RADIOACTIVE LINE EMISSION FROM SOLAR FLARES

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ABSTRACT

We have studied the radioactive line emission expected from solar active regions after large flares, following the production of long-lived radioisotopes by nuclear interactions of flare-accelerated ions. Total cross sections for the formation of the main radioisotopes by proton, ^{3}He and α-particle reactions have been evaluated from available data combined with nuclear reaction theory. We point out several delayed lines that appear to be promising for detection, e.g. at 1434 keV from the radioactivity of both the ground state and isomer of ^{52}Mn. The calculated solar delayed line emission is compared with a gamma-ray spectrum obtained in a recent experiment in which a sample of the Allende meteorite was activated by proton irradiation.

Key words: nuclear reactions, nucleosynthesis, abundances – Sun: flares – Sun: X-rays, gamma rays.

1. INTRODUCTION

Gamma-ray lines from solar flares were first observed in 1972 with the gamma-ray spectrometer (GRS) aboard the OSO-7 satellite [1]. Since then, repeated observations of prompt gamma-ray lines excited by nuclear interactions of flare-accelerated particles with the solar atmosphere have furnished valuable information on the composition of the ambient flare plasma, as well as on the composition, energy spectrum and angular distribution of the accelerated ions (e.g. [2]).

The bombardment of the solar atmosphere by flare-accelerated ions can also synthesize radioactive nuclei, whose decay can produce observable, delayed gamma-ray lines in the aftermath of large flares [2]. The observation of solar radioactivity can be important because (1) the radioisotopes can serve as tracers to study mixing processes in the solar atmosphere and (2) their detection should provide a new insight into the spectrum and fluence of flare-accelerated ions. We have recently performed a systematic study of the delayed X- and gamma-ray line emission from solar flare radioactivity [3]. We have considered the production of 25 radioisotopes with half-lives between ∼10 minutes, which is the typical duration of large gamma-ray flares, and 77.2 days (^{56}Co half-life). We neglected radioisotopes with mean lifetime τ_r greater than that of ^{56}Co, because (1) their activity ($\dot{N}_r = N_r/\tau_r$) is lower and (2) their chance of surviving at the solar surface is also lower.

2. RADIOISOTOPE PRODUCTION CROSS SECTIONS

Most of the radioisotopes we studied are proton-rich, positron emitters. Their production by proton, α-particle and ^{3}He reactions with the abundant constituents of cosmic matter was treated in detail by Kozlovsky et al. [4-5]. However, new laboratory measurements have allowed us to significantly improve the evaluation of cross sections for the formation of ^{34}Cl^m, ^{52}Mn^g, ^{52}Mn^m, ^{55}Co, ^{56}Co, ^{57}Ni, ^{58}Co^g, ^{60}Cu, and ^{61}Cu. We also evaluated cross sections for the production of ^{7}Be, ^{24}Na, ^{56}Mn and ^{58}Co^m, which are not positron emitters.

Most of the cross section data were extracted from the EXFOR database. When laboratory measurements were not available, we performed calculations with both EMPIRE-II (version 2.19; [6]) and TALYS (version 0.64; [7]). These computer codes account for major nuclear reaction models for direct, compound, pre-equilibrium and fission reactions below 250 MeV. They include comprehensive libraries of nuclear structure parameters, such as masses, discrete level properties, resonances and gamma-ray parameters. Above this energy, we used the semiempirical ”Silberberg & Tsao code” [8], which was developed for cosmic-ray physics.

The TALYS and EMPIRE-II calculations were systematically compared with available data and a satisfactory agreement was generally found. As an example, we show in Fig. 1 a comparison of TALYS simulations with available data for the production of the ground state of ^{52}Mn (^{52}Mn^g) and the isomeric level at 377.7 keV (^{52}Mn^m) in p+^{nat}Cr collisions. We see the ability of this code to accurately predict both ground state and isomeric state populations.

