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THE ISOTOPIC COMPOSITION OF HYDROGEN AND HELIUM IN LOW-ENERGY COSMIC RAYS

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ABSTRACT

The isotopes ^{2}H and ^{3}He have been identified in low-energy cosmic rays during solar-quiet periods from 1973 January to 1974 October. These observations, made with the Caltech Electron/Isotope Spectrometer on IMP-7, cover the energy intervals 5–29 MeV per nucleon for ^{2}H and 7–50 MeV per nucleon for ^{3}He. We find that the energy spectra of ^{1}H, ^{2}H, and ^{3}He all fall rapidly with decreasing energy, giving ^{2}H/^{1}H and ^{3}He/^{1}H ratios which are essentially independent of energy as expected from current theories of the solar modulation of galactic cosmic rays. The measured ^{4}He spectrum, however, is essentially flat below $\sim$40 MeV per nucleon, suggesting that there may be contributions from a local, nonsolar source of ^{4}He. Comparisons of the ^{1}H, ^{2}H, and ^{3}He observations with calculated spectra at 1 AU imply a mean interstellar path length of 7 ± 2 g cm^{-2}. However, present low-energy measurements of H and He isotopes at 1 AU do not discriminate between possible cosmic-ray source spectra.

Subject heading: cosmic rays: abundances

I. INTRODUCTION

The rare isotopes ^{2}H and ^{3}He in cosmic rays are generally believed to be of secondary origin, resulting mainly from the nuclear interaction of primary cosmic-ray protons and ^{4}He with the interstellar medium. It is therefore expected that the relative abundances of the H and He isotopes will reflect the mean path lengths of cosmic-ray ^{1}H and ^{4}He in the interstellar medium, the energy spectra of these nuclei, and the energy dependence of the relevant nuclear interaction cross sections.

Measurements of ^{2}H and ^{3}He in the years prior to 1972 have been summarized by Baity *et al.* (1971), and by Hsieh, Mason, and Simpson (1971). Recently, Meyer (1974) and Ramadurai and Biswas (1974) have calculated possible spectra for the H and He isotopes and compared predicted ^{2}H/^{4}He and ^{3}He/^{4}He ratios with measurements at Earth. Unfortunately, discrepancies between some ^{2}H measurements (Baity *et al.* 1971; Hsieh, Mason, and Simpson 1971) and uncertainties in the effects of solar modulation have limited interpretation of the ^{2}H and ^{3}He results. More recent measurements have further complicated this picture. Observations of H and He isotopes in and since 1972 have found ^{2}H/^{4}He ratios significantly lower than in earlier years (Hurford *et al.* 1973; Teegarden *et al.* as reported in Stone 1973; Anglin, Simpson, and Zamow 1974; Teegarden *et al.* 1975), due mainly to an enhanced low-energy ^{4}He flux (Garcia-Munoz, Mason, and Simpson 1973; Van Hollebeke, Wang, and McDonald 1973).

In this paper we report 1973–1974 measurements of the H and He isotopes between 5 and 50 MeV per nucleon and compare these observations with the results of interstellar propagation and solar modulation calculations. A preliminary account of this work has been given by Mewaldt, Stone, and Vogt (1975*a*, *b*).

II. OBSERVATIONS

The observations reported here were made with the Caltech Electron/Isotope Spectrometer (EIS) which was launched on the IMP-7 spacecraft in 1972 September. The detector system, which consists of a stack of 11 fully depleted silicon surface barrier detectors with anticoincidence shielding, has been described by Hurford *et al.* (1974). Hydrogen and helium event data were summed over specific time intervals during the periods 1972 December 28 to 1973 October 1 and 1973 November 16 to 1974 October 22. For the ^{2}H and ^{3}He measurements, periods during which the flux of 4–10 MeV protons was greater than 0.15 cm^{-2} s^{-1} sr^{-1} were excluded, thereby eliminating large solar flares, but not small events. Small "^{3}He rich" solar flares were identified (Hurford *et al.* 1975) and eliminated by analyzing the isotopic composition of 3–15 MeV per nucleon He nuclei on a day-by-day basis. Examination of the spectra and counting rates during the remaining 510 days showed no evidence for solar ^{2}H or ^{3}He contamination at energies >5 MeV per nucleon. In order to minimize solar contamination, the ^{1}H and ^{4}He spectra were obtained over a more restricted sample of 25 very quiet days distributed over this 2 year period, when the flux of 1.3–2.3 MeV protons was $<5 \times 10^{-3}$ cm^{-2} s^{-1} sr^{-1}. The flux of $\sim$30 MeV protons during the 25 day sample was within $\leqslant 10$ percent of the flux at that energy averaged over the 510 day period. This suggests that the 25 day ^{1}H spectrum is indicative of the lower energy galactic ^{1}H flux over the entire 510 day period.

