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Solar Gamma-Ray Lines as Probes of Accelerated Particle Directionalities in Flares

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ABSTRACT

Anisotropies of charged particles accelerated in solar flares can be studied by observing Doppler shifts of selected gamma-ray lines. We have calculated the spectral shape of the 6.1-MeV line of ^{16}O. If the accelerated particles are isotropic, the line remains centered at E_0 = 6129.4 keV, and its width (FWHM) is about 100 keV. However, for particle anisotropies that may be produced in solar flares, the line is shifted to lower energies by about 30 to 40 keV.

I. INTRODUCTION

Emission lines in the gamma-ray band have been detected from the large solar flares of 4 and 7 August 1972 (Chupp et al. 1973). The observed lines, at 0.5, 2.2, 4.4 and 6.1 MeV, are due to positron annihilation, neutron capture on hydrogen, and the deexcitation of nuclear levels in ^{12}C and ^{16}O, respectively (Lingenfelter and Ramaty 1967). The basic mechanism for the production of gamma-ray lines in flares is interactions between primary accelerated particles and atomic nuclei in the solar atmosphere (Ramaty et al. 1975).

The positrons and neutrons which result from these energetic interactions are thermalized by the ambient medium before they annihilate or get captured (Wang and Ramaty 1974, 1975). Therefore, any directional anisotropies in the primary particles would be lost before the gamma rays at 0.51 MeV and 2.2 MeV and produced. On the other hand, the ^{12}C and ^{16}O nuclei, which emit the lines at 4.4 MeV and 6.1 MeV, are excited by protons of energies of several tens of MeV which also impart kinetic energy to these nuclei. Because the gamma rays are subsequently emitted in a time interval short compared with the slowing-down time of the nuclei, any directional anisotropy in the primary particles would cause a Doppler shift in the energy of the lines. In the present letter we calculate the Doppler shift of the 6.1-MeV line for various angular distributions of the primary particles, and we show that observable Doppler shifts result from particle anisotropies which might be present in solar flares.

II. Calculation of Line Profiles

The 6.1-MeV line in solar flares is produced by the reactions $^{16}O(p,p')^{16}O^{*6.1}$ and $^{16}O(\alpha,\alpha')^{16}O^{*6.1}$. Since both of these reactions result in two bodies in the final state, the kinematics are straightforward, and the spectral shape of the deexcitation line is readily determined from data on the differential cross sections of the reactions. The 4.4-MeV line is produced by the corresponding reactions in ^{12}C, $^{12}C(p,p')^{12}C^{*4.4}$ and $^{12}C(\alpha,\alpha')^{12}C^{*4.4}$. In addition, the three-body reaction, $^{16}O(p,p\alpha)^{12}C^{*4.4}$, contributes to the 4.4-MeV line. Because there are no data on the differential cross section for this reaction, we limit our quantitative study in the present letter to the 6.1-MeV line.

We use nonrelativistic kinematics. Because the total excitation cross sections and the particle energy spectra decrease with increasing energy, the energy range in which the majority of the contributing interactions occur is limited to values less than about 100 MeV. For such low kinetic energies, all the nuclear velocities are nonvelativistic.

Consider a projectile of mass m and velocity β (proton or α-particle) interacting with an oxygen nucleus of mass M. Let the excited nucleus emerge from the reaction with a velocity β_s^* and directional cosine μ_s^* with respect to the projectile's velocity vector in the center of mass frame. (The speed of light is taken to be unity.) Because there are only 2 bodies in the final state, β_s^* is uniquely determined by β:

$$\beta_s^{*} = \beta_c^{2} - 2(\Delta E)m/[M(m + M)]. \quad (1)$$

Here $\beta_c = \beta m/(m + M)$ is the velocity of the center of mass, and $\Delta E = 6130.66 \pm .18$ keV (Ajzenberg-Selove 1971) is the energy of the 3^- level in ^{16}O. This level decays to the ground state by an electric octopole transition and has a lifetime of about 10^{-11} s (Hellwege and Hellwege 1961). The velocity and directional cosine of the oxygen nucleus in the frame of the Sun are

$$\beta_s^{2} = \beta_c^{2} + \beta_s^{*2} + 2\beta_c\beta_s^{*}\mu_s^{*}, \quad (2)$$

