A SEARCH FOR SOLAR FLARE POSITRONS

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The detection of solar $\gamma$-ray line emission and observations of the isotopes $^2$H, $^3$H and $^3$He in solar cosmic rays provide direct evidence for the occurrence of high energy nuclear reactions in solar flare events. Appreciable numbers of other reaction products, including positrons with energies near ~1 MeV, should also be produced in such events. We have searched for positrons in the 0.16-1.6 MeV energy interval during 5 "$^3$He rich" solar particle events observed by the Caltech Electron/Isotope Spectrometers on IMP 7 and 8. Based on calculations of positron and $^3$He production at the sun, and using a simplified model of interplanetary propagation, we might expect comparable fluences of positrons and $^3$He to be observed. Summing over these 5 events, however, we find the 0.16 to 1.6 MeV positron fluence to be $< 10\%$ of the $> 1$ MeV/nuc $^3$He fluence. This suggests that other processes, such as preferential trapping by the solar magnetic field, may be important.

1. Introduction. Chupp et al. (1973) have reported the identification of a line flux of 0.5 MeV $\gamma$-radiation during the large solar particle events of August 1972. These observations imply the existence of appreciable numbers of solar positrons during periods of intense solar activity, presumably the products of nuclear interactions of flare accelerated particles with the ambient solar atmosphere. Additional evidence for nuclear reactions on the sun has been provided by the identification of the rare isotopes $^2$H, $^3$H, and $^3$He in solar cosmic rays, including a number of events that had anomalously large relative abundances of $^3$He without corresponding enhancement in $^2$H or $^3$H (Garrard et al., 1973; Anglin et al., 1974; Serlemitsos and Balsubrahmanyan, 1974; Hurford et al., 1975a). In these unusual events, labeled "$^3$He rich flares", the $^3$He/$^4$He ratio ranges from ~0.2 to $\geq 6$, while the $^3$He/$^2$H ratio can be as large as ~1.

Models that attempt to explain this unusual isotopic composition have been proposed by Ramaty and Koslovsky (R & K) (1974a, 1974b) and Rothwell (1974). Appreciable production of other nuclear reaction products, including nuclear $\gamma$-rays, neutrons, and positrons is also predicted in such models (Ramaty and Lingenfelter, 1973; Ramaty et al., 1975; Wang and Ramaty, 1975). A principal source of positrons is the $\beta^+$-decay of short-lived nuclear reaction products such as $^{11}$C, $^{13}$N, and $^{15}$O. The $\beta^+$-decay energies of these nuclei are within the 0.16-1.6 MeV energy range covered by this experiment. Simultaneous observation of solar flare positrons and rare isotopes of secondary origin would provide important information for studying solar flare regions, acceleration processes, and particle propagation.

In this paper we report upper limits to the fluence of ~1 MeV solar flare positrons in 5 $^3$He rich solar particle events, and compare these results with calculated fluxes of solar flare positrons.

2. The Instruments. The observations reported here were made with the Caltech Electron/Isotope Spectrometers (EIS) on IMP-7 (launched September 1972) and IMP-8
(launched October 1973). The IMP-7 detector system, shown in Figure 1, consists of a stack of eleven silicon surface-barrier detectors, D0 through D10, surrounded by a plastic-scintillator anticoincidence cup D11. Detectors D0, D1, D3, and D4 are annular devices. All silicon detectors except D2 have nominal thicknesses of 1 mm and thresholds of 160 keV, and are thus fully sensitive to penetrating minimum-ionizing particles.

The EIS instruments have two modes of charged particle detection relevant to the present discussion. In the narrow geometry mode, the annular detectors serve as an active collimator, and we analyze events in detectors D2, and D5 through D9. The 50 μm detector, D2, allows clean electron-nuclei separation. The isotopes of nuclei that trigger D2 and D5 can be identified using conventional dE/dx-β techniques. For H and 4He nuclei, the D2D5 energy range is 2.4-12.7 MeV/nuc, while for 3He it is 2.9-15 MeV/nuc. In the Wide Geometry Mode, we analyze events which trigger D0 without penetrating to D10 or D11. A more complete discussion of the IMP-7 EIS can be found in Hurford et al. (1974), while the IMP-8 EIS is of similar design and operation with somewhat improved positron detection sensitivity.