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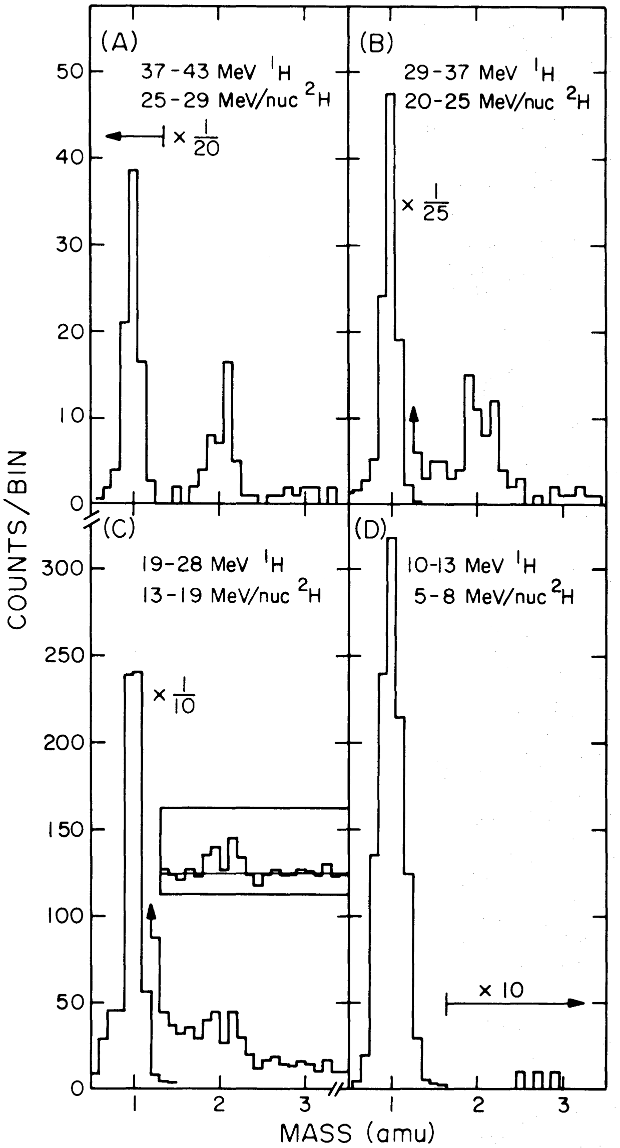

