INTERSTELLAR PROPAGATION AND THE ISOTOPIC COMPOSITION OF HYDROGEN IN THE GALACTIC COSMIC RAYS

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__Abstract__ Preliminary results of a study of the propagation of the quartet of stable isotopes of hydrogen and helium are reported. A mean pathlength of 7.5±0.5 g/cm^2 at $\sim$300 MeV/nucleon is required to explain the low-energy deuterium spectrum. This pathlength is consistent with pathlengths derived from the elements with Z>2, but is a factor $\sim$2 lower than the value required to explain the (^{3}He/^{4}He) measurement of Jordan and P. Meyer (1984). The propagation calculations reported here incorporate the preliminary results of an updated nuclear-interaction cross section survey covering the period since the review by J.P. Meyer (1972).

__Introduction.__ The quartet of isotopes of hydrogen and helium constitute a closely-coupled set of nuclides which provide strong constraints on the cosmic ray source spectra and on the escape pathlength of cosmic rays from the galaxy. (See Simpson (1971) for a review.) The recent measurements of (^{3}He/^{4}He) in the energy range 5-10 GeV/nucleon by Jordan and P. Meyer (1984) and Jordan (1985) require a pathlength of $\sim$15 g/cm^2 to account for the experimental data, which is inconsistent with the value $\sim$6 g/cm^2 inferred from CNO and their secondaries. (e.g. Garcia-Munoz et. al. (1981)) In this paper, the pathlength traversed by low-energy H and He during interstellar propagation is studied using the high-resolution, low energy spectra of ^{1}H, ^{2}H and ^{4}He determined using the University of Chicago IMP-8 telescope under solar minimum (1976-1977) conditions (Beatty et. al. 1985 and references therein). It is found that the observed fluxes of these nuclei at low-energy are consistent with the pathlength deduced from the elements with Z>2, but not with the much longer pathlengths required by the high energy He isotopic ratio.

__Measurements.__ The ^{2}H measurements used in this work were obtained using the University of Chicago IMP-8 telescope during the period June 1976 to April 1977, at solar minimum modulation. ^{2}H is identified by the (dE/dx) vs. residual E method. The measurement of ^{2}H is most reliable near the end-of-range, where the ^{2}H energy deposit in the CsI(Tl) residual E detector (D4) is $\sim$30% greater than the largest energy deposited by the more abundant ^{1}H (Figure 1,insert).

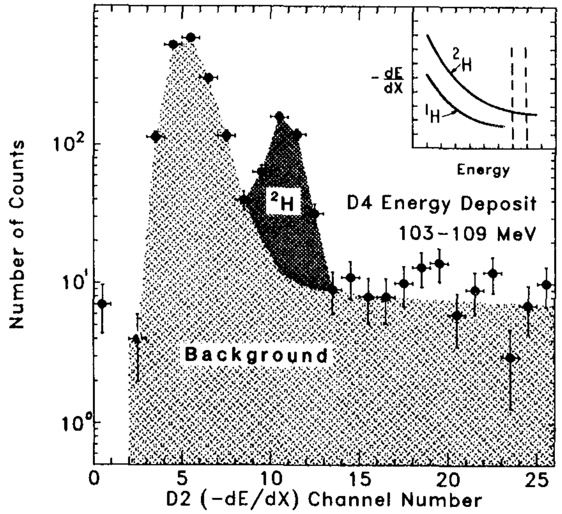

__Figure 1__

Plotting the number of counts per (-dE/dx) channel (D2), the ^{2}H appears as a peak superposed on a high energy interaction background. At solar minimum, subtraction of this background leads to a correction of only 25%. The r.m.s. width of the ^{2}H peak is 0.13 amu, corresponding to a FWHM of 0.31 amu. A more detailed discussion of the data analysis has been presented in Beatty et. al. (1985).

