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DIRECTIONALITY OF FLARE-ACCELERATED α-PARTICLES AT THE SUN

Gerald H. Share and Ronald J. Murphy
E. O. Hulburt Center for Space Research, Naval Research Laboratory, 4555 Overlook Avenue SW, Washington, DC 20375;
gerald.share@nrl.navy.mil, ronald.murphy@nrl.navy.mil
David M. Smith[1] and Robert P. Lin
Space Sciences Laboratory and Department of Physics, University of California at Berkeley, Berkeley, CA 94720;
dsmith@ssl.berkeley.edu, rlin@ssl.berkeley.edu
and
Brian R. Dennis and Richard A. Schwartz
NASA Goddard Space Flight Center, Greenbelt, MD 20771; brian.r.dennis@nasa.gov, richard.schwartz@gsfc.nasa.gov
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ABSTRACT

The *Reuven Ramaty High Energy Solar Spectroscopic Imager* (*RHESSI*) has observed the ^{7}Be and ^{7}Li γ-ray lines from fusion of accelerated α-particles with ambient helium produced during the 2002 July 23 solar flare that erupted at a heliocentric angle of 73°. This is the first observation of the lines with a germanium spectrometer. We have fitted the measured lines with calculated shapes for different energy and angular distributions for the interacting α-particles. A particle distribution from saturated pitch-angle scattering in the corona provides the best fit, but isotropic, downward-isotropic, or fan-beam distributions also provide acceptable fits. We can rule out a downward-beamed distribution with 99.99% confidence. *RHESSI* measurements of other Doppler-shifted nuclear de-excitation lines are consistent with a forward isotropic distribution of interacting particles in a magnetic loop tilted by ~40° from the normal to the solar surface toward Earth. Such a distribution is also consistent with the α-^{4}He line shape with ~15% confidence.

Subject headings: Sun: flares — Sun: particle emission — Sun: X-rays, gamma rays

1. INTRODUCTION

The shape of γ-ray lines emitted in solar flares provides information on the angular distribution of energetic particles interacting in the chromosphere. Ramaty & Crannell (1976) performed the first calculations of Doppler shifts from recoil of excited ^{16}O nuclei after impact by protons and α-particles. Kozlovsky & Ramaty (1977) recognized that the shapes of γ-ray lines at 0.429 and 0.478 MeV can be used to infer the angular distributions of flare-accelerated α-particles where they interact. These lines result from de-excitation of ^{7}Be and ^{7}Li, respectively, produced in fusion of accelerated α-particles with ambient ^{4}He (Kozlovsky & Ramaty 1974). Ramaty, Kozlovsky, & Lingenfelter (1979) compiled the fundamental cross sections for determining the production of γ rays and included the kinematics to calculate the shapes and shifts of γ-ray lines. This compilation, which has recently been updated (Kozlovsky, Murphy, & Ramaty 2002), formed the basis of a Monte Carlo code used in several solar studies. Murphy, Kozlovsky, & Ramaty (1988) used this code to calculate the expected shapes of the α-^{4}He lines for four different angular distributions of particles: isotropic, fan beam, broadened fan beam, and downward beam. They presented line profiles for flares at Sun center and at the limb.

Murphy et al. (1990) continued this study using a magnetic loop model for transport of the ions, including the effects of mirroring and MHD pitch-angle scattering (PAS). PAS can be characterized by the average distance for particle isotropization, assumed to be independent of energy (Hua, Ramaty, & Lingenfelter 1989). With no PAS, particles with large initial pitch angles mirror and tend to interact at their mirror points where the density is greatest. Particles with pitch angles too small to mirror enter the "loss cone" and either undergo a nuclear reaction as they are moving downward or are thermalized. Without PAS, most particles are moving parallel to the solar surface at their mirror points when they interact (i.e., a fan beam). Scattering causes the loss cone to be continuously repopulated and results in more downward-directed interacting particles. As PAS is increased, the distribution becomes even more downward-directed until saturation is reached. At saturation, particles are scattered into the loss cone as quickly as they are removed by interactions (Hua et al. 1989). Murphy et al. (1990) also folded their calculations through the instrument response of the *Solar Maximum Mission* (*SMM*) gamma-ray spectrometer (GRS) and compared the results with spectra observed from the 1981 April 27 solar flare. These comparisons provided convincing evidence for the presence of the α-^{4}He fusion lines in that flare. Their fits also suggested that a downward beam of particles did not fit the data as well as an isotropic or fan-beam geometry.

