General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

Produced by the NASA Center for Aerospace Information (CASI)

NASA

Technical Memorandum 79623

Solar Gamma Rays
Above 8 MeV

**Carol Jo Crannell, Hall Crannell
and Reuven Ramaty**

August 1978

SOLAR GAMMA RAYS ABOVE 8 MeV

Carol Jo Crannell

Laboratory for Astronomy and Solar Physics

NASA-Goddard Space Flight Center

and

Hall Crannell

Department of Physics

The Catholic University of America

and

Reuven Ramaty

Laboratory for High Energy Astrophysics

NASA-Goddard Space Flight Center

ABSTRACT

Processes which lead to the production of γ rays with energy greater than 8 MeV in solar flares are reviewed and evaluated. Excited states which can be produced by inelastic scattering, charge exchange, and spallation reactions in the abundant nuclear species are considered in order to identify nuclear lines which may contribute to the γ-ray spectrum of solar flares. The flux of 15.11-MeV γ rays relative to the flux of 4.44-MeV γ rays from the de-excitation of the corresponding states in ^{12}C is calculated for a number of assumed distributions of exciting particles. This flux ratio is shown to be a sensitive diagnostic of accelerated particle spectra. Other high-energy nuclear levels are not so isolated as the 15.11-MeV state and are not expected to be so strong. The spectrum of γ rays from the decay of π^{0} is shown to be sensitive to the energy distribution of particles accelerated to energies greater than 100 MeV.

I. INTRODUCTION

In astronomical observations, as well as in laboratory measurements, γ-ray lines serve as probes of energetic particle interactions. Solar γ-ray lines were first detected from the Importance 3B solar flares of 1972 August 4 and 7 by Chupp et al. (1973) with the γ-ray spectrometer aboard the OSO-7 satellite. Theoretical treatments of γ-ray production made prior to 1972 have been reviewed by Ramaty, Kozlovsky and Lingenfelter (1975). They present, in addition, updated interpretations of γ-ray observations, relating them to the spectrum, number, and energy content of accelerated particles. The solar γ-ray spectrum in the energy range 4 to 8 MeV has been studied further by Ramaty, Kozlovsky and Suri (1977) with the conclusion that the emission in that energy range is due almost entirely to nuclear processes, and that the ratio of electrons to protons does not exceed 5%. They suggest that the observations are best fit by a relatively flat spectrum of particles whose velocity vectors do not point predominantly towards the photosphere.

Because most of the higher energy states are particle unstable and lead to little or no γ-ray emission, the significance of γ-ray lines more energetic than the 7.12-MeV line of ^{16}O has only recently been considered (Crannell and Crannell 1976, 1978; Crannell, Ramaty and Crannell 1977). The information to be gained from observations of a high-energy γ-ray line should not, however, be overlooked. Pairs of γ-ray lines,

from the same nuclear species but resulting from the de-excitation of nuclear levels with widely separated thresholds, provide a unique measure of the spectra of high-energy particle within their source.

In the present work, the γ-ray line emission and continuum radiation above 8 MeV are investigated. A number of nuclear states are identified as possible candidates for producing high-energy γ-ray line emission. For one high-energy line, resulting from the decay of $^{12}C^*(15.11 \text{ MeV})$, the excitation cross sections and branching ratios have been studied extensively. These measured cross sections and branching ratios are used to calculate the expected intensity of the 15.11-MeV line emission relative to that of the 4.44-MeV line from a lower-lying state in ^{12}C.

If the spectrum of energetic charged particles extends with sufficient intensity to hundreds of MeV/nucleon in solar flares, high-energy gamma radiation will result from the production and decay of π^0 mesons. The spectra of π^0-decay γ rays have been calculated by Lingenfelter and Ramaty (1967) and by Chong (1972) with the approximation that all π^0 mesons are produced at the mean π^0 energy for the given incident proton energy. In the present work, the total flux of π^0 mesons is re-evaluated and the resultant γ-ray spectra are calculated from measured differential cross sections for π^0 production.

In the next section, the nuclear processes which contribute to line emission and continuum radiation above 8 MeV are described in detail and the relative flux densities are determined.

The resultant γ-ray spectrum, with an estimated upper limit for the bremsstrahlung contribution, is presented in Section III. In the final section, the significance and observability of the predicted spectrum are summarized.

II. NUCLEAR PROCESSES

The strength of γ-ray line emission is proportional to the product of three factors: cross section, branching ratio, and nuclear abundances. Abundances are relatively well known and branching ratios for electromagnetic decay have been determined adequately for most of the states of interest. The cross sections for production of most high-energy states are, however, sparsely measured. One of the well-studied γ-ray transitions, which is also one of the strongest, is produced by decay of the 15.11-MeV state in ^{12}C. In the subsection that follows, the technique for predicting the strength of the 15.11-MeV line relative to that of the 4.44-MeV line is developed, and predictions based on measured cross sections and branching ratios are presented. In Subsection b, the strengths of other γ-ray lines with energies above 8 MeV are compared to the strength of the 15.11-MeV line. The processes which can be expected to make significant contributions to the γ-ray continuum above 8 MeV are bremsstrahlung and π° decay. In Subsection c, the relevant cross sections for production of neutral pions are presented, and the spectral distribution of the subsequent γ-ray continuum is evaluated.

a)   Gamma Rays from the 15.11-MeV State in ^{12}C

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 lowest-
energy, single-particle emission threshold by 0.85 MeV and is
thus stable against neutron or proton emission. If this level
were a pure T = 1 state, decay by alpha emission would be for-
bidden 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, Zurmühle and
Tabor 1974). Because electromagnetic transitions can change
the nuclear isospin by 1 unit, the state can decay readily by
emission of a γ ray. In the case of 15.11-MeV excitation, the
decay directly to the ground state is dominant. A weighted
average of the experimentally measured branching ratios
(Ajzenberg-Selove 1976) yields a value of 0.952 ± 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 ± 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. In the present analysis, the
cross sections for producing 4.44-MeV γ rays by proton inter-
actions are taken from the work of Ramaty, Kozlovsky, and Suri
(1977) which includes measurements up to 10^3 MeV. Their results
are represented by the solid curve. At low energies, this curve
is a smoothed average of the ^{12}C(p,p') ^{12}C*(4.44 MeV) cross sec-
tion. At higher energies, it includes important contributions
due to production of a 4.44-MeV state in ^{11}B from the reaction
^{12}C(p, 2p) ^{11}B*(4.44 MeV). The cross sections for producing

4.44-MeV γ rays by alpha-particle interactions are also taken from the work of Ramaty, Kozlovsky, and Suri (1977) represented by the dashed curve. This is an important process in the solar medium because of the magnitude of the cross section and because of the abundance of alpha particles.

