THE ASTROPHYSICAL JOURNAL, 244:L171–L174, 1981 March 15

OBSERVATION OF THE 2.223 MeV GAMMA-RAY LINE ON THE *SMM* SATELLITE—THE EVENT OF 1980 JUNE 7

E. L. CHUPP, D. J. FORREST, J. M. RYAN, AND M. L. CHERRY
University of New Hampshire, Durham, New Hampshire

C. REPPIN, G. KANBACH, E. RIEGER, AND K. PINKAU
Max Planck Institute for Physics and Astrophysics, Munich, Germany

AND

G. H. SHARE, R. L. KINZER, M. S. STRICKMAN, W. N. JOHNSON, AND J. D. KURFESS
Naval Research Laboratory, Washington, D.C.
Received 1980 October 27; accepted 1980 December 1

ABSTRACT

The Gamma-Ray Spectrometer on the *Solar Maximum Mission* satellite observed γ-ray lines during the 0312 UT solar flare on 1980 June 7. The impulsive X- and γ-ray event lasted for <50 s and consisted of a series of quasi-periodic pulses on a time scale of a few seconds over the range of energies from 20 keV to 7 MeV. We report here preliminary results on the strongest γ-ray line observed at an energy of 2.232 ± 0.012 MeV with a maximum flux of $(7.1 \pm 1.2) \times 10^{-2}$ cm^{-2} s^{-1}. The energy of this line and its flux time history clearly identify it to be the 2.223 MeV line from neutron capture in the solar photosphere. The observed time history of this line is consistent with a spectrum of fast neutrons, extending to $\gtrsim 50$ MeV, produced during a ~ 40 s interval overlapping the impulsive photon emission time interval. A total production of 4×10^{29} neutrons is required, if they were produced isotropically.

Subject headings: gamma rays: general — Sun: flares

I. INTRODUCTION

The γ-ray line at 2.223 MeV from the reaction ^{1}H$(n, \gamma)^2$H is the most intense emission observed when energetic ions accelerated by solar flares interact with the solar atmosphere (Chupp *et al.* 1973; Chupp, Forrest, and Suri 1975; Ramaty, Kozlovsky, and Lingenfelter 1975; Hudson *et al.* 1980). The observation of this and other γ-rays during a solar flare gives important data on solar flare phenomena. (For recent reviews, see Chupp 1976; Ramaty and Lingenfelter 1979.) We report here observations of this γ-ray line with the *SMM* Gamma-Ray Spectrometer in association with a flare on 1980 June 7. This measurement, for the first time, resulted in an optimum combination of flare duration, γ-ray flux, and spectrometer sensitivity to provide a detailed time history of the 2.223 MeV line intensity. Detailed studies discussing the complete γ-ray data obtained on the event are in progress.

Basically, the instrument consists of a NaI(Tl) spectrometer operating in the energy range from 0.3 to 9 MeV with an energy resolution better than 7% (FWHM) at 662 keV. A complete 476 channel pulse-height spectrum is accumulated every 16.38 s and higher time resolution data, 64 ms, are provided in a 50 keV *burst window* centered on 330 keV. Auxiliary hard X-ray detectors which operate in the energy range 10–140 keV accumulate data every 1.024 s (cf. Forrest *et al.* 1980).

II. OBSERVATIONS

The Hα solar flare commenced at 0312 UT on 1980 June 7 in region 2495 at heliographic coordinates N17 W70. The ground-based observations of this event are discussed in some detail by Rust *et al.* (1981). In Figure 1 we show the time history of the flare emissions from 10 keV to >8 MeV. Panels 1*a*–1*f* have an intrinsic time resolution of 1.02 s, while 1*g*–1*j* have time resolution of 16.38 s. In panel 1*h*, the successive 16.38 s spectral scans are numbered from 1 to 16. Note that there is strong emission over the full energy range from 10 keV to 8 MeV, and in particular the emission in panel 1*h*, which covers the 2.223 MeV line, continues after the impulsive phase ends. Figure 2 shows the pulse-height spectrum for scans 9 and 10 with a fitted continuum and Gaussian line for the feature near 2.2 MeV. The energy of the fitted line is 2.232 ± 0.012 MeV and the count rate corresponds to a line flux at the spectrometer of $(7.1 \pm 1.2) \times 10^{-2}$ cm^{-2} s^{-1}. Figure 3 shows the count rate variation versus time for this line. The measured energy and time history clearly identify it as the 2.223 MeV line from the reaction ^{1}H$(n, \gamma)^2$H.

