Relative Abundances of Energetic Hydrogen Isotopes Produced in Solar Flares*

C. J. WADDINGTON AND P. S. FREIER
School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota
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The relative abundances of protons, deuterons, and tritons have been studied in photographic nuclear emulsions flown during the 18 July 1961 solar-flare event. These emulsions were exposed at a time and locality where there was a geomagnetic threshold. The effects of this threshold on the different particles have been calculated on the basis of theoretical assumptions, and the resulting enrichment of the abundance ratios has been used to assist in reducing the abundance limits to lower values than those previously quoted. By including the results of previous α-particle measurements in these emulsions, it has been found that the relative abundances of solar-produced H^1, H^2, H^3, and He above a given *rigidity* at this time were $1:\leq 1.4\times10^{-2}:\leq 2.8\times10^{-2}:0.17$, and above an energy of 50 MeV per nucleon, i.e., above a given velocity, were $1:\leq 2\times10^{-3}:\leq 6\times10^{-4}:2.4\times10^{-2}$. The consequences of these observations are briefly discussed.

INTRODUCTION

It has been known for many years that some solar flares are associated with transient increases in the intensity of the energetic particles falling on the earth. These "solar-flare events" were originally observed with cosmic-ray detectors located on the earth's surface but have, in the past few years, been extensively studied with detectors carried to great altitudes. From such observations considerable information has been obtained regarding the mass composition of the energetic particles produced by the sun, although as yet the data are still in an inchoate state. A detailed knowledge of this mass composition would be of great theoretical interest because of its relevance to the dual problems of the nature of the acceleration and propagation mechanisms that control these particles. In addition, it is possible that additional information regarding the general solar composition may be deduced from these observations.

The experiment reported here represents an attempt to measure the relative abundances of the hydrogen isotopes among the energetic particles produced in one particular solar-flare event, whose characteristics and properties had previously been quite thoroughly investigated. A photographic nuclear-emulsion detector flown over Minneapolis on a high-altitude balloon was used in this experiment.

THEORY OF PROCEDURE

Previous observations[1,2,3] in nuclear emulsions of low-energy ($\approx$20–200-MeV) solar protons had indicated that the abundances of deuterons or tritons were not high. Indeed, it seemed reasonable to expect that the number ratio of deuterons to protons above a given velocity, $\Gamma_{dp}(>v)$, or equivalently, above a given energy per nucleon, $\Gamma_{dp}(>E)$, was certainly less than 5×10^{-2}, while the similar ratios for tritons were still lower. Thus, to measure either $\Gamma_{dp}(>E)$ or $\Gamma_{tp}(>E)$ it is clearly necessary either to examine a very large number of particles with high-mass resolution, or to consider detectors exposed under conditions where the ratios are enhanced. If there is no enhancement, the measurement of these small ratios is beyond the presently available mass resolution of counter detectors and could only be achieved in nuclear emulsions by extremely laborious experimental techniques. However, conditions of considerable ratio enhancement may exist when the detectors are exposed in a geomagnetic field. Since deuterons and tritons have mass-to-charge ratios different from protons, they are differently affected by the presence of a geomagnetic threshold, and will be admitted to a given geographic locality with lower velocity than are the protons. Consequently, by suitable selection of the locality and thus of the geomagnetic threshold, it should, in principle, be possible to observe in a certain velocity interval a pure sample of deuterons or tritons uncontaminated by protons. In practice, geomagnetic thresholds are not sharp experimentally but tend to fall off in an exponential manner,[4] so that the differential intensity dJ at some magnetic rigidity R that is less than the nominal threshold R_c is given by

$$dJ=dJ_0\exp[-\beta(R_c-R)], \qquad (1)$$

where dJ_0 is the differential intensity in the absence of a geomagnetic field.

