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**GAMMA RAYS FROM THE
DE-EXCITATION OF
 $^{12}\text{C}^*(15.11 \text{ MeV})$ AND $^{12}\text{C}^*(4.44 \text{ MeV})$
AS PROBES OF
ENERGETIC PARTICLE SPECTRA**

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AND C-12 RESONANCE 4.44 MeV AS PROBES OF
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Presented at the 12th ESLAB Symposium, "Recent Advances in Gamma-Ray Astronomy,"
Frascati, Italy, 1977 May 24-27



GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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ABSTRACT

The flux of 15.11 MeV γ rays relative to the flux 4.44 MeV γ rays has been calculated from measured cross sections for excitation of the corresponding states of ^{12}C and from experimental determinations of the branching ratios for direct de-excitation of these states to the ground state. Because of the difference in threshold energies for excitation of these two levels, the relative intensities in the two lines are particularly sensitive to the spectral distribution of energetic particles which excite the corresponding nuclear levels. For both solar and cosmic emission, the observability of the 15.11 MeV line is expected to be enhanced by low source-background continuum in this energy range.

Keywords: γ Rays, Line Emission, Solar Flares, Astrophysics

1. INTRODUCTION

In astronomical observations, as well as in laboratory measurements, γ ray lines serve as probes of energetic particle interactions. Gamma ray line emission is evidence that the nuclear species with the corresponding nuclear energy level has been excited by particles with kinetic energies above the excitation threshold. The γ ray spectrum expected during solar flares was first studied extensively by Dolan and Fazio (1965). The nuclear interactions of accelerated charged particles in solar flares were treated in considerable detail by Lingenfelter and Ramaty (1967). The first detection of solar γ ray lines did not occur, however, until the importance of 3B flare of 1972 August 4. Lines at 0.51, 2.22, 4.44, and 6.13 MeV were reported by Chupp *et al.* (1973) from observations with the γ ray spectrometer aboard the OSO-7 satellite. Ramaty *et al.* (1975) have reviewed the theory of the solar γ rays, relating the observations to the spectrum of accelerated particles in the flare region. The γ ray spectrum in the energy range 4 to 8 MeV has been evaluated by Ramaty *et al.* (1977) with the conclusion that all the emission in that energy range is due to nuclear processes, with the ratio of electrons to protons not exceeding 5%. They further suggest that the observations are best fit by a relatively flat spectrum of

particles whose velocity vectors do not point predominantly towards the photosphere.

The significance of γ ray lines more energetic than the 7.12 MeV line of ^{16}O has not been considered previously because most of the higher energy states are particle unstable and lead to little or no γ ray emission. The information to be gained from observations of a high energy γ ray line should not, however, be overlooked. A γ ray line from a high energy state, observed together with a line from a low energy state well separated in energy but in the same nucleus, would provide a very sensitive measure of the energetic particle spectrum in solar flares or other astrophysical processes. One high energy line, resulting from the decay of $^{12}\text{C}^*(15.11\text{MeV})$, has been extensively studied in laboratory measurements. In the present work, the expected 15.11 MeV line emission relative to the 4.44 MeV line emission from a lower lying state in ^{12}C has been calculated from the measured cross sections. The results, for various functional dependences of the accelerated particle spectrum, are presented in the following section. In Section 3 the expected bremsstrahlung and π^0 decay contributions to the γ ray continuum above 10 MeV are shown to be well below the predicted flux density for the 15.11 MeV line in solar flares. The significance and observability of 15.11 MeV line emission are summarized in the final section.