FIG. 1

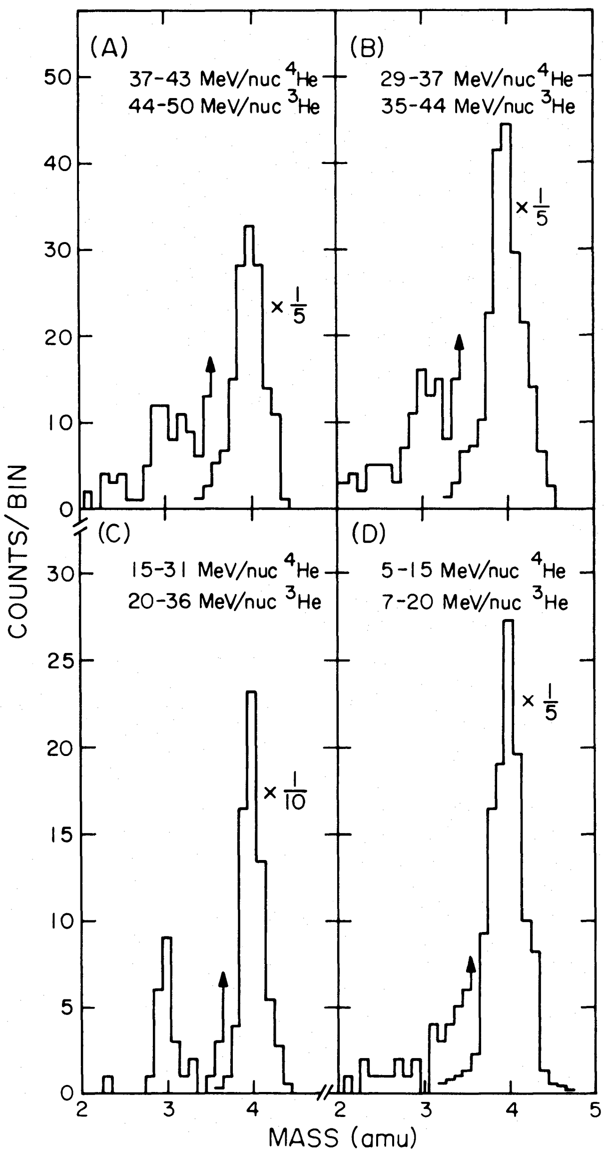

FIG. 2

FIG. 1.—Hydrogen mass spectra. Note the use of scale factors for the ^{1}H peaks. The inset in Fig. 1*c* shows the result of subtracting the background in the 13–19 MeV per nucleon ^{2}H region where the horizontal line is at zero counts.

FIG. 2.—Helium mass spectra. Note the use of scale factors for the ^{4}He peaks.

Hydrogen and helium isotope identification was accomplished by the dE/dx-E-range technique (Hurford *et al.* 1973). Examples of the hydrogen and helium mass spectra obtained are shown in Figures 1 and 2. The observed mass resolution (σ_m) ranges from $\sim$0.05 to $\sim$0.15 a.m.u. for the ^{1}H peaks, and from $\sim$0.12 to $\sim$0.20 a.m.u. for the ^{4}He peaks. At energies $\geq$20 MeV per nucleon the ^{2}H peaks (Figs. 1*a* and 1*b*) are clearly resolved and well separated from the ^{1}H peaks, with signal-to-noise ratios better than earlier experiments in this energy range. The background level is considerably higher for 13–19 MeV per nucleon ^{2}H (Fig. 1*c*). The inset in Figure 1*c* shows the results of subtracting the background in the 13–19 MeV per nucleon ^{2}H region, as determined from a simultaneous least-squares fit to ^{1}H and ^{2}H peaks and to the background. At the lowest energies the relative ^{2}H (Fig. 1*d*) and ^{3}He (Fig. 2*d*) abundances are much smaller, and only upper limits to their intensity can be obtained. Table 1 summarizes the observed number of events (signal + background) within $\pm 2\sigma_m$ of the predicted ^{2}H and ^{3}He peak locations, along with the calculated number of ^{2}H and ^{3}He events after subtracting background. Note that differences in the background levels and absolute counting rates in the various energy intervals result from differences in the geometry

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TABLE 1

^{2}H AND ^{3}He EVENT DATA

Isotope	Energy Range (MeV per nucleon)	Observed Number of Events* ($\pm 2\sigma_m$)	Calculated† Number of ^{2}H or ^{3}He
^{2}H.......	25–29	39	34 ± 9
	20–25	51	34 ± 9
	13–19	208	45 ± 18
	8–11	5	3^{+4}_{-3}
	5–8	0	< 1.84
^{3}He......	44–50	52	40 ± 10
	34–44	70	44 ± 12
	20–36	19	19 ± 5
	7–20	11	< 10

* Signal + background.

† As determined from a simultaneous least-squares fit to the stable isotope peaks and to the background. The background was assumed to have an exponential dependence on mass in the H mass distributions and a flat distribution in the He mass distributions. All isotope peaks were assumed to be Gaussian. The 68% confidence intervals result from Poisson statistics and background correction uncertainties.

factors and background rejection capabilities of the various instrumental analysis modes (see Hurford *et al.* 1973, 1974).

III. RESULTS

The quiet-time energy spectra obtained for hydrogen and helium isotopes are shown in Figure 3. Notice in particular that while the ^{1}H, ^{2}H, and ^{3}He spectra are approximately proportional to kinetic energy, the ^{4}He intensity is to first approximation independent of energy, and from ~ 5 to ~ 20 MeV per nucleon ^{4}He exceeds ^{1}H in abundance. This relatively flat ^{4}He spectrum was a feature present over the entire time interval covered by these observations.