To calculate the abundance ratios, it is necessary to consider the velocity distribution of the solar-flare particles. It has been shown[5] that in general this distribution is best represented as a rigidity spectrum with an exponential form $J=J_0\exp(-R/R_0)$, where J_0 and R_0 are constants. Furthermore, while J_0 is a function of the mass number A, R_0 apparently is generally not, at least for protons, α particles and heavier nuclei. Consequently, R_0 is presumably the same for deuterons and tritons as for protons. This assumption is basic to the analysis that follows and depends on the independ-

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[1] S. Biswas, C. E. Fichtel, and D. E. Guss, Phys. Rev. **128**, 2756 (1962).
[2] P. S. Freier (unpublished).
[3] S. Biswas and C. E. Fichtel, Astrophys. J. **139**, 941 (1964).
[4] J. A. Earl, J. Geophys. Res. **66**, 3095 (1961).
[5] P. S. Freier and W. R. Webber, J. Geophys. Res. **68**, 1605–1629 (1963).

ence of R_0 with the mass number. Experimentally R_0 has been measured separately for at least two different charge components on some 20 distinct occasions[3,5,6] and only twice[3] has it been found to differ significantly between the components. With this assumption, at any given rigidity, the differential intensity of protons, $(dJ/dR)_p$, is given by

$$(dJ/dR)_p = -\phi(J_{p0}/R_0)\exp(-R/R_0), \qquad (2)$$

where J_{p0} is the value of J_0 appropriate for protons, and ϕ is the fractional reduction produced by the geomagnetic field; from Eq. (1), ϕ is unity when $R>R_c$, but $\exp[-\beta(R_c-R)]$ when $R<R_c$. Similar expressions, with J_{p0} replaced by J_{d0} and J_{t0} would give the differential intensities of deuterons, $(dJ/dR)_d$, and tritons, $(dJ/dR)_t$.

In an experiment where the particles are detected in a balloon-borne particle detector, the individual particles will be observed with rigidities, which when extrapolated to the top of the atmosphere, will range from the air cutoff value to some maximum value dependent on the technique of identification used. If these lower and upper rigidity limits for protons are represented by $R_a(p)$ and $R_m(p)$, then the total proton intensity observed, ΔJp is given by

$$\Delta Jp = \int_{R_a(p)}^{R_c} \phi dJ_p + \int_{R_c}^{R_m(p)} dJ_p \qquad (3)$$

if $R_a(p)<R_c<R_m(p)$.

Similar expressions, in terms of $R_a(d)$ and $R_m(d)$; $R_a(t)$ and $R_m(t)$, would be obtained for the total intensities of deuterons and tritons. From these equations, the observed ratio of deuterons to protons, $\Gamma_{dp}(\text{obs}) = \Delta J_d/\Delta J_p$, is found to be related to the ratio above a given rigidity, $\Gamma_{dp}(>R)$ $(=J_{d0}/J_{p0})$ by

$$\Gamma_{dp}(\text{obs}) = \Gamma_{dp}(>R) \times \frac{e^{-\beta R_c}(e^{\eta R_c}-e^{\eta R_a(d)})\eta^{-1}+R_0(e^{-R_c/R_0}-e^{-R_m(d)/R_0})}{e^{-\beta R_c}(e^{\eta R_c}-e^{\eta R_a(p)})\eta^{-1}+R_0(e^{-R_c/R_0}-e^{-R_m(p)/R_0})}, \qquad (4)$$

where $\eta=\beta-(1/R_0)$. The observed ratio of tritons to protons, $\Gamma_{tp}(\text{obs.})$ is related to the ratio above a given rigidity, $\Gamma_{tp}(>R)$, by a similar expression but with $R_a(d)$ and $R_m(d)$ replaced by $R_a(t)$ and $R_m(t)$. Obviously Eq. (4) or the similar equation for $\Gamma_{tp}(\text{obs.})$ will simplify if any of $R_m(p)$, $R_m(d)$, $R_m(t)$ are less than R_c.

