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OBSERVATIONS OF LOW ENERGY HYDROGEN AND HELIUM ISOTOPES DURING SOLAR QUIET TIMES

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We report a new quiet-time measurement of the relative abundance of cosmic-ray ^2H and ^4He. The observations were made in selected time intervals between September 1972 and February 1973 with the Caltech Electron/Isotope Spectrometer on IMP-7. In the energy interval 13-29 MeV/nucleon, we find an upper limit to the ^2H to ^4He ratio of $\Gamma(^2H/^4He) < 0.06$. This new upper limit is significantly lower than finite $^2H/^4He$ ratios measured in earlier years by other workers. Possible implications of this new result are discussed.

1. Introduction. The rare isotopes ^2H and ^3He in cosmic rays are generally believed to be of secondary origin, produced by the nuclear interaction of cosmic rays with the interstellar medium. Because of the relatively low abundance of cosmic-ray nuclei with $Z \geq 3$, ^2H and ^3He result mainly from interactions involving ^1H and ^4He. This close generic relationship suggests that the cosmic-ray abundance ratios $^2H/^4He$ and $^3He/^4He$ will reflect the mean pathlength (g/cm^2) of ^1H and ^4He in the interstellar medium, the energy spectra of these nuclei, and the energy dependence of the relevant nuclear interaction cross-sections.

Theoretical calculations of the relative abundances of these four isotopes have been performed by a number of workers, including Ramaty and Lingenfelter (1969), Meyer (1971), and Comstock et al. (1972). The predictions of these calculations suggest that observations of the H and He isotopes can play a unique role in investigating the characteristics of cosmic-ray sources, interstellar particle propagation, and solar modulation.

Unfortunately, uncertainties in the deuterium abundance seriously limit this investigation. Above 60 MeV/n, the only reported finite fluxes of deuterium are the 1963-5 balloon observations of Freier and Waddington (1968). At lower energies, serious discrepancies between reported satellite observations remain unresolved. Reported observations of finite low-energy deuterium fluxes have been made by the Chicago group from experiments on IMP's 3, 4, and 5 in 1965, 1967, and 1969 (see Hsieh et al., 1971) and by Meyer et al. (1968) from IMP-3 in 1965. However, measurements by the Goddard-New Hampshire group on IMP-4 and Pioneer 8 in 1967-8 gave upper limits to the deuterium flux significantly below the Chicago measurements made at the same time (Baity et al., 1971).

In this paper we report preliminary results on a new measurement of the $^2H/^4He$ ratio below 30 MeV/n, made with a high-resolution detector system.

2. Instrument. The observations reported here were made with the Caltech Electron/Isotope Spectrometer (EIS) launched on IMP-7 in September 1972 into a circular earth orbit of ~35 R_e. Figure 1 shows a cross section of the telescope, which consists of 11 fully-depleted silicon surface-barrier detectors, D0 through D10, surrounded by a plastic-scintillator anti-coincidence cup, D11. Detectors D0, D1, D3 and D4 are annular devices. All the silicon detectors are nominally 1 mm thick except D2 which is 50 μm thick. With the exception of D10 and D11, all detectors are pulse-height analyzed with exceptionally stable and linear ADC's. D2 and D5 are equipped with 4096 channel analyzers having 41 keV channel width, while the remaining analyzed detectors have 1024 channel analyzers with matched gains of 165 keV/channel.

The EIS has 2 modes of operation relevant to the present discussion. In the Wide Geometry mode, analysis is initiated by the requirement D0 $\overline{\text{D10}}$ $\overline{\text{D11}}$. This includes events that stop in detectors D0 through D9. For these events the D0 pulse height determines the energy loss ΔE, and the residual energy loss E' = E - ΔE is determined by a digital sum of the pulse heights from D1, and D3 through D9.

