SOLAR FLARE GAMMA-RAY LINE SPECTROSCOPY

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1. INTRODUCTION. In a previous paper (1), we have outlined the techniques and presented the results of solar elemental abundance determinations using observations of gamma-ray lines from the April 27, 1981 solar flare. Here, we elaborate on these techniques, present the observed and the best-fitting theoretical spectra, present numerical values for the photon fluences and derive the total number of protons involved in the thick-target production of these gamma rays.

2. DETECTOR RESPONSE. The gamma-ray spectrometer (GRS) on SMM is an actively-shielded, 7-crystal NaI scintillation detector (2) with 476 pulse-height channels. Its pulse-height resolution corresponds to an energy resolution of ~7% at 662 keV and its effective area is energy-dependent, varying from ~20 to ~200 cm^2. Using a numerical model for the detector response, a photon spectrum $a(j)$ incident on the detector can be transformed into a pulse-height spectrum $\rho(i) = \sum_j D(i,j)\, a(j)$, where $D(i,j)$ represents the detector response, and i and j are the pulse-height and photon energy channel numbers, respectively. This numerical model takes into account the effective area, the pulse-height resolution and the photopeak, first escape peak and Compton continuum fractions. In particular, the Compton continuum includes an edge feature resulting from the escape of photons through its unshielded aperture. The details of this model will be published elsewhere.

3. ANALYSIS. We have calculated deexcitation spectra resulting from thick-target nuclear reactions and combined them with spectra expected from bremsstrahlung, neutron capture and positron annihilation. The total spectrum, binned into photon energy channels j defined in ref. (3), can be expressed as $a(j) = \sum_\ell n(\ell)A(j,\ell)$, where, for $1<\ell<12$, $n(\ell)$ is the abundance of element ℓ and $n(\ell)A(j,\ell)$ is the contribution of interactions of all the energetic particles with this element (see ref.(1)), $n(13)A(j,13)$ is the bremsstrahlung spectrum, $n(14)A(j,14)$ is the neutron capture spectrum taken to be a delta-function at 2.223 MeV and $n(15)A(j,15)$ is the positron-annihilation spectrum assumed to be the sum of a delta-function at 0.511 MeV and the orthopositronium annihilation function normalized such that 67% of the positrons annihilate via positronium. For a power-law bremsstrahlung spectrum, we

find that a good fit to the data is obtained with an index equal to 2.1. Using the detector response, we obtain the pulse-height spectrum, $\rho(i) = \sum_\ell n(\ell) \mathcal{A}(i,\ell)$, where $\mathcal{A}(i,\ell)$ are partial pulse-height spectra.

To obtain the best fit between the calculated pulse-height spectrum, $\rho(i)$, and the observed spectrum, $c(i)$, we minimize χ^2_ν by varying the $n(\ell)$'s. Here, $\chi^2_\nu = \sum_i \omega(i)[c(i)-\rho(i)]^2/\nu$, where ν is the number of degrees of freedom (450 usable detector channels less the 15 free variables $n(\ell)$), $\omega(i)$ is the statistical weight of channel i and $c(i) = O(i)-fB(i)$, where $O(i)$ is the number of counts accumulated during the flare integration time, $B(i)$ is the number of counts accumulated during the background integration time and f is a factor adjusting background integration time to flare integration time. We take $\omega(i)$ to be $1/\sigma^2(i)$, where $\sigma^2(i)$ is the mean-square error for channel i. For the Poisson statistics assumed here, $\sigma^2(i) = O(i) + f^2B(i)$.

The values of $n(\ell)$ which minimize χ^2_ν are obtained by solving the set of equations resulting from taking partial derivatives of χ^2_ν with respect to each of the $n(\ell)$'s and setting them to zero. The solutions of these equations can be written as $\vec{n} = E\,\mathcal{A}^+\,W\,\vec{c}$, where $\vec{n}$ is a vector whose elements are the $n(\ell)$, $\mathcal{A}$ is a matrix whose elements are $\mathcal{A}(i,\ell)$, $\mathcal{A}^+$ is its transpose, W is a diagonal matrix whose elements are the statistical weights $\omega(i)$, $\vec{c}$ is the vector of the observed pulse-height spectrum and $E = (\mathcal{A}^+ W \mathcal{A})^{-1}$ is the error matrix. If the only source of error is observational counting statistics (i.e., fluctuations in $c(i)$), then the mean-square errors of the $n(\ell)$'s are the diagonal elements of E multiplied by χ^2_ν (4,5).

