A SEARCH FOR ^{2}H, ^{3}H, and ^{3}He IN LARGE SOLAR FLARES

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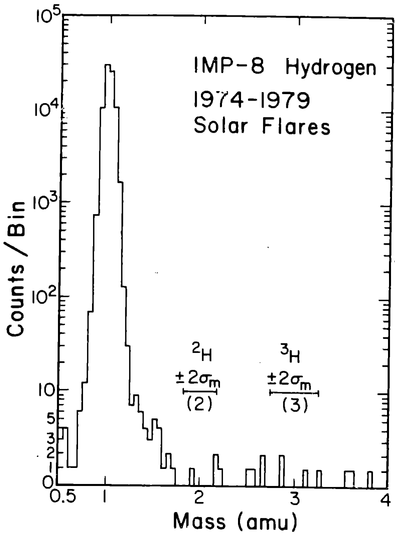
Abstract: The results of a new study of solar flare H and He isotopes imply that earlier observations have significantly overestimated the abundances of ^{2}H, ^{3}H, and ^{3}He in large solar flares. We find no evidence that solar flare nuclei have suffered any significant amount of fragmentation before escaping from the Sun.

1. Introduction: The rare isotopes ^{2}H, ^{3}H, and ^{3}He can be produced by nuclear interactions of accelerated ^{1}H and ^{4}He nuclei as they pass through the solar atmosphere. Earlier studies[1,2,3,4] of solar energetic particles (SEPs) have reported finite abundances of each these isotopes in data summed over many large flares, as well as enhanced abundances of ^{3}He in so-called "^{3}He-rich" events[5]. Although the finite ^{2}H and ^{3}H observations[1,4] require that SEPs have traversed ~0.1 to ~1 g/cm^2, at least one theoretical model[6] requires that SEPs traverse $\leq$2% of this amount during acceleration. Thus it appears important to re-examine the evidence for nuclear reaction products in SEPs.

2. Observations: The observations reported here were made with the Caltech Electron/Isotope Spectrometers on IMP-7 and IMP-8 and include IMP-8 data from 1/74 to 12/79 and IMP-7 data from 1/74 to 6/78. The flare periods included were selected by requiring that the daily average flux of 6-13 MeV protons be >0.4 cm^{-2}sr^{-1}sec^{-1}, thereby minimizing background events due to galactic cosmic rays (GCR). Background for ^{2}H and ^{3}H due to "pileup" during high count-rate periods was then minimized by excluding from the IMP-8 H-isotope data those days when the 4-13 MeV proton flux was > 100 cm^{-2}sr^{-1}sec^{-1}(~20% of IMP-8 data).

The mass of nuclei stopping in the telescopes is determined by conventional ΔE by E' techniques. Fig. 1 shows the H-isotope data from IMP-8. Since the ^{1}H mass resolution of 0.048 amu agrees with that expected we can predict accurately the mass interval ($\pm$ 2 σ_m) within which 95% of all real ^{2}H and ^{3}H would fall. Note that there are only 2 (for ^{2}H) and 3 (for ^{3}H) events within these limits, and considering the relatively smooth background level, no evidence for a finite flux of either ^{2}H or ^{3}H. In the IMP-7 data there is only 1 event with mass > 1.5 amu. Summing the IMP-7 and IMP-8 data, and taking into account the observed background distribution and the GCR ^{2}H flux, we find 95% confidence upper limits of ~5 events each for ^{2}H and ^{3}H. Table 1 summarizes these upper limits relative to ^{1}H and ^{4}He.

In Fig. 2 we show He data from both instruments, where 2 ^{3}He-rich events previously identified by other groups are shown separately. In the bottom two panels there is no convincing evidence for ^{3}He (~2 GCR ^{3}He are expected), and we find a 95% confidence upper limit of ~9 ^{3}He of SEP origin from IMP-7 and -8 combined. Table 1 includes the resulting ^{3}He/^{4}He upper limit, and a finite ratio for the total data sample (including the 2 ^{3}He-rich flares).