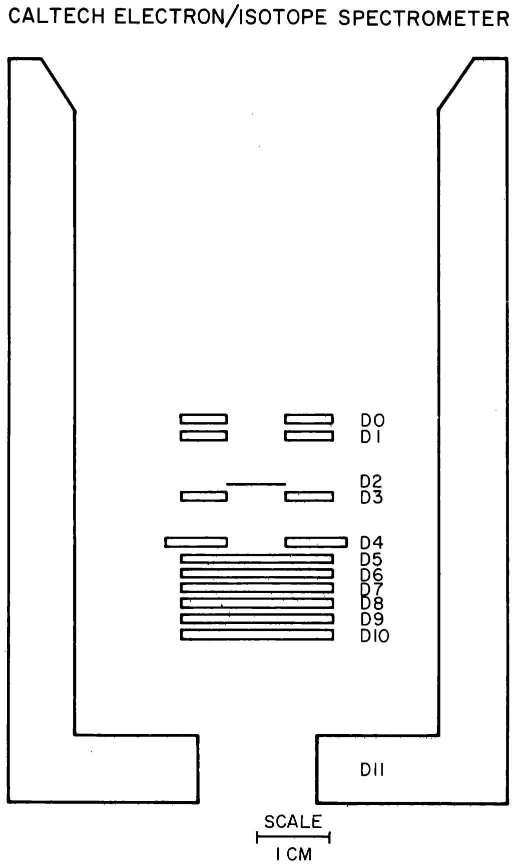

Fig. 1. A schematic cross-section of the EIS telescope.

In the Narrow Geometry mode, analysis can be initiated by the requirement $\overline{\text{D0}}$ $\overline{\text{D1}}$ $\overline{\text{D3}}$ $\overline{\text{D4}}$ D5H $\overline{\text{D10}}$ $\overline{\text{D11}}$, with the 4 annulars serving as an active collimator. In this mode D5 measures ΔE, and the digital sum of D6 through D9 determines E'.

In addition to pulse-height information, we receive complete range information for each analyzed event, specifying each detector triggered. The simultaneous measurement of energy loss, total energy, and range permits a redundant determination of the charge, mass, and total energy of an incident particle. The response and resolution of EIS to the isotopes of H and He have been calculated in detail and verified by prelaunch accelerator calibrations at energies up to 26 MeV, and by flight data.

3. Observations. In order to study the isotopic composition of galactic cosmic-ray nuclei, specific time intervals between 29 September 1972 and 5 February 1973 have been selected to minimize the possibility of contamination by particles of solar origin. Basis for this selection has been the rate of 4-12 MeV protons, which, for typical solar-particle energy spectra, are a much more sensitive indicator of solar-particle activity than the nuclei above 13 MeV/n under study here. Periods during which the 4-12 MeV

proton rate was significantly enhanced have been excluded from the analysis. Within the remaining quiet-time periods, the rate of 13-29 MeV/n ^{4}He nuclei was independent of the 4-12 MeV/n proton rate.

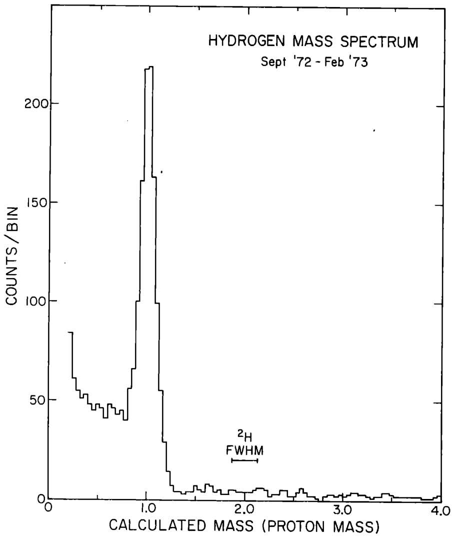

Fig. 2. Mass spectrum of Z=1 Wide Geometry events. The proton peak contains about 1200 particles between 19 and 43 MeV.