2. NUCLEAR PROCESSES

With one exception, all excited states in the nucleus ^{12}C with energies above the threshold for alpha emission at 7.367 MeV decay predominantly by direct particle emission and thus produce few nuclear γ rays. The one exception is the lowest energy isospin $T = 1$ state, the analog to the ground state in ^{12}B and ^{12}N , at 15.11 MeV. This state lies below the most favorable single particle emission threshold, $^{12}\text{C} \rightarrow ^{11}\text{B} + p$, by 0.85 MeV and is thus stable against neutron or proton emission. If this level were a pure $T = 1$, decay by alpha emission would be forbidden by isospin conservation. There is a small admixture of $T = 0$ in this state, but the measured alpha to gamma decay branching ratio is only 0.041 ± 0.009 (Balamuth *et al.* 1974). Since electromagnetic transitions

can change the nuclear isospin by 1, the state can decay by emission of a γ ray. In the case of 15.11 MeV excitation, the decay directly to the ground state is dominant. A weighed average of the experimentally measured branching ratios (Ajzenberg-Selove 1976) gives $\Gamma_{0\gamma}/\Gamma_{\gamma} = 0.952 \pm 0.009$. Thus de-excitation of the 15.11 MeV state in ^{12}C proceeds by γ ray emission directly to the ground state $91 \pm 2\%$ of the time.

The important cross sections for producing 4.44 and 15.11 MeV γ rays are shown in Figure 1 as a function of the kinetic energy of the incident particle. The dotted curve showing the cross section for excitation of the 4.44 MeV level in ^{12}C by protons is obtained from the data of Martin *et al.* (1953) for $4.4 \leq E_p \leq 6.5$ MeV, Reich *et al.* (1956) for $4.4 \leq E_p \leq 5.5$ MeV, Barnard *et al.* (1966) for $6.6 \leq E_p \leq 11.6$ MeV, and Nagahara (1961) for $9.5 < E_p < 16$ MeV, where E_p is the kinetic energy of the incident proton. Up to an energy of 19 MeV, the cross section for excitation of the 4.44 MeV state in ^{12}C shows considerable structure. In the work of Martin *et al.* and Reich *et al.* the excitation cross section was measured by detecting the 4.44 MeV de-excitation γ ray at 90° . The total cross section represented by the dotted curve was obtained by assuming that the cross section for proton emission is isotropic. Differential cross sections measured by Reich *et al.* at three different energies located near the first resonance, at 5.188, 5.297, and 5.425 MeV, show that this assumption of isotropy leads to errors in the total cross section of more than 60% in the first two resonances. Since the integral under these peaks is a very small percentage of the total

cross section integrated over all energies, this uncertainty in the region of the first two resonances does not significantly affect the results of this work. In the experiments of Barnard *et al.* and Nagahara, differential cross sections were measured for a wide range of angles of the recoil proton at each incident proton energy. The cross sections shown here as the dotted curve include the total cross sections given by these authors.

In the present analysis, the cross sections for producing 4.44 MeV γ rays by proton interactions are taken from the work of Ramaty *et al.* (1977) represented by the solid curve. At low energies, this curve is an average of the $^{12}\text{C}(p,p')^{12}\text{C}^*(4.44 \text{ MeV})$ cross sections. At higher energies, it includes important contributions due to production of a 4.44 MeV state in ^{11}B from the reaction $^{12}\text{C}(p,2p)^{11}\text{B}^*(4.44 \text{ MeV})$. The cross sections for producing 4.44 MeV γ rays by alpha particle interactions are also taken from the work of Ramaty *et al.* (1977) represented by the dashed curve. This is an important process in the solar medium because of the significant cross section and the abundance of alpha particles.

The total cross sections for production of the 15.11 MeV state in ^{12}C by protons has been measured by a number of workers. The dotted line shown in Figure 1 indicating the 15.11 MeV excitation in ^{12}C is taken from the $^{12}\text{C}(p,p')^{12}\text{C}^*(15.11 \text{ MeV})$ measurements of Warburton and Funsten (1962) for $14 \leq E_p \leq 20$ MeV and from Measday *et al.* (1963) for $14 \leq E_p \leq 48$ MeV. In both of these experiments the 15.11 MeV γ ray was detected only at 90° in the laboratory. The total proton excitation cross sections plotted in Figure 1 were obtained by assuming that the γ ray emission is isotropic in the laboratory and by reducing by 0.8 and 0.9 the results of Warburton and Funsten and Measday *et al.* respectively to obtain agreement with the $^{12}\text{C}(p,p')^{12}\text{C}^*(15.11)$ experiment of Scott *et al.* (1967) at an incident proton energy of 21 MeV.