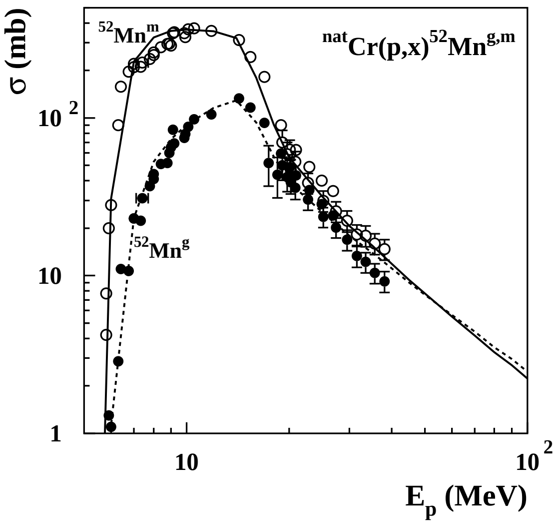

Figure 1. Comparison of TALYS calculations with experimental data for the reaction $^{nat}Cr(p,x)^{52}Mn^{g,m}$. Solid curve and open symbols: production of $^{52}Mn^m$. Dashed curve and solid symbols: production of $^{52}Mn^g$. Data: [9-11].

3. DELAYED X- AND GAMMA-RAY LINE EMISSION

We calculated the production of radioactive nuclei in solar flares from a thick target interaction model, taking into account nuclear destruction and catastrophic energy loss (e.g. interaction involving pion production) of the fast particles in the interaction region. We assumed for the accelerated ions a composition based on the abundances measured in impulsive solar energetic events [12] and a source energy spectrum in power-law form extending to 1 GeV/nucleon. We provide in [3] radioisotope yields in tabular form for three values of the power law spectral index: s=2, 3.5 and 5. We also give thick-target yields for the production of the 4.44 and 6.13 MeV deexcitation lines from ambient ^{12}C and ^{16}O, respectively. These prompt narrow lines are produced in reactions of accelerated protons and α-particles with solar atmospheric ^{12}C, ^{14}N, ^{16}O and ^{20}Ne. They are often detected in large solar flares and can allow determination of the ion irradiation fluence during the flare. Thus, the results presented in [3] can be readily used to predict fluxes of all of the major delayed lines at any time after a gamma-ray line flare.

Synthetic delayed X- and gamma-ray line spectra are shown in Figs. 2-4. The calculated fluxes do not take into account attenuation of the line photons in the solar atmosphere. Unless the flare is very close to the solar limb, the attenuation of the delayed gamma-ray lines should not be significant (see [14]), as long as the radioactive nuclei do not plunge deep in the solar convection zone. The delayed X-ray lines can be more significantly attenuated by photoelectric absorption. However, we estimated [3] that the attenuation of the important Co Kα line at 6.92 keV (Figs. 2-4) should be $\lesssim$ 10% for flares occuring at low

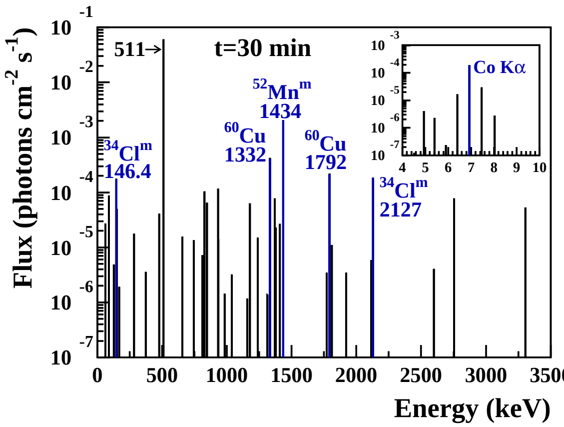

Figure 2. Synthetic spectrum of the solar high-energy line emission at t=30 minutes after a large gamma-ray flare. The inset shows the simulated delayed X-ray lines. The calculations assume a flare duration of 10 minutes and an accelerated ion power-law spectral index s=3.5. The delayed line fluxes are normalized to a total fluence of the summed 4.44 and 6.13 MeV prompt narrow lines of 300 photons cm^{-2}, which is the approximate fluence observed in the 2003 October 28 flare with INTEGRAL/SPI [13].