These values of $\Gamma_{dp}(\text{obs.})$ and $\Gamma_{tp}(\text{obs.})$ may be compared with those that would have been obtained in the absence of a geomagnetic threshold, where

$$\Gamma_{dp}(\text{obs}) \text{ without threshold} = \Gamma_{dp}(>R)\frac{e^{-R_m(d)/R_0}-e^{-R_a(d)/R_0}}{e^{-R_m(p)/R_0}-e^{-R_a(p)/R_0}}. \qquad (5)$$

Thus, a measure of the effectiveness of the threshold is

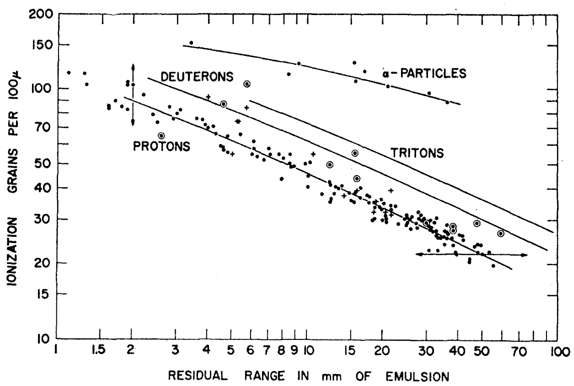

FIG. 1. Experimental distribution of grain density per 100 μ against the residual range in the emulsions. Selection limits are shown by arrows. Points measured more than once are represented by ⊙, while the results of remeasurement appear as crosses.

provided by considering the ratio Φ given by

$$\Phi_d = \Gamma_{dp}(\text{obs.}) \text{ with threshold}/\Gamma_{dp}(\text{obs.}) \text{ without threshold}, \qquad (6)$$

together with a similar expression for tritons.

The value of $\Gamma_{dp}(>R)$ is related to the ratio above a given energy per nucleon, $\Gamma_{dp}(>E)$ by the equation

$$\Gamma_{dp}(>E) = \Gamma_{dp}(>R)\exp\left[-\frac{\pi}{R_0}\left(\frac{A_d}{Z_d}-\frac{A_p}{Z_p}\right)\right], \qquad (7)$$

where

$$\pi = \{E_a(d)[E_a(d)+2m_0c^2]\}^{1/2}$$

and A_d and Z_d are the mass and charge numbers of a deuteron. A similar equation holds for $\Gamma_{tp}(>E)$ with $E_a(d)$ replaced by $E_a(t)$ and A_d and Z_d replaced by A_t and Z_t.

EXPERIMENTAL PROCEDURE

In order to apply these considerations to a particular case, the stack of emulsions selected for study was one exposed over Minneapolis to solar-flare radiation on 18 July 1961. This stack was flown under a mean residual atmosphere of 6 g/cm² from 1535-1750 UT. The protons and α particles produced by the flare and recorded in the emulsions were previously investigated by Freier.[6] From these measurements, it can be deduced that $\beta=7.3$, $R_c=0.80$ BV and $R_0=0.16$ BV. It may be noted that over the range of rigidities of interest in this experiment, the intensities of the solar-flare particles are at least two orders of magnitude greater than those of the quiet time cosmic radiation,[7] whose influence can consequently be largely neglected. The emulsions were scanned along a line 1 cm below the top edge for the tracks of particles with zenith angles less than 26°, and

[6] P. S. Freier, J. Geophys. Res. **68**, 1805–1810 (1963).
[7] P. S. Freier and C. J. Waddington, Phys. Rev. Letters **13**, 108 (1964).

azimuth angles less than 4.5°. These tracks were required to have a residual range of at least 2 mm at the scan line. These conditions lead to values for $R_a(p)$, $R_a(d)$ and $R_a(t)$ of 0.45, 0.63, and 0.97 BV, respectively, with corresponding values for $E_a(p)$, $E_a(d)$ and $E_a(t)$ of 102, 69, and 54 MeV per nucleon. The tracks were also required to have a grain density greater than 20 grains per 100 μ although the selection was eventually imposed that only tracks with greater than 22 grains per 100 μ should be accepted. In these emulsions, a proton producing the latter gain density had a residual range of 5 cm. The resulting values for $E_m(p)$, $E_m(d)$, and $E_m(t)$ were 174, 154, and 147 MeV per nucleon, respectively. Thus, $R_m(p)$, $R_m(d)$ and $R_m(t)$ were 0.60, 1.12, and 1.65 BV.

