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^{3}He IN GALACTIC COSMIC RAYS

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ABSTRACT

Cosmic-ray ^{3}He/^{4}He observations, including a new measurement at ~65 MeV per nucleon from *ISEE 3*, are compared with interstellar propagation and solar modulation calculations in an effort to understand the origin of cosmic-ray He nuclei. We survey spacecraft and balloon observations of the ^{3}He/^{4}He ratio and find improved consistency among measurements in the ~50–300 MeV per nucleon energy range when a previously neglected contribution from atmospheric secondary ^{3}He is taken into account. These low-energy observations imply a mean escape length of 6–8 g cm^{-2} in the standard "leaky box" model for cosmic-ray propagation in the galaxy, a value consistent with that derived from studies of heavier nuclei. Thus, we find no evidence for an excess of low-energy ^{3}He such as that reported at higher energies. Recent propagation models designed to explain the excess of cosmic-ray antiprotons observed at GeV energies also predict an excess of ^{3}He that is not observed at low energies.

Subject heading: cosmic rays: abundances

I. INTRODUCTION

The rare isotopes ^{2}H and ^{3}He in cosmic rays are believed to be of secondary origin, produced by nuclear interactions of primary ^{1}H and ^{4}He with the interstellar medium, and thus the secondary/primary ratios ^{3}He/^{4}He and ^{2}H/^{4}He have often been used to determine the amount of material traversed by cosmic-ray ^{4}He nuclei. There has recently been renewed interest in the cosmic-ray abundance of these isotopes as a result of indications from high-energy antiproton, positron, and ^{3}He observations that the origin of some primary H and He nuclei may differ from that of heavier cosmic rays. Thus, the flux of cosmic-ray antiprotons observed at GeV energies has been found to be a factor of ~4 greater than expected from secondary antiproton production in standard propagation models (Golden *et al.* 1979; Bogomolov *et al.* 1979), while there is also evidence for an excess of cosmic-ray positrons at high energies (Buffington, Orth, and Smoot 1975; Muller and Tang 1985; Golden *et al.* 1985; see also the calculations by Protheroe 1982).

The reported overabundance of cosmic-ray antiprotons has stimulated a variety of new theoretical models for cosmic-ray origin and propagation. A common element of many of these models is that some fraction of cosmic-ray nuclei is assumed to have traversed a great deal of material (see, e.g., Lagage and Cesarsky 1985, and references therein). Observations of secondary products such as ^{2}H and ^{3}He can be used to test such models. Recently, Jordan and Meyer (1984) reported a measurement of the ^{3}He/^{4}He ratio at ~6 GeV per nucleon that is substantially greater than that predicted by standard propagation models. In addition, they concluded that lower energy ^{3}He observations were consistent with the much longer pathlength apparently required by their high-energy measurement. In this paper we report a new observation of low-energy ^{3}He, examine previously reported ^{3}He/^{4}He measurements at both low and high energies, and compare these with the expected ^{3}He/^{4}He ratio based on interstellar propagation and solar modulation calculations. We find no evidence for an excess of low-energy ^{3}He such as that reported at high energies. A preliminary report of this work appears in Mewaldt (1985).

II. OBSERVATIONS

The new observation reported here was made with the Caltech Heavy Isotope Spectrometer Telescope (HIST) on *ISEE 3* (now renamed *ICE*) during quiet-time periods from 1978 August 13 to 1978 December 1. Details of the method of resolving isotopes in the HIST solid-state detector telescope are discussed in Mewaldt *et al.* (1979), and a description of the instrument can be found in Althouse *et al.* (1978). Figure 1 shows the He isotope distribution obtained from the two highest-energy intervals covered by HIST. These data result in a ^{3}He/^{4}He ratio of 0.066 ± 0.016 from 48 to 77 MeV per nucleon.