Modeling of Cosmic Ray Propagation. The effects of interstellar propagation on an assumed cosmic ray source spectrum are computed using a weighted-slab model (WSM), in which solutions of the equation describing the passage of nuclei through interstellar matter

$$\frac{\partial J}{\partial x} = \frac{\partial}{\partial E}\left(\frac{dE}{dx} J_i\right) + \sum_k \int \frac{J_k}{\Lambda_{ki}} dE' - \frac{J_i}{\Lambda_i}$$

are weighted by a pathlength weighting function (PLWF) to obtain the local interstellar cosmic ray flux:

$$J_{c.r.}(E) = \int dx\ P(E,x) J_{slab}(E,x)$$

For a leaky-box model (LBM) with energy-independent escape pathlength , it can be shown that the PLWF is an exponential: $P(x)=\exp(-x/\lambda)$. (Lezniak,1979)

The calculation procedure used in this work includes the effect of ionization energy loss at all energies, and includes kinematic energy-changing effects in the reactions H(p,d π+) and He(p,d) He. Kinematic effects in other reactions and energy losses due to elastic scattering are small and have been neglected. Results of calculations including the small effects neglected here will be published elsewhere (Beatty, 1985).

The nuclear interaction cross sections used here are the preliminary result of a survey in this laboratory of the experimental cross section measurements performed since the compilation by J.P. Meyer (1972). The remaining uncertainties in the cross sections are largest for the production of deuterium by the spallation of cosmic ray helium on the interstellar medium at energies above $\sim$500 MeV per nucleon.

Solar modulation has been taken into account using the model of Evenson et. al. (1983). For the solar minimum data discussed here, the adiabatic deceleration parameter is 440 MV.

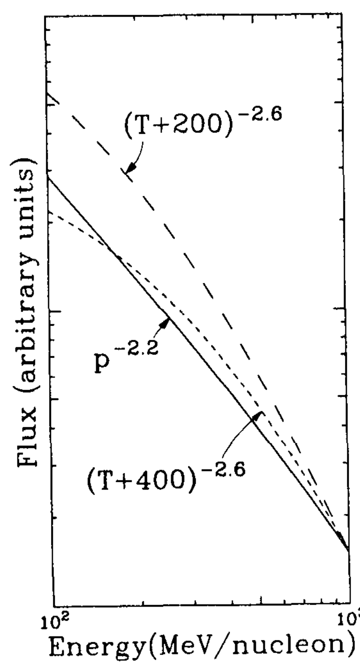

Figure 2

The Primary Energy Spectra. In the leaky box propagation model, the local interstellar spectra of ^{1}H and ^{4}He are simply related to the source spectrum and to the functional form of $\lambda(E)$. The pathlength for nuclear inelastic interaction with the interstellar medium is long compared with the expected escape pathlength. Secondary production of these species can be neglected because of their large source abundances. Energy loss effects are less important than for heavier elements: the lowest energy local interstellar particles which are seen at Earth (i.e., which have local interstellar energies greater than the energy lost during solar modulation) have lost <20% of their initial energy during interstellar propagation. Under these conditions, the leaky box model solution can be approximated by the simple algebraic result $J(E) = \lambda(E)\, Q(E)$. In this paper, momentum power law source spectra of the form $\frac{dN}{dP} = \frac{dJ}{dT} \propto p^{-\gamma}$ have been used. Figure 2 compares the chosen source spectrum $p^{-2.2}$ with the spectra $(T+200\text{MeV})^{-2.6}$ used by J.P. Meyer (1974), and $(T+400\text{MeV})^{-2.6}$ used by Garcia-Munoz et. al. (1981). The latter two spectra lead to a spectrum which is too steep when the energy dependence of $\lambda(E)$ at high energies is taken into account, but are similar to the momentum power-law spectrum above at energies below several GeV/nucleon.