The dotted curve showing some of the structure in the cross section for production of 4.44-MeV γ rays by proton interactions with ^{12}C is obtained from the data of Martin, Schneider and Sempert (1953) for $4.4 \leq E_p \leq 6.5$ MeV; Reich, Phillips and Russell (1956) for $4.4 \leq E_p \leq 5.5$ MeV; Barnard, Swint and Clegg (1966) for $6.6 \leq E_p \leq 11.6$ MeV; and Nagahara (1961) for $9.5 \leq E_p \leq 16$ 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 works of Martin, Schneider and Sempert and of Reich, Phillips and Russell, 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 photon emission is isotropic. Differential cross sections measured at additional angles by Reich, Phillips and Russell at three energies near the first resonance, 5.188, 5.297, and 5.425 MeV, show that this assumption of isotropy leads to discrepancies as large as 60% in the first two resonances. In the experiments of Barnard, Swint, and Clegg and of 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.

The cross sections obtained with alternate methods, by detecting the scattered proton and by detecting the de-excitation γ ray, give satisfactory agreement within the limitations of the experimental measurements. The resonance structure, which would be important for narrow distributions of proton energies, is effectively smoothed when folded with the proton spectra assumed for purposes of the present work.

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}C$(p,p'\gamma)$ ^{12}C*(15.11 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 of Measday et al., respectively, to obtain agreement with the measurement of Scott, Fisher and Chant (1967) for an incident proton energy of 21 MeV.

Above a proton energy of 20 MeV, ^{12}C(p,p') ^{12}C*(15.11 MeV) differential cross sections have been measured by Scott, Fisher and Chant (1967) for proton energies between 20.5 and 30.3 MeV, Geramb et al. (1975) for $22.5 \leq E_p \leq 45$ MeV, Dickens, Haner and

Waddel (1963) at 31 MeV, Petersen et al. (1967) at 46 MeV,
Amos et al. (1974) at 61 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 section
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
representing the measurements of Warburton and Funsten. 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 alpha
particles 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 $^{16}O(p,p'\alpha)$ $^{12}C^*(15.11$ MeV$)$
have not been reported in the literature. Preliminary measure-
ments of the ratio of this cross section to the cross section
for the direct process $^{12}C(p,p')$ $^{12}C^*(15.11$ MeV$)$ (Lapides et al.
1978) have shown that it is approximately the same as the equi-
valent ratio for producing the 4.44-MeV state in ^{12}C. Thus
these secondary reactions on ^{16}O are expected to enhance the
intensities of both lines without significantly altering the
ratio of line intensities. For consistency, all (p,p'α) inter-
actions 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 decrease approximately as $1/E_p$. The cross sections represented by the solid lines, along with interpolations between the higher-energy measurements, 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, Kozlovsky, and Lingenfelter (1975). The energy in the particle 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

$$\frac{dN_p}{dE_p} = \left\{ \begin{array}{ll} C , & E \leq E_c \\ C \left(\frac{E_c}{E_p} \right)^s , & E \geq E_c \end{array} \right\} . \tag{1}$$

The ratio of alpha particle to proton flux is assumed to be 0.07, in accord with abundances given by Trimble (1975). The ratios of the fluxes of the two lines, $\phi(15.11)/\phi(4.44)$ is thus

given by the expression

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

$$+ 0.07 \int_0^\infty \sigma_{4.44}(\alpha,\alpha')v\left(\frac{dN_p}{dE_p}\right)dE_p \Bigg\} , \qquad (2)$$

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, Kozlovsky, and Suri 1977) the intensity of the 15.11-MeV line is greater than 1% of the 4.44-MeV line for all values of s.

b) Gamma Rays from Other Nuclear States above 8 MeV

Production of γ-ray lines above an energy of 8 MeV in the solar atmosphere is restricted by the scarcity of high-energy γ-ray transitions associated with the small number of relatively abundant isotopes. In the present work, excited states which can be produced by inelastic scattering, charge exchange, and spallation reactions in the abundant nuclear species have been considered. Since even the 15.11-MeV line will be difficult to detect with present instrumentation, only those lines which have a relative intensity of at least 5% of the 15.11-MeV line are tabulated here.

Three factors other than the spectrum of incident particles are important in determining the relative strengths of nuclear lines: first, the relative abundance of the target nuclei; second, the cross section for producing the excited state; and third, the branching ratio for electromagnetic decay of the excited state to a suitable level. For most nuclei, cross sections for production of any of the high-energy states are known only at a few selected energies, if at all. Those inelastic scattering cross sections which have been determined are within a factor of three of the cross section for producing the 15.11-MeV state in ^{12}C. Spallation and charge exchange cross sections (p,n) are generally smaller. For purposes of this investigation, therefore, it is assumed that none of the unknown cross sections is significantly greater than that for the 15.11-MeV state in ^{12}C, and hence only those nuclei with moderate abundances relative to ^{12}C have been considered. The nuclear species with abundances greater than 1% that of ^{12}C and their relative abundances in the solar photosphere (Trimble 1975) are presented in Table 1.

In order for an excited state to exhibit a significant γ-ray branching ratio, it must be particle stable. Thus all states above the single-nucleon threshold have been ignored. States above the alpha-particle threshold also were ignored unless alpha decay is forbidden by isospin considerations. The list of excited states is further restricted to those which can be excited by relatively simple reactions with the abundant nuclei listed in Table 1. These reactions are (p,p'), (p,2p),

(p,d), (p,p',α), (p,n), (α,α'), and (α,γ). Hydrogen has no
excited nuclear states below the delta resonance at 294 MeV.
This resonance does decay by γ-ray emission 0.6% of the time
but does not produce line emission because of its intrinsic
width of 115 MeV. The excited states in helium are all above
the particle disintegration threshold. Furthermore, γ-ray
transitions from the first three excited states, which lie in
the energy range 19 to 23 MeV, are either forbidden or inhibited
by the spin and the parity of the nuclear states. In oxygen
and iron there are no particle-stable nuclear levels above 8 MeV.

In Table 2 a list of the energies of strong γ-ray tran-
sitions together with the excited nuclei and the γ-ray branching
ratios (Ajzenberg-Selove 1972, 1975, 1976, 1977; Aizenberg-Selove
and Lauritsen, 1974; Auble, 1977; Endt and Van der Leun 1973;
Fiarman and Hanna 1975; Fiarman and Meyerhof, 1973) are presented.
For the most part, the γ rays are the result of transitions
from an excited nuclear state to the ground state. In a few
cases, those marked with an asterisk, the dominant transition
is to the first excited state of the nucleus. The last column
labeled "strength factor" gives the product of the γ-ray
branching ratio times the relative abundance of the target
nucleus, normalized to a value of 100 for the 15.11-MeV tran-
sition in ^{12}C. If the total (p,p') cross sections were the
same for each of these states, the relative intensities of the
γ-ray emissions would be directly proportional to the strength
factors listed. The cross sections for the spallation reactions,
on the other hand, are generally more than an order of magnitude

lower than the inelastic scattering cross sections. Strength factors for those transitions would, therefore, be misleading in relationship to the γ-ray flux. For this reason, strength factors for those transitions produced by spallation reactions are not listed in Table 2. It is not expected that the γ-ray flux from any of the transitions listed in Table 2 will exceed 30% of that of the 15.11-MeV line.

