\textbf{\textsuperscript{6}Li FROM SOLAR FLARES}

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Received 2000 February 11; accepted 2000 March 22; published 2000 May 4

**ABSTRACT**

By introducing a hitherto ignored \textsuperscript{6}Li producing process, due to accelerated \textsuperscript{3}He reactions with \textsuperscript{4}He, we show that accelerated particle interactions in solar flares produce much more \textsuperscript{6}Li than \textsuperscript{7}Li. By normalizing our calculations to gamma-ray data, we demonstrate that the \textsuperscript{6}Li produced in solar flares, combined with photospheric \textsuperscript{7}Li, can account for the recently determined solar wind lithium isotopic ratio, obtained from measurements in lunar soil, provided that the bulk of the flare-produced lithium is evacuated by the solar wind. Further research in this area could provide unique information on a variety of problems, including solar atmospheric transport and mixing, solar convection and the lithium depletion issue, and solar wind and solar particle acceleration.

**Subject headings: nuclear reactions, nucleosynthesis, abundances — solar wind — Sun: abundances — Sun: flares**

1. INTRODUCTION

The solar wind lithium isotopic ratio, (\textsuperscript{6}Li/\textsuperscript{7}Li)\textsubscript{sw} = 0.032 \pm 0.004, has recently been determined from measurements in lunar soil (Chaussidon & Robert 1999). As these authors point out, this value greatly exceeds the expected photospheric ratio, based on the fact that \textsuperscript{7}Li in the photosphere is depleted by over a factor of 100 relative to its protosolar value (i.e., the photospheric vs. the meteoritic abundance; Grevesse, Noels, & Sauval 1996) and that this depletion, because of burning at the bottom of the convection zone (Brun, Turck-Chieze, & Zahn 1999), should lead to a much more severe depletion of \textsuperscript{6}Li, which burns at a lower temperature than \textsuperscript{7}Li. In addition, there exist observational upper limits on the photospheric ratio: (\textsuperscript{6}Li/\textsuperscript{7}Li)\textsubscript{ph} \leq 0.01 (Müller, Peytre, & de la Reza 1975) and (\textsuperscript{6}Li/\textsuperscript{7}Li)\textsubscript{ph} \leq 0.03 (Ritzenhoff, Schröter, & Schmidt 1997). Chaussidon & Robert (1999) thus suggest that the measured solar wind \textsuperscript{6}Li must be produced by solar flares. However, they only consider \textsuperscript{7}Li production by spallation from C, N, and O. The demonstration that solar flares can indeed account for the \textsuperscript{6}Li in the solar wind has very important implications on many problems in solar physics.

Light-element production by accelerated particle interactions was treated in detail (e.g., Ramaty et al. 1997). In nonsolar settings and for accelerated particles of predominantly low energy, the dominant reactions are \textsuperscript{4}He(\textsuperscript{4}He, p)\textsuperscript{2}Li, \textsuperscript{4}He(\textsuperscript{4}He, n)\textsuperscript{7}Be (with \textsuperscript{7}Be decaying to \textsuperscript{7}Li), and \textsuperscript{4}He(\textsuperscript{4}He, x)\textsuperscript{x}Li (where x stands for either a proton and a neutron, or a deuteron). In solar flares, however, the reaction \textsuperscript{4}He(\textsuperscript{4}He, p)\textsuperscript{2}Li is also very important (Mandzhavidze, Ramaty, & Kozlovsky 1997a, b), both because of its very low threshold energy and because for solar energetic particles \textsuperscript{4}He/\textsuperscript{2}Li can be as large as 1 or even larger (e.g., Reames 1998). Such \textsuperscript{4}He/\textsuperscript{2}Li enhancements are one of the main characteristics of the acceleration mechanism responsible for impulsive solar energetic particle events, as distinguished from gradual events, based on the duration of the accompanying soft X-ray emission. The \textsuperscript{4}He enrichment is thought to be due to stochastic acceleration through gyroresonant wave particle interactions which preferentially accelerate the \textsuperscript{4}He (Temin & Roth 1992; Miller & Viñas 1993). Concerning the particles that interact at the Sun, evidence for accelerated \textsuperscript{4}He enrichment was obtained from the detection (Share & Murphy 1998) of a gamma-ray line at 0.937 MeV produced by the reaction \textsuperscript{5}O(\textsuperscript{4}He, p)\textsuperscript{18}F* (Mandzhavidze, Ramaty, & Kozlovsky 1997b, 1999). Using gamma-ray data from 20 flares, Mandzhavidze et al. (1999) showed that for essentially all of these flares \textsuperscript{4}He/\textsuperscript{2}Li can be as large as 0.1, while for some of them values as high as 1 are possible. In addition, they showed that for the particles that interact and produce gamma rays, \textsuperscript{4}He enrichments are present for both impulsive and gradual flares. Thus, we can expect \textsuperscript{4}He/\textsuperscript{2}Li \geq 0.1 for most flares that produce gamma rays and isotopes at the Sun.

