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Gamma-Ray Measurement of Energetic Heavy Ions at the Sun

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Abstract

We have derived the γ-ray line spectra from accelerated heavy ions at the Sun in data from the *Solar Maximum Mission (SMM)* Gamma Ray Spectrometer and the *Compton Gamma Ray Observatory (CGRO)* OSSE instrument. These lines are Doppler-broadened and, perhaps shifted, reflecting the transport of the particles. They provide the only source of information on the composition of accelerated heavy ions at the Sun. Analysis of the integrated spectrum from 19 flares suggests that accelerated Fe is enhanced by about a factor of five over its ambient abundance. Future measurements with *CGRO* can be compared with observations of solar energetic particles by ACE.

1 Introduction:

Murphy et al. (1991) first used *SMM* γ-ray spectra from the 1981 April 27 flare to show that the composition of accelerated heavy ions resembles that observed in solar energetic particles (SEPs) in ^{3}He-rich flares. More recently Ramaty et al. 1997 analyzed spectra from the 1991 June 1 flare observed with *Granat/*PHEBUS and also found enhancements in accelerated heavy ions. In this paper we demonstrate a new technique applied to γ-ray spectra of solar flares that directly reveals the presence of heavy-accelerated nuclei through their Doppler-broadened lines. Lines from C and Fe are resolved and their shapes provide information on the directionality and transport of these particles at the flare site; their relative intensities provide information on the composition of accelerated ions.

2 Revealing Broad Lines in Gamma-Ray Spectra:

We illustrate our technique for revealing the broadened γ-ray lines using the integrated spectrum plotted in Figure 1a) of 19 nuclear-line flares observed by the *SMM* spectrometer (Share and Murphy 1995, Share and Murphy 1998). This spectrum has been fitted with an incident photon model containing the sum of two power laws representing the bremsstrahlung continuum, 21 Gaussians representing narrow-resolved lines, and 5 Gaussians representing broadened lines and unresolved continuum (Murphy et al. 1990). The narrow-resolved lines include de-excitations from ambient nuclei excited by proton and α-particle interactions, and the e^{+}-annihilation and neutron-capture lines. The broadened lines are produced by the de-excitation of heavy accelerated ions (e.g. C, O, Mg, Fe, etc.) after interaction with ambient H and He; these lines are expected to be Doppler-broadened by ~20% (FWHM) for ions having an isotropic distribution (Murphy 1985). The unresolved continuum is comprised of several lines from excited nuclei in both the ambient medium and accelerated particles that are too weak to be resolved individually. The solid line drawn through the data points shows the best fit. We also plot the fitted bremsstrahlung and summed contributions from the 21 narrow lines after modification by the instrumental response. In the next step we subtract the bremsstrahlung and narrow line components from the total spectrum. This residual count spectrum, plotted in Figure 1b), is well behaved except at low energies where the strong bremsstrahlung contribution has been removed and near 2.2 MeV where the intense neutron-capture line as been subtracted. The latter deviations occur because the Gaussian is only an approximation to the actual line shape. The residual spectrum exhibits clear features that are not just artifacts of either the fit or the subtractions of the contributions from the narrow lines or power-law continuum.

3 Fits to Broad-Line Spectra:

In order to explore this residual spectrum in the least model-dependent manner, we fitted it with the five-Gaussians suggested by Murphy et al. (1990), but we allowed both the energies and the widths to be free. This fit is plotted through the data points in Fig 1b) along with the individual broad Gaussians that are modified by the instrument response. The parameters derived from these fits are listed in Table 1 along with possible identifications. The spectrum reveals Doppler-broadened lines that are attributable to the first excited states of Fe (847 keV) and C (4.443 MeV), as well as composites from Fe, Mg, Ne, and Si in the 1 - 2 MeV range, and from O and N in the 5 - 7 MeV range. The broadened lines due to accelerated Fe and C appear to be redshifted relative to the energies found in our fits of the narrow lines from ambient Fe and C that have been excited by high-energy protons and α-particles. These narrow-line energies are consistent with those observed at rest in the laboratory. The broadened Fe line appears redshifted by ~3% and the broadened C line by ~9%.