Share & Murphy (1997) compared the ^{7}Be and ^{7}Li line profiles calculated by Murphy, Kozlovsky, & Ramaty (1988) with the spectra from 19 solar flares observed by the *SMM* GRS. They found that a downward beam of α-particles could be ruled out with high confidence in two disk flares and that isotropic and fan-beam distributions of interacting particles were both consistent with all the data. In a subsequent study in which the flare spectra were summed by heliocentric angle, Share et al. (2002) concluded that the resolution of the *SMM* NaI detector was not sufficient to unambiguously distinguish between isotropic, downward-isotropic, and fan-beam distributions of interacting α-particles.

In this Letter, we present *Reuven Ramaty High Energy Solar Spectroscopic Imager* (*RHESSI*) high-resolution observations of the α-^{4}He fusion lines emitted during the 2002 July 23 solar

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[1] Now at the Department of Physics and Santa Cruz Institute for Particle Physics, University of California at Santa Cruz, 1156 High Street, Santa Cruz, CA 95064.

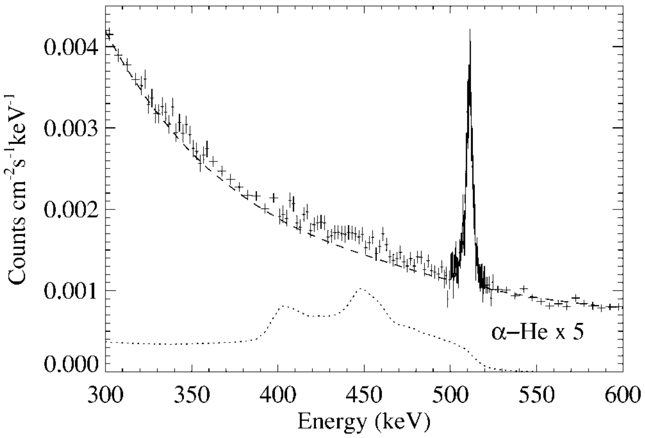

FIG. 1.—Background-corrected count spectrum accumulated from 00:27:20 to 00:43:20 UT. Solid curve is the best fit to the data. Dotted curve shows the *RHESSI* response to the best-fit α-^{4}He line model for an α-particle distribution that undergoes saturated PAS in the corona, multiplied by a factor of 5 for clarity. Dashed curve shows the response to the fitted bremsstrahlung, annihilation, and nuclear-line components (excluding the α-^{4}He lines).

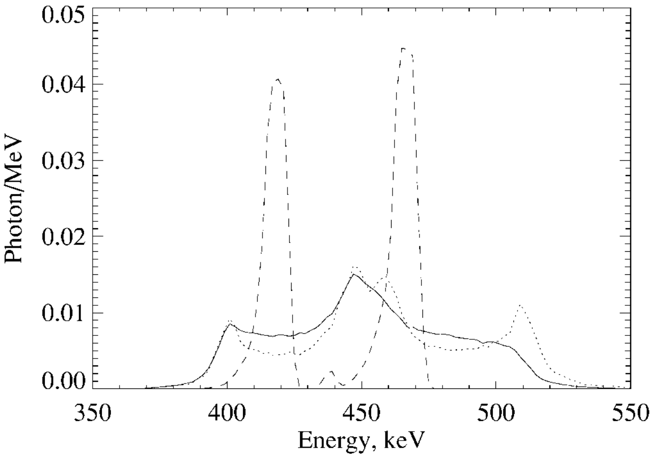

FIG. 2.—Comparison of the calculated α-^{4}He line shapes for a flare at a heliocentric angle of 73°. *Solid curve*: Downward-isotropic distribution (similar to one for α-particles undergoing saturated PAS in the corona). *Dotted curve*: Fan-beam distribution. *Dashed curve*: Downward beam.

flare. We compare these observations with line-shape calculations to estimate the angular distribution of interacting α-particles. We compare our results on the angular distribution with those obtained for the same flare from redshifts of deexcitation lines (Smith et al. 2003) and from the delayed time profile of the neutron-capture line (Murphy et al. 2003).

2. THE α-HELIUM LINE OBSERVATION AND MODELS

Lin et al. (2002) and Smith et al. (2002) discuss the *RHESSI* experiment and its spectroscopic capabilities. Soft X-ray emission from the X4.8 class flare (NOAA Active Region 0039, S13°, E72°) on 2002 July 23 was observed by *GOES* beginning at 00:18 UT and peaking at 00:34 UT. *RHESSI* observed the flare until about 01:16 UT when it was occulted by the Earth. We accumulated 960 s of spectral data from 00:27:20 to 00:43:20 UT to study the solar α-^{4}He lines. We estimated the background during the flare using 960 s spectral accumulations on the previous and subsequent days ($\pm$15 orbits) when the satellite passed over similar geographic locations (Smith et al. 2003; Share et al. 2003). In Figure 1, we plot the count spectrum observed by *RHESSI* between 370 and 600 keV, after subtracting this background. The spectrum is dominated by the positron-electron annihilation line and the bremsstrahlung continuum.