In the present Letter, we carry out new calculations of \textsuperscript{Li} production and recalculate (see Ramaty & Simnett 1991) the average accelerated ion irradiation of the Sun to show that flare-accelerated particle interactions produce enough \textsuperscript{6}Li which, combined with photospheric \textsuperscript{7}Li, can account for the solar wind \textsuperscript{6}Li/\textsuperscript{7}Li measured in lunar soil.

2. \textsuperscript{6}Li PRODUCTION

We employ the nuclear code described in detail in Ramaty et al. (1997) which includes, in addition to the \alpha\alpha reactions mentioned above, \textsuperscript{Li} production from C, N, and O. The cross section for the additional reaction \textsuperscript{4}He(\textsuperscript{4}He, p)\textsuperscript{2}Li is shown in Figure 1, together with the cross sections for the \alpha\alpha reactions producing \textsuperscript{6}Li and \textsuperscript{7}Li. For the \textsuperscript{4}He-induced reaction we obtained the cross section for \textsuperscript{6}Li production in the ground state, from threshold (2.34 MeV nucleon\textsuperscript{—1}) to 8.2 MeV nucleon\textsuperscript{—1}, by detailed balance using the cross section for the inverse exo-
thermic reaction \(^{6}\text{Li}(p, \alpha)^{3}\text{He}\) (Angulo et al. 1999). We added the contribution of the reaction for producing \(^{6}\text{Li}\) in the 3.56 MeV excited state which decays to the ground state by photon emission, using data from Harrison (1967). The total cross section at 9.3 MeV nucleon\(^{-1}\) is from Koepke & Brown (1977), and at 18 and 20.4 MeV nucleon\(^{-1}\) from Halbert, van der Woude, & O’Fallon (1973). At higher energies we extrapolated the cross section as expected for reactions with two particles in the exit channel.

Gamma-ray production in solar flares results predominantly from thick-target interactions, meaning that particles accelerated in the upper portions of coronal loops produce nuclear reactions as they slow down in the denser chromospheric region of the loops (e.g., Ramaty & Murphy 1987). We adopt the same model for Li production. The top panel in Figure 2 shows the resultant thick-target \(^{6}\text{Li}\) yields, normalized to unit incident total number of protons of energy greater than 30 MeV, \(N_p(>30) = 1\). The energy spectra of the accelerated particles are power laws in kinetic energy per nucleon, with spectral index \(s\) (Ramaty, Mandzhavidze, & Kozlovsky 1996). The evidence for enhanced \(^3\text{He}/^{4}\text{He}\) was mentioned above. There is also evidence that \(\alpha/p\) could exceed the canonical 0.1, with possible value around 0.5 (Share & Murphy 1997; Mandzhavidze et al. 1999). Thus in Figure 2 we show results for \(\alpha/p = 0.1\) and 0.5, and \(^3\text{He}/^{4}\text{He} = 0, 0.1,\) and 1. We see in the top panel that the \(^3\text{He}\) enrichment very significantly increases the lithium production, especially for steep spectra. That the lithium production is mainly due to \(\alpha\) particles and \(^3\text{He}\) nuclei can be seen by comparing the six upper curves with the lowest one, for which we set the \(\alpha\) particle and \(^3\text{He}\) abundances to zero, so that all the \(^{6}\text{Li}\) in this case is produced in C, N, and O interactions. Considering the flare-produced isotopic ratios in the bottom panel, we see that while in the absence of \(^3\text{He}\) \(^{6}\text{Li}/^{7}\text{Li}\) is at most unity, much larger ratios are possible with enhanced \(^3\text{He}/^{4}\text{He}\).