Two additional lines, with branching ratios less than 40%, are included in Table 2 because both are produced by transitions in ^{12}C and because their intensities relative to the 15.11-MeV line are well known. The 15.11-MeV state decays to the 4.44-MeV state, producing a line at 10.67 MeV with a flux 3% that of the 15.11-MeV line. The state at 12.61 MeV, (1^+, $T = 0$) is known to decay electromagnetically to the ground state 2% of the time (Ajzenberg-Selove 1976). The cross sections for production of this state are not as well measured as those for the 15.11-MeV state, but values for the cross section have been reported by Measday et al. (1963) for $14.9 \leq E_p \leq 19$ MeV, and Geramb et al. (1975) for $24 \leq E_p \leq 45$ MeV. Under the assumption that the proton spectrum is constant up to an energy $E_c = 30$ MeV, the integral production rate of the 12.71 MeV state, based on those cross sections, is found to be a factor of 3 greater than that for the 15.11-MeV state. The 12.71-MeV level in ^{12}C would therefore produce a line with approximately 6% the strength of the 15.11-MeV line.

A summary, indicating the number of γ-ray transitions by energy and by excited nuclear species, is presented in Table 3.

It is readily seen that the total number of lines is a decreasing function of energy, with most of the transitions having energies less than 10 MeV. The only known γ-ray line above 13 MeV is the well resolved and isolated transition due to the 15.11-MeV state in ^{12}C. Other possible sources of γ-ray line emission at energies characterizing the nuclear binding energy, approximately 8 MeV, are reactions involving thermal neutron capture. These (n,γ) reactions have not been considered in this work, but are known to be powerful diagnostics in remote sensing, as discussed by Trombka et al. (1978).

c) Production of π° Mesons

Stecker (1970, 1973) has compiled the π° production cross sections times multiplicities for the reactions

$$p + p \rightarrow n\pi^\circ + anything,$$

and

$$p + \alpha \rightarrow n\pi^\circ + anything,$$
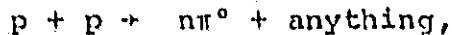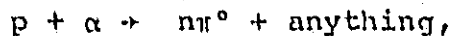
where n is the π° multiplicity. The parameterized fit (Stecker 1973) for π° production by proton-proton interactions covers a range of energies from a few hundred up to greater than 10^6 MeV, applicable to the cosmic ray particle spectrum. The spectrum of particles accelerated in solar flares is not expected to extend significantly above an energy of 10^3 MeV, so that the range of energies from production threshold to cutoff is relatively narrow. As can be seen in Figure 3, the cross section for the reaction $p + p \rightarrow p + p + \pi^\circ$ rises rapidly in this range, then flattens abruptly, remaining constant up to an energy above the

two-pion production threshold. It is precisely in this range that the parameterized fit based on a much wider energy range is poorest, differing from the measured values by as much as a factor of two. The experimental points of Baldoni et al. (1962) and of Bugg et al. (1964) have been included in Figure 3 along with those referenced by Stecker (1973). For purposes of the present work, the π° production rates have been evaluated from a numerical integration of the smooth curve drawn through the measured points shown as the solid line in Figure 3. As no additional measurements are available for π° production from proton-alpha interactions, the values reported by Stecker (1970) have been employed in the present work.

The proton-alpha particle interactions have a lower threshold for π° production than the proton-proton interactions. The importance of proton-alpha particle interactions is further enhanced by energetic alpha particles which interact with ambient solar protons. In the present analysis, the differential alpha-particle flux is assumed to scale as the relative abundance times the differential proton flux as a function of kinetic energy per nucleon. The total contribution of proton-alpha plus alpha-proton is then twice the π° yield due to proton-alpha particle interactions. The abundances given in Table 1 have been assumed for the relative number of alpha particles per proton. In Table 4, the fractional contributions due to proton-proton and to proton-alpha plus alpha-proton interactions are shown for three values of the energetic particle spectral index. The increasing importance of the lower-energy particles

and consequently the lower-threshold proton-alpha and alpha-proton reactions, a function of increasing spectral index, can be seen from a comparison of the relative contributions to the energy ranges above and below 700 MeV/nucleon.

The spectra of π° γ rays shown in Figure 4 have been calculated from detailed differential cross sections for π° production available for proton kinetic energies of 560 MeV (Baldoni et al. 1962) and 970 MeV (Bugg et al. 1964). The expected solar γ-ray spectra can be represented well by mixtures of the spectra for these two proton energies, weighted in proportion to the fractional contributions due to incident energetic particles in the two ranges of kinetic energy: $\leq$ 700 and $\geq$ 700 MeV/nucleon.

III. CONTINUUM AND LINE EMISSION ABOVE 8 MeV

The predicted spectrum of solar-flare γ-ray emission is summarized in Figure 5. The observed nuclear-line emission and continuum radiation in the 1972 August 4 solar flare have been employed for normalization (Chupp, Forrest, and Suri 1975; Suri et al. 1975). The expected line emission at 15.11 MeV and the continuum radiation due to π° decay are based on calculated cross sections and multiplicities presented in the previous section.

The 4.44-MeV line emission observed in the 1972 August 4 flare is shown in Figure 5, normalized to that differential flux expected for an idealized line width of 90 keV, FWHM. This is the expected width of the line due to Doppler broadening alone, calculated by Ramaty, Kozlovsky, and Suri (1977) under the simplifying assumption that there is no correlation between the direction of the incident proton and the emitted γ ray.

The corresponding 15.11-MeV line emission is shown for a Doppler width of 300 keV and an instantaneous proton spectrum which is constant 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.

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 5. The total flux observed in the interval 4 to 8 MeV, including both line emission and continuum radiation, is 0.2 photons cm^{-2} 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, Kozlovsky,and Suri (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 5. 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 observed in a large number of solar flares (Datlowe 1971).

The yield of π° γ rays per flare proton has been calculated for proton-proton interactions using the π° production cross

sections times multiplicities presented in Figure 3. For proton-alpha particle interactions, the yield of π^0 γ rays has been calculated from the π^0 production cross sections times multiplicities given for this process in Figure 5 of Stecker (1970). The π^0 γ-ray yield has been normalized to the number of protons required to produce the 4.44-MeV γ-ray flux observed in the 1972 August 4 flare.

The γ-ray continuum due to π^0 decay has been calculated for three cases. In each, the instantaneous proton spectrum is assumed to be constant up to an energy of 30 MeV and to follow a power law in energy with a spectral index of 2 for energies between 30 and 100 MeV. In the first case, the proton spectrum is assumed to continue with a spectral index, s, of 2 up to an energy of 10^3 MeV, at which the spectrum is terminated and the proton flux is set equal to zero. In the other two cases, the spectrum is assumed to break at 100 MeV and to drop with a spectral index of 3 or 4 up to an energy of 10^3 MeV, at which it is again terminated. The resultant spectra of γ rays due to π^0 decay are shown in Figure 5.