Positrons are identified by detecting their annihilation γ-radiation, as illustrated in Figure 1. If an incident positron stops in D0, one of the 0.51 MeV annihilation γ-rays may Compton scatter in another detector such as D6, D7, D8, or D9. Thus the coincidences DODD, DODD, DODD, or DODD, in anticoincidence with all other detectors, would be positron signatures. Pulse height information can then be used to assign an energy to the particle stopping in D0, and to ensure that the energy loss in the 2nd detector is consistent with the maximum Compton recoil energy of a 0.51 MeV γ-ray.

The instruments' efficiency for identifying positrons has been established by calibration and calculation. For positrons stopping in D0 it is $3 \times 10^{-3}$ for the IMP-7 EIS, and $9 \times 10^{-3}$ for the IMP-8 EIS. The principal background source of events with positron-like signatures is γ-rays which Compton scatter in two separate detectors, a possible example of which is illustrated in Figure 1.

During solar quiet times we measure a very constant rate of positron-type events, a significant fraction of which is known to be due to double-Compton-scattered γ-rays (Hurford et al., 1973). A significantly enhanced flux of positrons during a solar flare would result in a temporary increase in the rate of positron-type events above this quiet time level.
3. Solar Flare Observations. We have searched for solar flare positrons during five $^3$He rich solar flares identified by the IMP-7 EIS (see e.g. Hurford, 1974, Hurford et al., 1975a, b). In these events, summarized in Table 1, the 2.9-15 MeV/nuc $^3$He/$^4$He ratio ranged from $\approx 0.2$ to $\geq 6$ while the observed $^3$He fluences were all comparable. Note that the last two events occurred after the launch of IMP-8, permitting significantly improved positron detection sensitivity. An analysis of daily event rates for 20 day periods centered on each of these five flares showed no statistically significant ($\geq 3\sigma$) increases in the rate of positron-like events. Figure 2 shows a superposition of data from two $^3$He rich events observed by IMP-8, and the five $^3$He rich events observed by IMP-7, centered on the days during which $^3$He nuclei were first detected at 1 AU. Note that the average counting rates of positron-like events near the time of the $^3$He rich flares do not differ significantly from the mean counting rates averaged over longer time periods.