III. INTERPRETATION

The detection of the 2.223 MeV line requires a flux of neutrons produced by nuclear reactions near the time of the flare. To determine the time interval over which the nuclear reactions took place and the intensity and energy spectrum of the resulting neutrons, we must analyze the sequence of events leading to emission of the 2.223 MeV photon flux.

The fast neutrons, produced in nuclear reactions, must be thermalized by elastic scattering in the dense photosphere. The thermal neutrons can then be lost by several modes, one of which is capture by ^1H resulting in the emission of a 2.223 MeV photon which must escape unscattered from the photosphere to be detected as a line at 1 AU.

This behavior of solar flare–produced neutrons has been modeled in some detail by Wang and Ramaty (1974), Wang (1975), and Kanbach *et al.* (1975). In particular, the first two authors assumed an impulsive isotropic emission of fast neutrons ($E_n = 0.5$–200 MeV) at an altitude of 3×10^9 cm above the photosphere. They considered neutron losses due to nonradiative capture on ^3He, decay, escape by scattering out of the photosphere, and capture on ^1H.

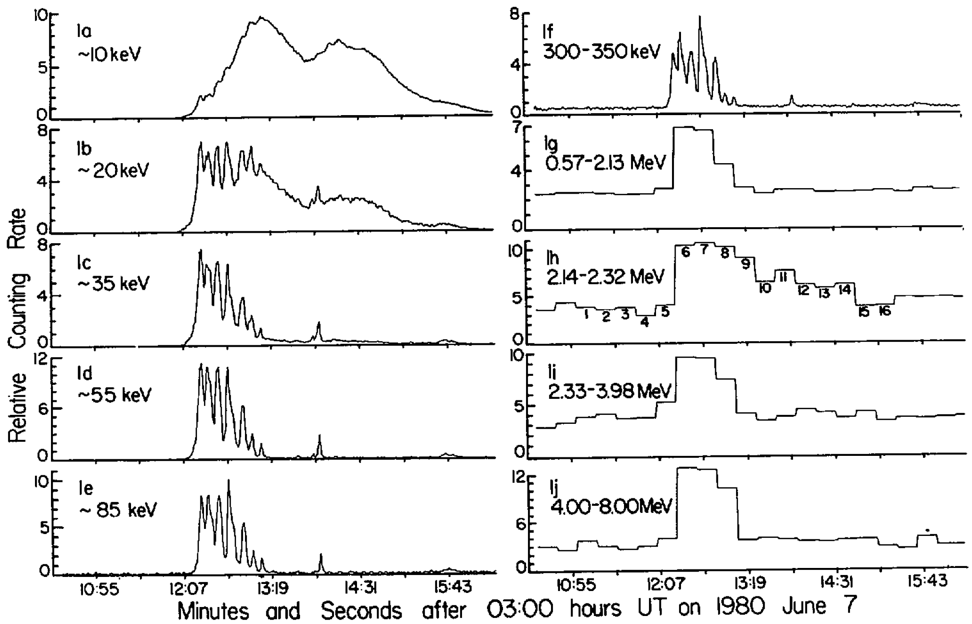

FIG. 1.—The time history of energetic photon emissions is shown for several energy intervals from 10 keV to 8 MeV. Time resolution for panels 1*a*–1*f* is 1.02 s and for 1*g*–1*j* is 16.38 s.

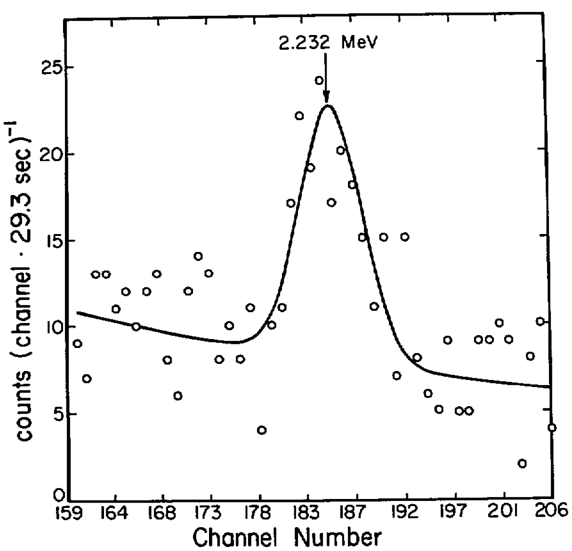

FIG. 2.—A portion of the pulse height spectrum near 2.2 MeV is shown for data scans 9 and 10 indicated in Fig. 1. Also shown are the best-fit continuum and the best-fit Gaussian peak. The best-fit Gaussian parameters are $E = 2.232$ MeV, $\sigma = 46.5$ keV, and $A = 106$ counts.