### 3. AVERAGE SOLAR PROTON IRRADIATION

To calculate the average flare-produced lithium, we estimate the average proton irradiation of the Sun, \(N_p(>30\text{ MeV})\) measured in protons per second, where the average is taken over a solar cycle. We follow the method described by Ramaty & Simnett (1991). We start with the flare size distribution measured in 0.3–1 MeV bremsstrahlung because observations in this energy range give the most complete sample of solar flare gamma-ray emission (see Vestrand et al. 1999). To minimize the effects of anisotropic electrons (e.g., Miller & Ramaty 1989), we employ the distribution derived for flares near the solar limb (Dermer 1987). For flares at heliocentric longitudes \(60^\circ\)–\(90^\circ\), observed from 1980 March to 1986 February (approximately half a solar cycle), the size distribution, measured in number of flares per unit, can be approximated by

\[
dN/dF_p = 8.5 F_p^{-1.1}, \quad 10 < F_p < 6500 \text{ photons cm}^{-2} \text{ is the observed 0.3–1 MeV bremsstrahlung fluence at Earth per flare.}
\]

The total number of flares emitting photons of energies greater than 0.3 MeV per solar cycle is obtained by integrating the above expression multiplied by a factor of 12, where a factor of 6 takes into account the whole solar surface and a factor of 2 the other half of the solar cycle. We thus obtain 375 flares, which compares well with the 175 flares listed by Vestrand et al. (1999) from which bremsstrahlung of energy greater than 0.3 MeV was observed with the Solar Maximum Mission (SMM) over almost a whole solar cycle. This latter number should be corrected for anisotropy effects and must be multiplied by a factor of 2, since SMM only observes half the solar...
surface. The required average irradiation is then given by

$$\dot{N}_p(> 30) = \frac{12}{T} \int_0^{6500} dE_p \frac{dn_{p}}{dE_p} N_p(F_p),$$

(1)

where $T$ is the number of seconds in 11 yr and $N_p(F_p)$ is the number of protons above 30 MeV expressed as a function of $F_p$. To derive this relationship, we first employ the result of Murphy et al. (1990) that for flares near the limb $F_p/F_9 = 4.5$, where $F_9$ is the total nuclear deexcitation line-emission fluence observed at Earth. Next we use the nuclear deexcitation code (e.g., Ramaty et al. 1996) to derive $N_p(> 30)/F_9$. This ratio depends on the spectrum and composition of the accelerated particles, in particular $a/p$. Ramaty et al. (1996) have derived the distribution of power-law spectral indexes from gamma-ray data, showing that for a sample of 19 flares the mean $s = 4$. For this value of $s$ we find that $N_p(> 30)/F_9 = 1.7 \times 10^{10}$ and $6.6 \times 10^{10}$ protons (nuclear deexcitation photons cm$^{-2}$)$^{-1}$, for $a/p = 0.5$ and 0.1, respectively. By using $F_9/F_9 = 4.5$ and these $N_p(> 30)/F_9$ to derive $N_p(F_9)$, equation (1) yields $N_p(> 30$ MeV) $= 3.5 \times 10^{23}$ and $1.4 \times 10^{24}$ protons s$^{-1}$, for $a/p = 0.5$ and 0.1, respectively.

4. THE SOLAR WIND $^6$Li/$^7$Li

Even though a detailed treatment of the time-dependent evolution of Li in the solar atmosphere is beyond the scope of this Letter, we now show that $^6$Li production in solar flares could indeed account for the solar wind $^6$Li/$^7$Li. To demonstrate this we assume the following: (1) all the flare-produced $^6$Li is evacuated by the solar wind, (2) the photospheric $^6$Li that is the remnant of its protosolar abundance is negligible, and (3) the solar wind ($^6$Li/$^7$Li)$_w$ is equal to the photospheric value ($^6$Li/$^7$Li)$_ph$. Ramaty et al. (1997a) that production in flares does not make a significant contribution to the average photospheric lithium. If this were true, since the solar wind acceleration is not expected to significantly alter the lithium isotopic ratio, the solar wind $^6$Li/$^7$Li should exceed 0.2 (Fig. 2), contrary to the observed value of 0.03. This confirms the previous result of Mandzhavidze et al. (1997a) that production in flares does not make a significant contribution to the average photospheric lithium. But the fact that as many as $10^{30}$ Li atoms could be produced in large flares suggests that flare-produced lithium may be detected in a small area of the solar surface near the footpoints of the flaring loops shortly after the time of the flare (see Livshits 1997). In this connection, it is interesting to point out that Ritzenhoff et al. (1997) do not rule out the presence of $^6$Li near a sunspot at a value close to their reported upper limit $^6$Li/$^7$Li $\leq 0.03$, which in fact coincides with the measured solar wind value.

Further research in this area requires direct measurement of lithium and its isotopic ratio in the solar wind, spectroscopic measurements of $^6$Li in the photosphere, and the detection of gamma rays from small flares that would lead to a more precise determination of the proton irradiation of the Sun. All of these should lead to new insights into the processes of transport and mixing in the solar atmosphere and of the acceleration of the solar wind.

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