

MEASUREMENTS OF GALACTIC HYDROGEN AND HELIUM ISOTOPES  
FROM 1978 THROUGH 1983\*

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**ABSTRACT.** We have measured the differential flux of the hydrogen and helium isotopes using our instrument on the ISEE-3 spacecraft during solar quiet time periods from August 1978 through December 1983. These measurements cover the energy range from 26 MeV/nucleon through 138 MeV/nucleon for both  $^1\text{H}$  and  $^4\text{He}$ , from 24 to 89 MeV/nucleon for  $^2\text{H}$ , and from 43 to 146 MeV/nucleon for  $^3\text{He}$ . During the observations, the level of solar activity varied from near minimum to maximum conditions causing the observed flux of galactic cosmic rays to modulate by an order of magnitude. To describe the propagation in the galaxy, we find that the standard leaky box approximation with an escape path length of  $6.7 \text{ g/cm}^2$  forms a self-consistent model for the light cosmic ray nuclei at the observed energies.

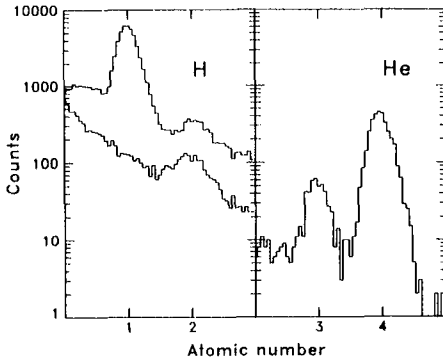
1. **INTRODUCTION.** Both cosmic ray  $^2\text{H}$  and  $^3\text{He}$  are secondary particles resulting from spallation of primary cosmic rays on interstellar matter. Measurements of the local flux of these particles are particularly interesting because the light cosmic rays have a path length for nuclear destruction which is greater than the mean confinement path length in the galaxy. Therefore, they are sensitive to the average amount of matter penetrated by the cosmic rays but not to details of the path length distribution.

We present here new measurements of the hydrogen and helium isotopes  $^1\text{H}$ ,  $^2\text{H}$ ,  $^3\text{He}$ , and  $^4\text{He}$  (the "quartet") made with the University of Chicago experiment on the ISEE-3 spacecraft. Although this instrument was primarily designed to observe the electron component, it achieves excellent isotopic resolution of the light nuclei, and permits reliable background determination over the energy range of nuclei stopping in the detector. A complete description of this instrument is given by Meyer and Evenson [1]. Isotopic resolution is achieved using the standard  $\Delta E$  vs.  $E$  method. Details of the analysis procedure will be given by Kroeger [2]. We achieved a mass resolution of approximately  $\pm 0.34$  amu FWHM (see figure 1).

2. **RESULTS.** The abundance ratios of secondary to primary particles are presented in figure 2. The average ratios are  $^2\text{H}/^4\text{He}=0.127\pm 0.006$  (65-87 MeV/n),  $^3\text{He}/^4\text{He}=0.075\pm 0.008$  (65-87 MeV/n), and  $^3\text{He}/^4\text{He}=0.074\pm 0.005$  (87-120 MeV/n). These ratios are not affected by anomalous helium fluxes

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*Figure 1*

Mass histograms showing the isotopic resolution of the ISEE-3 instrument. The data were collected in 1979 in an energy range of 65-87 MeV/n for both  $^2\text{H}$  and  $^3\text{He}$ . The two hydrogen histograms are from using different detectors for the  $\Delta E$  measurement. The bottom curve is composed of events classified as  $^2\text{H}$  by the upper curve. Note the effective elimination of the structured background due to protons.