IV. SUMMARY

The γ-ray spectrum above 8 MeV is a rich and relatively unexplored region which is populated by emission from the highest-energy interactions in solar flares. The large number of γ-ray emitting levels in the energy interval between 8 and 10 MeV will make a significant contribution to the continuum emission. Line emission with relatively narrow Doppler widths may be expected to be accompanied by greatly broadened line emission due to excitation of accelerated heavy ions which interact with the ambient solar atmosphere. The density of possible γ-ray lines between 8 and 10 MeV, all with similar strength factors, will increase the difficulty of resolving and identifying the in-dividual lines. Accurate predictions of the relative strengths of these lines will require a much better knowledge of the important cross sections. Because of their sensitivity to the spectrum of energetic flare particles, identification of any of these high-energy γ-ray lines would provide significant, new constraints on the energetics of solar flares.

Line emission from the 15.11-MeV excited state of ^{12}C is 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 $^{16}O(p,p'\alpha)$ ^{12}C*(15.11 MeV). A know-ledge 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 γ rays in this energy range is less than 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.

Observations of γ rays resulting from the production and decay of π° would provide clear evidence that nuclei are accelerated to kinetic energies of many hundreds of MeV/nucleon in solar flares. Even with spectra cut off at 10^3 MeV, more than 40% of the π°-decay γ rays are due to interactions with particles of kinetic energy greater than 700 MeV/nucleon. Interactions involving alpha particles contribute nearly 50% of the π° γ rays, independent of the spectral index. Measurements of π°-production

cross sections for proton-alpha particle interactions are re-
quired for experimental confirmation of the calculations on
which the present work is based.

Observability of π^a γ rays depends on flare intensity and
detector sensitivity. The energy resolution available with
both NaI and CsI scintillation spectrometers is more than
adequate to resolve the general features of the expected spec-
trum. No other continuum radiations are expected to confuse
the observations. The detection probability for those γ rays
is high due to the pair production cross section. The actual
detector areas required depend on details of instrumental
shielding and background. Areas of approximately 500 cm^2,
however, should enable positive observations for a proton
spectral index of 3 or less, and definitive upper limits if
the spectrum falls off more steeply.

V.   ACKNOWLEDGEMENTS

REFERENCES

Amos, K. A., Geramb, H. V., Sprickmann, R., Arvieux, J., Buenerd, M., and Perrin, G. 1974, Phys. Lett. 52B, 138.

Ajzenberg-Selove, F. 1972, Nucl. Phys. A190, 1.

Ajzenberg-Selove, F. 1975, Nucl. Phys. A248, 1.

Ajzenberg-Selove, F. 1976, Nucl. Phys. A268, 1.

Ajzenberg-Selove, F. 1977, Nucl. Phys. A281, 1.

Ajzenberg-Selove, F. and Lauritsen, T. 1974, Nucl. Phys. A227, 1.

Auble, R. L. 1977, Nucl. Data Sheets 20, 253.

Baldoni, B., Focardi, S., Hromadnik, H., Monari, L., Saporetti, F., Femino, S., Mezzanares, F., Bertolini, E., and Gialanella, G. 1962, Nuova Cimento 26, 1377-1388.

Balamuth, D. P., Zurmühle, R. W. and Tabor, S. L. 1974, Phys. Rev. C 10, 975.

Barnard, A. C. L., Swint, J. B. and Clegg, T. B. 1966, Nucl. Phys. 86, 130.

Barnes, V. E., Bugg, D. V., Dodd, W. I., Kinson, J. B. and Riddiford, L. 1961, Phys. Rev. Letters 7, 288-290.

Batson, A. P. and Riddiford, L. 1956, Proc. Roy. Soc. 237, 175-185.

Batson, A. P., Culwick, B. B., Hill, J. G. and Riddiford, L. 1959, Proc. Roy. Soc. 251, 218-232.

Bugg, D. V., Oxley, A. J., Zoll, J. A., Rushbrooke, J. G., Barnes, V. E., Kinson, T. B., Dodd, W. P., Doram, G. A., and Riddiford, L. 1964, Phys. Rev. 133, B1017-B1031.

Cence, R. J., Lind, D. L., Mead, G. D. and Moyer, B. J. 1963, Phys. Rev. 131, 2713.

Cheng, C. C. 1972, Space Science Reviews 13, 2713.

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

Chupp, E. L., Forrest, D. J. and Suri, A. N. 1975, Solar γ-, X-, and EUV Radiation, IAU Symposium No. 68, S. R. Kane, Editor, Reidel Publishing Company, Dordrecht, Holland, 341.

Crannell, C. J. and Crannell, H. 1976, Bull. Am. Phys. Soc. 21, 587.

Crannell, C. J. and Crannell, H. 1978, NASA Tech. Mem. 79563; to be published in Proc. Symposium on Gamma Ray Spectroscopy in Astrophysics, June 1978.

Crannell, C. J., Ramaty, R. and Crannell, H. 1977, Proc. 12th ESLAB Symposium, 213.

Datlowe, D. 1971, Solar Phys. 17, 436.

Dickens, J. K., Haner, D. A. and Waddel, C. N. 1963, Phys. Rev. 129, 743.

Eisner, A. M., Hart, E. L., Louttit, R. I. and Morris, T. W. 1965, Phys. Rev. 138, B670.

Endt, P. M. and Van der Leun, C. 1973, Nucl. Phys. A214, 1.

Fiarman, S. and Hanna, S. S. 1975, Nucl. Phys. A251, 1.

Fiarman, S. and Meyerhof, W. E. 1973, Nucl. Phys. A206, 1.

Fields, T., Fox, J. and Sutton, R. 1956, quoted by J. Ashkin in the CERN Symposium Proceedings 2, Geneva, Switzerland, 339.

Geramb, H. V., Amos, K., Sprickmann, R., Knöpfle, K. T., Rogge, M., Ingham, D. and Mayer-Böricke, C. 1975, Phys. Rev. C, 12, 1697.

Hasselgren, D., Renberg, P. U., Sundberg, O. and Tibell, G. 1965, Nucl. Phys. 69, 81.

Hughes, I. S., March, P. V., Muirhead, H. and Lock, W. O.
    1956, CERN Symposium Proceedings 2, Geneva, Switzerland, 344.

Lapides, J. R., Crannell, C. J., Crannell, H., Hornyak, W. F.,
    Seltzer, S. M., Trombka, J. I., and Wall, N. S. 1978, NASA
    Tech. Mem. 79560; to be published in Proc. Sumposium on
    Gamma Ray Spectroscopy in Astrophysics, June 1978.

Lingenfelter, R. E. and Ramaty, R. 1967, High-Energy Nuclear
    Reactions in Astrophysics, B. S. P. Shen, Editor, W. A.
    Benjamin Inc. New York, 99.