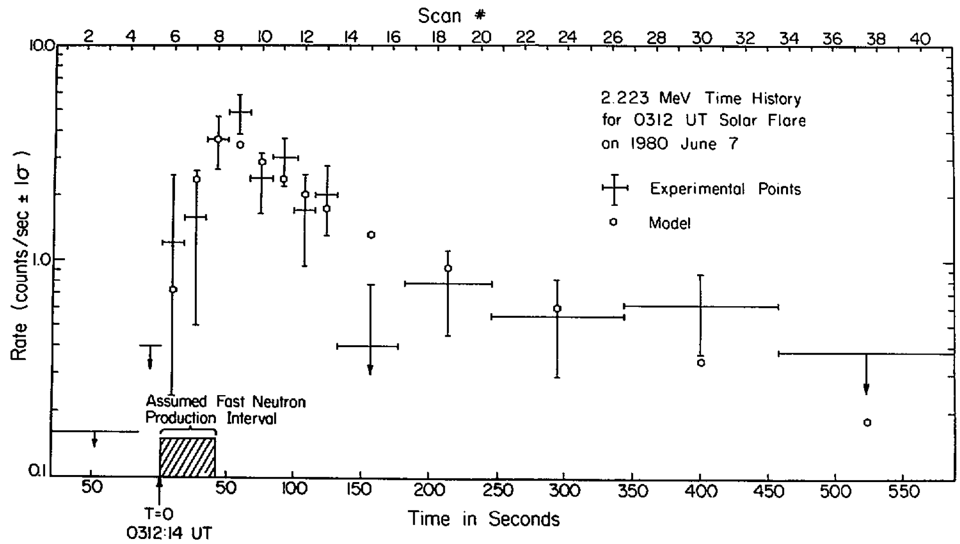

FIG. 3.—The time history of the 2.223 MeV line count rate is shown along with the predicted rates based on a model using two neutron populations (see text).

The propagation of the resulting 2.223 MeV photons out of the photosphere was followed for flares located at various heliographic longitudes. The yield of 2.223 MeV photons per neutron is a function of the ^{3}He abundance, the initial neutron energy, and the flare location. The time distribution of the 2.223 MeV flux for a delta function production of fast neutrons is described by a rise time dominated by the neutrons' flight time before scattering and a decay time due to the total loss rate of neutrons. This decay time depends on the ^{3}He abundance and ambient particle density. The highest-energy neutrons are captured at higher densities, which result in shorter capture times.

An analytical functional form can be used to compare our measured data with the tabular results of Wang (1975). If the production rate of fast neutrons, I_n, is constant over a time interval T, then the time varying 2.223 MeV line intensity, I_γ, can be shown to be:

$$I_\gamma = fI_n\left(1 + \frac{\lambda_2}{\lambda_1 - \lambda_2}\, e^{-\lambda_1 t} - \frac{\lambda_1}{\lambda_1 - \lambda_2}\, e^{-\lambda_2 t}\right), \quad (1)$$

for $t < T$, and

$$I_\gamma = fI_n \frac{\lambda_2}{\lambda_1 - \lambda_2}\left[\frac{\lambda_1}{\lambda_2}\,(1 - e^{-\lambda_2 T})e^{-\lambda_2 t'} - (1 - e^{-\lambda_1 T})e^{-\lambda_1 t'}\right], \quad (2)$$

for $t > T$ ($t' = t - T$). The parameter f is a number ≤ 1 and accounts for the various loss modes of the neutrons, as well as 2.223 MeV photon losses due to Compton scattering in the photosphere. This f is identical to the photon yield per neutron, $f(\theta, E_n)$, given by Wang and Ramaty (1974), where θ is the heliographic longitude of the solar flare site. The parameter λ_1 is the combined neutron transport and thermalization probabilities per unit time, and λ_2 is the total neutron loss probability per unit time.

In order to determine the neutron energy dependence of f, λ_1, and λ_2, we use equation (2) with $T = 0$ to model the tabulated Monte Carlo results given by Wang (1975) for $\theta = 75°$ and ^{3}He/^{1}H $= 5 \times 10^{-5}$ and 0 over all values of E_n with the results shown in Table 1. Using parameters given in Table 1 and equations (1) and (2) we model the 2.223 MeV time history shown in Figure 3 and obtain the following results: (1) The peak intensity in data scan 9 shows that strong neutron production stopped at or before this interval, and (2) the data both during and after a 40 s production interval is consistent with two line intensity distributions, I_γ, with decay time constants, λ_2, of (50 s)$^{-1}$ and (200 s)$^{-1}$. Hence, monoenergetic fast neutrons apparently cannot explain the data, and a spectrum of neutrons is required.