and

$$\mu_s = (\beta_c + \beta_s^{*}\mu_s^{*})/\beta_s. \quad (3)$$

We denote by μ_γ' the cosine of the angle between the 6.1-MeV gamma ray and the velocity vector of the oxygen nucleus in the rest frame of this nucleus. In the frame of the Sun, this directional cosine is

$$\mu_\gamma = (\beta_s + \mu'_\gamma)/(1 + \beta_s\mu_\gamma'). \quad (4)$$

Taking into account the Doppler shift, the energy of the gamma ray is given by

$$E_\gamma = E_o(1 + \beta_s\mu_\gamma), \quad (5)$$

where E_o is its energy in the rest frame of the emitting nucleus. Because the oxygen nucleus recoils when it emits a photon, E_o is slightly less than ΔE,

$$E_o = \Delta E - (\Delta E)^2/(2M) = 6129.4 \text{ keV} \quad (6)$$

Finally, the cosine of the angle between the gamma ray and the velocity vector of the projectile is

$$\mu = \mu_s\mu_\gamma + (1-\mu_s^{2})^{1/2}(1-\mu_\gamma^{2})^{1/2}\cos(\phi_s-\phi_\gamma), \quad (7)$$

where $\phi_s - \phi_\gamma$ is the difference between the azimuths of the projectile and gamma ray in a plane perpendicular to the velocity of the oxygen.

We used a Monte-Carlo simulation to calculate the energy distribution of the gamma rays. The directional cosines μ_s^* and μ_γ' are assumed to be uniformly distributed random numbers in the range -1 to 1. For μ_s^* this assumption is consistent with data on the differential cross section for the reactions $^{16}O(p,p')^{16}O^{*6.1}$ and $^{16}O(\alpha,\alpha')^{16}O^{*6.1}$ (Kobayashi 1960, Bergman and Hobbie 1971). For μ_γ' the above assumption simply means that the gamma rays are emitted isotropically in the rest frame of the oxygen nucleus. A random number is also assigned to the projectile velocity, β. The distribution of this number is determined by the energy spectrum of the primary particles and the energy dependence of the total cross section. We have used the data compiled by Ramaty et al. (1975), and we assumed that the differential number spectrum of the primary particles is a power law with spectral index 2.

If the distribution of projectile velocities is isotropic, all the gamma rays generated by the simulation contribute to the spectrum, regardless of the value of μ, the cosine of the angle between the projectile and the gamma ray. The results for this case are shown by the solid curves in Figures 1a and 1b, for proton and α-particle induced reactions, respectively. As can be seen, the resultant spectra are almost symmetric. The small blue shift, however, is real. It is caused by the finite velocities of the emitting nuclei which transform the isotropic rest—frame radiation patterns into patterns peaked in the direction of motion. The blue shift is due to the fact that radiation seen by any observer comes, on the average, more from nuclei having velocity components toward the observer than away from him.

We consider now gamma-ray spectra resulting from projectiles with anisotropic velocity distributions. The dashed curves in Figures 1a and 1b show the gamma-ray spectrum produced by projectiles whose velocity vectors are uniformly distributed in hemisphere away from the observer, and the dashed-dotted curves represent a case in which the projectiles are directed away from the observer in a cone of half angle 60°. In the Monte-Carlo simulation the angle μ is obtained from equation (5) with $\phi_s - \phi_\gamma$ being a uniformly distributed random number between 0 and 2π; only those events which satisfy the conditions $-1\leq\mu\leq0$ or $-1\leq\mu\leq-0.5$ contribute to the respective spectra.

Both anisotropic angular distributions cause large red shifts. For proton-induced reactions, the shift in the peak of the spectrum ranges from about 25 keV to 35 keV. For α-particle induced reactions the shift ranges from about 40 keV to 60 keV. The relative contribution of the protons and alpha particles depends on the spectral indices of the particle-energy distributions (Ramaty et al. 1975). For a spectral index of 2, as was assumed in the present calculations, 20% of the gamma rays result from α-particle-induced reactions. The shift of the composite gamma-ray spectrum then ranges from approximately 30 to 40 keV. If the angular distribution of the projectiles were more sharply peaked forward, rather than being uniform within the prescribed boundaries, the shift of the gamma-ray spectrum would be even larger.

The excited state $^{16}O^{*6.1}$ can also be produced by accelerated oxygen nuclei interacting with ambient hydrogen and helium. Since the Doppler widths of the resultant line are about 1 MeV, this radiation cannot be distinguished from the continuum and does not contribute to line emission.