Every particle was examined by measuring the ionization, i.e., the grain density, at the scan line and by following through the emulsion until the particle came to rest, made or came from a nuclear interaction, left the stack, or was conclusively shown to be moving upwards. These latter particles, together with those coming from interactions below or above the scan line and those making interactions above the scan line were rejected as being of secondary origin. Of the remaining 162 tracks, 16 were readily identified as having been produced by α particles, leaving 146 particles of charge one. Of these, 130 were brought to rest in the emulsions and the mass determined from a comparison of the residual range and the grain density. Figure 1 shows the experimental distribution of these two parameters, together with an estimated proton curve and the derived deuteron and triton curves. Figure 2 gives the resulting mass histogram, which shows a clear mass resolution. There are four deuterons and one triton in this sample. The remaining 16 particles either interacted or left the stack before coming to rest. They were identified from measurements of the multiple coulomb scattering and of the change in ionization as being 15 protons and one deuteron. Thus $\Gamma_{dp}(\text{obs.})=3.6\times10^{-2}$ and $\Gamma_{tp}(\text{obs.})=7.1\times10^{-3}$, where in each case these ratios are just those of the numbers of observed particles.

From Eq. (4) and the equivalent equation for the triton ratio, under the conditions of this experiment:

$$\Gamma_{dp}(\text{obs.})=2.58\Gamma_{dp}(>R)$$

and

$$\Gamma_{tp}(\text{obs.})=0.252\Gamma_{tp}(>R).$$

Also Φ_d and Φ_t are 5.1 and 4.0, respectively, so that it can be seen that this experiment corresponds to the observation of between 700 and 550 protons. The resulting values of $\Gamma_{dp}(>R)$ and $\Gamma_{tp}(>R)$ are 1.4×10^{-2} and 2.8×10^{-2}, respectively.

From Eq. (7), $\Gamma_{dp}(>E)=0.101\Gamma_{dp}(>R)$ above 69 MeV per nucleon, and $\Gamma_{tp}(>E)=1.78\times10^{-2}\Gamma_{tp}(>R)$ above 54 MeV per nucleon, so that $\Gamma_{dp}(>E)$ and $\Gamma_{tp}(>E)$ are 1.4×10^{-3} and 5×10^{-4}, respectively.

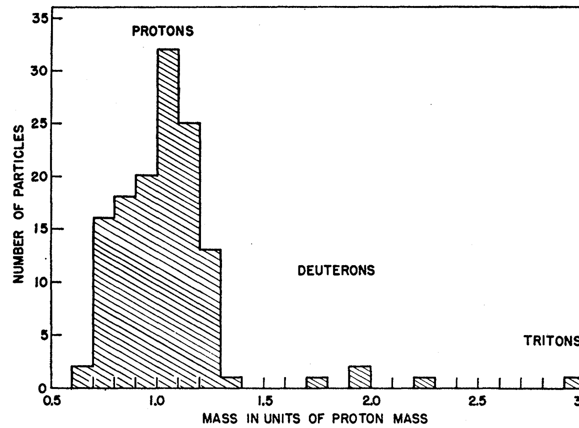

FIG. 2. Mass histogram derived from the data shown in Fig. 1. The somewhat asymmetric shape of the proton peak is at least in part due to the remeasurement of particles which could have been deuterons.

These values for the abundances ratios must all be upper limits to the true values since no corrections have been made for the production of secondary deuterons or tritons in the overlying atmosphere. The presence of these secondary particles sets a limit on the values of the ratios that can be determined in this manner since it is impossible to calculate the intensity of these particles with much precision.

