Weisberger sum rule, constitute a useful tool for investigating the nature of the dynamical approximations that underlie higher symmetry schemes.

The purpose of the present note is to report on a set of sum rules which follow from an infinite-dimensional algebra, which contains (and may be regarded as the most natural extension of) an algebra suggested by Gell-Mann.[7] In order to specify the algebra we consider the function

$$M_{\mu\nu}^{\alpha\beta}(k',k)i(2\pi)^4\delta^4(p'+k'-p-k)$$

$$=\int d^4x d^4y\, e^{i(k'\cdot x-k\cdot y)}\langle p'|[T\{J_\mu^{\alpha}(x)J_\nu^{\beta}(y)\}-i\rho_{\mu\nu}^{\alpha\beta}(x)\delta^4(x-y)]|p\rangle. \quad (1)$$

Here α,β are isotopic indices, μ,ν are Minkowski indices, k',k (p',p) are outgoing and incident "photon" (nucleon) momenta, and J_μ^{α} is the conserved isospin current which participates in weak interactions, $\partial^\mu J_\mu^{\alpha}=0$.

The second term in the right-hand side of Eq. (1) is designed to compensate for the noncovariant nature of the T-product,[8] so that $M_{\mu\nu}^{\alpha\beta}$ is a covariant object. The simplest equal-time commutation relations which ensure this covariance are[8]

$$[J_0^{\alpha}(x),J_0^{\beta}(y)]_{x_0=y_0}=i\epsilon^{\alpha\beta\gamma}J_0^{\gamma}(x)\delta^3(x-y), \quad (2)$$

$$[J_0^{\alpha}(x),J_n^{\beta}(y)]_{x_0=y_0}=i\epsilon^{\alpha\beta\gamma}J_n^{\gamma}(x)\delta^3(x-y)+i\partial_m[\rho_{mn}^{\alpha\beta}(x)\delta^3(x-y)] \quad (3)$$