The energy dependence of the 1973–1974 spectra reported here is consistent with 1972 ^{2}H and 1972–1973 ^{3}He observations by the Goddard Space Flight Center–University of New Hampshire (GSFC–UNH) group (Teegarden *et al.* 1975), and with 1973–1974 ^{1}H, ^{3}He, and ^{4}He observations by the University of Chicago group (Garcia-Munoz, Mason, and Simpson 1975). Differences in absolute intensity between the observations made during 1972–1974 appear to result in large part from changes in the level of solar modulation between the different times of measurement. Over the time interval covered by this study we have observed quiet-time variations of a factor of ~ 2 in absolute intensity, with no significant changes in the spectral shapes shown in Figure 3. It is therefore important that observations of the relative abundances of the H and He isotopes be made over identical time periods. For example, we find ^{2}H/^{3}He ≈ 2, while the GSFC–UNH measurements of ^{2}H from IMP-7 and of ^{3}He from *Pioneer 10* give ^{2}H/^{3}He ≈ 1 (Teegarden *et al.* 1975). It is probable that this difference is due to the fact that the GSFC–UNH ^{2}H and ^{3}He measurements were made during nonidentical time periods and at different radial distances from the Sun.

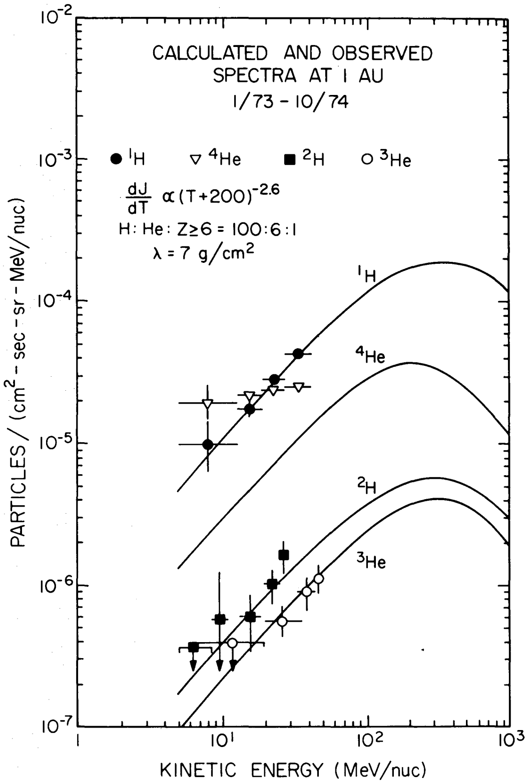

FIG. 3.—Calculated and observed H and He isotope spectra at 1 AU. The assumed source abundances were H : He : $Z \geq 6 = 100:6:1$, with source spectra of the form $dJ/dT \propto (T + 200)^{-2.6}$.

The only satellite observations of ^{2}H and ^{3}He from earlier years obtained under solar minimum conditions are from 1965–1966. An extrapolation of our 1973–1974 spectra is consistent with 1965–1966 ^{2}H and ^{3}He results at ~ 50 MeV per nucleon (Fan, Gloeckler, and Simpson 1966; Hsieh 1970; Meyer 1974, as quoted by Teegarden *et al.* 1975). Because of discrepancies between some of the ^{2}H spectra measured at other times in the solar cycle, we will restrict the following discussion to the 1973–1974 observations. A recent discussion of the earlier results appears in Teegarden *et al.* (1975).

IV. CALCULATED SPECTRA AT 1 AU

In order to interpret the observations reported here, we have performed interstellar propagation and solar modulation calculations for a cosmic-ray source composed of ^{1}H, ^{4}He, and $Z \geq 6$ nuclei, and identical source spectra of the form $dJ/dT \propto (T + E_0)^{-2.6}$, where T is the kinetic energy per nucleon, and the free parameter E_0 was varied from 938 MeV per nucleon (total energy power law) to 0 MeV per nucleon (kinetic energy power law). We assumed an exponential path-length distribution with mean path length λ for cosmic rays in an interstellar medium with He/H = 0.1, and used the cross sections for ^{2}H and ^{3}He production summarized by Meyer (1974). Ionization energy loss and nuclear reaction kinematics

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effects were included. The resulting equilibrium interstellar spectra were consistent with those of Meyer (1974) when identical initial parameters were used; however, we found it necessary to use somewhat different source abundances in order to achieve agreement of the modulated high energy (> 100 MeV per nucleon) spectra of ^{4}He and $Z \geq 6$ with measurements at 1 AU.