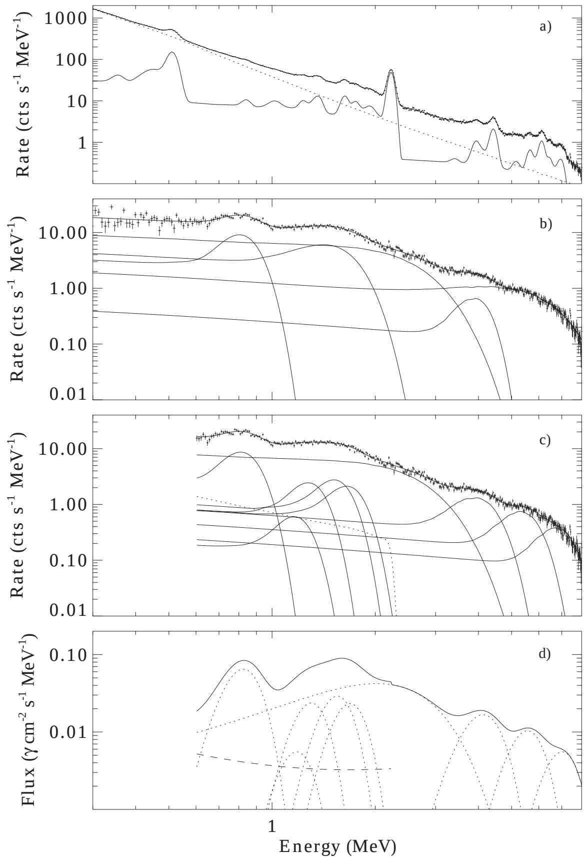

Figure 1: a) Summed spectrum from 19 flares observed by *SMM;* b) spectrum with narrow lines and bremsstrahlung removed fit by 5 broad Gaussians; c) same as 1b) but fit by several components from 0.6 to 8.0 MeV (see text); d) derived incident photon spectrum.

The Gaussian features listed in Table 1 at 1.5, 2 and 5.2 MeV are likely to be composites of several unresolved lines. Broadened de-excitation lines from Fe, Mg, Ne, and Si likely comprise the 1.5 MeV feature. The 2 MeV Gaussian is exceptionally broad and may be dominated by unresolved lines from several nuclei. Radiation from the 2.223 MeV neutron-capture line that is Compton-scattered in the photosphere may also contribute in this energy range. Vestrand (1990) calculated the amount of scattered radiation for various accelerated proton spectra and angular distributions, and found that the scattered radiation in the 1 to 2.2 MeV range amounts to ~20 – 40% of the 2.223 MeV line flux. The wide Gaussian near 5.2 MeV is likely to be a composite of broadened, and perhaps redshifted, 6.13 MeV and 6.919/7.028 MeV line features.

With these considerations in mind we repeated the fit of the 19-flare spectrum with additional components. We fit the 1.5 MeV complex with four lines fixed at a 5% redshift from the laboratory energies of the Fe, Mg, Ne, and Si lines and with widths fixed at 23% (FWHM) of the line energies. We left the energy and width of the 2 MeV Gaussian free but added a function that reflected the shape expected from Compton scattered 2.2 MeV radiation. We also separated the single 5.2 MeV Gaussian into two Gaussians whose widths were fixed at 23% of their energies and whose energies were free to vary from the starting energies redshifted by 5% from 6.1 and 7 MeV for the O and N lines. The fits were performed over a more limited range 0.6 to 8.0 MeV to closer reflect the range of the calculations performed by Vestrand (1990).

TABLE 1

FITS TO SUMMED SPECTRUM FROM 19 FLARES

Energy, MeV	Width(FWHM), MeV	Flux, $10^{-2}\gamma/\mathrm{cm}^2$-s	Possible Identification (MeV)
5 Broad Lines			
0.819 ± 0.005	0.214 ± 0.016	1.58 ± 0.15	^{56}Fe (0.847)
1.515 ± 0.012	0.619 ± 0.039	3.62 ± 0.42	^{56}Fe (1.238); ^{24}Mg (1.369); ^{20}Ne (1.633); ^{28}Si (1.779)
1.979 ± 0.072	1.870 ± 0.094	8.09 ± 0.69	Unresolved lines; n-capture; ^{14}N (2.313); ^{16}O (2.75)
4.050 ± 0.034	0.791 ± 0.117	0.82 ± 0.16	^{12}C (4.439)
5.175 ± 0.174	3.712 ± 0.242	4.37 ± 0.40	^{16}O (6.13, 6.919); ^{14}N (7.028)
9 Broad Lines & Scattered n-capture			
0.825 ± 0.005	0.210 ± 0.023	1.42 ± 0.26	^{56}Fe (0.847)
1.180 ± 0.000	0.271 ± 0.000	0.17 ± 0.19	^{56}Fe (1.238)
1.300 ± 0.000	0.299 ± 0.000	0.77 ± 0.17	^{24}Mg (1.369)
1.550 ± 0.000	0.357 ± 0.000	1.10 ± 0.19	^{20}Ne (1.633)
1.690 ± 0.000	0.389 ± 0.000	0.98 ± 0.19	^{28}Si (1.779)
2.018 ± 0.098	1.909 ± 0.213	8.76 ± 1.14	Unresolved lines; ^{14}N (2.313); ^{16}O (2.75)
4.126 ± 0.040	1.150 ± 0.110	2.10 ± 0.26	^{12}C (4.439)
5.560 ± 0.063	1.330 ± 0.000	1.51 ± 0.07	^{16}O (6.13)
7.017 ± 0.056	1.610 ± 0.000	0.97 ± 0.05	^{16}O (6.919); ^{14}N (7.028)
		0.80 ± 0.20	Compton scattered n-capture

4 Discussion:

The results of these expanded fits with 9 Gaussians and the Compton scattered 2.223 MeV line are also given in Table 1 (uncertainty of '0' indicates fixed parameter) and plotted in Figure 1c). We plot the derived incident photon spectrum in Figure 1d). The energy, width and intensity of the ~0.82 MeV Fe line did not change significantly from the original fit. The center energy is ~4σ below the laboratory energy for this de-excitation, representing a redshift of 2.6 ± 0.6%. Such a shift may result from the higher probability for nuclei moving away to interact when they encounter higher solar densities. The line is broadened (FWHM) by 25.5 ± 2.8%, corresponding to an ion kinetic energy of 8.6 ± 2.1 MeV/nucleon.

