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The Role of Nuclei-Nuclei Interactions in the Production of Gamma-ray Lines in Solar Flares *

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Abstract Dramatic extensions of experimental possibilities (spacecraft RHESSI, CORONAS-F and others) in solar gamma-ray astronomy call for urgent, detailed theoretical consideration of a set of physical problems of solar activity and solar-terrestrial relationships that earlier may have only been outlined. Here we undertake a theoretical analysis of issues related to the production of gamma-radiation in the processes of interactions of energetic (accelerated) heavy and middle nuclei with the nuclei of the solar atmosphere (the so-called *i*-*j* interactions). We also make an estimate of the contribution of these interactions to the formation of nuclear and isotopic abundances of the solar atmosphere in the range of light and rare elements. The analysis is carried out for solar flares in the wide range of their intensities. We compare our theoretical estimates with RHESSI observations for the flare of 2002 July 23. It was shown that the ^{24}Mg gamma-ray emission in this event was produced by the newly generated Mg nuclei. With a high probability, the gamma-ray line emission of ^{28}Si nuclei from this flare was generated by the same processes.

Key words: acceleration of particles — nuclear reactions — Sun: flares — Sun: X-rays, gamma-rays

1 INTRODUCTION

There are many nuclear reactions between energetic particles accelerated in solar flares and the nuclei of elements that make up the solar atmosphere (Lingenfelter & Ramaty 1967; Kuzhevskij 1968; Ramaty et al. 1975; Ramaty et al. 1979; Kuzhevskij 1982; Kuzhevskij 1985; Gan et al. 2004). High-energy solar flare emissions (gamma-rays and neutrons) are produced when flare

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accelerated particles interact with ambient solar atmosphere. In particular, nuclear de-excitation lines result from bombardment of ambient carbon ^{12}C and heavier nuclei by the accelerated protons (p) and alpha-particles (α), and from the inverse reactions in which ambient hydrogen ^{1}H and helium ^{4}He are bombarded by accelerated carbon and heavier nuclei (e.g., Ibragimov & Kocharov 1977; Ramaty et al. 1979). As is well known, in solar energetic particles (SEP) the middle and heavy nuclei are not so abundant as the protons and α-particles. Moreover, the abundances of middle and heavy elements in the solar atmosphere are also less than that of hydrogen and helium.

Earlier, interactions between accelerated and ambient heavy nuclei, because of their low relative abundances, were not considered particularly important (Ramaty et al. 1979). Furthermore, since H and He have no bound excited states, p-p and p-He interactions could also be ignored (e.g., Ramaty & Mandzhavidze 1994). However, interactions of α-particles with ambient He (hereafter α-α interactions) produce two strong lines, at 0.478 MeV from ^{7}Li and at 0.429 MeV from ^{7}Be. As the shape of the spectral feature resulting from the superposition of these α-α lines is strongly dependent on the angular distribution of the interacting α-particles, measurements with good spectral resolution in the energy range from 0.4 to 0.5 MeV could turn out to be particularly useful in the study of the anisotropy of the interacting particles.

The gamma-ray lines from ^{7}Be and ^{7}Li produced when flare-accelerated α particles interact with ambient He (in particular, the $\sim$0.45 MeV line, see Ramaty & Mandzhavidze 1998) have been found to be surprisingly intense from measurements made by gamma-ray spectrometers on the SMM and COMPTON satellites (Share & Murphy 1997; Murphy et al. 1997; Share & Murphy 1998; Ramaty & Mandzhavidze 1998). These high intensities suggest that either an accelerated α/p ratio greater than 0.5 and/or a He/H abundance greater than 0.1 in the sub-coronal regions where the particles interact (Share & Murphy 1998). It should be noted that Mandzhavidze et al. (1997) outlined how to distinguish between the two possibilities by resolving and comparing the intensities of additional lines at 0.339, 1.00, 1.05, and 1.19 MeV produced by α-particles interacting with Fe with the intensity of the 0.847 MeV line produced by protons interacting with Fe. They also noted that the ^{16}O(^{3}He, p)^{18}F reaction produces lines at 0.937, 1.040, and 1.080 MeV. These lines complicate the analysis but offer the possibility of making an in-situ measurement of accelerated ^{3}He in flares. Preliminary analysis of Share & Murphy (1998) suggested, in particular, that the accelerated ^{3}He/^{4}He ratio is significantly less than unity in most flares observed by SMM (see Vestrand et al. 1999).