In our solar modulation calculations we used the numerical techniques of Fisk (1971) to solve the full Fokker-Planck equation, including the effects of diffusion, convection, and adiabatic deceleration, and used the solar-minimum (1965–1966) modulation parameters determined by Cummings, Stone, and Vogt (1973*a*) from a study of the solar modulation of electrons and positrons. A constant factor multiplying the diffusion coefficient was allowed to vary within the limits set by the uncertainty in the interstellar electron spectrum determined from the galactic nonthermal radio emission (Cummings, Stone, and Vogt 1973*b*). Figure 3 shows fits to the observations at 1 AU for one choice of possible source spectra, $dJ/dT \propto (T+200)^{-2.6}$ similar to a power law in rigidity. The only parameters adjusted in order to achieve this fit were the constant factor multiplying the diffusion coefficient, the mean path length λ, and the source abundances of ^{4}He and $Z \geq 6$ nuclei. Since the origin of the enhanced ^{4}He, nitrogen, and oxygen fluxes observed below ~ 50 MeV per nucleon (see, e.g., McDonald *et al.* 1974) in 1972–1974 is not yet known, the ^{4}He and $Z \geq 6$ abundances were adjusted to fit solar minimum observations in the 100–300 MeV per nucleon interval, as summarized by Webber and Lezniak (1974). Notice that we obtain very reasonable fits to the ^{1}H, ^{2}H, and ^{3}He spectra, but fall far below the low-energy ^{4}He observations.

V. DISCUSSION

It can be seen in Figure 3 that the calculated spectra at 1 AU are approximately proportional to kinetic energy below ~ 100 MeV per nucleon. This $j \approx AT$ behavior (Rygg and Earl 1971) is characteristic of the predictions of current theories of the solar modulation of galactic cosmic rays, in which the modulation of low-energy particles is dominated by adiabatic deceleration (see, e.g., Goldstein, Fisk, and Ramaty 1970). Since the calculated *interstellar* ^{2}H and ^{3}He spectra (see also Meyer 1974) are essentially independent of energy below ~ 100 MeV per nucleon for a wide range of assumed source spectra, in contrast to our observed spectra, we conclude that adiabatic deceleration *does* dominate the modulation of ^{1}H, ^{2}H, and ^{3}He, while the 1972–1974 ^{4}He observations are inconsistent with this picture. A similar conclusion has been reached by Teegarden *et al.* (1975). If adiabatic deceleration dominates, then we expect that low-energy particles observed at 1 AU had energies of several hundred MeV per nucleon in interstellar space, and we expect the abundance ratios observed at 1 AU to be essentially independent of energy, as is observed, for example, for ^{2}H/^{1}H and ^{3}He/^{1}H.

It is evident from Figure 3 that the observed ^{2}H/^{4}He and ^{3}He/^{4}He ratios decrease with decreasing energy, becoming less than ~ 2 percent at ~ 10 MeV per nucleon. Similarly, the nitrogen isotopic composition is energy-dependent, with ^{15}N/(^{14}N + ^{15}N) ≤ 0.26 at ~ 10 MeV per nucleon (Mewaldt *et al.* 1975*a*) and ^{15}N/(^{14}N + ^{15}N) ~ 0.5 at several hundred MeV per nucleon (Webber *et al.* 1973; Garcia-Munoz, Mason, and Simpson 1974). A somewhat similar energy dependence has been observed (McDonald *et al.* 1974; Mewaldt *et al.* 1975*b*) in comparisons of the 1972–1974 spectra of Li, Be, B, and C, with those of N and O. For example, at ~ 10 MeV per nucleon B/O ≈ 0.01, compared to B/O ≈ 0.3 at several hundred MeV per nucleon (see, e.g., Webber, Damle, and Kish 1972). This evidence, along with the highly correlated temporal behavior of the ~ 10 to ~ 30 MeV per nucleon ^{4}He and O intensities (Mewaldt, Stone, and Vogt 1975*c*), suggests that the enhanced fluxes of low-energy ^{4}He, N, and O observed since 1972 represent a separate nonsolar cosmic-ray component that is largely uncontaminated by nuclear-reaction secondaries. Because of the uncertain origin of the enhanced ^{4}He flux (see, e.g., Fisk, Kozlovsky, and Ramaty 1974), we will focus our attention on the ^{1}H, ^{2}H, and ^{3}He spectra.