The simplest neutron distribution consistent with the Wang and Ramaty (1974) model is a constant isotropic production of 5.9×10^{27} neutrons s^{-1} at 0.5 MeV together with 3.4×10^{27} neutrons s^{-1} at 50 MeV. The required production interval, overlaps the impulsive photon emission interval (see Fig. 1). The expected 2.223 MeV γ-ray count rate resulting from these two neutron distributions, after necessary corrections, is compared to the data in Figure 3. Also shown is the inferred 40 s fast neutron-production interval.

The time interval during which the neutrons were produced, and the total number produced are strongly constrained by the data. The total number of neutrons given above assumes isotropic neutron emission. However, Kanbach *et al.* (1975) have shown that for the case of a vertically incident beam of fast neutrons, the photon yield

TABLE 1

PHOTON TIME CONSTANT PARAMETERS, λ_1 AND λ_2, AND PHOTON YIELD PER NEUTRON, f, OBTAINED USING EQUATION (3) AND THE TABULATED MONTE CARLO DATA OF WANG (1975)

NEUTRON ENERGY (MeV)	$f(75°, E_n)$ (photons/neutrons)		λ_1^{-1} (s)		λ_2^{-1} (s)	
	a	*b*	*a*	*b*	*a*	*b*
0.5	0.107	0.075	6	9	274	195
1	0.107	0.087	11	4	205	165
2.5	0.135	0.091	8	4	189	158
5.5	0.130	0.090	<3	<5	150	112
10	0.131	0.092	2	<2	143	110
15	0.131	0.085	<2	<4	130	87
30	0.102	0.060	<4	<1	109	59
60	0.060	0.039	<2	<4	94	51
100	0.045	0.023	<3	1	109	54
200	0.020	0.012	<3	<3	116	55

NOTE.—Columns labeled *a* are for the case $^3He/^1H = 0$. Columns labeled *b* are for the case $^3He/^1H = 5 \times 10^{-5}$.

per neutron only increases by a factor of ~3 as compared to the case of isotropic emission. Hence, the number of neutrons required for any emission model is still $\gtrsim 10^{29}$ produced over a 40 s interval.

IV. CONCLUSIONS

The impulsive continuum emission above 20 keV and a longer-lived γ-ray line at 2.223 MeV show that *both* energetic electrons and nucleons were accelerated in association during the solar flare at 0312 UT on 1980 June 7. Statistically significant measurements of the 2.223 MeV intensity over a ~500 s interval, during and after the impulsive phase, allow us to place strong constraints on the production of neutrons by the accelerated ions. If the neutrons are emitted isotropically, the $(50\ s)^{-1}$ time constant requires a flux of energetic neutrons $\gtrsim 50$ MeV impinging on the solar photosphere with a $^3He/^1H$ ratio of $\sim 5 \times 10^{-5}$. With this $^3He/^1H$ ratio, the two time constants require a spectrum of neutrons from 0.5 MeV to > 50 MeV. Most importantly, since the neutron production interval is strongly constrained to an ~40 s interval overlapping the impulsive event, then the energetic ions must have been accelerated either before or in near time coincidence with the energetic electrons.

We thank the *SMM* Project under Peter Burr for excellent operation of the *SMM* spacecraft, Peter Hoyng and Reuven Ramaty for helpful comments, and David Speich for NOAA flare reports. We also thank Mary Chupp for editing and Celeste Dietterle for typing and Philip Dunphy for valuable assistance. We thank Steven Matz and Barbara Gardner for help in data analysis. (Work was supported by NASA contract NAS 5-23761 and in the Federal Republic of Germany by BFFT contract 010K 017-ZA/WS/WRK 0275:4.)

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M. L. CHERRY: University of Pennsylvania, Department of Physics, Philadelphia, PA 19104

E. L. CHUPP, D. J. FORREST, and J. M. RYAN: University of New Hampshire, Department of Physics, Durham, NH 03824

W. N. JOHNSON, R. L. KINZER, J. D. KURFESS, G. SHARE, and M. STRICKMAN: Naval Research Laboratory, 4555 Overlook Avenue, S.W., Washington, DC 20375

G. KANBACH, K. PINKAU, C. REPPIN, and E. RIEGER: Max Planck Institute for Physics and Astrophysics, Institute for Extraterrestrial Physics, 8046 Garching, Federal Republic of Germany