During the 1972 to 1978 solar minimum period there was an extra source of low-energy ^{4}He observed at low energies superposed on the Galactic cosmic ray (GCR) component. This "anomalous" cosmic-ray (ACR) ^{4}He component is believed to represent interstellar neutral particles that have been singly ionized and locally accelerated (Fisk, Kozlovsky, and Ramaty 1974). The presence of ACR ^{4}He, which has a maximum intensity at ~10 to 20 MeV per nucleon at 1 AU, results in a ^{3}He/^{4}He ratio that decreases below its Galactic cosmic ray value at energies below ~80 MeV per nucleon (see, e.g., the summary of data in Mewaldt, Spalding, and Stone 1984). To correct for the presence of anomalous ^{4}He we have used the decomposition of the ACR and GCR fluxes given by Cummings, Stone, and Webber (1984) and measurements of the low-energy ^{4}He time history. For our HIST measurement we derive a correction factor of 1.12 ± 0.06 resulting in an "observed" GCR ^{3}He/^{4}He ratio of 0.074 ± 0.018.

Figure 2 shows our new measurement along with selected other ^{3}He/^{4}He observations. The lowest energy observations in Figure 2 are spacecraft observations from the 1972–1978 solar minimum period and are limited to energies ≥50 MeV per nucleon where contamination by ACR ^{4}He is minimized. Since most of these observations still include some ACR ^{4}He, they have been individually corrected as summarized in Table 1. Figure 2 also includes solar-minimum observations from ~100 to 300 MeV per nucleon made by balloon-borne instruments (here referred to as "the balloon observations"). As dis-

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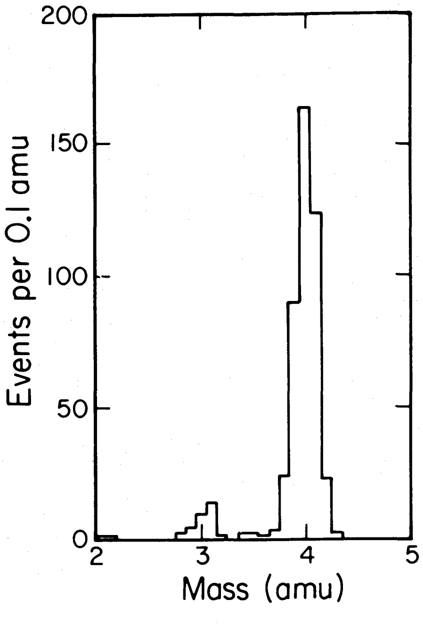
cussed in the Appendix, we believe that the observations as reported have not been adequately corrected for ^{3}He produced in the overlying atmosphere by the breakup of energetic ^{4}He, and a proposed correction (typically $\sim 16\%$) has therefore been applied to the balloon observations shown in Figure 2 and in subsequent figures. At energies > 300 MeV per nucleon the only observations to date use the geomagnetic method, including the recent Jordan and Meyer (1984) measurement at ~ 6 GeV per nucleon (see also Jordan 1985), and an earlier result at somewhat lower energy (Jodko, Karakadko, and Romanov 1977). These experiments also fly on balloons but are not subject to the atmospheric corrections discussed above.

In addition to the measurements shown, there are also spacecraft and balloon observations from earlier years and somewhat different levels of solar modulation that are generally consistent with those included in Figure 2 (see, e.g., the summary of data in Meyer 1974).