The situation is much more complicated and less studied if we attempt to estimate the role of interactions between energetic middle and heavy nuclei and nuclei of elements making up the solar atmosphere. Note, however, that the cross-sections of middle and heavy nuclei-nuclei interactions (i-j interactions), as a rule, are bigger than that of interactions between energetic protons (or α particles) and nuclei of elements making up the solar atmosphere. Besides, the threshold for an i-j interaction is less than that for interactions between protons or α particles and other elements. Therefore, i-j interactions may be of great importance for solar gamma-ray astronomy itself and for such phenomena as (1) formation of the composition of light elements (Li, Be, and B) in the solar atmosphere (and hence, in the solar wind); and (2) production of the radioactive nuclei in the solar atmosphere that stimulates gamma-ray emission from the quiet Sun.

To illustrate the importance of i-j interactions we consider below several characteristic examples. Section 2 contains, first of all, a theoretical consideration of the i-j interactions in the solar atmosphere. Next, in Sect. 3 we apply the results of our theoretical estimation to the analysis of the gamma-ray data for the RHESSI flare of 2002 July 23. Then, separately in Sect. 4, we estimate the contribution of i-j interactions to the nuclear and isotopic abundances of light and rare elements of the solar atmosphere. Finally, we give a brief summary (Sect. 5). In the context of our results, some prospects of the future gamma-ray observations of solar flares are also discussed.

2 THEORETICAL RESULTS

The full flux of gamma quanta of a given energy from an emitting volume V at the distance r can be calculated by the following formula (e.g., Kuzhevskij 1982, 1985):

$$F_\gamma = \frac{V}{4\pi r^2}[n_k \int_{E_1'}^{E_2'} F_p(E)\sigma_{pk}^{\gamma}(E)dE + \sum_{i,j} n_j \int_{E_1}^{E_2} F_i(E)\sigma_{ij}^{\mathrm{k},\gamma}(E)dE], \tag{1}$$

where n_j is the concentration of nuclei j in the emitting region during the interaction of energetic (accelerated) solar particles with the solar atmosphere, $F_p(E)$ the differential energy spectrum of protons accelerated in the solar flare, σ_{pk}^{γ} the cross-section for generation of excited nuclei k by energetic proton (p-k interactions), n_k the concentration of nuclei k in the same region of interaction, $F_i(E)$ the differential energy spectrum of nuclei i accelerated in the flare, $\sigma_{ij}^{k,\gamma}$ the cross-section for generation of excited nuclei k from interaction of energetic nuclei i with nuclei j of the solar atmosphere (i-j interactions). The first and second terms in the parenthesis describe respectively the contributions of the accelerated protons and energetic i nuclei to the production of the total gamma ray flux F_γ.

The ratio of gamma quantum fluxes produced by p-k and i-j interactions, G, occurring in Eq. (1),

$$G = \frac{\sum_{i,j} n_j \int_{E_1}^{E_2} F_i(E)\sigma_{i,j}^{k,\gamma}(E)dE}{n_k \int_{E_1'}^{E_2'} F_p(E)\sigma_{p,k}^{\gamma}(E)dE} \tag{2}$$

is expected to be strongly dependent on the spectral forms of accelerated protons $F_p(E)$ and accelerated i nuclei $F_i(E)$. The energy spectrum of solar energetic particles (or solar cosmic rays, SCR) in the source typically has a power-law form $F(E) = F_0 E^{-s}$ with a spectral index s in the range of 2 to 6 (e.g., Miroshnichenko et al. 1999; Miroshnichenko 2001; Gan & Wang 2002). As was shown in the early estimates by Kuzhevskij (1985), the value of G is to be $\geq$1 at $s \geq$3. To demonstrate it in more detail, we consider, as an example, two reactions:

$$^{12}\mathrm{C} + ^{16}\mathrm{O} \longrightarrow ^{24}\mathrm{Mg} + \gamma, \qquad E_\gamma = 1.37\,\mathrm{MeV}; \tag{3}$$

$$^{24}\mathrm{Mg} + p \longrightarrow ^{24}\mathrm{Mg} + p + \gamma, \qquad E_\gamma = 1.37\,\mathrm{MeV}. \tag{4}$$

Relative abundances of these two elements in the solar atmosphere are known in two versions:

$$\frac{n_\mathrm{O}}{n_\mathrm{Mg}} = 36.4, \qquad \frac{n_\mathrm{C}}{n_\mathrm{Mg}} = 20.8; \tag{5}$$

$$\frac{n_\mathrm{O}}{n_\mathrm{Mg}} = 22.2, \qquad \frac{n_\mathrm{C}}{n_\mathrm{Mg}} = 13.3. \tag{6}$$

The former, named variant 'a', is taken from Aller (1963) and the latter, named variant 'b', from Cameron (1973). In a solar flare, with the source spectra of accelerated protons $F_p(E)$ and C nuclei $F_\mathrm{C}(E)$, at the same energy per nucleon E, we obtain a ratio of the numbers of accelerated C nuclei to protons (Kuzhevskij 1985) as:

$$\frac{F_c(E)}{F_p(E)} \approx 0.001 \sim 0.005. \tag{7}$$

According to some estimates (Dyer et al. 1981; Kuzhevskij 1985), the cross-section for i-j interaction is from 250 to 300 mb in the energy range 0.73 to 7.2 MeV nucleon^{-1}, while the cross-section for p-k interaction is from 300 to 550 mb in the energy range 5 to 30 MeV. Therefore, the ratio of the corresponding cross-sections for i-j and p-k interactions is about

$$\frac{\sigma_{ij}^{k,\gamma}}{\sigma_{pk}^{\gamma}} \approx 0.5 \sim 0.7, \tag{8}$$

and the ratios of the corresponding fluxes in these energy intervals increase rapidly and approach ~1 for $s \geq 3$. If we take into consideration all of these findings, we obtain from (2) for the excited ^{24}Mg nuclei the G values given in Table 1. Here the $G_{\rm C}$ ratio takes into account only the interactions between accelerated ^{12}C nuclei and background ^{16}O nuclei, while the sum $G_{\rm C} + G_{\rm O}$ also includes the interactions between accelerated ^{16}O nuclei and background ^{12}C nuclei.

Table 1 Contribution of ^{12}C and ^{16}O into Gamma-ray Flux from Excited ^{24}Mg Nuclei

s	2	3	4	5	6	7
$G_{\rm C}$	0.016	0.20	1.70	15.4	25.90	154
$G_{\rm C} + G_{\rm O}$	0.035	0.4	3.4	30	50	300

If we try to treat the results of above calculations in terms of thin-target and thick-target interaction models (e.g., Ramaty et al. 1975), the conclusion is that in the case of thin-target model and with a continuous compensation of energy losses by the acceleration process, i-j interactions provide substantial contribution to the production of excited nuclei (Kuzhevskij 1985). In the case of thick-target model the role of i-j interactions is 10 to 35 times less because of ionization losses. Nevertheless, the i-j processes still remain important for $s \geq 4$. Meanwhile, it is necessary to take into account that we are looking at a rather small energy interval for i-j interactions.