Secondary deuterons can be produced in nuclear interactions in at least three different modes. Firstly, as a result of semielastic collisions with quasideuterons in the nucleus (the knock-on process) deuterons will be produced with an energy roughly equal to that of the incident proton.[8,9] Secondly, the high-energy tail of the nuclear evaporation process (the pickup process) produces deuterons with a range of energies appreciably less than that of the incident proton. Thirdly, deuterons will be produced by α-particle-initiated interactions, principally as fragments of the incident α particle. The evaluation of the relative contributions due to these effects depends on parameters, such as fragmentation rates and production rates, which are not well known. However, using the best available values, and assuming that the production is entirely due to the solar-flare radiation, i.e., neglecting the effect of the numerically minor primary cosmic-radiation intensity, a value for $\Gamma_{dp}(>R)$ of 1.5×10^{-2} might be expected due to secondary deuterons. It is apparent, therefore, that the results of this experiment are consistent with there being no deuterons in the solar-flare radiation, and that the value quoted above for $\Gamma_{dp}(>E)=1.4\times10^{-3}$ represents an extreme upper limit.

For tritons the calculation of the expected secondary contribution is still more uncertain, as essentially nothing

[8] V. T. Cocconi, T. Fazzini, G. Fidecaro, M. Legros, N. H. Lipman, and A. W. Merrison, Phys. Rev. Letters 5, 19 (1960).

[9] S. T. Butler and C. A. Pearson, Phys. Rev. Letters 7, 69 (1961).

is known about the necessary parameters. However, clearly one particle can always be secondary in origin and the value of $\Gamma_{tp}(>E)$ quoted previously should also be regarded as being most probably only an upper limit to the true value.

DISCUSSION

Present knowledge of the composition of particle radiation from solar flares is somewhat sparse. The most recent summary is that of Biswas.[10] Essentially there are at present three observations on the composition which appear to be related to the problems of the production and propagation of these particles. The first of these is the virtual absence of beryllium and boron nuclei (L nuclei) as compared with heavier nuclei, reported[3] from a study of nuclear emulsions exposed on sounding rockets during the solar events of 12 and 15 November 1960. In these experiments, less than 0.2 L nuclei were observed for every 20 heavier nuclei having energies greater than about 43 MeV per nucleon. This result suggests that these heavier nuclei cannot have passed through more than 0.15 g/cm^2 (10^{23} atoms/cm^2) of hydrogen from the time their energy exceeded a few MeV per nucleon to the time they were detected. This estimate may be compared with that independently made by Biswas.[10] from this datum, that the path length cannot exceed $0.1-0.2$ g/cm^2.

The second relevant observation is that of Tilles *et al.*[11,12] who found an appreciable abundance of tritium in the surface layers of the recoverable satellite Discoverer XVII after it had been exposed to the radiation of the flare on 12 November 1960. These authors state that the quantity of tritium observed was greatly in excess of that which could have been produced by local nuclear interactions. This conclusion has been disputed, e.g., Lal,[13] and it is possible that the value of $\Gamma_{tp}(>E)$ quoted by these authors of 4×10^{-3} represents an upper limit to the true value above 30 MeV per nucleon. That this might be the case is, at first sight, suggested by the fact that the value of $\Gamma_{tp}(>E)$ $\leq5\times10^{-4}$ obtained in the present experiment is not consistent with that quoted above, even if the differing energy limits are taken into account. Using Eq. (7), it is apparent that, provided it can be assumed that R_0 was approximately the same in the two flares, which is not unreasonable, a value of $\Gamma_{tp}(>E=30$ MeV/nucleon $=4\times10^{-3}$ implies $\Gamma_{tp}(>R)\simeq8\times10^{-2}$ instead of the $\leq2.8\times10^{-2}$ observed. However, if three tritons had been observed instead of one, and if these tritons were primary rather than secondary, then there would be no conflict. In addition, and possibly of more fundamental significance, it should be noted that a comparison is being made here between two entirely different flares, and it is known that composition differences exist from flare to flare. For example, observed values of $\Gamma_{\alpha p}(>R)$ vary from 1.0 to at least 0.03 in different flares, and it is conceivable that a similar, if not proportional, variation occurs in $\Gamma_{tp}(>R)$. In the November flare[3,14] $\Gamma_{\alpha p}(>R)$ was measured as being about 1.0 while in the July flare[6] it was 0.17. Since, from a rigidity viewpoint, a deuteron is indistinguishable from an α particle, it *might* be expected that a similar trend would be observed in $\Gamma_{dp}(>R)$ and presumably, since tritons are even less affected by magnetic fields than α particles, in $\Gamma_{tp}(>R)$. Such an effect would be in the right direction to explain the apparent discrepancy between the results of this experiment and those from the Discoverer satellite.