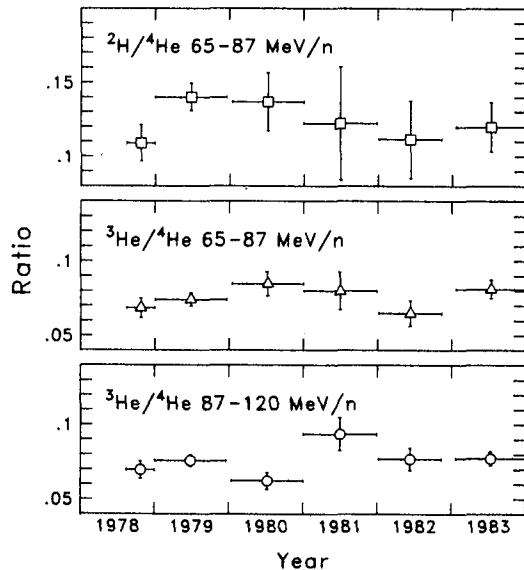
since these are significant only below 60 MeV/n. Calculations of solar modulation indicate that these ratios should vary by a factor of 1.26 for  $^2\text{H}/^4\text{He}$  (top panel) with the lowest ratio occurring in 1978 and the highest in 1981. The  $^3\text{He}/^4\text{He}$  ratio should vary by 1.15 in the same manner (bottom two panels). The modulation effects are within the statistical errors of our measurements.

3. DISCUSSION. The abundance ratios are interpreted using a leaky box approximation for the confinement of cosmic rays in the galaxy. In this model effects due to interactions with the interstellar medium are included (i.e. energy loss due to ionization, nuclear destruction and production). It is assumed that the source spectrum of cosmic rays is a power law in rigidity with a spectral index of  $-2.2$ , and that the mean escape path length is given by,

$$\Lambda_e = \begin{cases} X & \text{for } R < 5.5 \text{ GV} \\ X (R / 5.5)^{-0.6} & \text{for } R > 5.5 \text{ GV,} \end{cases}$$

where  $R$  is rigidity and  $X$  is the mean escape path length. We determine the path length  $X$  which best fits our data.

During our measurements, solar activity changed from near minimum conditions to solar maximum. Consequently, the flux of galactic particles changed by an order of magnitude as measured at 1 AU. We account for modulation using a spherically symmetric convection diffusion model [3]. This model requires a suitable choice of the diffusion coefficient for particles in the heliosphere in order to simulate particular levels of modulation. The selection we make enables us to match the local interstellar  $^4\text{He}$  spectrum calculated from the leaky box model to our



*Figure 2*

measured data. The diffusion coefficient we use is derived by interpolating between the solar maximum and solar minimum diffusion coefficients obtained from Garcia-Munoz [4]. His choice of diffusion coefficients were gained originally from a comparison of the interstellar electron spectra with local measurements. In figure 3 we display the local interstellar  $^4\text{He}$  spectrum and the modulated spectra that fit our 1978 and 1981 data. Figure 4 compares our calculation of the modulated proton spectra with the measurements using the same diffusion coefficients that were determined from the  $^4\text{He}$  fit. The fit to the proton data is excellent for the years 1978-1980. However, the calculation predicts too many protons for the years when modulation is strongest (a factor of 1.3). This apparent discrepancy can easily be resolved by small changes in the assumptions used in the leaky box model which effect the shape of the calculated interstellar spectra. However, rather than introduce additional free parameters we prefer to use the simplest model possible and neglect this discrepancy. Both  $^2\text{H}$  or  $^3\text{He}$  are expected to follow the modulation of  $^4\text{He}$  more closely than protons since their rigidities are closer to that of  $^4\text{He}$  for a given energy/nucleon.