III. Discussion and Conclusions

Redshifts of the order of several tens of keV are large compared with the energy resolution (~ 3 keV) of presently available detectors (Metzger 1973), and hence such detectors should be able to measure these redshifts. The detection of redshifts in solar gamma-ray lines would support flare models in which particle acceleration occurs at coronal heights and the nuclear interactions are produced by particle fluxes directed downward towards the Sun (e.g. Sturrock 1973). Since the magnitude of the redshift depends on the angle between the particle beam and direction of observation, the location of the flare on the Sun will also have an effect on the observed redshifts. Because of their limited energy resolution, the present measurements of Chupp et al. (1973) cannot provide information on the spectral shape or precise energy of the 4.4-and 6.1-MeV lines.

The determination of the spectral shapes of nuclear deexcitation lines from solar flares will be complicated by background radiations and confusion between lines. For example, the 6.1-MeV line of ^{16}O could be confused with the 6.3-MeV line of ^{15}N. The latter is produced by the reaction $^{16}O(p,2p)^{15}N^{*6.3}$ with comparable intensity to that of the 6.1-MeV line (Ramaty et al. 1975). However, because the separation between these two lines, 198 keV, is larger than their broadening, we expect that they will be separable with detectors having high energy resolution.

As discussed in the Introduction, the energies of the 2.2-MeV and 0.51-MeV lines are not affected by the anisotropy of the primary particles.

The 2.2-MeV line, in particular, has a very narrow width of only 100 eV and its energy is accurately known to be 2223.3 keV independent of any solar parameter (Ramaty et al. 1975). Therefore, this line can be used as a calibration point of the flare spectrum, independent of charged particle anisotropies. For the 4.4-MeV line of ^{12}C we expect comparable redshifts and spectral broadening as for the 6.1-MeV line.

In summary, high-resolution observations of the spectral-shape and mean energy of selected γ-ray lines would provide a new measure of the role of accelerated particles in the dynamics of solar flares.

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REFERENCES

Ajzenberg-Selove, F. 1971, Nuclear Physics A, 166, 1.

Bergman, C. and Hobbie, R. K. 1971, Physical Review C, 3, 1729.

Chupp, E. L., Forrest, D. J., Higbie, P. R., Suri, A. N., Tsai, C., and Dunphy, P. P. 1973, Nature, 241, 333.

Hellwege, A. M. and Hellwege, K. H. 1971, Energy levels of Nuclei: A = 5 to A = 257, (Springer-Verlag, Berlin).

Kobayashi, S. 1960, J. Phys. Soc. Japan, 15, 1164.

Lingenfelter, R. E. and Ramaty, R. 1967, High Energy Nuclear Reactions in Astrophysics, edited by B. S. P. Shen (W. A. Benjamin, New York), p. 99.

Metzger, A. 1973, Gamma Ray Astrophysics, edited by F. W. Stecker and J. I. Trombka, NASA SP-339, (National Aeronautics and Space Administration, Washington, D. C.), p. 97.

Ramaty, R., Kozlovsky, B. and Lingenfelter, R. E. 1975, Space Science Reviews, in press.