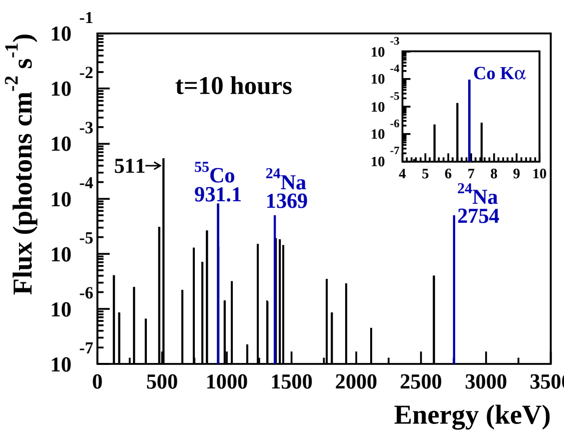

Figure 3. Same as Fig. 2 but for t=10 hours after the flare.

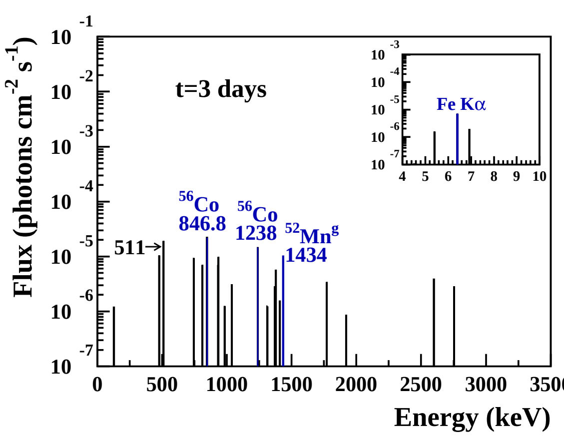

Figure 4. Same as Fig. 2 but for t=3 days after the flare.

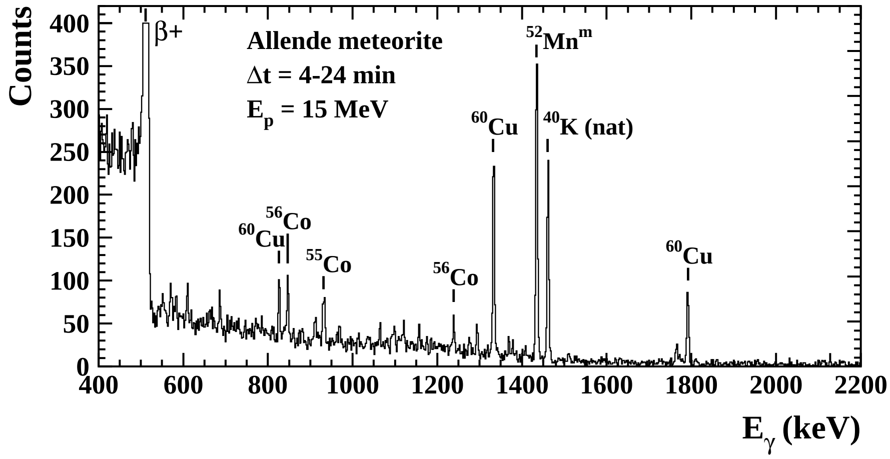

Figure 5. Observed activation gamma-ray spectrum from the bombardment of a sample of the Allende meteorite with a 15 MeV proton beam. The gamma-ray counts were accumulated from 4 to 24 minutes after the stopping of the proton irradiation. The most intense lines are labeled with their parent radioisotopes. The background line at 1461 keV arises from the decay of ambient ^{40}K.

heliocentric angles.

The brightest delayed line in Figs. 2 and 3 is the electron-positron annihilation line at 511 keV. It is mainly produced from the decay of ^{13}N ($T_{1/2}$=9.97 minutes), ^{11}C ($T_{1/2}$=20.4 minutes), ^{18}F ($T_{1/2}$=110 minutes), and ^{55}Co ($T_{1/2}$=17.5 hours). After $\sim$2 days however, the flux of the 511 keV line can become lower than that of the 846.8 keV line from the decay of ^{56}Co (Fig. 4). Our study has revealed other delayed gamma-ray lines that appear to be promising for detection, e.g. at 1434 keV from the radioactivity of both the isomer ^{52}Mn^m ($T_{1/2}$=21.1 min; see Fig.2) and the ground state ^{52}Mn^g ($T_{1/2}$=5.59 days; Fig. 4), 1332 and 1792 keV from ^{60}Cu ($T_{1/2}$=23.7 min; Fig. 2), and 931.1 keV from ^{55}Co (Fig. 3).