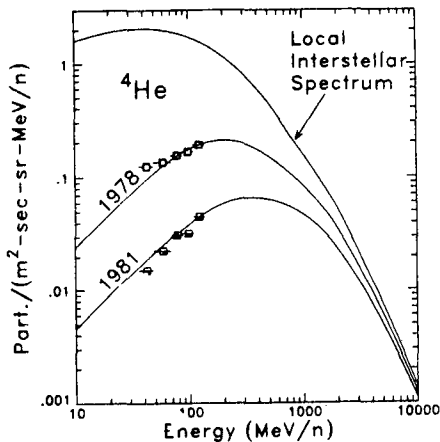


Figure 3

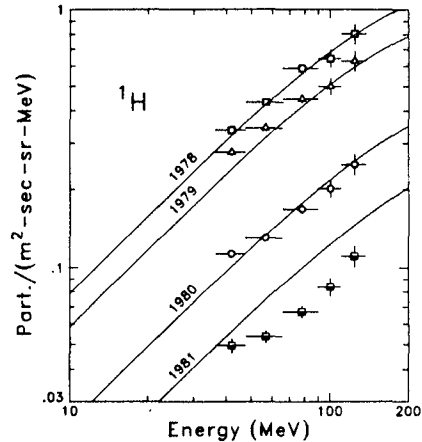


Figure 4

All of the parameters in the propagation and modulation models have been either specified or determined except for the mean escape path length,  $X$ . Figure 5 shows our calculation of the  $^2\text{H}/^4\text{He}$  ratio as a function of energy for various path lengths  $X$ . The shaded region in this figure represents the range of variability caused by changing solar modulation. The upper side of the shaded region results from modulation for 1981. We compare our measurements (closed circles) with other recent measurements (open symbols, references 6-10) in this figure. Figure 6 is a similar display, but for the ratio  $^3\text{He}/^4\text{He}$ .

The mean path length  $X$  that best fits our measured abundance ratios is  $7.6 \pm 0.4 \text{ g/cm}^2$  for the  $^2\text{H}/^4\text{He}$  ratio (65-87 MeV),  $6.0 \pm 0.3 \text{ g/cm}^2$  for the  $^3\text{He}/^4\text{He}$  ratio (65-87 MeV), and  $5.6 \pm 0.2 \text{ g/cm}^2$  for the  $^3\text{He}/^4\text{He}$  ratio (87-120 MeV). These ratios are weighted averages of the results from all six years. The difference between the best fit path length for H and He may be due to uncertainties in the production cross sections [5] used in this calculation. The mean between the two determinations is approximately  $X=6.7 \text{ g/cm}^2$ .

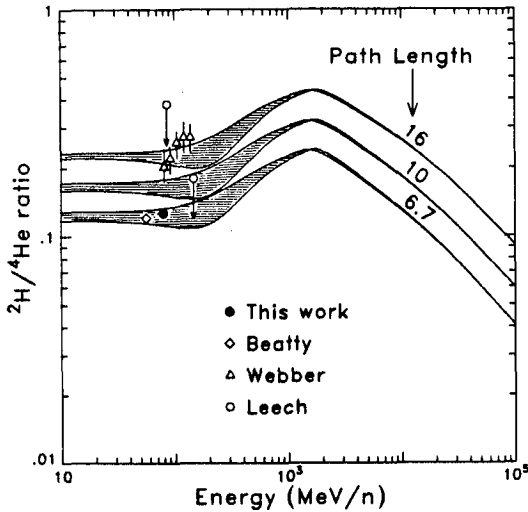


Figure 5

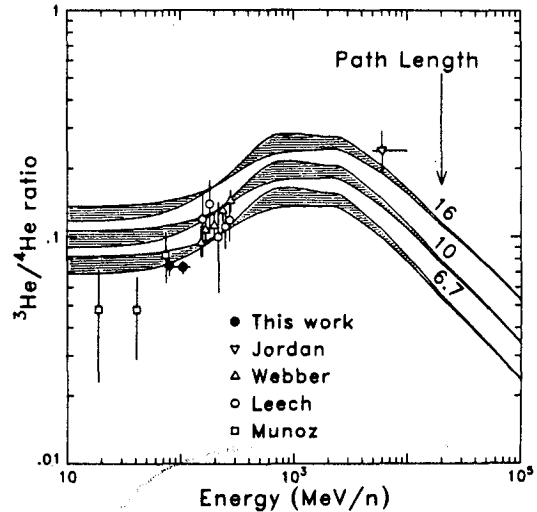


Figure 6

4. **CONCLUSION.** Our measurements of the spectra and fluxes of  $^1\text{H}$ ,  $^2\text{H}$ ,  $^3\text{He}$ , and  $^4\text{He}$  can be fit using a standard leaky box model for galactic cosmic ray confinement. This model is essentially the same as that used by other authors to fit the B/C ratio with a similar leakage path length [11,12]. This model has also been successful in explaining the abundances of iron secondaries at higher energies [13].

5. **ACKNOWLEDGEMENTS.** We would like to thank L. Krawczyk and C. Sethuraman for their valuable assistance in data processing and reduction.

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