**TABLE 1. SOLAR PARTICLE FLUENCES**

<table>
<thead>
<tr>
<th>YEAR</th>
<th>START</th>
<th>END</th>
<th>INSTRUMENT</th>
<th>POSITRONS 0.16-1.6 MeV (cm$^{-2}$sr$^{-1}$)</th>
<th>TOTAL ELECTRONS 0.16-16 MeV (cm$^{-2}$sr$^{-1}$)</th>
<th>$^3$He 2.9-15 MeV/nuc (cm$^{-2}$sr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1973</td>
<td>2/14</td>
<td>2000</td>
<td>IMP-7</td>
<td>$&lt; 2 \times 10^3$</td>
<td>$- 10^5$</td>
<td>$- 3 \times 10^2$</td>
</tr>
<tr>
<td>1973</td>
<td>6/29</td>
<td>0000</td>
<td>IMP-7</td>
<td>$&lt; 10^3$</td>
<td>$- 10^5$</td>
<td>$- 3 \times 10^2$</td>
</tr>
<tr>
<td>1973</td>
<td>9/5</td>
<td>0300</td>
<td>IMP-7</td>
<td>$&lt; 2 \times 10^3$</td>
<td>$\leq 10^4$</td>
<td>$- 3 \times 10^2$</td>
</tr>
<tr>
<td>1974</td>
<td>2/20</td>
<td>1200</td>
<td>IMP-7,8</td>
<td>$&lt; 1.2 \times 10^3$</td>
<td>$- 3 \times 10^5$</td>
<td>$- 6 \times 10^2$</td>
</tr>
<tr>
<td>1974</td>
<td>5/9</td>
<td>0800</td>
<td>IMP-7,8</td>
<td>$&lt; 4 \times 10^2$</td>
<td>$\leq 2 \times 10^4$</td>
<td>$- 6 \times 10^2$</td>
</tr>
<tr>
<td>IMP-7</td>
<td>5-FLARE SUM</td>
<td>IMP-7</td>
<td>$&lt; 5 \times 10^3$</td>
<td>$- 5 \times 10^5$</td>
<td>$- 2 \times 10^3$</td>
<td></td>
</tr>
<tr>
<td>IMP-7,8</td>
<td>2-FLARE SUM</td>
<td>IMP-7,8</td>
<td>$&lt; 1.0 \times 10^3$</td>
<td>$- 3 \times 10^5$</td>
<td>$- 1.2 \times 10^3$</td>
<td></td>
</tr>
</tbody>
</table>
In order to obtain upper limits to the solar positron fluence, data from more restricted time intervals were analyzed, starting -2 to 4 hours before the particle onset at 1 AU, and extending to include at least 90% of the flare associated $^{3}$He and total electron fluences observed. The results of this analysis are summarized in Table 1, where the upper limits to the solar positron fluence represent the 84% confidence limits after subtracting the quiescent event rates shown in Figure 2. Also shown are the $^{3}$He and total electron fluences that we observe.

4. Discussion. The results in Table 1 indicate that positrons comprise $\leq 1\%$ of the total electrons near 1 MeV in $^{3}$He flares, a result similar to that found for flares of normal isotopic composition (Hurford et al., 1973). Note, however, that it is more meaningful to compare the positron and $^{3}$He fluences, since both these species are believed to be of secondary origin. For this purpose it is useful to obtain a better estimate of the total $^{3}$He fluences, including particles with energies less than our D205 coincidence threshold of 2.9 MeV/nuc. For the two $^{3}$He rich events observed by IMP-8, Gloeckler and Hovestadt (1975) have determined that the $^{3}$He spectrum extends down to $\leq 1$ MeV/nuc. Assuming $d\psi/dE \propto E^{-3}$ in this and later estimates (Hurford, 1974), we estimate a total $^{3}$He fluence $\psi_{^{3}$He/nuc of $-10^{4}$ cm$^{-2}$ s$^{-1}$ for the 20 Feb. and 9 May 1974 flare sum, giving a ratio of positron to $^{3}$He fluences of $< 0.1$. Note that this is a conservative estimate since there is no evidence to suggest that the $^{3}$He spectrum cuts off at 1 MeV/nuc.

In order to estimate the relative abundances of positrons and $^{3}$He produced in nuclear reactions at the sun, we consider the thick target model of R & K (1974a, b) which is designed to explain the observed enhancement of $^{3}$He relative to other secondary nuclei such as $^{2}$H and $^{3}$H. In this model a primary beam of $^{1}$H, $^{3}$He and CNO nuclei is directed downwards on the ambient solar atmosphere of similar composition. Based on reaction kinematics calculations, R & K find that for products produced in the backward hemisphere of the laboratory reference frame, which includes $\sim 30\%$ of the total $^{3}$He, it is possible to obtain $^{3}$He/$^{2}$H $\geq 30$ at energies $\leq 1$ MeV/nuc. A post-production acceleration process is then required for the $^{3}$He nuclei to escape from the sun.