The third and final observation relevant to this discussion is that of Schaeffer and Zahringer.[15] These authors observed, also in material from the Discoverer XVII satellite, a relatively enormous amount of He^3 nuclei. The interpretation of this observation is uncertain, due to the difficulty of making the necessary corrections for secondary production, but the authors state that they observe a He^3/He^4 ratio, $\Gamma_{He^3\,He^4}(>E)$, of 0.2 and that this value probably represents the incident radiation to within a factor of 3. However, Biswas[10] presents arguments to suggest that the true value of this ratio is more probably less than 10^{-2}.

The equilibrium abundances of tritium and He^3 nuclei in the solar atmosphere are unknown, but must be much less than those observed in these experiments. It is therefore necessary to invoke some production mechanism to explain their presence. At first sight, the most reasonable explanation is to assume that they are fragments of energetic α particles and heavier nuclei produced in nuclear interactions occurring during their passage through solar and interstellar matter after acceleration has commenced. The influence of the heavy nuclei can be essentially neglected since they have a relative abundance to the α particles of only some 2%. Thus, the production processes of interest must be those of α -particle fragmentation in a predominately hydrogen medium. The amount of matter that would have to be traversed to produce $\Gamma_{tp}(>E)$ of 4×10^{-3} had been estimated by Biswas[10] as being at least 1.3 g/cm^2 (8×10^{23} atoms/cm^2) and more probably five times greater. Similarly, Fireman[16] estimates a path length of approximately 10 g/cm^2 as being neces-

[10] S. Biswas, in *Proceedings of the 1963 IUPAP Cosmic Ray Conference, Jaipur, India* [Tata Institute of Fundamental Research, Bombay, India (to be published)].
[11] D. Tilles, J. De Felico, and E. L. Fireman, (to be published).
[12] E. L. Fireman, J. De Felico, and D. Tilles, Phys. Rev. **123**, 1935 (1961).
[13] D. Lal, in *Proceedings of the 1963 IUPAP Cosmic Ray Conference, Jaipur, India* [Tata Institute of Fundamental Research, Bombay, India (to be published)].
[14] E. P. Ney and W. A. Stein, J. Geophys. Res. **67**, 2087 (1962).
[15] O. A. Schaeffer and J. Zähringer, Phys. Rev. Letters **8**, 389 (1962).
[16] E. L. Fireman, in *Proceedings of the 1963 IUPAP Cosmic Ray Conference, Jaipur, India* [Tata Institute of Fundamental Research, Bombay, India (to be published)].

sary to explain the observed value of $\Gamma_{tp}(>E)$. These values are clearly inconsistent with that derived from the L nuclei and in addition would predict that $\Gamma_{dp}(>E)$ should be approximately 8×10^{-2} instead of the $\leq1.4\times10^{-3}$ actually observed. This difference is far too great to be due to the mechanism which causes $\Gamma_{\alpha p}(>R)$ to vary by a factor of 6 between the two flares. However, if the path length is really less than 0.15 g/cm^2, as suggested by the absence of L nuclei, then $\Gamma_{dp}(>E)$ would be less than 6×10^{-3}, which is not inconsistent with the observed limit when the difference between the flares is taken into account. Clearly, therefore, a fragmentation process is inadequate to explain the reported abundance ratios.