Above a proton energy of 20 MeV, $^{12}\text{C}(p,p')^{12}\text{C}^*(15.11 \text{ MeV})$ differential cross sections have been measured by Scott *et al.* (1967) for proton energies between 20.5 and 30.3 MeV, Dickens *et al.* (1963) at 31 MeV, Petersen *et al.* (1967) at 46 MeV, and Hasselgren *et al.* (1965) at 185 MeV. The differential cross sections reported by these authors have been integrated to obtain the total cross sections shown in Figure 1. The total cross section obtained from the work of Hasselgren *et al.* of 0.5 mb is not shown in Figure 1, but was used in the analysis. For proton energies above 24 MeV these cross sections fall above those given by the dashed curve. This is almost certainly due to the nonisotropic nature of the 15.11 MeV γ ray emission.

Other nuclear reactions which produce the 15.11 MeV state are significantly reduced when compared to inelastic proton scattering. The excitation of the 15.11 MeV state by alphas has been observed (Spuller *et al.* 1975) but is suppressed by more than an order of magnitude due to the parity and isospin of the state, and is thus not important in stellar processes. The cross sections for $^{16}\text{O}(p,p')^{12}\text{C}^*(15.11 \text{ MeV})$ have not been measured. The ratio of this cross section to the cross section for the direct process $^{12}\text{C}(p,p')^{12}\text{C}^*(15.11 \text{ MeV})$ may be assumed to be approximately the same as the

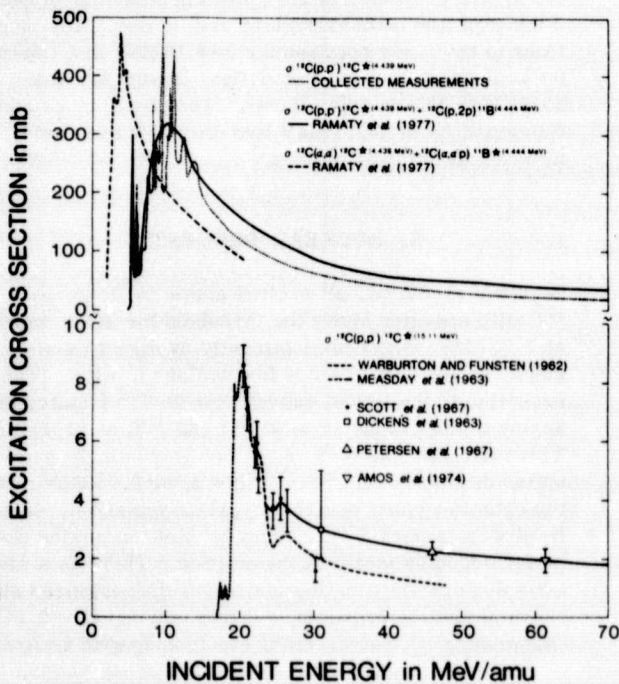


Figure 1. Cross sections for production of $^{12}\text{C}^*(4.439 \text{ MeV})$, $^{11}\text{B}^*(4.444 \text{ MeV})$, and $^{12}\text{C}^*(15.11 \text{ MeV})$ as a function of the kinetic energy of the exciting particle.

equivalent ratio for producing the 4.44 MeV state in ^{12}C . Thus these secondary reactions on ^{16}O would be expected to enhance the intensities of both lines without significantly altering the ratio of line intensities. For consistency, all $p, p'\alpha$ interactions are omitted in the following considerations.