We constructed a model solar photon spectrum, passed it through the instrument response function, and fitted the background-corrected data from 150 to 8500 keV (Lin et al. 2003; Share et al. 2003). This model spectrum included a double–power-law bremsstrahlung spectrum, the solar annihilation line and its positronium continuum, a nuclear deexcitation line function made up of 15 narrow and broad Gaussians (Smith et al. 2003), the neutron-capture line (Murphy et al. 2003), and a model for the α-^{4}He fusion line complex. We plot the calculated line shapes of this complex for three representative angular distributions of interacting α-particles in Figure 2 for a flare at a heliocentric angle of 73°. The most distinctive shape is for a downward beam, for which the ^{7}Be and ^{7}Li lines would be clearly resolved by *RHESSI*. A downward-isotropic distribution (i.e., one that is isotropic in the hemisphere toward the solar surface and has no component away from the Sun) exhibits a broad structure from ~400 to 500 keV, peaking near 450 keV where the two lines sum together. At this heliocentric angle the downward-isotropic and fully isotropic distributions of interacting particles produce line shapes that are indistinguishable. The line shape for a fan-beam distribution, expected for particles interacting at their mirror points (Murphy et al. 1988, 1990), is almost indistinguishable from the downward-isotropic distribution.

We have fitted the *RHESSI* count spectrum shown in Figure 1 using these and other angular distributions for α-particles with power-law energy spectra having indices ranging from 3.5 to 4.5. We find no significant change in the fits for the different spectral indices. The fit over the full range in energy, from 150 to 8500 keV, is acceptable with χ^2/degrees of freedom $= 0.91$ for 767 degrees of freedom. Share et al. (2003) list the best-fitting parameters derived from this fit. Even though the bremsstrahlung continuum for this flare was very strong and dominated over the α-^{4}He lines, the presence of these lines is required with 99.99% confidence. We base this conclusion on the increase of 16 in χ^2 when we force the flux in the α-^{4}He lines to 0, with all other parameters free to vary. The positronium continuum, lying just below the 511 keV annihilation line, has a distinctly different shape from the α-^{4}He fusion line complex and is readily separated. We have only been able to set an upper limit on this continuum for the flare (Share et al. 2003). We have multiplied our best-fitting line shape by a factor of 5 for clarity and plotted it separately in Figure 1. This shape was derived for an interacting angular distribution of α-particles after they undergo saturated PAS in the corona (Hua et al. 1989; Murphy et al. 2003); this calculation has been done only for magnetic loops perpendicular to solar surface at the footpoints. We also plot the count spectrum derived by passing the fitted bremsstrahlung, annihilation, and nuclear line components (excluding the α-^{4}He lines) through the instrument response function. This reveals the relative contribution of the α-^{4}He line complex to the spectrum.

In Figure 3, we plot the *RHESSI* count spectrum from 370 to 500 keV, after removing all the fitted components except for the α-^{4}He line complex; the solid curve is the calculated best-fitting line shape after passing it through the instrument response function. The spectrum is relatively structureless but exhibits evidence for a peak near 450 keV that is expected for α-particles undergoing saturated scattering in the corona. The downward-isotropic and isotropic distributions produce similar

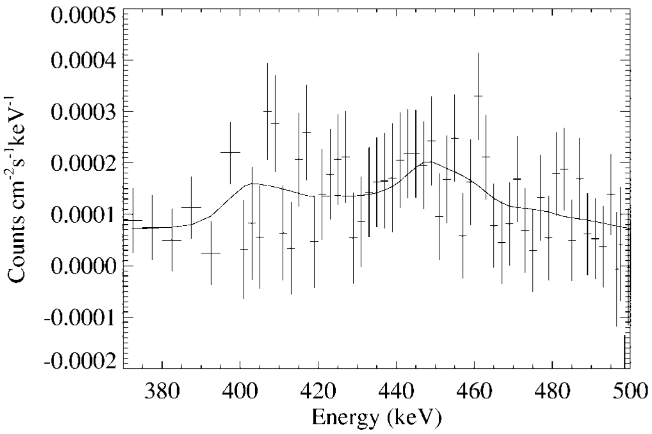

FIG. 3.—Count spectrum of the α-^{4}He line measured by *RHESSI* derived by subtracting the best-fitting bremsstrahlung and other components found to contribute to the background-corrected spectrum. The curve shows the *RHESSI* response to the line shape derived for an α-particle distribution that undergoes saturated PAS in the corona for magnetic loops perpendicular to the solar surface at a heliocentric angle of 73°.

shapes that are not significantly worse fits to the data; a fan-beam distribution would have a 15% chance of fitting the count spectrum as well as the others, based on $\Delta\chi^2$. In contrast, we find that a downward beam of α-particles interacts to produce a line shape with two relatively narrow peaks near ∼418 and 467 keV (see Fig. 2) that is a poor fit to the *RHESSI* count spectrum; there is only an $\sim 10^{-4}$ probability ($\Delta\chi^2 = 14.7$) that such a distribution would fit as well as the others.