Martin, M., Schneider, H. and Sempert, M. 1953, Helv. Phys.
    Acta 26, 595.

Measday, D. F., Fisher, P. S., Kalmykov, A., Nikolaev, F. A.
    and Clegg, A. B. 1963, Nucl. Phys. 45, 98.

Meshcheriakov, M. G., Zrelov, V. P., Neganov, B. S., Vzorov,
    I. K., and Shabudin, A. F. 1956, CERN Symposium Proceedings
    2, Geneva, Switzerland, 347-352.

Nagahara, Y. 1961, J. Phys. Soc. Japan 16, 133.

Petersen, E. L., Slaus, I., Verba, J. W., Carlson, R. F. and
    Richardson, R. 1967, Nucl. Phys. A102, 145.

Prokoshkin, Iu. D. 1956, CERN Symposium Proceedings 2, Geneva,
    Switzerland, 385-397.

Ramaty, R., Kozlovsky, B. and Lingenfelter, R. E. 1975, Space
    Science Reviews 18, 341-388.

Ramaty, R., Kozlovsky, B. and Suri, A. N. 1977, Ap. J. 214, 617.

Reich, C. W., Phillips, G. C. and Russell, J. L., Jr. 1956,
    Phys. Rev. 104, 143.

Scott, D. K., Fisher, P. S. and Chant, N. S. 1967, Nucl. Phys.
    A99, 177.

Spuller, J., Hasinoff, M. D., Lim, S. T., Measday, D. F. and
    Mulligan, T. J. 1975, Nucl. Phys. A248, 276.

Stecker, F. W. 1970, Ap. and Space Sci. 6, 377-389.

Stecker, F. W. 1973, Ap. J. 185, 499-504.

Suri, A. N., Chupp, E. L., Forrest, D. J. and Reppin, C. 1975,
    Solar Phys. 43, 415.

Trimble, V. 1975, Rev. Mod. Phys. 47, 877-976.

Trombka, J. I., Crannell, C. J., Evans, L. E., Bielefeld, M. J.
    and Metzger, A. E. 1978, to be published.

Warburton, E. K. and Funsten, H. O. 1962, Phys. Rev. 128, 1810.

Table 1
Nuclear Species Considered

	ABUNDANCE RELATIVE TO ^{12}C IN %	
^1H	25×10^4	
^4He	2×10^4	
^{14}N	30	
^{16}O	160	
^{20}Ne	10	
^{24}Mg	8	
^{28}Si	10	
^{32}S	4	
^{56}Fe	6	

Table 2
Gamma-Ray Transitions Above 8 MeV*

γ-RAY ENERGY IN MeV	EMITTING NUCLEUS	MEASURED BRANCHING RATIO	STRENGTH FACTOR
8.05	^{27}Al	100	
8.13	^{32}S	84	4
8.29	^{32}S	60	3
8.31	^{15}N	79	
8.32	^{20}Ne	90	10
8.33	^{28}Si	59	6
8.36	^{23}Na	53	
8.43*	^{28}Si	50	6
8.44	^{24}Mg	80	8
8.49	^{28}Si	100	10
8.53*	^{28}Si	50	6
8.56	^{11}B	56	
8.59	^{20}Ne	90	10
8.65	^{23}Na	100	
8.67	^{23}Na	100	
8.69*	^{24}Mg	100	9
8.76*	^{28}Si	100	11
8.89*	^{28}Si	100	11
8.90	^{28}Si	59	6
9.00	^{24}Mg	55	5
9.05	^{15}N	92	
9.15	^{14}Mg	45	4
9.15	^{15}N	100	
9.17*	^{28}Si	85	9
9.36*	^{24}Mg	48	4
9.48	^{28}Si	100	11
9.50	^{28}Si	76	8
9.76	^{15}N	82	
9.83*	^{24}Mg	85	7
9.84*	^{24}Mg	83	7
9.93	^{15}N	78	
9.97	^{24}Mg	90	8
10.07	^{15}N	96	
10.31	^{28}Si	50	6
10.59	^{28}Si	100	11
10.62	^{20}Ne	100	11
10.67*	^{12}C	2	3
10.72	^{28}Si	100	11
10.73	^{24}Mg	40	4
10.90	^{28}Si	68	8
11.23	^{20}Ne	100	11
11.45	^{28}Si	100	11
12.71	^{12}C	2	2
15.11	^{12}C	91	100

*The asterisks designate the lines which result from a transition to an excited state rather than to the ground state.

Table 3
Number of γ-Ray Lines Above 8 MeV[a]

EXCITED NUCLEUS	PRODUCTION REACTIONS	8-9 MeV	9-10 MeV	10-11 MeV	11-12 MeV	12-13 MeV	>13 MeV
^{11}B	^{12}C(p,2p)	1					
^{12}C	^{12}C(p,p') ^{16}O(p,p'a)			1*		1	1
^{15}N	^{16}O(p,2p)	1	4				
^{20}Ne	^{20}Ne(p,p')	2*		1*(1)	1	(2)	
^{23}Na	^{24}Mg(p,2p)	3(1)					
^{24}Mg	^{24}Mg(p,p')	1,1*	4,2*(1)	1			
^{27}Al	^{28}Si(p,2p)	1(6)					
^{28}Si	^{28}Si(p,p')	2,5*	2,1*(1)	4	1		
^{32}S	^{32}S(p,p')	2					
TOTALS		19(7)	13(2)	8(1)	2	1(2)	1

[a] The asterisks designate the numbers of lines in each interval which result from a transition to an excited state rather than to the ground state. The parenthesis designate the numbers of possible additional lines based on excited states for which the γ-ray branching ratios have not been measured.

Table 4

Percentage Contribution of pp and pα + αp Interactions to the Production of n°-Decay γ Rays by Energy Range for Three Values of the Energetic-Particle Spectral Index

	Range of Kinetic Energy in MeV/Nucleon		
	0–700	700–1000	0–1000
s = 2			
pp	20	30	50
pα + αp	20	30	50
Sum	40	60	100
s = 3			
pp	23	26	49
pα + αp	26	25	51
Sum	49	51	100
s = 4			
pp	26	22	48
pα + αp	32	20	52
Sum	58	42	100

FIGURE CAPTIONS

Figure 1.   Cross sections for $^{12}C(p,p')$ $^{12}C^*(4.44\ MeV)$ and $^{12}C(p,p')$ $^{12}C^*(15.11\ MeV)$ as a function of the kinetic energy of the exciting proton.

Figure 2.   Ratio of the flux of 15.11-MeV to the flux of 4.44-MeV γ rays as a function of the spectral index of the exciting proton.

Figure 3.   Cross sections times multiplicity for the production of π° as a function of the kinetic energy of the exciting proton. References are given by first author only.

Figure 4.   Spectra of γ rays resulting from the decay of π° produced by proton beams of kinetic energies 560 and 970 MeV.