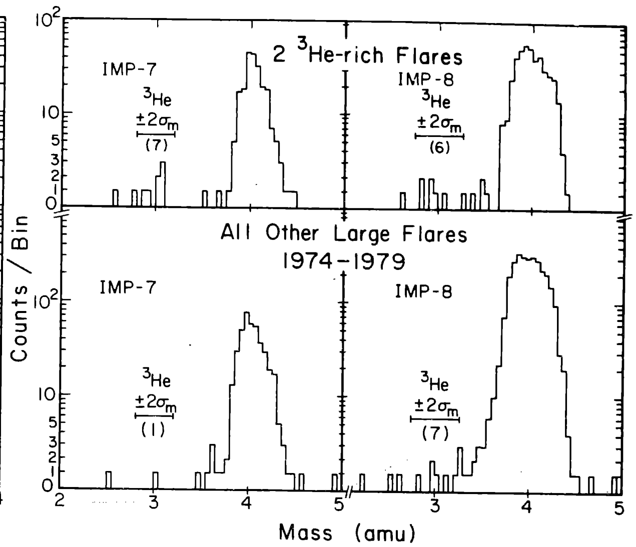


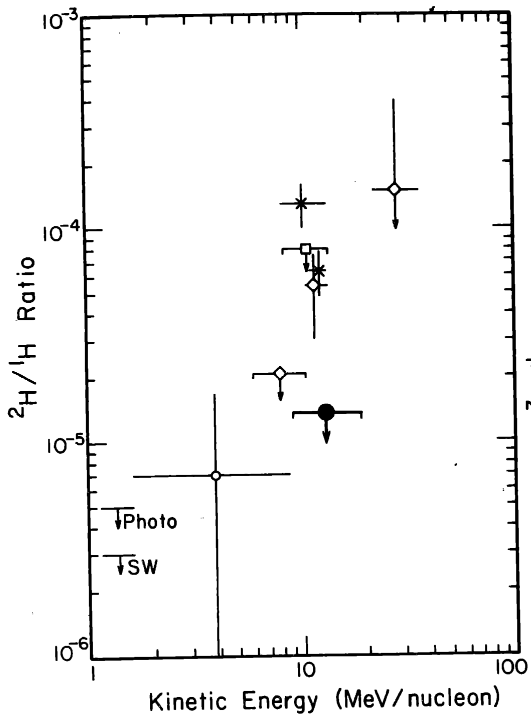
Fig. 1 (left): IMP-8 hydrogen isotope data. Mass intervals ($\pm 2\ \sigma_m$) for ^{2}H and ^{3}H are indicated, with the number of events in parentheses. Note the vertical scale is linear from 0 to 3.

Fig. 2 (right): Mass histograms of SEP He nuclei. The top panels each include 2 ^{3}He-rich events (9/24/77 and 10/12/77).

3. Discussion: Figs. 3,4, and 5 compare our results with earlier measurements. For ^{2}H and ^{3}H the only reported finite fluxes are those from the Chicago experiments on IMPs 5 and 6[1,4], and an earlier, lower-energy measurement from our IMP-7 instrument[3]. Note that our upper limits for both ^{2}H/^{1}H and ^{3}H/^{1}H are significantly lower than the Chicago finite measurements at essentially the same energy/nuc. There also appear to be significant experimental differences for ^{3}He/^{4}He.

For ^{3}He/^{4}He, which is known to vary by orders of magnitude from flare to flare, we cannot exclude the possibility that sampling effects might explain the large differences evident in Fig. 5, if e.g., the earlier studies happened to include more ^{3}He-rich flares (such ^{3}He enhancements are no longer attributed to nuclear interactions[5]). However, our new measurements, those from Pioneer-10[7], and our ISEE-3 data[9] lead us to conclude that typical large solar events have considerably lower ^{3}He/^{4}He ratios than indicated by earlier studies. Although our results are somewhat closer to the meteoritic measurements which find ^{3}He/^{4}He $\approx 4\times10^{-4}$ for the long-term SEP fluence at $\gtrsim$1 MeV/nuc, detailed comparison requires that the ^{3}He contributions from individual flares be weighted by fluence.

In the case of ^{2}H and ^{3}H, it does not appear possible that flare-sampling differences could explain the discrepancies evident at ~10 MeV/nuc in Figs. 3 and 4. Anglin[4] found no evidence for flare-to-flare variations in the IMP-5 ^{2}H/^{1}H and ^{3}H/^{1}H ratios. Since the Chicago IMP-6 data[1] typically included ~20 ^{2}H+^{3}H events from each flare studied, flare-to-flare variations of the required magnitude (factor of >10) would have been easily detectable. Another possibility is that the IMP-5 and IMP-6 results include substantial ^{2}H and ^{3}H produced by nuclear interactions within the instruments (see refs. 2 and 11), as might also be suggested