Although weaker than the main prompt gamma-ray lines, these delayed lines can have fluences within the detection capabilities of the *RHESSI* spectrometer or future space instruments. It is noteworthy that multiple flares originating from the same active region of the Sun can build up the radioactivity, thus increasing the chance for detection. The lines will be very narrow, because the radioactive nuclei are stopped by energy losses in the solar atmosphere before they decay. However, a major complication to the measurements can arise from the fact that the same radioactivity lines can be produced in the instrument and spacecraft materials from interactions of cosmic-rays and solar energetic particles.

The concomitant detection of several gamma-ray lines after a large solar flare would obviously furnish valuable information on the flare-accelerated particle composition and energy spectrum. A measurement of the decay curve of the e^+–e^- annihilation line or of other delayed gamma-ray lines would also be very useful for studying solar atmospheric mixing. The lines should be strongly attenuated by Compton scattering when the radioactive nuclei plunge deep in the solar interior. The use of several radioisotopes with different lifetimes would place unique constraints on the extents and timescales of mixing processes in the solar outer convection zone.

The strongest delayed X-ray line for $\sim$2 days after the flare is found to be the Co Kα at 6.92 keV (Figs. 2 and 3), which is produced from both the decay of the isomer ^{58}Co^m ($T_{1/2}$=9.04 hours) by the conversion of a K-shell electron and the decay of ^{57}Ni ($T_{1/2}$=35.6 hours) by orbital electron capture. After $\sim$2 days, the strongest X-ray line becomes the Fe Kα at 6.40 keV (Fig 4), which is emitted in the electron-capture decay of ^{55}Co, ^{56}Co, and ^{58}Co^g ($T_{1/2}$=70.9 days).

Given the sensitivity and imaging capabilities of modern X-ray telescopes, the delayed emission of these two X-ray lines could in principle allow accurate measurement of the size and development of the radioactive patch on the solar surface. This would provide unique information on both the transport of flare-accelerated particles and dynamics of solar active regions.

However, a serious complication to the X-ray line measurements could arise from the confusion of the radioactivity lines with the intense thermal emission from the flare plasma. In particular, this could prevent a detection of the delayed X-ray lines for hours after the impulsive flaring phase, until the thermal emission has become sufficiently low. The necessary distinction of thermal and nonthermal photons would certainly benefit from an X-ray instrument with high spectral resolution, because Kα lines from neutral to low-ionized Fe, Co or Ni are not expected from thermal plasmas at ionization equilibrium. The neutral Co line at 6.92 keV could still be confused, however, with the thermal Kα line of Fe XXVI at 6.97 keV.

4. COMPARISON WITH EXPERIMENT

In a recent experiment performed at the 14-MV tandem accelerator of the IPN Orsay [15], a sample of the Allende meteorite was irradiated by a proton beam of energy E_p=15 MeV and the delayed gamma-ray emission of the activated material was measured at different times after the stopping of the proton beam. The Allende meteorite belongs to the class of carbonaceous chondrites and has a composition close to solar, except for the volatile elements. The proton charge accumulated on the sample was 1 μC. The gamma-ray emission was measured with high purity Ge detectors with bismuth germanate (BGO) shields for Compton suppression. The efficiency of each detector at 1333 keV was $\sim 2.3\times10^{-4}$.

Fig. 5 shows a gamma-ray count spectrum accumulated from 4 to 24 minutes after the stopping of the proton irradiation. We see that the strongest activation lines arise from the decay of ^{52}Mn^{m} and ^{60}Cu, in good agreement with the calculations shown in Fig. 2. At E_p=15 MeV, ^{52}Mn^{m} and ^{60}Cu are mainly produced by the reactions ^{52}Cr(p,n)^{52}Mn^{m} (see Fig. 1) and ^{60}Ni(p,n)^{60}Cu, respectively. On the other hand, the 2127 keV line from the decay of ^{34}Cl^{m} ($T_{1/2}$=32 minutes) is not observed in the experimental spectrum, whereas it is relatively strong in the simulated spectrum of Fig. 2. This is because the production of ^{34}Cl^{m} in solar flares is predicted to be mainly due to ^{3}He and α reactions with ^{32}S.

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