III. INTERPRETATION OF ^{3}He/^{4}He OBSERVATIONS

We interpret the available ^{3}He/^{4}He data in the context of the standard "leaky-box" model for cosmic-ray propagation, in which there is a mean-free-path λ_e for escape from the galaxy referred to as the "escape length," which may be energy-dependent. In this paper we make use of the extensive propagation calculations by J. P. Meyer (1974), who calculated *interstellar* spectra for the primary species ^{1}H, ^{4}He, and "CNO" that originate in the cosmic-ray source. The source spectra were of the form $dJ/dT \propto (T + U)^{-2.6}$, where T is kinetic energy per nucleon and $0 \leq U \leq 938$ MeV per nucleon. Meyer calculated spectra for escape lengths of 3, 6.3, and 10 g cm^{-2}; we obtained spectra for other values of λ_e by interpolation and extrapolation. Using these interstellar spectra, we then calculated the effects of solar modulation using the solar-minimum form of the interplanetary diffusion coefficient from Cummings, Stone, and Vogt (1973) and numerical solutions of the Fokker-Planck equation including the effects of diffusion, convection, and adiabatic deceleration. Typical results of these calculations are shown in Figure 2, for source spectra with $U = 500$ MeV per nucleon.

Each of the observations in Figure 2 can be compared with the calculations to determine a value for λ_e, as summarized in Figure 3 for $U = 500$ MeV per nucleon spectra. Note that the spacecraft and (corrected) balloon observations all favor $\lambda_e \approx$ 6–8 g cm^{-2}; the only measurement indicating a value of $\lambda_e \geq$ 10 g cm^{-2} is the Jordan and Meyer measurement at ~ 6 GeV per nucleon.



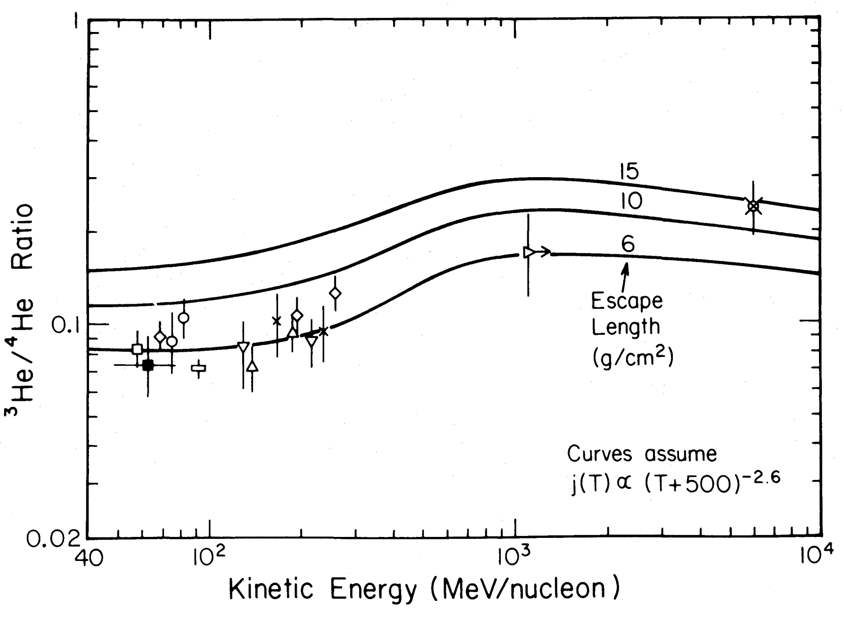


FIG. 1.—The distribution of quiet-time ^{3}He (48–77 MeV per nucleon) and ^{4}He (41–67 MeV per nucleon) observed by the Caltech experiment on *ISEE 3* during late 1978.

FIG. 2.—Measured and calculated ^{3}He/^{4}He ratios. Spacecraft Observations: (*closed square*) this work; (*open square*) Goddard-UNH (Teegarden *et al.* 1975); (*diamond*) *Voyager 1* (Webber and Yushak 1983); (*open circles*) Chicago (Garcia-Munoz, Mason, and Simpson 1975*a*, *b*); (*horizontal rectangle*) Chicago (Evenson *et al.* 1985). Balloon Observations: (*downward triangle*) Rochester (Badhwar *et al.* 1967); (*upward triangle*) UNH (Webber and Schofield 1975); (*diamonds*) UNH (Webber and Yushak 1983); (*crosses*) UMd (Leech and O'Gallagher 1978); Geomagnetic method: (*tilted triangle*) Ioffe (Jodko, Karakadko, and Romanov 1977); (*circled cross*) Chicago (Jordan and Meyer 1984). The spacecraft observations have been corrected for the presence of anomalous ^{4}He and the balloon observations corrected for ^{3}He produced in the atmosphere, as discussed in the text. Note that in some cases two or more data points reported from a given experiment have been combined. The predicted ^{3}He/^{4}He ratio is shown for three values of the assumed escape length.