Hydrogen isotope data reported here are from the Wide Geometry analysis, and include particles that stop in detectors D3 through D9. Within the selected time periods, events from each range signature were sorted into 2-dimensional matrices according to their ΔE and E' pulse heights. From these matrices, a charge and mass were determined for each event on the basis of its location relative to the predicted response of various nuclei, based on both flight data and accelerator calibrations. Note that in such a procedure locations that fall between the predicted tracks of various isotopes are assigned non-integer mass values. Events which were found to have range signatures inconsistent with their calculated mass, charge, and total energy were eliminated, and the remaining events were combined into mass histograms.

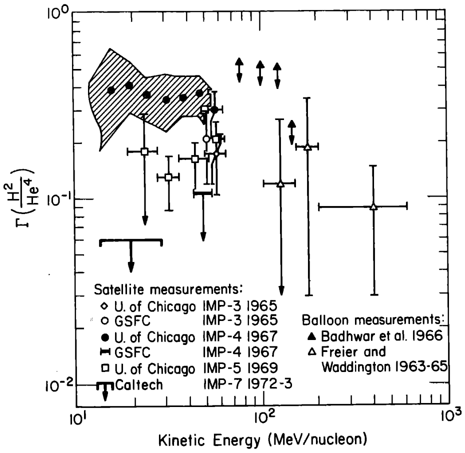

Fig. 3. Observations of the ratio of ^2H to ^4He. The earlier data shown were summarized in Hsieh et al. (1971). In addition to the points shown, Baity et al. (1971) have reported upper limits of ~15% in the 10-50 MeV/n range.

Figure 2 shows the combined Wide Geometry hydrogen mass spectrum. The striking resolution of the proton peak ($\sigma \approx 0.09$ proton mass units) is in agreement with our calculated mass resolution. The background level below the proton peak is due mainly to particles that escape from the side of the detector stack near the end of their range. For such an event, we obtain a valid ΔE measurement but an underestimate of the total energy. The calculated mass in such cases always lies below the true mass. The calculated mass of an incident particle may also be underestimated if the particle passes through the edge of D0, causing an underestimate in the ΔE measurement. An essentially flat background contribution of relatively low magnitude is alsc visible above the proton peak, starting at ~1.3 proton mass units. This background is presently under investigation.

1973ICRC....1...93H

The expected full-width-half-maximum (FWHM) of the deuterium peak is indicated in Figure 2. We see no evidence for any enhancement above background at this point in the mass spectrum.

4. Results. In the absence of a statistically significant ^{2}H peak in the hydrogen mass spectrum, the area under the expected ^{2}H FWHM can be considered "deuterons and background". This procedure gives a maximum deuterium flux of 1.3×10^{-2} / m^{2}sr-sec-MeV/n for the energy interval 13 to 29 MeV/n. Examination of Figure 2 suggests that the actual deuterium flux is much less than this value. The energy range 13 to 29 MeV/n is common to both our ^{2}H and ^{4}He measurements. Using both Narrow and Wide Geometry analyses, we measure a flux of 2.1×10^{-1}/m^{2}sr-sec-MeV/n for 13 to 29 MeV/n ^{4}He nuclei during the same time interval. This flux leads to an upper limit of .06 for the 13-29 MeV/n ^{2}H/^{4}He ratio.

5. Discussion. In Figure 3 we compare our new upper limit to previous measurements of $\Gamma(^2H/^4He)$ by other groups. Our upper limit is significantly lower than the 1967 Chicago results (Hsieh et al., 1971). It is also lower than the upper limits of Baity et al. (1971), made on the same satellite as the 1967 Chicago measurements.

Although the ^{2}H/^{4}He upper limit that we determine is ~6x lower than the 1967 Chicago finite ratio, the upper limit to our deuterium flux [$J(^2H) < 1.3 \times 10^{-2}$/m^{2}sr-sec-MeV/n] in the 13 to 29 MeV/n interval is only slightly less than the 1967 Chicago ^{2}H flux at these energies (~1.4×10^{-2}/m^{2}sr-sec-MeV/n) (Hsieh et al., 1971). Thus the difference in the ^{2}H/^{4}He ratio is mainly due to the larger ^{4}He flux measured in 1972-3. An enhanced 1972 ^{4}He intensity has also been noted by Garcia-Munoz et al. (1973) and Van Hollebeke et al. (1973).