The solid curves shown in Figure 1 are visual fits to the excitation cross section data. Above a proton kinetic energy, E_p , of 30 MeV, the cross sections for excitation of both the 4.44 and 15.11 MeV states are assumed to decrease as $1/E_p$, in agreement with the available experimental data. The cross sections represented by the solid lines, along with the $1/E_p$ extrapolation to high proton energies, were employed in arriving at the flux estimates presented in this paper.

As is made clear in Figure 1, the cross sections for production of the two nuclear states have different energy dependences, and thus the relative intensities of the 15.11 MeV and 4.44 MeV lines depend on the functional form of the energy spectra of incident protons and alpha particles. In this work the energy spectrum is parameterized by two variables as in the solar γ ray review of Ramaty *et al.* (1975). The energy in spectrum is assumed to be constant from 0 to some cutoff energy E_c , and then to decrease with a power law with exponent s , or

$$\frac{dN_p}{dE_p} = \begin{cases} C & E \leq E_c \\ C \left(\frac{E_p}{E_c} \right)^{-s} & E > E_c \end{cases} \quad (1)$$

The ratio of alpha particle to proton flux is assumed to be 0.07, in accord with Cameron (1973) abundances. The ratios of the fluxes of the two lines $\phi(15.11)/\phi(4.44)$ is thus given by the expression

$$\frac{\phi(15.11)}{\phi(4.44)} = 0.91 \int_0^\infty \sigma_{15.11}(p,p') v \left(\frac{dN_p}{dE_p} \right) dE_p / \left\{ \int_0^\infty \sigma_{4.44}(p,p') v \frac{dN_p}{dE_p} dE_p + 0.07 \int_0^\infty \sigma_{4.44}(\alpha,\alpha') v \frac{dN_p}{dE_p} dE_p \right\}, \quad (2)$$

where $\sigma_{15.11}(p,p')$ and $\sigma_{4.44}(p,p')$ are the cross sections for producing the 15.11 and 4.44 MeV states in ^{12}C by proton collisions, $\sigma_{4.44}(\alpha,\alpha')$ is the cross section for producing the 4.44 MeV state by alpha collisions, and v is the velocity of the incident particle. In Figure 2 the ratio predicted by Equation (2) is plotted as a function of s for four different values of E_c ranging from 0 to 30 MeV. For the more probable cases with $E_c \geq 20$ MeV (Ramaty *et al.* 1977) the intensity of the 15.11 MeV line is greater than 1% of the 4.44 MeV line for all values of s .

3. CONTINUUM AND LINE EMISSION ABOVE 10 MeV

The expected line emission at 15.11 MeV has been calculated from the cross sections presented in the previous section. The observed nuclear-line emission and the continuum radiation in the 1972 August 4 solar flare have been employed for normalization.

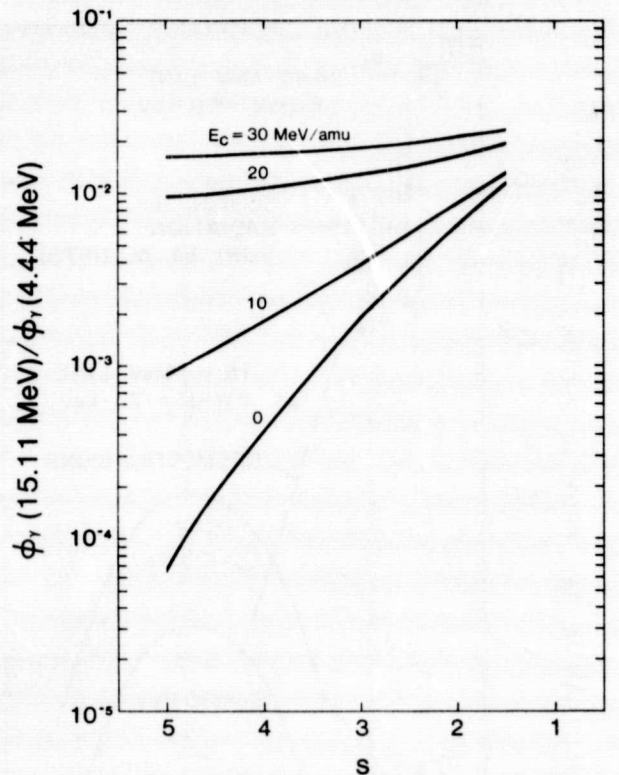


Figure 2. Ratio of the flux of 15.11 MeV to the flux of 4.44 MeV gamma rays as a function of the spectral index of the exciting particle.

