Cosmic Ray ^{3}He Measurements

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Cosmic ray $^3He/^4He$ observations, including a new measurement at ~65 MeV/nucleon from ISEE-3, are compared with interstellar propagation and solar modulation models in an effort to understand the origin of cosmic ray He nuclei.

1. 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. There has recently been renewed interest in 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. In this paper we report a new observation of low-energy ^{3}He, examine previously reported $^3He/^4He$ measurements at both low and high energies, and compare these with calculations of the expected $^3He/^4He$ ratio at 1 AU. We find no evidence for an excess of low-energy ^{3}He such as that reported at high energies.

2. 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 8/13/78 to 12/1/78. Figure 1 shows the He isotope distribution from the two highest energy intervals covered by HIST. This data results in a $^3He/^4He$ ratio of 0.066±0.016 from 58 to 77 MeV/nucleon. Some of the ^{4}He in this energy interval is "anomalous" cosmic ray (ACR) ^{4}He, which has been corrected for using a decomposition of the ACR and galactic cosmic ray (GCR) fluxes [1], and their time history. The derived correction factor of 1.12±0.06 results in an "observed" GCR $^3He/^4He$ ratio of 0.074±0.018.

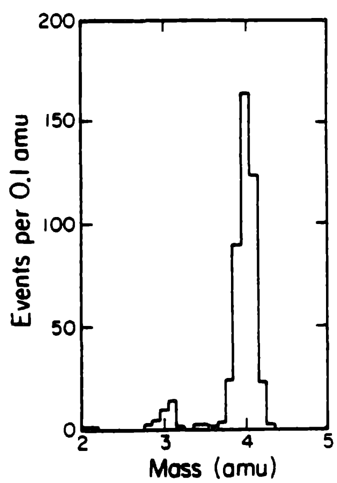

Figure 1: The distribution of quiet-time ^{3}He (48 to 77 MeV/nucleon) and ^{4}He (41 to 67 MeV/nucleon) observed by the Caltech experiment on ISEE-3 during late 1978.

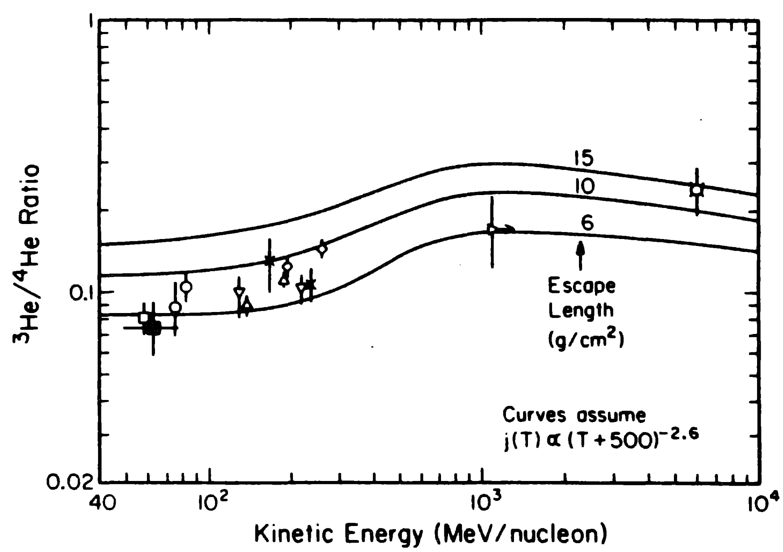

Figure 2: Measured and calculated $^3He/^4He$ ratios. Spacecraft observations: ■ This work, 1978; □ Goddard-UNH, 1972 [2]; ○ Chicago, 1973-1974. Balloon data: ▽ Rochester, 1966 [5]; △ UNH, 1972 [6]; ✕ UMd., 1972 [7]; ◇ UNH, 1977 [8]. Geomagnetic method: ▷ Ioffe, 1976 [11]; ⌑ Chicago, 1981 [9,10].

Figure 2 shows our new measurement along with selected other $^3He/^4He$ observations. The spacecraft observations [2,3,4] are from the 1972-1978 solar minimum period and are limited to the 50 to 100 MeV/nucleon interval where contamination by ACR ^4He is minimized. Since the reported observations include ACR ^4He, each has been corrected as described above. Figure 2 also includes observations from ~100 to 300 MeV/nucleon by balloon-borne instruments [5,6,7,8] (here referred to as "the balloon observations"). As discussed in the Appendix, we believe that the observations as reported (and as plotted in Figure 2) have not adequately corrected for ^3He produced in the atmosphere, and a proposed correction (typically ~16%) is therefore applied in subsequent Figures. At >300 MeV/nucleon the only observations use the geomagnetic method, including the recent Jordan and Meyer (J&M) measurement at ~6 GeV/nucleon [9,10], and an earlier result [11]. These experiments also fly on balloons, but are not subject to the same atmospheric corrections.