TABLE 1

SPACECRAFT ^{3}He/^{4}He OBSERVATIONS

Year of Observation	Energy Interval (MeV per nucleon)	Observed Ratio	Correction Factor for Anomalous ^{4}He	Galactic Cosmic-Ray Ratio	Reference
1978	48–77	0.066 ± 0.016	1.12 ± 0.06	0.074 ± 0.018	1
	65–120	0.070 ± 0.006	1.03 ± 0.02	0.072 ± 0.006	2
1977	49–88	0.072 ± 0.009	1.27[a]	0.092 ± 0.011	3
1974	56–110	0.100 ± 0.014	1.06 ± 0.03	0.106 ± 0.015	4
1973	56–95	0.082 ± 0.020	1.08 ± 0.04	0.089 ± 0.022	5
1972–1973	51–66	0.071 ± 0.008	1.19 ± 0.10	0.084 ± 0.012	6

[a] Correction factor for this observation taken from Webber and Yushak 1983.

REFERENCES.—(1) This work. (2) Evenson *et al.* 1985. (3) Webber and Yushak 1983. (4) Garcia-Munoz, Mason, and Simpson 1975*b*. (5) Garcia-Munoz, Mason, and Simpson 1975*a*. (6) Teegarden *et al.* 1975.

Table 2 summarizes the mean escape lengths obtained from the satellite and balloon observations for spectra with $U = 500$ and $U = 200$ MeV per nucleon. Note that the proposed atmospheric correction (see Appendix) lowers the mean escape length for the balloon observations by ~1.6 to 1.9 g cm^{-2} (depending on the spectrum), and generally improves the agreement between the spacecraft and the balloon observations. The correction for ACR ^{4}He has a smaller effect on the mean escape length for the spacecraft observations (~0.5–0.6 g cm^{-2}), such that with the assumed uncertainty in this correction (see Table 1) there is a resulting systematic uncertainty of ~0.3 g cm^{-2} in the spacecraft determinations of λ_e. Table 2 indicates that softer source spectra (e.g., $U = 200$) lead to a somewhat greater λ_e at low energies. This is partly a propagation effect (see Meyer 1974), but also a result of the increased solar modulation required for soft spectra combined with the different charge to mass ratios of ^{3}He and ^{4}He.

TABLE 2

MEAN ESCAPE LENGTHS (g cm^{-2})

SOURCE SPECTRUM	SPACECRAFT OBSERVATIONS (~75 MeV per nucleon)	BALLOON OBSERVATIONS (~200 MeV per nucleon)	
		Corrected[a]	Uncorrected
$(T + 500)^{-2.6}$.....	5.7 ± 0.6	6.4 ± 1.1	8.0 ± 0.6
$(T + 200)^{-2.6}$.....	7.9 ± 0.9	7.8 ± 1.3	9.7 ± 0.7

[a] The proposed correction for secondary ^{3}He produced in the atmosphere is discussed in the Appendix. The uncertainty in λ_e includes the estimated uncertainty in this correction.