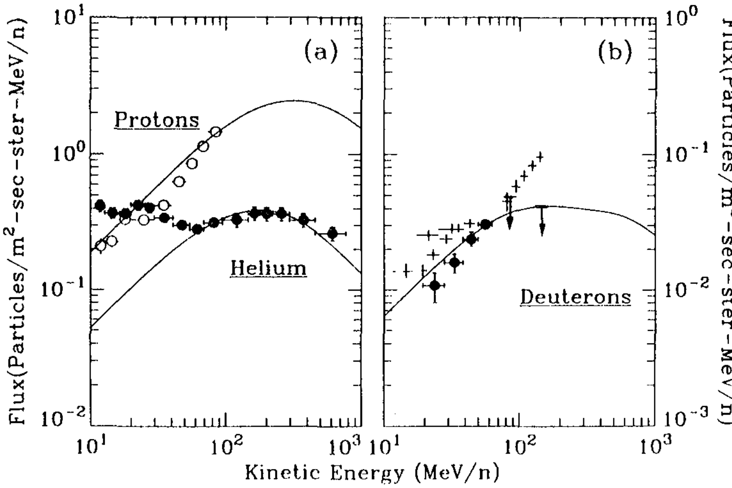

Figure 3 Computed 1 A.U. H, H, and He spectra for a 7.5 g/cm pathlength under 1976-1977 solar minimum conditions. Panel (a): open circles, protons; filled circles, helium; Garcia-Munoz et. al. (1977). Panel (b), deuterium: filled circles, Beatty et. al. (1985); crosses, Webber and Yushak (1983); upper limits, Leech and O'Gallagher (1978).

The source abundances used in this work are those of J.P. Meyer (1985), except that the ratio $^{1}H/^{4}He$ at constant energy/nucleon is determined to be $\sim$12.2 at low energy.

Deuterium Production. The pathlength is determined by the requirement that the modulated deuterium flux at 1 A.U. match the value measured under solar minimum conditions by the University of Chicago telescope on IMP-8. Figure 3 shows the computed ^{1}H, ^{2}H, and ^{4}He spectra together with experimental data from this period. (See caption) The pathlength required is 7.5 g/cm^2, using the model of Evenson et. al. (1983) to describe the effects of modulation during the 1976-1977 solar minimum. The error in this pathlength due to the experimental uncertainties in the measured fluxes is 0.5 g/cm^2.

Figure 4 illustrates the relative importance of contributions from cosmic ray ^{1}H, ^{4}He, and CNO. The local interstellar spectrum has been divided by the momentum power law source spectrum used in the calculations. Because the contribution from cosmic ray ^{1}H is entirely due to energy-changing kinematic processes, the importance of these reactions is strongly dependent on the source spectral form and on the low-energy behavior of $\lambda(E)$.

Difficulties in the interpretation of weighted-slab models arise when energy-changing processes become important. Lezniak (1979) has compared the LBM to the WSM, and has noted cases in which the mean of the WSM exponential PLWF and the value of the LBM escape pathlength are not equivalent. We have investigated the importance of these effects on the quartet. For the case where λ(E) increases with increasing energy as $E^{0.5}$ (Garcia-Munoz et. al. 1981; Ormes and Protheroe 1983), the effect of ionization energy loss will increase ^{2}H production by ∿5%, and the effect of energy-changing processes involving cosmic ray ^{1}H will increase ^{2}H by ∿10-20%. It should be noted that in both cases the WSM underestimates the production of ^{2}H relative to the corresponding LBM, and therefore overestimates the pathlength traversed in the case where λ(E) increases with increasing energy. The quantitative analysis of the case of energy-dependent PLWFs will be published elsewhere (Beatty, 1985).

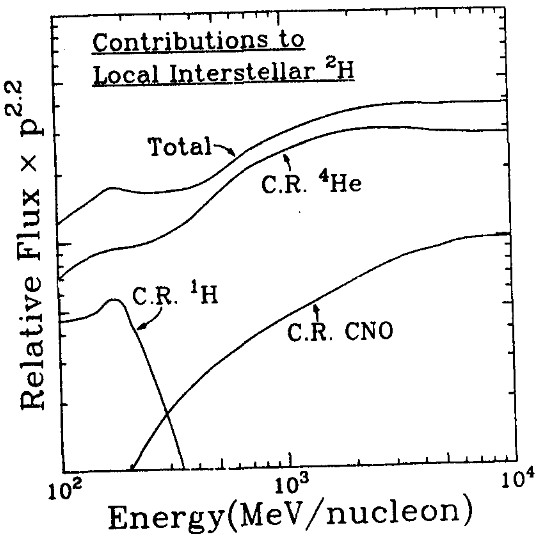

Figure 4

Acknowledgements. Discussions with M. Garcia-Munoz, T.G. Guzik, R.A. Kroeger, K.R. Pyle, and J.A. Simpson are greatly appreciated. This research was supported in part by NASA Grant NGL 14-001-006 and NASA Contract NAS 5-28442.

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