The off-diagonal elements of E give information on the interference between the partial spectra. Interference arises when two partial spectra contribute significantly to an observed spectral feature. The interference coefficient is $F(k,\ell) = [E(k,\ell)]^2/[E(k,k)E(\ell,\ell)]$. When $F(k,\ell)$ is much less than 1, the interference is negligible. However, when $F(k,\ell)$ is large, $n(k)$ and $n(\ell)$ cannot be determined independently. Their sum can be determined with an error $[E(k,k)+E(\ell,\ell)]\,\chi^2_\nu$, but the overall fit will remain just as good if either $n(k)$ or $n(\ell)$ is varied by a factor $F(k,\ell)$ while keeping the sum $n(k)+n(\ell)$ constant.

4. RESULTS. The resultant $n(\ell)$'s for $1<\ell<12$, together with their respective mean-square errors, are given in the last column of Table 1 of ref.(1). As discussed there, the statistical errors in the derived abundances of C, O, Ne, Mg, Si and Fe are sufficiently small to allow meaningful comparisons with the local galactic and coronal abundances, but the statistical errors for N, Al, S and Ca, as well as the systematic errors for H and He, preclude such comparisons. In addition to these 12 elements, the fit of the calculations to the data also provides information on the bremsstrahlung and the neutron-capture and positron-annihilation radiation. We present this information in terms of photon fluences incident on the detector. We find that the >0.3 MeV bremsstrahlung fluence is (1060±14) photons/cm^2 for the power law index of 2.1, the neutron capture line fluence is (4.3±2.9) photons/cm^2 and the 0.51 MeV line fluence is (25.8±2.6) photons/cm^2. In comparison, the fluences resulting from interactions with ambient H, He, C, N, O, Ne, Mg, Al, Si, S, Ca and Fe are 27, 59, 15, 6.7, 30, 62, 35, <1.3, 56,

4.2, 1.9 and 56 photons/cm^2, respectively, with the same relative errors as given in ref.(1).

We have also considered the interference coefficients between the 15 components given above. We find that between the six reliably determined elements (C, O, Ne, Mg, Si, Fe) these coefficients are all less than 0.1. Interference, therefore, should introduce little additional uncertainty in the determination of the abundances of these elements. However, we find interference between S and neutron capture (F=0.3), and He and positron annihilation (F=0.21), resulting from the detector's inability to adequately resolve the 2.22 MeV line from the 2.23 MeV line of ^{32}S and the 0.511 MeV line from the α-α feature at $\sim$0.45 MeV, respectively. There is also interference between C and N (F=0.27), resulting from contributions to the 4.44 MeV line from C and N spallation. But, as already discussed, the abundances of S, N and He are not well determined. Also, the 2.22 MeV line fluence cannot be adequately determined because, for the April 27, 1981 flare, this line is strongly attenuated by Compton scattering in the photosphere.

The observed spectrum of the April 27, 1981 flare is compared to the calculated spectrum in Figure 1. Here, the lines of ^{16}O, ^{12}C, ^{20}Ne, ^{24}Mg and ^{56}Fe can be clearly seen. The feature marked n is due to the 2.22 MeV line, with additional contributions from ^{14}N (at 2.31 MeV) and ^{32}S. The lack of significant interference between the 2.22 and 2.31 MeV lines indicates that adequate detector resolution is available to distinguish between them. Even though the ^{28}Si line at 1.78 MeV is not clearly visible, the Si abundance can nevertheless be well determined since in the calculation the bulk of the photons above the line center energy are produced by interactions with Si. The dip just below the second ^{56}Fe line is probably due to the effects of a calibration line of ^{60}Co at 1.17 MeV.

From the fluences for the various components given above, the total nuclear radiation (including the 2.22 MeV line and all the positron annihilation radiation) is 372 photons/cm^2 and its ratio to the total observed bremsstrahlung above 0.3 MeV is 0.35. This value is of considerable importance for studies of the angular distribution of gamma rays from solar flares (6). Likewise, we find that in the 4-7 MeV band, 77 photons/cm^2 are from nuclear interactions and 28 photons/cm^2 are from bremsstrahlung. The fractional contributions of the various ambient elements to this 4-7 MeV nuclear radiation are the following: 0.1, 0.08, 0.18, 0.03, 0.30, 0.13, 0.06, 0.0, 0.08, 0.0, 0.0, 0.04 for the 12 elements from H through Fe. Thus, about 1/2 of the nuclear emission in the 4-7 MeV band is from interactions with ambient C, N and O.