The continuum radiation reported by Suri *et al.* (1975) in the energy interval 1 to 7 MeV for the 1972 August 4 flare are shown as data points with associated statistical uncertainties in Figure 3. The total flux observed in the interval 4 to 8 MeV, including both line emission and continuum radiation, is $0.2 \text{ photons cm}^{-2} \text{ s}^{-1}$, one third of which is reportedly observed in the 4.4 MeV and 6.1 MeV lines (Chupp *et al.* 1975). Calculations by Ramaty *et al.* (1977) suggest that all of the observed emission above 4 MeV is of nuclear origin, with the continuum radiation resulting from Doppler-broadened γ ray lines. Such extreme Doppler broadening is thought to be due to the de-excitation of energetic heavy nuclei which have been accelerated in solar flares. These nuclei are excited by interactions with the ambient solar medium and decay before slowing down.

The possible contribution of electron bremsstrahlung to the γ ray continuum above 8 MeV has been estimated under the assumption that the contribution for energies between 4 and 8 MeV is at most half of the total observed flux. Because best estimates indicate that electron bremsstrahlung above 4 MeV is entirely negligible, half the observed flux may be considered a very generous upper limit. The high energy bremsstrahlung spectrum is normalized in the interval 4 to 8 MeV and extrapolated with a spectral index of 3, as shown in Figure 3. For the energy range under consideration, an index of 3 for the photon spectrum corresponds to an instantaneous electron spectrum with a power-law index slightly less than 3, a typical value for the spectra of electrons