The summed flux in the four Fe, Mg, Ne, and Si lines is consistent with that found for the composite 1.5 MeV Gaussian in the original fit. It is difficult to draw firm conclusions about the relative fluxes of these lines in this range because they are not resolved. It does appear that the higher-energy Fe line is at least a factor of three weaker than the lower-energy (~0.82 MeV) line; this is consistent with the branching ratio found in the laboratory for 7 MeV protons incident on Fe (Lachkar et al. 1974).

The center energy of the ~4.1 MeV Gaussian is ~7σ below the laboratory energy for C and represents a redshift of 7.1 ± 0.9%, somewhat greater than found for the Fe feature. This might be attributable to the greater range of C ions relative to Fe. It is broadened by 27.9 ± 2.7% (FWHM), corresponding to an ion kinetic energy of 10.5 ± 2.1 MeV/nucleon. As can be seen in Table 1, the intensity and width of the ~4.1 MeV line is dependent on whether we restrict the width of the 5-7 MeV feature. In our expanded fit we used two Gaussians with fixed widths to separate the contributions from expected lines >5 MeV. If the Gaussian at 5.56 MeV is due to the 6.13 MeV ^{16}O line, then its redshift is ~9%. In order to make more definitive statements about possible Doppler broadening and redshifts in all the lines it is best to perform these studies on individual flares. This is the subject of another paper.

We can obtain a preliminary estimate of the mean composition of the accelerated particles at the Sun by comparing the fluxes observed in the narrow and broadened 0.847 and 4.439 MeV lines that we have attributed to Fe and C. The narrow lines are due to proton and α-particle interactions with ambient Fe and C while the broad lines are due to interactions of accelerated Fe and C with H and He. The flux in the broad

Fe line is ~70% of that observed in the broad C line, while the flux in the narrow Fe line is ~15% of that observed in the narrow C line. This suggests that, on average, Fe is enhanced by a factor of about 5 in the flare-accelerated particles. This is consistent with the ~6.7 Fe/C enhancement found in impulsive SEP events relative to the coronal abundance (Reames 1999). Our estimate is imprecise, however, because we have not considered the effects of spectral index, energy loss, and accelerated α/proton ratio.

One of the important uncertainties in this analysis is the contribution from unresolved nuclear lines. Ramaty, Kozlovsky, and Lingenfelter (1975) made an estimate of this component based on some approximations. Our fits suggest that the primary contribution may be in the form of a broad feature centered near 2 MeV. These fits also provided an estimate of the flux of 2.223 MeV γ rays scattered by the photosphere into the 0.6 - 2.2 MeV energy range. This flux is only ~10% that found in the narrow neutron capture line. This ratio is about a factor of 2 to 4 below that calculated by Vestrand for photons scattered into the 1 to 2.2 MeV range, suggesting that the capture line may not be produced as deep in the photosphere.

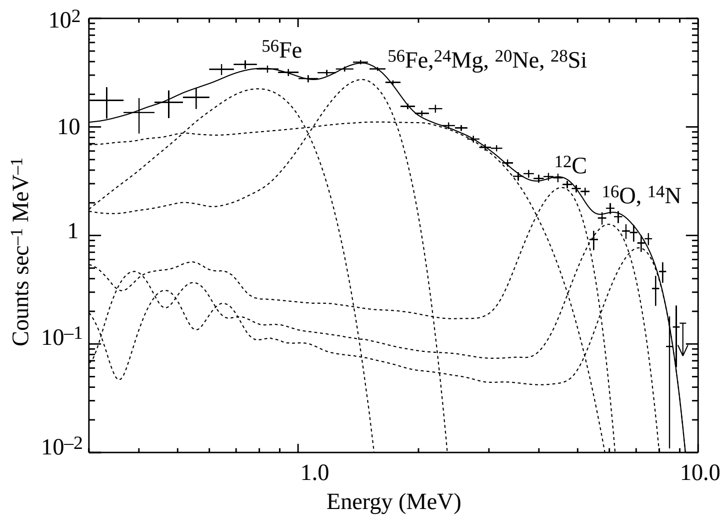

Figure 2: OSSE 1991 June 4 flare spectrum with narrow lines and bremsstrahlung removed.

We plan to use this technique to compare the accelerated particle abundance using *CGRO*/OSSE data with SEP data from *ACE*. We show the broad-line spectrum derived from OSSE for the 1991 June 4 solar flare in Figure 2. It is similar to what we have found for the *SMM* 19-flare sum and again suggests an enhanced concentration of Fe in the accelerated particles.

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