Figure 5.   Gamma-ray line emission and continuum radiation 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 γ-ray continuum due to π° 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.
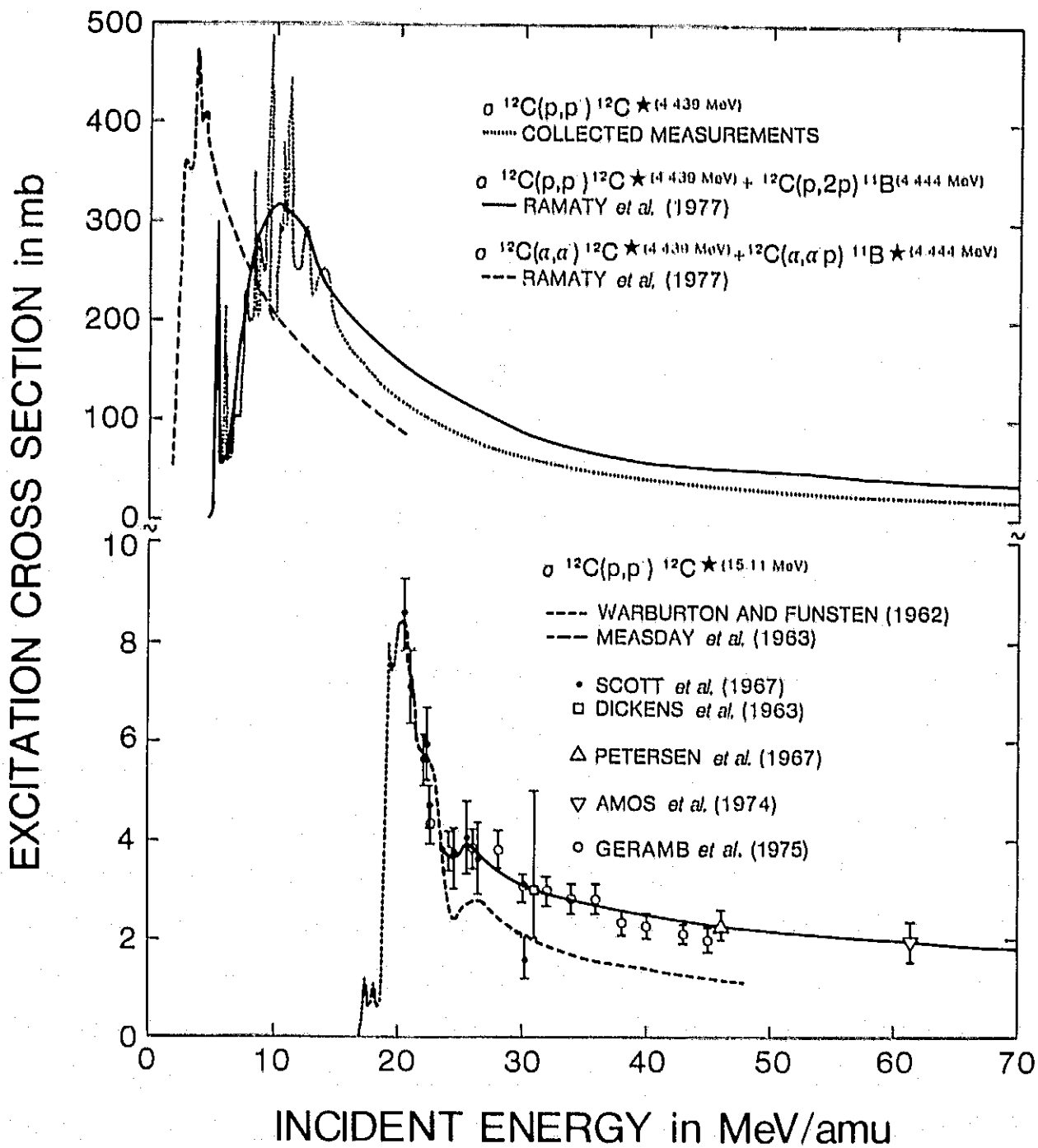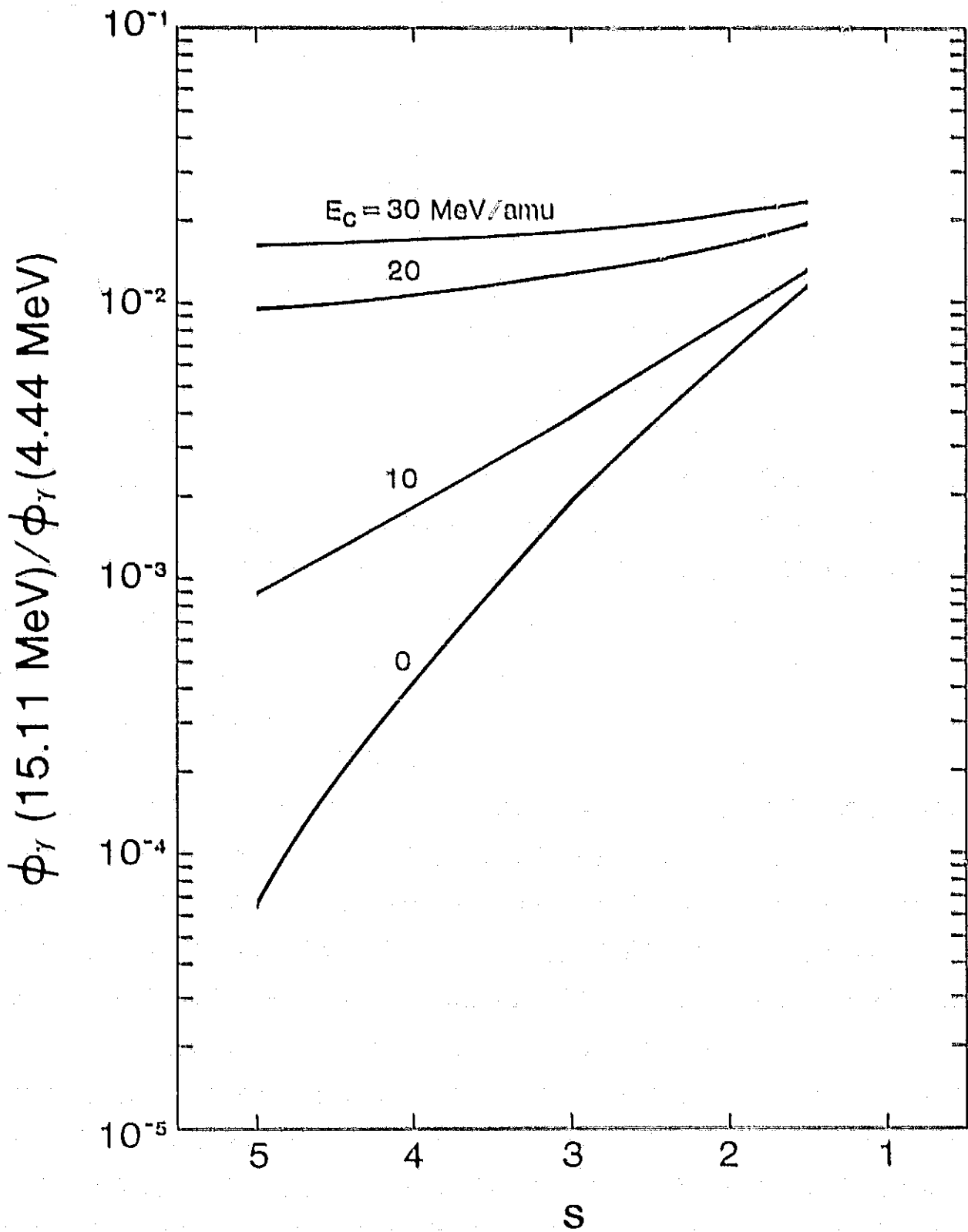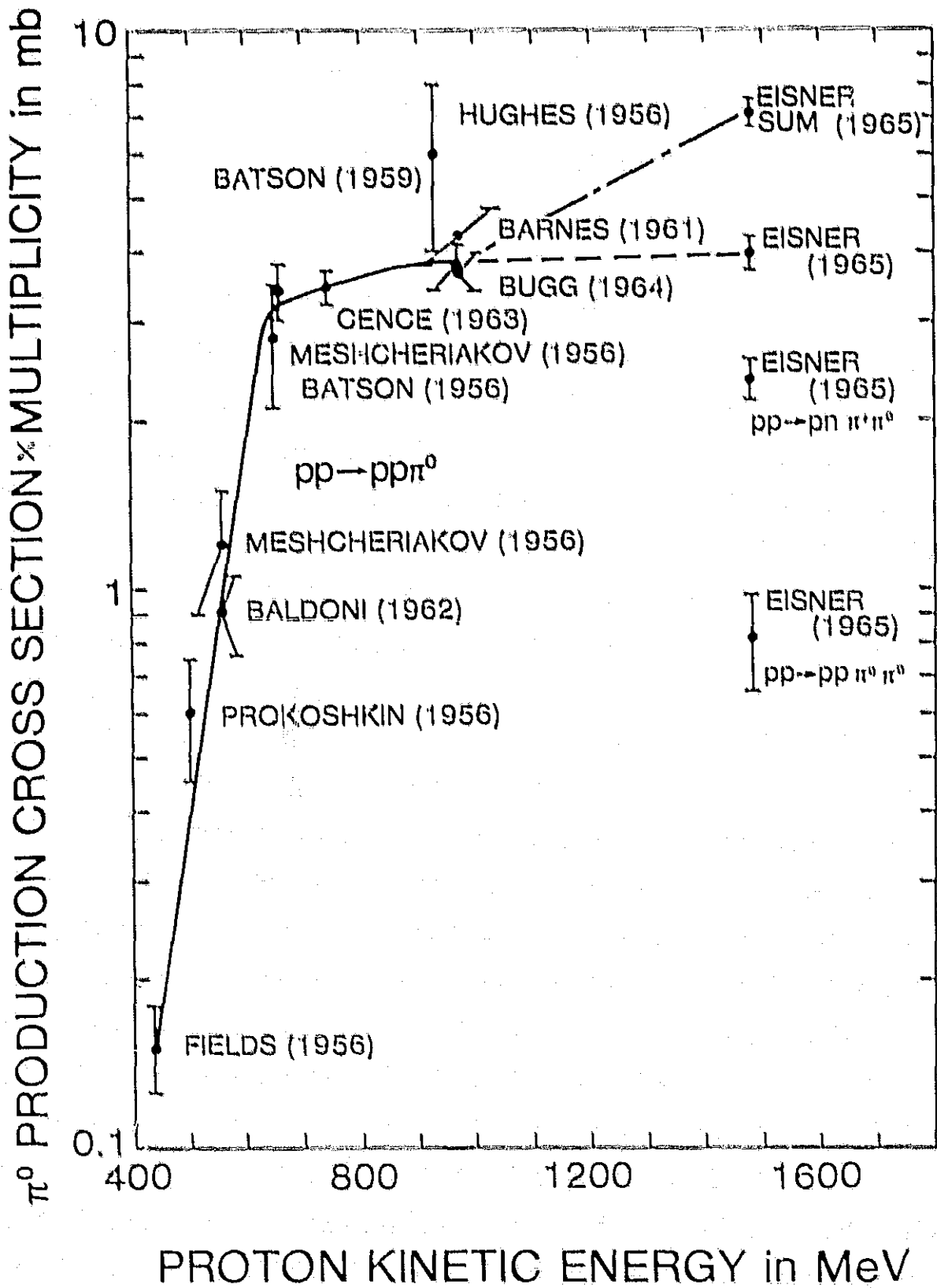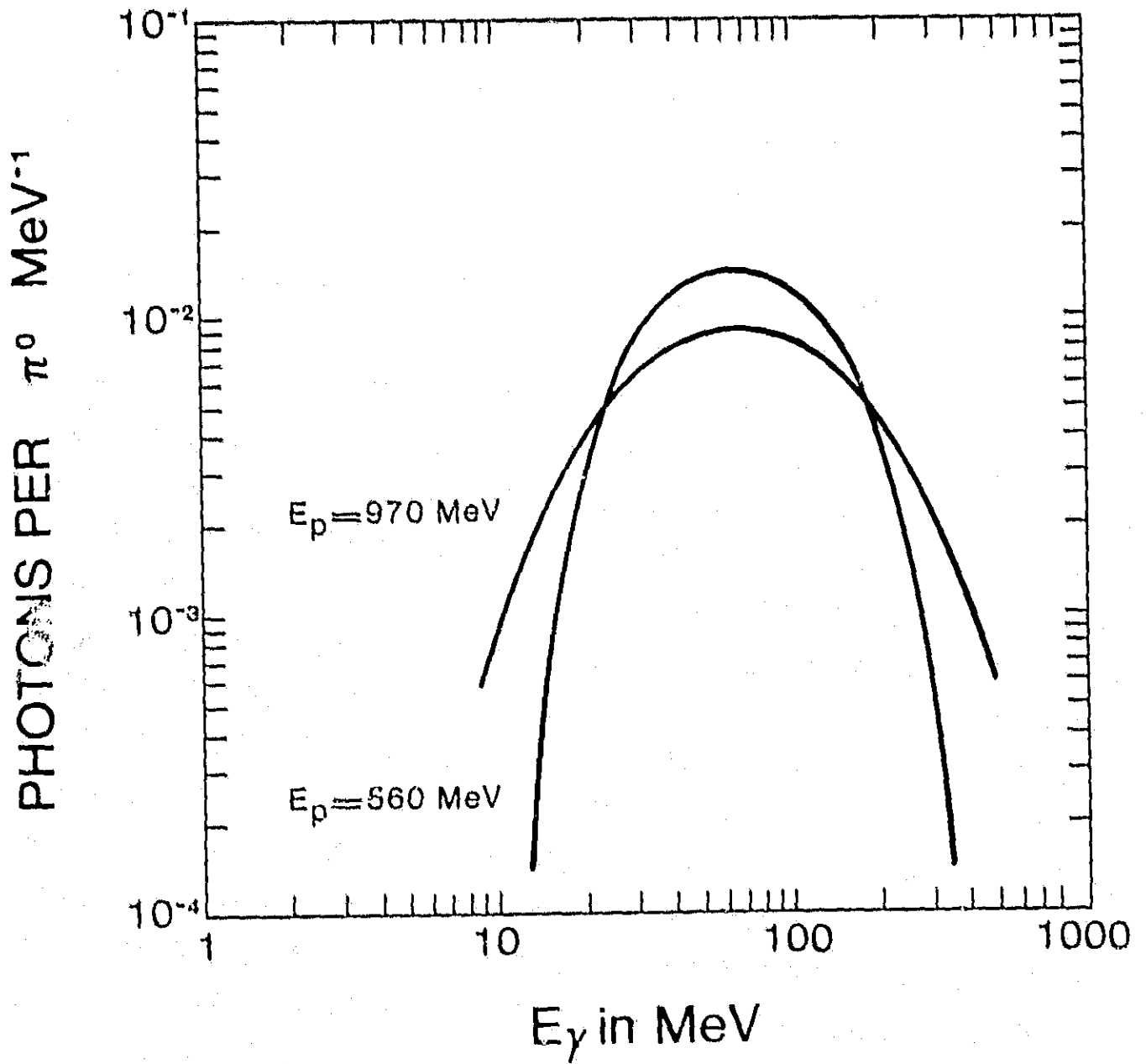
FIGURE 1