To determine the total number of protons involved in the gamma-ray production, we must assume a ratio of H to the heavier elements in the ambient medium. Using the abundances deduced from the gamma rays in ref.(1), we obtain Np(>30 MeV) = 3.8×10^{32} protons, where Np(>30 MeV) is the number of protons with kinetic energy greater than 30 MeV. But, as we have discussed, the H abundance in this sample is uncertain. Assuming abundances similar to the local galactic abundances (for which the ratio of H to heavier nuclei is higher than for the gamma-ray sample (1)), Np(>30 MeV) = 6.7×10^{32}.

5. REFERENCES

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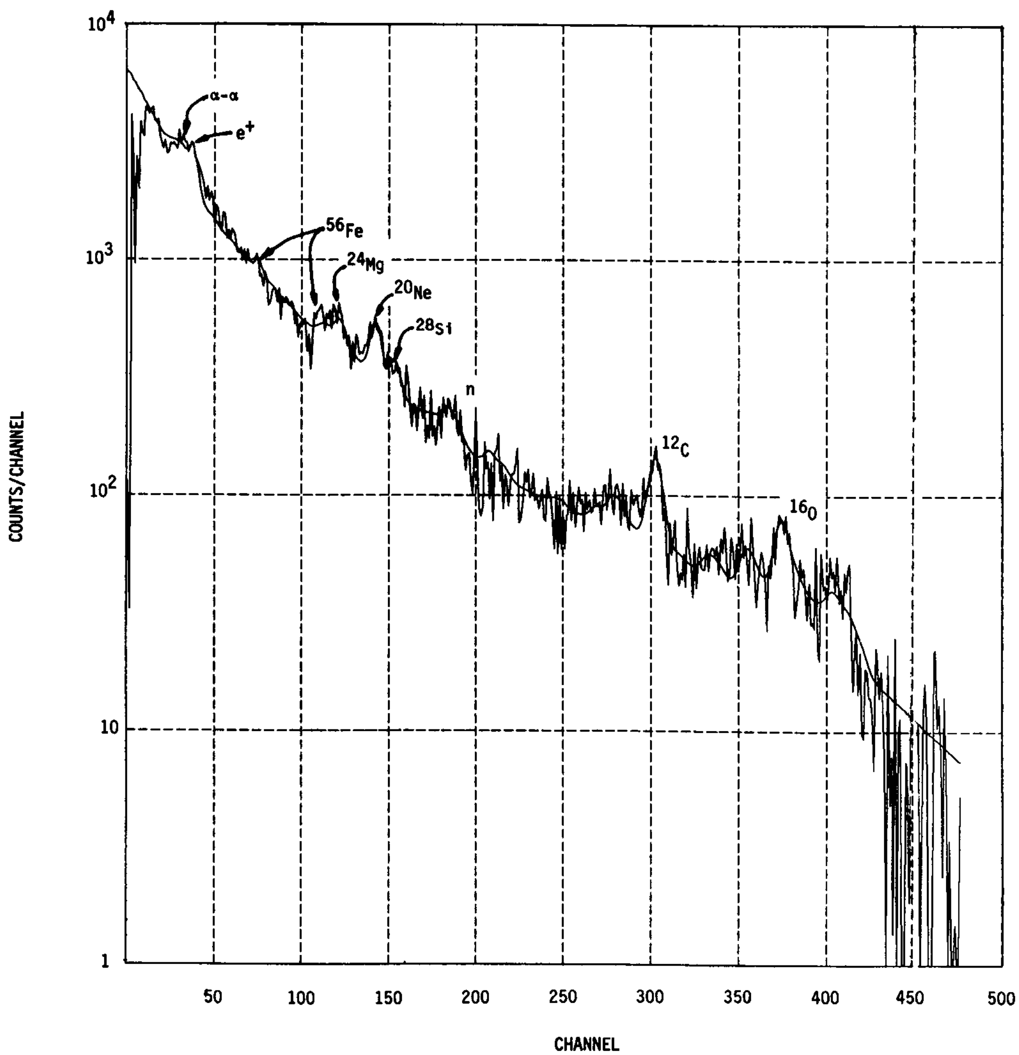

Figure 1. Observed and calculated (smooth curve) spectra of the April 27, 1981 solar flare.