It has been suggested instead that the H^3 and He^3-nuclei observed are the consequence of quasithermonuclear reactions occurring in the solar atmosphere near the flare region.[16] Reactions of the sort suggested would apparently also result in a deuteron abundance comparable with or exceeding the tritium abundance, although the cross sections are not well known. Deuterium would be produced by the reaction $H^1(\alpha,d)$-He^3 with a cross section at 30 MeV of $\simeq$25 mb and destroyed by the secondary reaction $H^1(d,pn)H^1$ with $\sigma\simeq250$ mb. Tritium would be produced in $H^1(\alpha,tp)H^1$ with $\sigma\simeq10$ mb and destroyed by $H^1(t,n)He^3$ with $\sigma\simeq250$ mb. Taken at face value, these reactions would suggest $\Gamma_{dp}(>E=30$ MeV per nucleon$)\simeq10^{-2}$ when $\Gamma_{tp}(>E=30$ MeV per nucleon$)=4\times10^{-3}$. Consequently $\Gamma_{dp}(>E=69$ MeV per nucleon) should be about 5×10^{-3}, which, while higher than the observed limit for $\Gamma_{dp}(>E)$ of 1.4×10^{-3}, is not unduly so when account is taken of the observed differences in $\Gamma_{\alpha p}(>R)$ between the two flares. It is not at all clear how such nuclear reactions are produced, since the production reactions are strongly endothermic, having thresholds of 20 MeV, and this would imply local temperatures of $>10^{11}$ degrees for them to be thermonuclear in origin. Conceivably these reactions could occur in a region of the flare where the initial density is sufficient to prevent α particles and heavier nuclei from being accelerated due to the ionization losses exceeding the energy gain, but where protons can be accelerated and make nuclear interactions. If the density of this region is later reduced, additional acceleration of all the nuclear species present at that time would then become possible and the observed results could be explained.

CONCLUSIONS

(I) The relative abundances of H^1, H^2, H^3, and He above a given rigidity observed at the earth during the flare of 18 July 1961 are $1:\leq1.4\times10^{-2}:\leq2.8\times10^{-2}$: 0.17 and above an energy of 50 MeV per nucleon are $1:\leq2\times10^{-3}:\leq6\times10^{-4}:2.4\times10^{-2}$.

(II) The observed upper limit to the value of $\Gamma_{dp}(>E)$ is far too small to be consistent with the tritium and He^3 nuclei abundances observed in other experiments if these nuclei are produced by fragmentation processes. This conclusion agrees with that deduced from the observations on the mass spectrum of multiply charged nuclei.

(III) The upper limit to the value of $\Gamma_{tp}(>E)$ observed in this experiment is not inconsistent with that observed previously, when the differing energy thresholds and the differing nature of the flares is taken into account.

(IV) $\Gamma_{dp}(>E)\leq1.4\times10^{-3}$ is consistent with Fireman's assumption of thermonuclear processes in the acceleration region of the flare, provided account is taken of the apparent difference between these flares. However, the physical processes involved in the production of these particles are not clearly understood. It might be noted that it would be unnecessary to invoke these nuclear reactions if the true ratios were appreciable less than the upper limits obtained here.

FUTURE EXPERIMENT

Improved and finite values of both Γ_{dp} and Γ_{tp} are needed in order to obtain a better understanding of the complex processes in solar flares. Detectors with high-mass discrimination should be exposed to solar-flare radiation above the atmosphere, thus greatly reducing the secondary contamination, at localities where the geomagnetic field provides a threshold. In such an experiment, the effective threshold and the shape of the flare particle spectrum could and should be measured by the same detector, or at least at the same time. The other abundance ratios, such as $\Gamma_{\alpha p}$ and Γ_{LM} should also be measured in the same events.

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