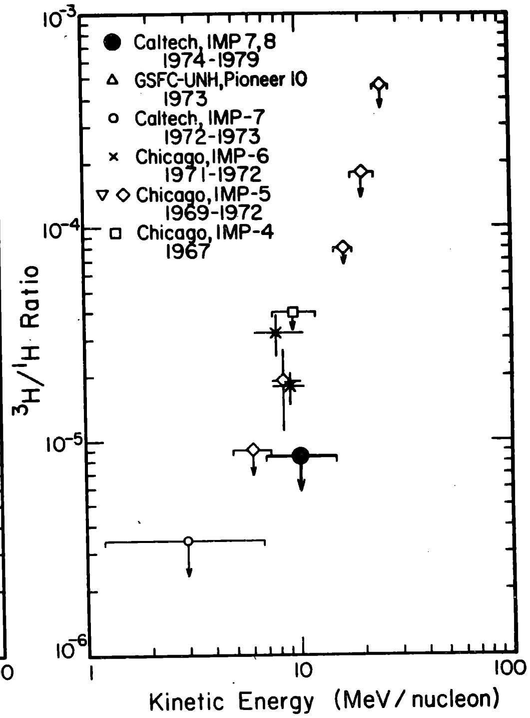


Fig. 3-5 (clockwise): SEP $^2H/^1H$, $^3H/^1H$ and $^3He/^4He$ observations, all summed over ≥ 4 flares. Data references (in brackets, see also Fig. 4): ● this work; △ [7]; ○ [3]; x [1,4]; ◇ [1,4]; ▽ "^{3}He-poor" flares [2,4]; □ [4]. In addition, McGuire et al. have reported upper limits for 8 individual flares [8]. Fig. 4 includes solar wind and photospheric upper limits

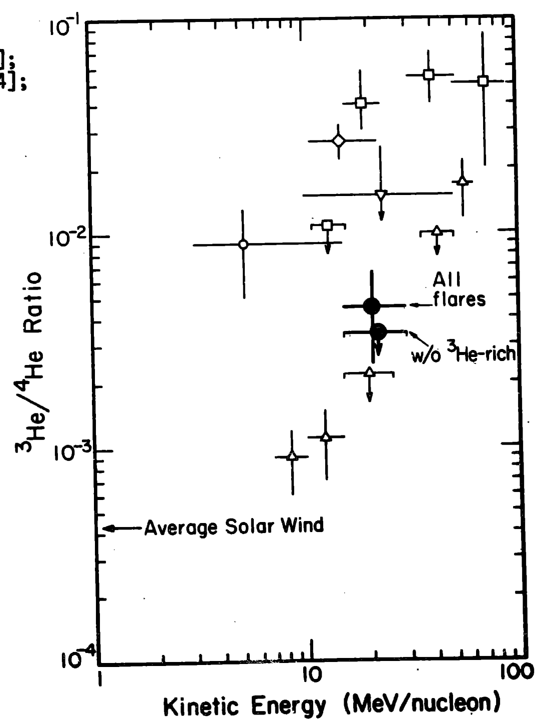


Table 1 - Solar Flare Isotope Ratios

Isotope Abundance Ratio	Energy Interval (MeV/nuc)	86% Confidence Interval or 95% Confidence Upper Limit
$^2H/^1H$	9-19	$< 1.4 \times 10^{-5}$
$^2H/^4He$	9-19	$< 9 \times 10^{-4}$
$^3H/^1H$	7-15	$< 9 \times 10^{-6}$
$^3H/^4He$	7-15	$< 6 \times 10^{-4}$
$^3He/^1H$ (w/o ^{3}He-rich)	15-30	$< 4 \times 10^{-5}$
$^3He/^4He$ (w/o ^{3}He-rich)	15-30	$< 3.4 \times 10^{-3}$
$^3He/^4He$ (all flares)	15-30	$4.5^{+2.3}_{-2.1} \times 10^{-3}$
$^4He/^1H$	13-24	1.3×10^{-2}

by the inconsistencies between these two experiments (for both $^2H/^1H$ and $^3H/^1H$ they are consistent at ~10 MeV/nuc, but differ by factors of ~3 to ~6 at slightly lower energy; see Figs. 3 and 4).

The results reported here indicate that the typical particle escaping from the Sun has not traversed any substantial amount of material, thus removing this constraint from solar flare acceleration models. From the "thin-target" model of Ramaty and Kozlofsky (which neglects dE/dx losses), and our $^2H/^1H$ upper limit, we estimate an upper limit to the average pathlength (x) of x(50 MeV) < 50 mg/cm^2, where 50 MeV is the typical energy for producing ^2H and ^3H in our energy interval. An even smaller limit (x < 30 mg/cm^2) results when dE/dx losses are included[4].

Although recent solar γ-ray observations provide conclusive evidence that nuclear reactions occur during flares, such γ-rays are believed to result mainly from nuclei that slow down and stop in the solar atmosphere, rather than from nuclei that escape the Sun.[13] Thus, for example, from Ramaty[13] it can be estimated that for x = 30 mg/cm^2, interactions involving particles that escape into interplanetary space would account for <1% of the γ-rays produced in the June 7, 1980 event. It is likely that the actual pathlength is much less, in which case improved instrumentation and larger data samples will be required to detect directly high-energy nuclear-interaction products such as ^2H and ^3H.

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