3. DISCUSSION

RHESSI has detected the γ-ray line complex from ^{7}Be and ^{7}Li produced when flare-accelerated α-particles interacted with ^{4}He in the chromosphere of the 2002 July 23 flare that occurred at a heliocentric angle of 73°. For a magnetic loop perpendicular to the solar surface at the footpoints, the calculated line shapes for most expected angular distributions of interacting α-particles are similar, except for a downward beam that produces two distinct relatively narrow line features. We passed these line shapes through the instrument response function and found that only the downward beam is an unacceptable fit to the *RHESSI* count spectrum (0.01% probability of fitting as well as the best-fitting shape based on the χ^2 statistic). The best-fitting line shape is produced by interacting α-particles that undergo saturated PAS in the corona (Hua et al. 1989; Murphy et al. 2003). Fits to shapes produced by generic isotropic, downward-isotropic, and fan-beam distributions are also acceptable (>15% probability of fitting as well as the best fit). These results are consistent with earlier studies of the α-^{4}He line made using *SMM* data (Share & Murphy 1997; Share et al. 2002).

Measurements of the redshifts of ^{12}C, ^{16}O, and ^{20}Ne from 19 flares observed by *SMM*, grouped by heliocentric angle, placed additional constraints on the angular distributions of interacting particles. Isotropic and fan-beam angular distributions could be ruled out with confidence greater than 99%, while a downward beam was excluded at 99.5% confidence (Share et al. 2002). The best fits were obtained for interacting particles that suffered significant PAS in the corona or for a generic isotropic distribution of particles that primarily interact in the forward hemisphere. In all these cases it was assumed that the magnetic loops containing the accelerated particles were perpendicular to the solar surface at the footpoints.

There are two Letters in this issue that also address the angular distribution of interacting ions in the 2003 July 23 flare (Smith et al. 2003; Murphy et al. 2003). Smith et al. (2003) have studied the line shifts and shapes of six de-excitation lines greater than 800 keV and find that the lines are redshifted from their laboratory values between 0.1% and 0.8%. These shifts are significantly larger than that produced by the distribution favored by the *SMM* analysis, i.e., an isotropic particle distribution that interacts primarily in the forward hemisphere perpendicular to the solar surface. Smith et al. (2003) offer two suggestions that could explain these large redshifts: (1) the magnetic loop containing the particles might be inclined by ∼40° toward Earth, and (2) the interacting particles might be highly beamed normal to the solar surface. The first suggestion is consistent with our α-^{4}He line measurements; we find that a forward isotropic distribution interacting in such a tilted loop would fit the data as well or better than our most favored distribution ∼15% of the time based on a $\Delta\chi^2$ analysis. In contrast, as discussed above, a narrow beam is inconsistent with the *RHESSI* spectrum with high confidence (99.99%).

Murphy et al. (2003) studied the time history of the 2.223 MeV neutron-capture line to infer the angular distribution of interacting particles that produce the neutrons. They used the same physically based model cited above, which includes PAS and transport of the interacting particles, to calculate the time history. Their calculations have been performed only for magnetic loops that are perpendicular to the solar surface at the footpoints. They find that the *RHESSI* data are fitted best by an interacting particle distribution produced with a modest amount of PAS; they cannot rule out saturated PAS that produces distributions of particles primarily interacting in the forward direction at a heliocentric angle of 73°. The best-fitting models to the neutron-capture line observations are also consistent with the α-^{4}He line measurements (>68% confidence). Murphy et al. (2003) note that had they been able to perform their calculations for a magnetic loop tilted toward Earth, as suggested by the de-excitation line measurements (Smith et al. 2003), more forward-directed interacting particle distributions would have fitted the data better.

In conclusion, we can conceive of only one scenario that is consistent with the high-energy de-excitation line, neutron-capture line, and α-^{4}He line measurements of the angular distribution of interacting particles for the 2003 July 23 flare. This requires a magnetic loop that is tilted toward Earth and a broad forward-directed particle distribution that impacts the solar atmosphere.

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