IV. DISCUSSION

We wish to determine whether the ^{3}He observations are consistent with the propagation/modulation models derived for heavier nuclei, or whether there is evidence for a second galactic component of He nuclei with a separate origin and/or history. It is known from measurements of various secondary/primary ratios involving $Z \geq 3$ nuclei that at energies above ~2 GeV per nucleon cosmic rays have passed through less material than at lower energies. This is usually interpreted as energy (or rigidity) dependent confinement to the galaxy with an escape mean-free-path that decreases from a maximum of ~8 to 10 g cm^{-2} at ~1 GeV per nucleon to only ~1 or 2 g cm^{-2} at ~100 GeV per nucleon (see, e.g., Protheroe, Ormes, and Comstock 1981; Ormes and Protheroe 1983). There is also evidence for an energy-dependent escape length at lower energies. Thus, measurements of the B/C ratio at ~100 MeV per nucleon imply $\lambda_e \approx 6$ g cm^{-2} (Garcia-Munoz *et al.* 1981, 1984), somewhat less than at higher energies, but consistent with the ^{3}He/^{4}He escape-length derived here of ~6 to 8 g cm^{-2} (see Table 2).

Figure 4 shows the expected ^{3}He/^{4}He ratio for a rigidity–

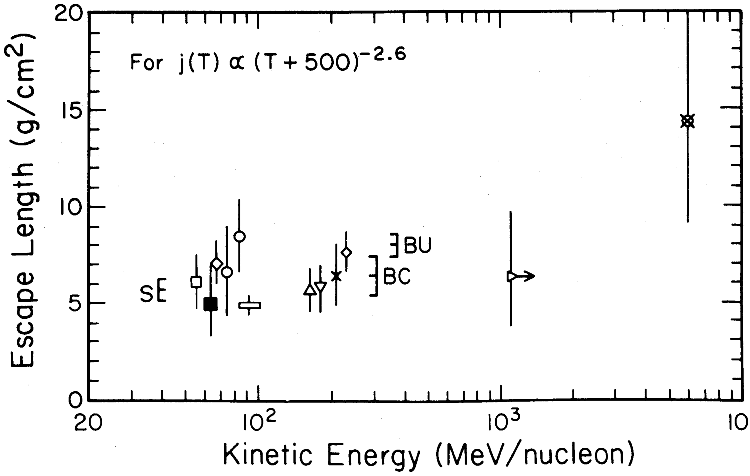


FIG. 3.—A plot of the average escape length derived from each of the experiments included in Fig. 2 for spectra with $U = 500$ MeV per nucleon. The mean and uncertainty of the spacecraft (S), corrected balloon (BC), and uncorrected balloon (BU) observations are also indicated. The symbols have the same meaning as in Fig. 2.