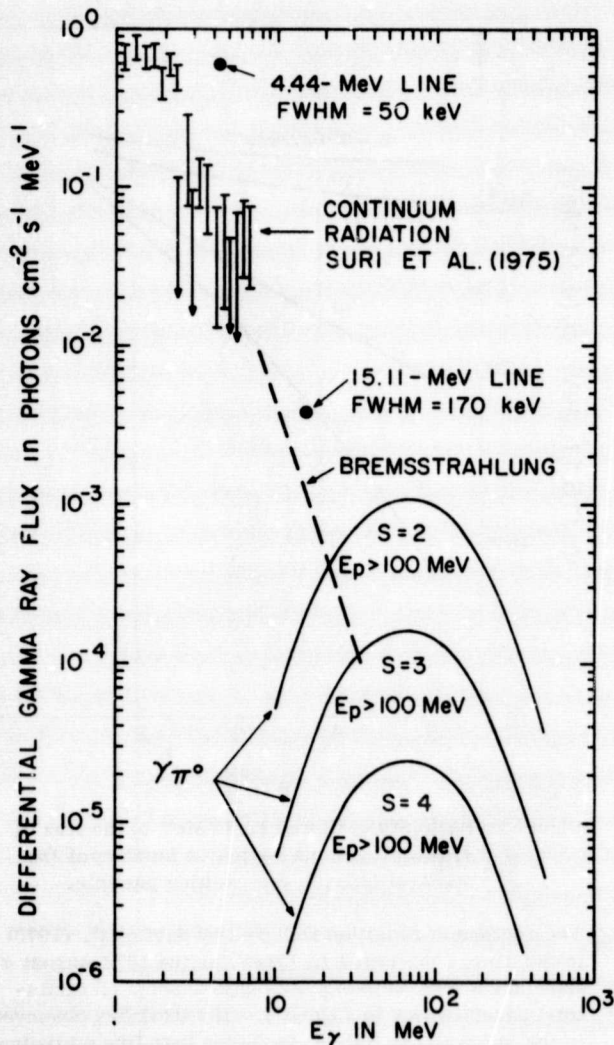


Figure 3. Gamma-ray line emission and continuum radiation above 10 MeV for a differential proton spectrum of the form $dN_p/dE_p \propto E_p^{-s}$ with $s = 0$ for $E_p \leq 30$ MeV and $s = 2$ for $30 \leq E_p \leq 100$ MeV. The calculated fluxes are normalized to the line emission and continuum radiation observed below 8 MeV in the 1972 August 4 solar flare. Three estimates of the gamma-ray continuum due to π^0 decay are presented: one with a proton spectrum which continues above 100 MeV with a power-law index of $s = 2$. The others break at 100 MeV, continuing with power-law indices of $s = 3$ or 4 . All three are cut off at an energy of 1000 MeV.

observed in a large number of solar flares (Datlowe 1971).

The spectra for π^0 γ rays, shown in Figure 3, have been taken from the work of Crannell et al. (1977). The fluxes were calculated from measured differential cross sections for π^0 production.

The 4.44 MeV line emission observed in the 1972 August 4 flare is shown in Figure 3, normalized to that

differential flux expected for an idealized line width of 50 keV, FWHM. This is the expected width of the line due to Doppler broadening alone, calculated by Ramaty et al. (1977) under the simplifying assumption that there is no correlation between the direction of the incident proton and the emitted γ ray. Recent measurements by N. S. Wall (private communication) and by P. Dyer (private communication), however, indicate that this assumption should be reevaluated in any detailed analysis of the 4.44 MeV line. The uncertainties reported by Chupp et al. (1975) are $\pm 33\%$ of the observed flux. The corresponding 15.11 MeV line emission is shown for a Doppler width of 170 keV and an instantaneous proton spectrum which is flat up to an energy of 30 MeV and which decreases with a spectral index of 2 above that energy. Both the 4.44 and the 15.11 MeV line emission are insensitive to steepening of the proton spectrum above 100 MeV. In addition to line emission at 15.11 MeV, continuum radiation with the same total flux is expected from the interactions of energetic carbon nuclei with the ambient solar medium.

4. CONCLUSIONS

Line emission from the 15.11 MeV excited state of ^{12}C has been shown to be a sensitive measure of the energy spectrum of the protons accelerated in solar flares. The results presented in Figure 2 demonstrate that the flux of 15.11 MeV γ rays relative to the flux of 4.44 MeV γ rays is a strong function of the characteristics of the proton spectrum in the energy range 10 to 100 MeV. Uncertainties in the expected spectral dependence of the flux ratio are due primarily to lack of measured cross sections for the process $^{16}\text{O}(p, p'\alpha)^{12}\text{C}^*(15.11 \text{ MeV})$. A knowledge of these cross sections is required for accurate quantitative interpretations of solar flare observations.

Observability of the 15.11 MeV line depends on the intensity of the line emission, the intensity of other emission within the band pass defined by the width of the line, and the instrumental resolution and sensitivity with which it is observed. The continuum radiation in an energy interval around 15.11 MeV is expected to be low and not to limit the observability of the line. The detection probability of 15.11 MeV γ rays is enhanced by the high interaction cross section, which rises in this energy range due to the pair-production process. The energy resolution characteristic of NaI scintillation spectrometers for gamma rays in this energy range is the same as the expected Doppler width of the line, so that no severe constraints on the instrumental resolution are required. For flare intensities comparable to the 1972 August 4 solar flare, detectors with 10 times the sensitive area of the OSO-7 instrument, or approximately 500 cm^2 , and 100% duty factor, continuous solar viewing, would enable positive detection of the 15.11 MeV line or definitive restrictions on the spectrum of flare protons.

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