In Figure 4 we show the dependence of the calculated ^{2}H/^{1}H and ^{3}He/^{1}H ratios as a function of the mean path length λ for three characteristic spectral shapes. Also shown are the 68 percent confidence intervals based on our observations. Note that our ^{2}H/^{1}H observations imply somewhat larger but not inconsistent values for λ than the ^{3}He/^{1}H observations. Possibly the best estimate for λ comes from the (^{2}H + ^{3}He)/^{1}H ratio, which for all three spectra is $\sim 7 \pm 2$ g cm^{-2}. This path length is consistent with that required by other nuclear species of secondary origin, including Li, Be, and B, and the products of Fe fragmentation (see, e.g., Shapiro, Silberberg, and Tsao 1973). Because the calculations are sensitive to the relative ^{4}He and ^{1}H abundances, there is a normalization uncertainty, since we do not have proton and alpha measurements of higher energy for this time interval. However, other normalizations also give path lengths in the 7 ± 2 g cm^{-2} range.

Figure 4 shows that the calculated abundance ratios with respect to ^{1}H are relatively insensitive to the source spectra, mainly because the largest interstellar spectral differences occur at low energies, where adiabatic deceleration severely limits the access of interstellar particles to 1 AU. The calculated ^{2}H/^{3}He ratios shown in Figure 4 suggest that this ratio, which is essentially independent of λ, might be a useful discriminator (see also Ramaty and Lingenfelter 1969) between possible source spectra. Note that for modulated ^{2}H and ^{3}He spectra of the form $j \approx AT$, this ratio will be essentially independent of energy below ~ 100 MeV per nucleon. In addition, we find that for the source spectra considered here, the calculated ^{2}H/^{3}He ratios at 1 AU vary by $\lesssim 20$ percent over the solar cycle. Thus, as indicated by Figure 4, observations at 1 AU of ^{2}H/^{3}He $\gtrsim 2$ imply steep interstellar spectra similar to a kinetic energy power law, while ^{2}H/^{3}He $\lesssim 1.5$ implies spectra similar to a