3. Interpretation of $^3He/^4He$ Observations - To interpret the available $^3He/^4He$ data we use propagation calculations by J. P. Meyer [12], who calculated *interstellar* spectra for ^1H, ^2H, ^3He, and ^4He for a variety of source spectra and mean pathlengths, using the standard "leaky-box" propagation model. The source spectra were of the form $dJ/dT \propto (T + U)^{-2.6}$, where T is kinetic energy per nucleon and $0 \leqslant U \leqslant 938$ MeV/nucleon. We calculated the effects of solar modulation on these spectra using the solar-minimum form of the interplanetary diffusion coefficient from Cummings et al. [13] and numerical solutions of the Fokker-Planck equation including the effects of diffusion, convection, and adiabatic deceleration. Results of these calculations are shown in Figure 2 for source spectra with U=500.

By comparison with the calculations (e.g., Figure 2) each observation determines a "leaky-box" escape-length (λ_e), as shown for U=500 spectra in Figure 3. Note that the spacecraft and (corrected) balloon observations all favor $\lambda_e \simeq 6$ to 7 g/cm^2; only the J&M measurement at ~6 GeV/nucleon indicates $\lambda_e \geqslant 10$ g/cm^2. Table 1 summarizes the mean escape-lengths obtained. 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 agreement with the spacecraft observations. Table 1 indicates that softer source spectra (e.g., U=200) lead to a somewhat greater λ_e at low energies. This is both a propagation effect (see [12]), and a result of the increased solar modulation required for soft spectra.

4. Discussion - We wish to determine whether the ^3He observations are consistent with the propagation/modulation models derived for heavier nuclei, or whether there is evidence for He nuclei with a separate origin and/or history. For the J&M measurement at ~6 GeV/nucleon we find a pathlength of ~15±6 g/cm^2 (in agreement with their value), independent of the assumed source spectrum. This value is significantly greater than derived from the B/C or other Z≥3 secondary/primary ratios, which imply $\lambda_e \simeq 5.5$ g/cm^2 at ~6 GeV/nucleon [14]. Thus, if the J&M measurement (and its interpretation) is correct, it does imply a high-energy ^3He excess, and a different origin for at least some high-energy He nuclei.

Figure 3: Plot of the escape length determined by the observations in Figure 2. The mean and uncertainty of the spacecraft (S), corrected (BC), and uncorrected (BU) balloon observations are indicated.

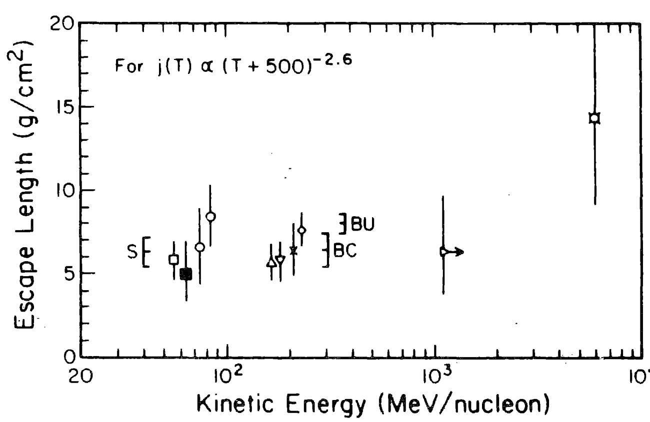

Table 1 - Mean Escape-Lengths (in g/cm²)

Source Spectrum	Spacecraft Observations (~ 70 MeV/nuc)	Balloon Observations (~ 200 MeV/nuc) w/o atm. corr.	atm. corr.(1)
$(T+500)^{-2.6}$	6.3±0.9	8.0±0.6	6.4±1.1
$(T+200)^{-2.6}$	8.9±1.0	9.7±0.7	7.8±1.3

(1) Uncertainty includes systematic uncertainty in the magnitude of the atmospheric correction.