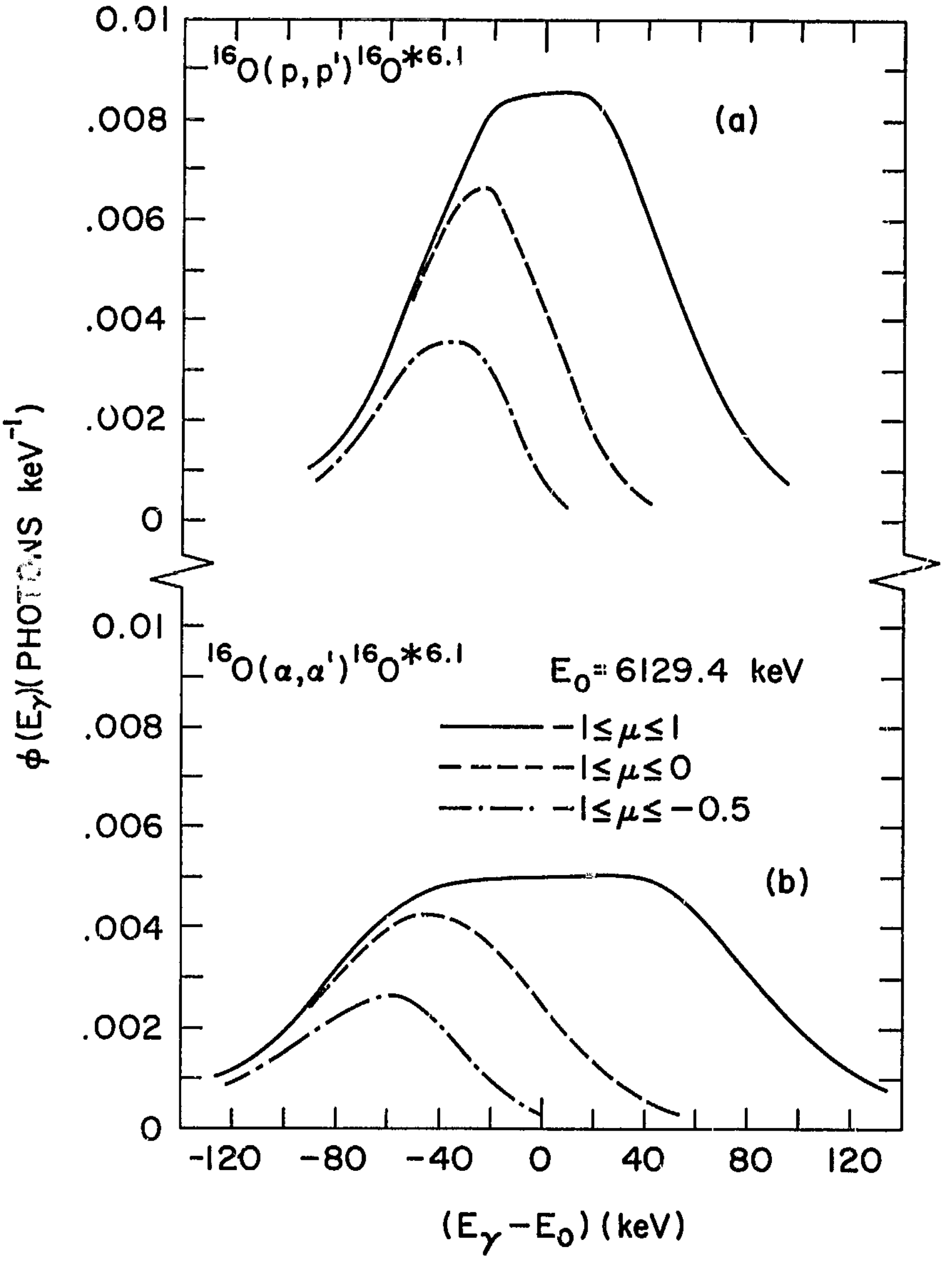
Sturrock, P. A. 1973, High Energy Phenomena on the Sun, edited by R. Ramaty and R. G. Stone, NASA SP-342 (National Aeronautics and Space Administration, Washington, D. C.), p. 3.

Wang, H. T. and Ramaty, R. 1974, Solar Physics 36, 129.

Wang, H. T. and Ramaty, R. 1975, to be published.

FIGURE CAPTION

Energy spectra of gamma rays from the reactions (a) $^{16}O(p,p')^{16}O^{*6.1}$ and (b) $^{16}O(\alpha,\alpha')^{16}O^{*6.1}$. The solid lines were obtained from an isotropic distribution of protons and alpha particles and are normalized such that the integral of $\phi(E_\gamma)$ is unity. The dashed and dashed-dotted curves are obtained from the same distribution, having the same normalization as the isotropic case, with the additional restriction that μ, the cosine of the angle between the direction of observation and proton or α-particle velocities, lies within the indicated ranges.



0.01
.008
.006
.004
.002
0
$^{16}O(p,p')^{16}O^{*6.1}$
(a)
$^{16}O(\alpha,\alpha')^{16}O^{*6.1}$
E_0 = 6129.4 keV
$-1 \le \mu \le 1$
$-1 \le \mu \le 0$
$-1 \le \mu \le -0.5$
(b)
$\phi(E_\gamma)$ (PHOTONS keV^{-1})
-120
-80
-40
0
40
80
120
$(E_\gamma - E_0)$ (keV)