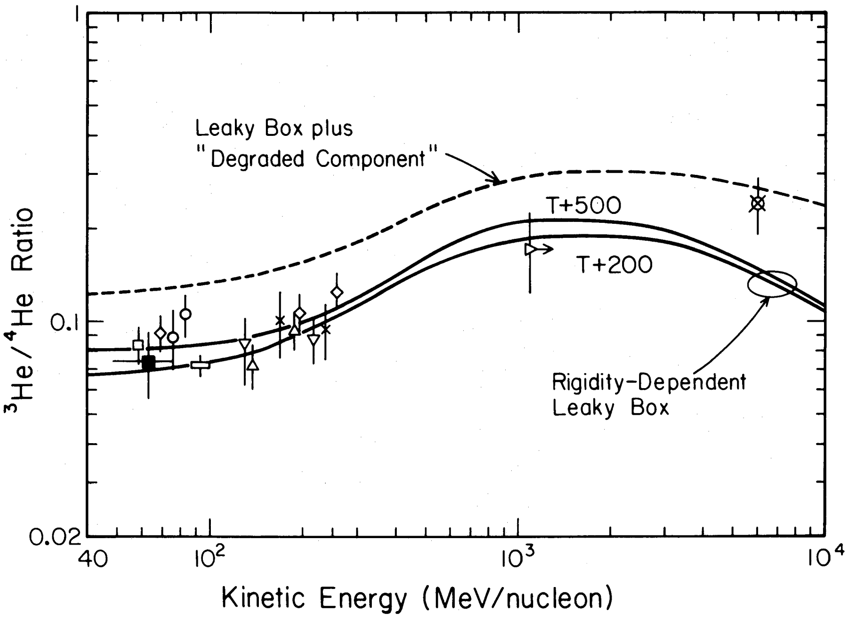


FIG. 4.—A comparison of ^{3}He/^{4}He observations with energy-dependent propagation models. The solid curves are for a leaky-box model with the rigidity-dependent escape-length described in the text, while the dashed curves are for the model of Cowsik and Gaisser (1981), assuming that 30% of high-energy cosmic rays originate in "thick" sources surrounded by 50 g cm^{-2} of material. Reference to the observations can be found in the caption to Fig. 2.

dependent escape length of the form derived to fit $3 \leq Z \leq 26$ nuclei by Soutoul *et al.* (1985), for which $\lambda_e = \lambda_0 \beta R^{-0.65}$ for $R > 5.5$ GV and $\lambda_e = \lambda_0 \beta (5.5 \text{ GV})^{-0.65}$ for $R \leq 5.5$ GV. Soutoul *et al.* used $\lambda_0 = 24$ g cm^{-2}, corresponding to a medium composed of pure hydrogen; we use $\lambda_0 = 28.5$ g cm^{-2}, corresponding to an interstellar medium with He/H = 0.11, as was assumed in the propagation calculations of Meyer (1974). It can be seen in Figure 4 that the ^{3}He/^{4}He observations from ~50 to ~300 MeV per nucleon are in excellent agreement with the escape length derived from studies of heavier nuclei. Although it is not possible with these data to distinguish between the two spectral shapes considered, studies of heavier nuclei favor a spectral form similar to $U \approx 500$ MeV per nucleon (Garcia-Munoz, Mason, and Simpson 1977; Ormes and Protheroe 1983). We conclude that low-energy observations of ^{3}He/^{4}He are in excellent agreement with the propagation and modulation parameters derived for heavier nuclei.

The above conclusion agrees with most other studies of low-energy H and He isotopes that have included *both* propagation and solar modulation effects (e.g., Mewaldt, Stone, and Vogt 1976; Garcia-Munoz, Mason, and Simpson 1975*b*; Leech and O'Gallagher 1978; Webber and Yushak 1983; Beatty 1985; Evenson *et al.* 1985). This conclusion is, however, in marked *disagreement* with the recent interpretation of low-energy observations by Jordan and Meyer (1984; see also Jordan 1985). They suggested that balloon observations at ~100 to 300 MeV per nucleon were consistent with the $\lambda_e \approx 15$ g cm^{-2} escape length apparently required by their own higher energy measurement. After repeating their analysis in detail we conclude that Jordan and Meyer have significantly overestimated the escape length required by the balloon data, as a result of a combination of factors, and that self-consistent interpretations of the low-energy data imply $\lambda_e(^4\text{He}) \leq 10$ g cm^{-2}. This conclusion is independent of the magnitude of the proposed atmospheric correction for the balloon data, but it is strengthened by the apparent need for this correction, and also by the spacecraft observations, which Jordan and Meyer did not consider.

Note in Figure 4 that only the Jordan and Meyer measurement at 6 GeV per nucleon differs significantly from the predictions based on the rigidity-dependent leaky-box model derived for heavy nuclei. For their reported ratio of ^{3}He/^{4}He = 0.24 ± 0.05 we obtain an escape length of ~15 ± 6 g cm^{-2} (in agreement with the value they obtain), which is significantly greater than that obtained from, e.g., the *B*/*C* ratio, which implies $\lambda_e \sim 5.5$ g cm^{-2} at ~6 GeV per nucleon (see, e.g., Ormes and Protheroe 1983). Thus, if the Jordan and Meyer measurement is correct, it does imply a high-energy ^{3}He excess, which would argue for a different origin for at least some high-energy He nuclei. It should also be kept in mind, however, that the Jordan and Meyer value is sensitive to the spectral index of the ^{4}He spectrum that they adopted in analyzing their observations, which may have introduced a significant systematic uncertainty into their quoted value, as they point out (see Jordan and Meyer 1984; Jordan 1985).