From the calculations of R & K (1974a, b) and Ramaty et al. (1975) for this model, we estimate a total yield of $\sim 0.1$ positron emitters per $^{3}$He produced, where we assumed that the primary beam directed into the sun had a spectrum $d\psi/dP = \exp (-P/P_{0})$, with characteristic rigidity $P_{0} = 150$ MV. About 1/3 of the positron emitters will be $^{3}$He unstable CNO nuclei yielding positrons in our energy range ($\sim 1$ MeV). Assuming isotropic $^{3}$He-decay emission, we estimate a positron to $^{3}$He ratio of $\sim 0.05$ for the backward lab hemisphere, and assume for convenience that this ratio is preserved in the particle fluxes escaping from the sun.

The relative $^{3}$He and $^{3}$He fluences observed at earth will depend on the nature of their propagation in the interplanetary medium. If scattering in the interplanetary magnetic field is sufficient to produce approximately isotropic particle fluxes, and if the $^{3}$He and $^{3}$He residence times near 1 AU are comparable, then we might expect the $^{3}$He and $^{3}$He number densities (cm$^{-3}$) to reflect their production ratio, i.e., $N(e^{+}) \sim 0.05 N(He^{3})$. In this case the greater velocity of the positrons implies a fluence ratio of $F(e^{+})/F(He^{3}) \sim 1$. If, in the other
extreme, the e⁺ and ³He propagation is scatter free, we expect F(e⁺)/F(He³) = 0.05. 
These estimated fluence ratios should be compared to the observed upper limit of 
F(e⁺)/F(He³) < 10⁻¹, which is obtained by considering the ³He fluence down to 1 
MeV/nuc. The actual ratio could, of course, be up to a factor of ∼100 lower if the ³He spectrum extends down to 0.1 MeV/nuc with the same slope.

The above considerations imply that ∼1 MeV positrons may not be released 
into the interplanetary medium as efficiently as ³He nuclei, suggesting that 
processes other than those discussed may be important. Since in the thick target 
model of R & K, both the positrons and ³He are produced at depths in the solar 
atmosphere of ∼1-10 g/cm², it is clear that some post-acceleration process is 
required (R & K, 1974a, b) for either the e⁺ or ³He to escape the sun. Such an 
acceleration process might favor ³He relative to positrons, or might accelerate 
the positrons to energies ≥ 2 MeV. Preferential trapping of positrons by the 
solar magnetic field might also be important. If, in fact, the majority of posi-
trons do annihilate at the sun, the resulting 0.51 MeV γ-radiation might be 
observable at 1 AU, although estimates of the γ-ray flux from ³He rich events 
(R & K, 1974a) are not so large as in the events observed by Chupp et al. (1973).

The uncertainties involved in the direct escape of ∼1 MeV positrons from 
the sun can be avoided if we consider only those positrons that result from the 
β-decay of flare accelerated nuclei which escape into the interplanetary medium 
before decaying. R & K (1974b) suggest that boron should also be enriched in 
³He rich events, with a B/C ratio comparable to the ³He/⁴He ratio, although 
observations to date have not tested this prediction. A principal source of 
boron production in the thick target model of R & K is reactions that produce 
¹¹C, such as ¹⁴N(p, α)¹¹C → ¹¹B + e⁺ + ν. Note that ¹¹C also happens to be the 
principal source of ∼1 MeV positrons in their model. Since the ¹¹C half-life 
is 20.5 min, the ¹¹C may be well into interplanetary space before it decays.
Assuming that other β-unstable secondary products will be enriched to the same 
extent in these events, we find from R & K (1974a) and R & L (1973) that the 
ratio of flare accelerated β⁺ emitters to ³He should be ∼10⁻², implying an 
interplanetary e⁺/³He ratio of this same magnitude, once these nuclei have 
decayed. For the two simple propagation models considered above, the positron 
to ³He fluence ratio will range from ∼10⁻² to ∼0.2. Notice that this more 
realistic estimate of the positron and ³He fluences, while not inconsistent with 
our observations, is well within the range of our measurement capabilities.
We conclude that further comparison of observation and theory may prove fruit-
ful for understanding high energy nuclear reaction processes which are associated 
with solar flares.

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6. References.