It is generally believed that because ^{2}H and ^{4}He have the same charge to mass ratio, their solar modulation should be the same. Therefore, one would not expect their relative abundance as a function of energy per nucleon to be greatly altered by modulation effects , unless their interstellar spectral shapes are markedly different.

Other explanations for these observations should also be considered. An additional source of low energy ^{4}He of solar or other origin might account for the enhanced 1972-3 ^{4}He intensity. However, there is no direct evidence for such a source.

It is also possible that instrumental effects are the cause of discrepancies in the various deuterium measurements. We have investigated whether our lower deuterium flux could have been caused by instrumental effects. We consider this very unlikely. The mass resolution of our proton peak is significantly better than that of the other experiments in Figure 3. For example, the ratio of proton peak width (FWHM) to proton-deuteron separation is ~0.2 for our measurement, compared to ~0.5 for previous measurements (Baity et al., 1971). Furthermore, the background level near the expected deuteron peak location is ~2% of the proton peak, compared to typical values of ~10% in these other instruments. Finally, the simultaneous measurement of energy-loss, total energy, and range in the EIS provides redundant information for particle identification that minimizes possible background contributions.

We now consider possible implications of a $^2H/^4He$ ratio of less than 6%. In the absence of appropriate calculations of $^2H/^4He$ at Earth, we assume that the particles we observe had energies of ~100-300 MeV/n outside the solar system. Theoretical calculations of interstellar $^2H/^4He$ ratios have generally assumed galactic propagation models of the steady state or "leaky box" type, employing a mean free path Λ_ℓ for leakage from the galaxy. Estimates of Λ_ℓ from other nuclear species vary from ~4 to 8 g/cm^2. Assumptions regarding the interstellar ^1H and ^4He spectra affect the calculated $^2H/^4He$ ratio, especially at low energies (see, e.g., Meyer, 1971). In general, however, existing calculations have not predicted local interstellar $^2H/^4He$ ratios as low as 6% in the 100-300 MeV/n region (Ramaty and Lingenfelter, 1969; Meyer, 1971; Comstock et al., 1972; and Biswas and Ramadurai, 1971). Note, however, that for interstellar spectra similar to power laws in kinetic energy, $^2H/^4He$ ratios of ~8% in the 100-300 MeV/n region were obtained by Meyer (1971) for $\Lambda_\ell = 6.3$ g/cm^2. Although this possibility cannot be excluded by our data at this time, values of $\Lambda_\ell < 6.3$ g/cm^2 would seem to be implied. For interstellar spectra that resemble total-energy power laws, the disagreement with our upper limit is much more severe, and $^2H/^4He$ ratios below 10% would seem to require a value for Λ_ℓ much less than that required by other nuclear species such as Li, Be and B. However, comparisons of data at different energies and levels of modulation would benefit greatly from realistic calculations of the modulated energy-spectra of the H and He isotopes at Earth, correctly taking into account all known modulation effects. Such calculations are in progress.

6. Conclusion.

The observations reported here, made with a new, high-resolution detector system, have resulted in the lowest $^2H/^4He$ ratio reported at any energy. Although the implications of this result are not yet clear, it is noted that low $^2H/^4H$ ratios can result from shorter leakage mean free paths than usually considered, from interstellar ^1H and ^4He energy spectra that are rich in low energy particles, from some feature of modulation which is not yet understood, or from a local source of ^4He. Measurements of the low energy $^3He/^4He$ ratio may help clarify this picture. Work is presently in progress to analyze ^3He-data and additional ^2H-data. The improved statistics will permit us to search for deuterium fluxes in more restricted energy intervals at intensity levels even lower than our present upper limit.

7. Acknowledgements.

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