Recent observations of an excess of antiprotons and positrons at high energies have led to several new cosmic-ray origin and propagation models in which some nuclei have traversed a great deal of material. Our calculations show that such models also produce an excess of ^{2}H and ^{3}He, as has also been pointed out by others (Stephens 1981*a*, *b*; Lagage and Cesarsky 1985). As an example, Figure 4 shows the predicted ^{3}He/^{4}He ratio for the model of Cowsik and Gaisser (1981), in which a "degraded" component of cosmic rays originates in "thick" sources surrounded by ~50 g cm^{-2} of material. Similar models have been discussed by Ginzburg and Ptuskin (1981) and Lagage and Cesarsky (1985). In this calculation all sources were assumed to accelerate the same composition, with identical energy spectra. While this model is consistent with the Jordan and Meyer observation, it predicts a ^{3}He/^{4}He ratio that exceeds all of the observations at lower energies. By relaxing the assumption that the "normal" and "thick" sources have the same energy spectra and/or composition, it might be possible to fit both the high-energy data (including the antiproton measurements at GeV energies) and the low-energy ^{2}H and ^{3}He observations.

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APPENDIX

Atmospheric secondaries are an important source of background for balloon-borne ^{2}H and ^{3}He observations. One such contribution, which arises from the breakup of atmospheric N and O nuclei, leads to steeply falling spectra of ^{2}H and ^{3}He that are most significant below ~ 100 MeV per nucleon (see, e.g., Freier and Waddington 1968; Hofmann and Winckler 1967). While this source *has* been taken into account in most previous balloon-borne studies of ^{3}He, an additional source, due to the breakup of *primary* ^{4}He and heavier nuclei, has generally been ignored.

Although we are not aware of any appropriate measurements of the cross section for ^{4}He breaking up into ^{3}He in collisions with CNO nuclei, there are measurements of $^4\text{He} + p$ cross sections at ~ 100–300 MeV per nucleon which show that ~ 0.5 ^{3}He and ~ 0.4 ^{2}H are produced per inelastic ^{4}He interaction (see Meyer 1972). Meyer also suggests that ^4He + CNO interactions should produce somewhat fewer ^{3}He (and more ^{2}H) than $^4\text{He} + p$ interactions, since CNO targets tend to fragment ^{4}He to a greater degree. As an estimate of the "fragmentation parameter" for producing ^{3}He from ^{4}He in interactions with CNO we take $P_{4,3} = 0.25 \pm 0.15$, in which case a typical $^3\text{He}/^4\text{He}$ ratio of 0.1 at 0 g cm^{-2} will increase by $\sim 17\%$ at 3 g cm^{-2} due to this process alone. Using this assumption we have recorrected the balloon observations considered in this paper to the top of the atmosphere. In making these corrections inelastic mean free paths of 45 and 50 g cm^{-2} were taken for ^{4}He and ^{3}He, respectively (Webber and Yushak 1983), and it was assumed that the energy/nucleon and the angle of the incident ^{4}He and outgoing ^{3}He are preserved. It should be pointed out that a similar correction should apply to balloon-borne observations of cosmic-ray ^{2}H. These presently uncertain cross sections could be measured at an accelerator, or they might be determined with observations of the $^3\text{He}/^4\text{He}$ and $^2\text{H}/^4\text{He}$ ratios as a function of depth in the atmosphere.

Note added in manuscript.—Webber, Golden and Mewaldt (1987) have reexamined the interpretation of the Jordan and Meyer measurement of $^3\text{He}/^4\text{He}$ at 6 GeV per nucleon and obtained a result that is consistent with the standard rigidity-dependent leaky box model (see, e.g., Fig. 4).

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