At low energies, the required λ_e ranges from ~6 to ~9 g/cm^2 (see Table 1), with the lower value appropriate to U≃500, a spectral form consistent with most studies of the propagation and solar modulation of Z≥3 nuclei (e.g., [15,14]). An escape length of 6 g/cm^2 agrees well with that derived from the B/C ratio at similar energies (see, e.g., [16,14]). 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 earlier studies of low-energy H and He isotopes that have included both propagation and solar modulation effects (e.g., [17,4,8]), but it is in marked *disagreement* with the recent interpretation of low-energy observations by J&M [9,10]. They suggested that balloon observations at ~100 to 300 MeV/nucleon were consistent with the λ_e≃15 g/cm^2 escape-length required by their own measurement. After repeating their analysis in detail we conclude that J&M have significantly overestimated the pathlength required by the balloon data, as a result of a combination of factors, and that self-consistent interpretations of the low-energy data imply λ_e(^{4}He)≤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.

Measurements of Z≥3 nuclei imply a energy-dependent escape-length that decreases with energy above several GeV/nucleon. Figure 4 shows the expected ^{3}He/^{4}He ratio for the energy-dependent escape-length (λ_{OP}(E)) of Ormes and Protheroe [14], for two spectral forms. Both spectra can be seen to be consistent with the low-energy ^{3}He/^{4}He observations and inconsistent with the J&M measurement. Although the U=500 curve falls somewhat above the data, it should be pointed out that λ_{OP}(E) ≃ 9 g/cm^2 at several hundred MeV/nucleon, which is also greater than required by the B/C ratio. Thus the marginal agreement for U=500 is most likely the result of an inadequacy of the energy dependence of λ_{OP} at low energies.

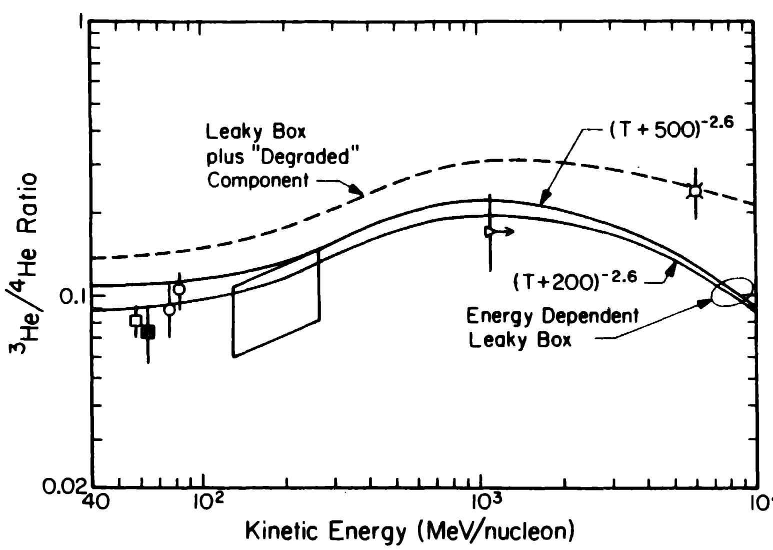

Figure 4: Comparison of the observations with various energy-dependent propagation models (see text). The box indicates the envelope of the corrected balloon observations.

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. Such models also produce an excess of ^{2}H and ^{3}He. As an example, Figure 4 shows the predicted ^{3}He/^{4}He ratio for the model of Cowsik and Gaisser [18], in which a "degraded" component of cosmic rays originates in "thick" sources surrounded by $\sim$50 g/cm^2 of material. While this model is consistent with the J&M observation, it exceeds the observed ^{3}He/^{4}He ratio at low energies. By relaxing the assumption that the "normal" and "thick" sources have the same energy spectra and composition, it might be possible to fit both the high energy data (including the antiproton data) 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 $\sim$100 MeV/nucleon (see, e.g., [19,20]). While this source *has* been taken into account in most previous studies, an additional source, due to the breakup of *primary* ^{4}He and heavier nuclei, has generally been ignored. Although we are not aware of appropriate cross section measurements for ^{4}He breaking up into ^{3}He in collisions with CNO, with ^{4}He + p cross sections [12] at $\sim$100 to 300 MeV/nucleon $\sim$0.5 ^{3}He and $\sim$0.4 ^{2}H are produced per inelastic ^{4}He interaction. We might expect ^{4}He + CNO interactions to produce somewhat fewer ^{3}He and more ^{2}H than ^{4}He + p interactions [12], 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 $P_{43}=0.25\pm0.15$, in which case a typical ^{3}He/^{4}He ratio of 0.1 at 0 g/cm^2 will increase by $\sim$17% at 3 g/cm^2 due to this process. Using this estimate (see also [21]) we have re-corrected the balloon observations in Figure 2 to the top of the atmosphere. This presently uncertain correction might be measured with observations of ^{3}He/^{4}He vs. atmospheric depth.

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