FIGURE 3

FIGURE 3

FIGURE 4

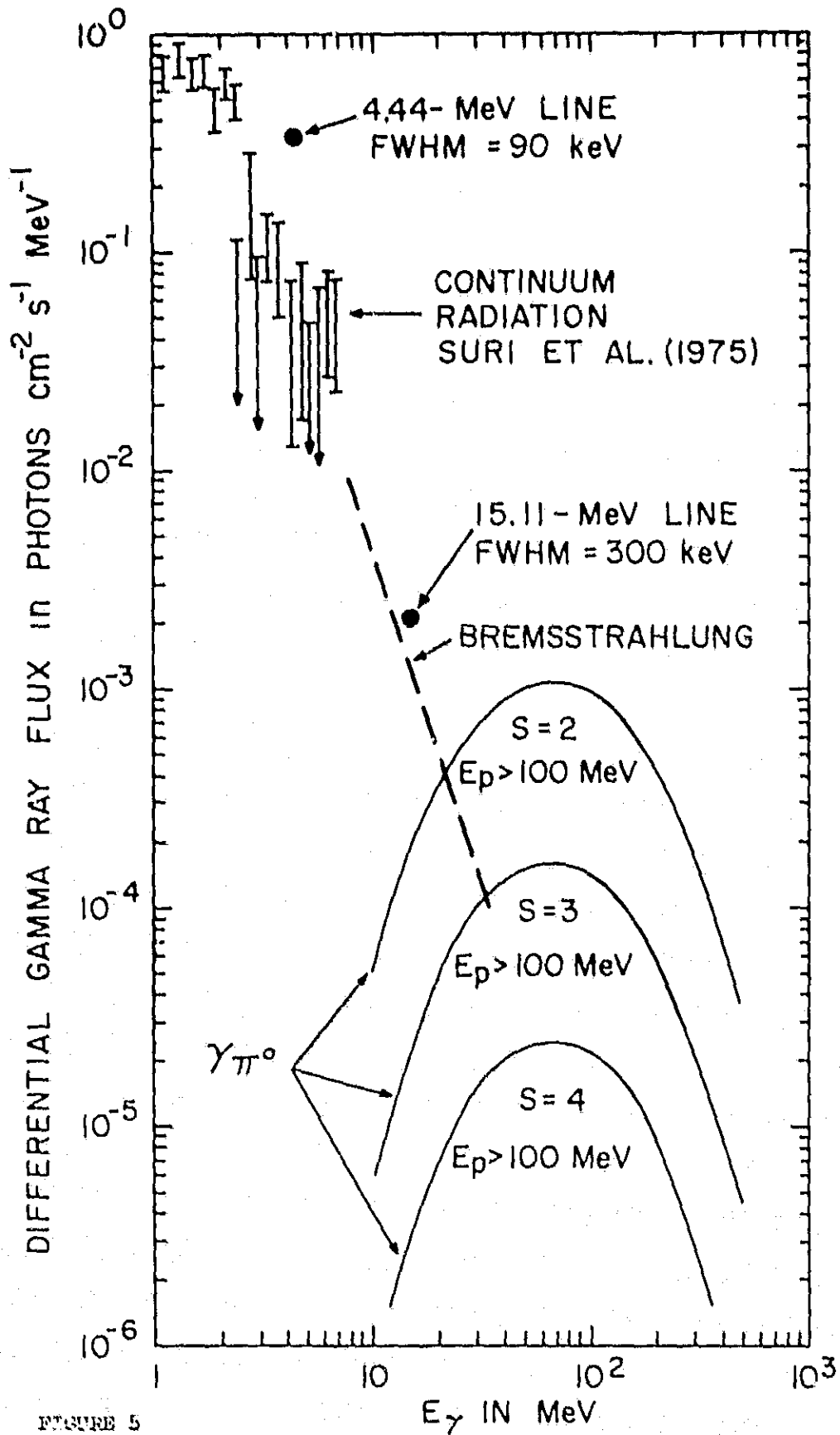FIGURE 5

1. Report No. 79623	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle SOLAR GAMMA RAYS ABOVE 8 MeV		5. Report Date
		6. Performing Organization Code
7. Author(s) Carol Jo Crannell, Hall Crannell and Reuven Ramaty		8. Performing Organization Report No.
9. Performing Organization Name and Address		10. Work Unit No.
		11. Contract or Grant No.
		13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address NASA/Goddard Space Flight Center Greenbelt, Maryland 20771		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

   Processes which lead to the production of γ rays with energy greater than 8 MeV in solar flares are reviewed and evaluated. Excited states which can be produced by inelastic scattering, charge exchange, and spallation reactions in the abundant nuclear species are considered in order to identify nuclear lines which may contribute to the γ-ray spectrum of solar flares. The flux of 15.11-MeV γ rays relative to the flux of 4.44-MeV γ rays from the de-excitation of the corresponding states in ^{12}C is calculated for a number of assumed distributions of exciting particles. This flux ratio is shown to be a sensitive diagnostic of accelerated particle spectra. Other high-energy nuclear levels are not so isolated as the 15.11-MeV state and are not expected to be so strong. The spectrum of γ rays from the decay of π° is shown to be sensitive to the energy distribution of particles accelerated to energies greater than 100 MeV.

17. Key Words (Selected by Author(s))		18. Distribution Statement	
19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*