3 APPLICATION TO THE FLARE OF 2002 JULY 23

The importance of i-j interactions can be clearly seen from the results of registration of gamma-rays from the RHESSI flare of 2002 July 23 (Smith et al. 2003). In this flare the de-excitation gamma-ray lines have been observed from the nuclei of ^{12}C (with quantum energy of E_γ=4.43 MeV), ^{20}Ne(1.63 MeV), ^{24}Mg(1.37 MeV), ^{28}Si(1.78 MeV), ^{16}O(6.13 MeV), and ^{56}Fe(0.847 MeV). This experiment, however, has demonstrated that the ratios between the fluences from different excited nuclei are not adequate to usual treatment, when one assumes that those fluences have been generated only during the process of interactions of energetic protons and α-particles with the corresponding elements in the solar atmosphere.

As an example, we note that the observed fluences of ^{12}C and ^{24}Mg nuclei turned out to be the same (about 28 photons cm^{-2}), i.e., their ratio is about 1.0 (maximum 1.9). In contrast to this, our calculations for the two versions of abundances of these elements in the solar atmosphere ('a' and 'b', see above) give some evidence that the ratios of fluxes of gamma-rays from ^{12}C and from other nuclei in this experiment should be as those given in Table 2, if we take into account only the processes of p-k and α-k interactions.

It follows from Table 2 that to explain the observed ratios we must assume that nuclei of ^{24}Mg and ^{28}Si have been effectively created in the solar active region during the flare due to

Table 2 Ratios of Gamma-ray Fluxes from ^{12}C to that from Other Nuclei

Ratio	Experiment	Calculations for p-k and α-k interactions
^{12}C/^{24}Mg	1.01, max 1.90	10.40 (variant 'a'); 4.40 (variant 'b')
^{12}C/^{20}Ne	1.34, max 2.47	2.65 (variant 'a'); 1.53 (variant 'b')
^{12}C/^{28}Si	1.67, max 3.31	31.0 (variant 'a'); 12.0 (variant 'b')
^{12}C/^{56}Fe	3.81, max 8.02	30.0 (variant 'a'); 2.60 (variant 'b')

i-j interactions (for example, the interactions between the nuclei ^{12}C and ^{16}O and between ^{16}O and ^{16}O). This explanation is supported by the recent work of Gan (2004) who obtained that the power-law index of energetic protons for this flare is about 3.52. As for the nucleus of ^{20}Ne, one can see that the contribution of interaction of nuclei C and O to its generation is small, because the initial concentration of this element in the solar atmosphere is comparatively high. The abundance of ^{20}Ne in the solar atmosphere is 5 to 7 times the abundance of Mg and Si (Aller 1963; Cameron 1973). As for ^{56}Fe, this nucleus cannot be created in the process of C-O and/or O-O interactions mentioned above.

In one of the recent reviews of standard solar composition, Grevesse & Sauval (1998) gave for C/Mg and O/Mg values that differ from the values used above by about 20% to 25% and are about 2 times the values given by Cameron (1973) and Aller (1963). Nevertheless, this does not change our main conclusion about important role of i-j interactions in the production of gamma-ray line emission from ^{24}Mg in the flare of 2002 July 23. The ratios of C/Si and O/Si in Grevesse & Sauval (1998) are even closer to the versions considered by us. Also, our conclusions concerning the contribution of i-j interactions to the creation of Ne and Fe nuclei become stronger with the new solar composition results of Grevesse & Sauval (1998).

4 PRODUCTION OF LIGHT AND RARE ELEMENTS

Reactions between energetic α particles from flares and one of the most abundant chemical elements in the solar atmosphere, the helium nuclei, lead to the creation of the new excited nuclei of stable ^{6}Li and ^{7}Li and radioactive ^{7}Be. The latter is a source of gamma-rays with quantum energies 431 keV and 478 keV. However, the i-j interactions, just the interactions between energetic nuclei of ^{12}C from the solar flare and the ^{16}O nuclei in the solar atmosphere, result in the creation of excited ^{23}Na nuclei which is a source of gamma rays of energy $E_\gamma =$ 439 keV.