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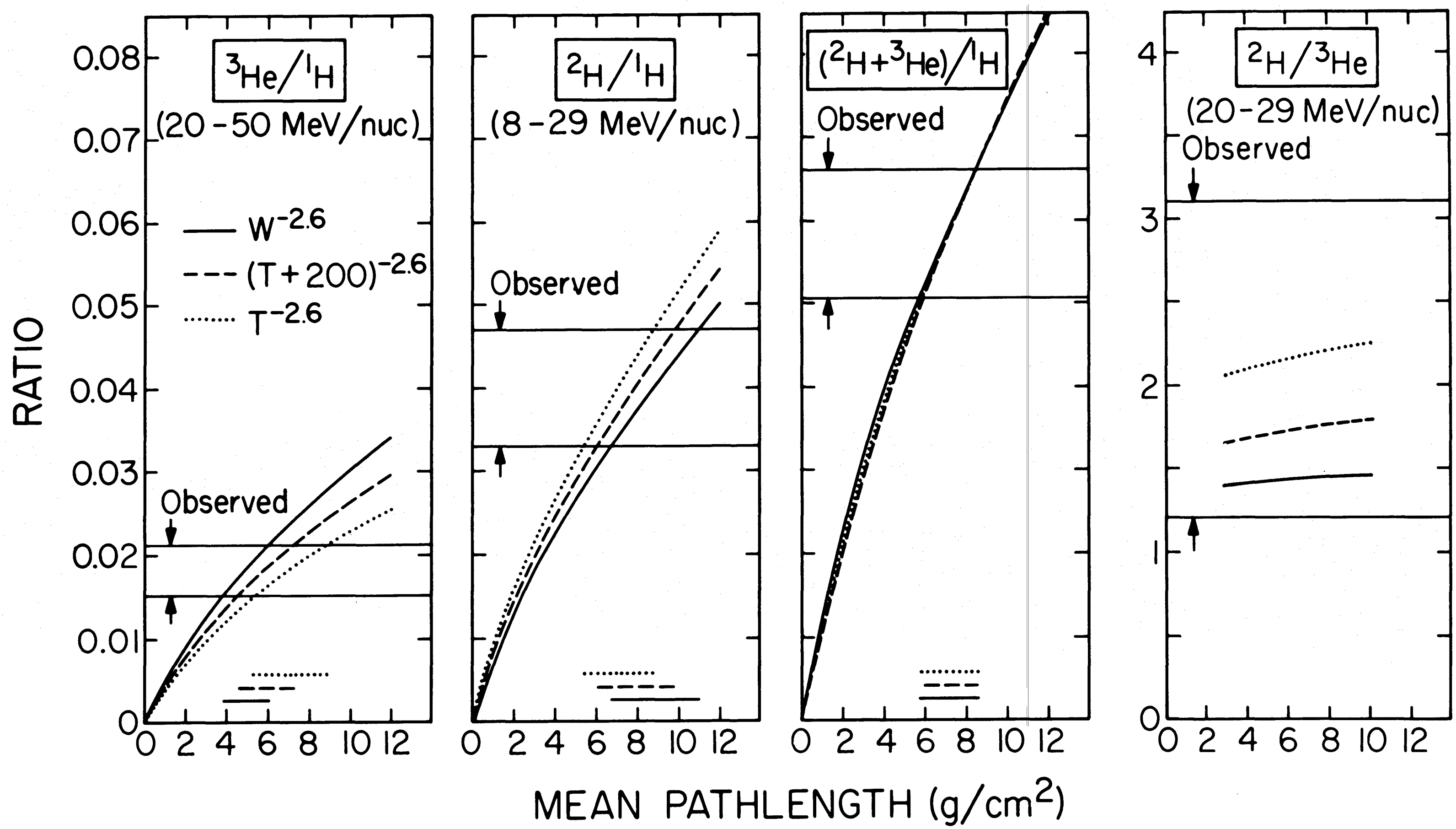

FIG. 4.—Calculated dependence of isotopic abundance ratios at 1 AU on the mean interstellar path length λ for three characteristic source spectra. Curves labeled $W^{-2.6}$ are for a power law in total energy per nucleon. The horizontal lines above the abscissa indicate the range of path lengths compatible with our observations. The measured ^{3}He/^{1}H ratio is based in part on an extrapolation of the ^{1}H observations above 43 MeV per nucleon. Note also that the measured ^{2}H/^{3}He ratio is based only on data from the 20–29 MeV per nucleon interval, which is common to both the ^{2}H and ^{3}He measurements.

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total energy power law. Unfortunately, our observed $^2H/^3He$ ratio is not sufficiently precise to discriminate between the spectra.

Comstock, Hsieh, and Simpson (1972) and Meyer (1974) concluded that only source spectra similar to a power law in total energy per nucleon were consistent with earlier observations, while Ramadurai and Biswas (1974) concluded that a somewhat steeper spectrum was required. The interstellar path length determined by those studies ranged from 4 to 6.3 g cm^{-2}. However, those analyses were based on the low-energy $^2H/^4He$ and $^3He/^4He$ ratios, which, because of the uncertain origin of the low-energy ^4He, are difficult to relate to the interstellar abundances of these isotopes. From a comparison of the 1972–1973 GSFC–UNH ^2H and ^3He measurements with calculated interstellar spectra, Teegarden *et al.* (1975) suggested that source spectra significantly steeper than a total energy power law could be required. However, that suggestion did not quantitatively account for solar modulation.

In summary, the ^1H, ^2H, and ^3He spectra that we observe can be fitted with models of interstellar propagation and solar modulation parameters designed to explain other cosmic-ray species. On the other hand, the low-energy ^4He spectrum observed since 1972 is not easily explained by this picture, suggesting that possibly the equilibrium interstellar spectra of ^1H and ^4He differ markedly (Stone 1973), or that there may be an additional source of ^4He of local origin (Hurford *et al.* 1973). A similar conclusion has been reached by Garcia-Munoz, Mason, and Simpson (1975) and Teegarden *et al.* (1975).

Second, we conclude that present low-energy measurements of ^2H and ^3He at Earth do not discriminate between possible cosmic-ray source spectra.

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