On one hand, since modern experiments do not allow separation of these gamma-lines (Share et al. 2003), we should be able to estimate the contribution of the i-j interactions that are well known to contribute significantly to background gamma emission in the same energy interval. On the other hand, as we saw above, the i-j reactions seem to be an important source of gamma-rays.

Now we consider the nuclear reactions mentioned above. The cross-section for the generation of ^{23}Na nucleus in the nuclear reaction of energetic ^{12}C with ^{16}O is $\sigma_{ij}^{k} =$ (300 $\sim$500) mb at energy of interaction about 15 to 30 MeV or 1.25 to 2.5 MeV nucleon^{-1} (Cheng et al. 1979; Kolata et al. 1979; Hulke et al. 1980). Taking into account the reaction of interactions of energetic ^{16}O with ^{12}C nuclei, we obtain a full cross-section for the generation of the ^{23}Na nuclei of $\sigma_{\rm CO}^{\rm Na} + \sigma_{\rm OC}^{\rm Na} = (700 \sim 1000)$ mb at particle energies of 1 to 3 MeV nucleon^{-1}.

Nuclear reaction caused by the nuclear interactions of energetic α particles with He nuclei has energetic threshold around 40 MeV, and in the energy range of 40 to 80 MeV or 10 to 20 MeV nucleon^{-1} the cross-section for generation of ^{7}Li and ^{7}Be nuclei is $\sigma_{\alpha{\rm He}}^{\rm Li+Be}$=100 mb. Using the solar abundances (Aller 1963; Cameron 1973) and ratios of the fluences of C and O nuclei to that of α particles for SEP events (Kuzhevskij 1985), we can calculate the value of G_1, the ratio of gamma quantum flux at E_γ=439 keV from created ^{23}Na in the i-j interactions to that at E_γ=478 keV from Li + Be nuclei produced in α-He interactions:

$$G_1 = \frac{n_{\mathrm{O}} \int_{E_1}^{E_2} F_{\mathrm{C}}(E)\sigma_{\mathrm{CO}}^{\mathrm{Na}}(E)dE + n_{\mathrm{C}} \int_{E_1}^{E_2} F_{\mathrm{O}}(E)\sigma_{\mathrm{OC}}^{\mathrm{Na}}(E)dE}{n_{\mathrm{He}} \int_{E_1'}^{E_2'} F_\alpha(E)\sigma_{\alpha\mathrm{He}}^{\mathrm{Li+Be}}(E)dE}. \tag{9}$$

Values of G_1 as a function of s (the power-law index for solar energetic particles) were calculated for the two target models (thin and thick) and the results are given in Table 3.

Table 3 Values of G_1 as a Function of Power-Law Index for Two Target Models

s	2	3	4	5	6	7
G_1 (thin target)	0.04	0.25	2.88	26.3	263	2632
G_1 (thick target)	0.004	0.02	0.30	2.60	26	263

5 SUMMARY AND CONCLUSIONS

In the light of recent progress in the solar gamma-ray astronomy, we re-visited the problem of nuclear reactions between energetic particles accelerated in solar flares and nuclei of elements that make up the solar atmosphere. The abundances of energetic middle and heavy nuclei are known to be less than that of energetic protons and α particles. Moreover, the abundances of middle and heavy elements in the solar atmosphere are also less than that of hydrogen and helium. Nevertheless, the nuclear cross-sections of middle and heavy nuclei-nuclei interactions (i-j interactions), as a rule, are larger than those of the interactions between energetic protons (or α particles) and the nuclei in the atmosphere. Besides, the threshold for the i-j interactions is less than that for the interaction involving protons or α particles.

Our analysis on the gamma-ray lines from the solar flare of 2002 July 23 observed with RHESSI confirms that i-j interactions are very important for nuclei whose initial abundances in the solar atmosphere are small. Amongst them are the light elements Li, Be and B, as well as some rare elements, e.g., Na, and even Mg, Si. The role of i-j interactions grows, especially, in cases where the SEP has a soft spectrum. Let us recall that such a situation is very often encountered in processes of particle acceleration at or near the Sun.

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