Photospheric ^{3}He to H Abundance Ratio Derived from Gamma-Ray Line Observation

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Abstract

Yohkoh observed the neutron capture line and prompt nuclear deexcitation lines from a flare on 6 November, 1997. We determined the photospheric ^{3}He to H abundance ratio from the time profiles of neutron capture line. Assuming that the time profile of neutron production is similar to that of prompt C and O lines and the photospheric H density is 1.3 x 10^{17} cm^{-3}, we obtained the best fit value of the ^{3}He to H ratio of (2.3 ± 1.4) x 10^{-5} which is consistent with the values reported previously.

1 Introduction:

^{3}He is thought to be primarily produced by nucleosynthesis in the early universe and its abundance is used to place a constraint on cosmological model. Since the photospheric ^{3}He abundance can not be determined spectroscopically, observations of the neutron capture line at 2.223 MeV from solar flares provide a direct means of determing the photospheric ^{3}He abundance. Neutrons which are produced simultaneously with prompt γ-ray lines by interactions of accelerated ions diffuse into the photosphere where the 2.223 MeV line are emitted by neutron capture on hydrogen. Because of the time required for neutrons to slow down and be captured, the 2.223 MeV line is produced about 100 s after the production of the neutrons. The competing capture reaction ^{3}He(n,p)^{3}H affects the delay of the 2.223 MeV line emission. The 2.223 MeV line flux from an instantaneous production of neutron is assumed to fall exponentially in time with a time constant τ given by $1/\tau = 1/\tau_H + 1/\tau_{He} + 1/\tau_d$ (Hua and Lingenfelter, 1987). Here τ_H is the time constant for capture on H, τ_{He} is the time constant for capture on ^{3}He and τ_d is the neutron decay time (918 s). τ_H and τ_{He} are approximated by 1.4 x $10^{19}/n_H$ s and 8.5 x $10^{14}/n_{He}$ s, respectively, where n_H and n_{He} are the number densities of hydrogen and ^{3}He. A simplified approach for determination of ^{3}He abundance was adopted by Prince *et al.* (1983) and Vestrand and Forrest (1993). Hua and Lingenfelter (1987) made detailed calculations of the time profile of 2.223 MeV line emission taking into account several effects on the accelerated particles and solar atmosphere. In a case of the simplified approach the time profile of the 2.223 MeV line emission F(t) is expressed by

$$F(t) = A \int_{t_0}^{t} [S(t') / \tau] \exp [- (t - t') / \tau] \, dt' ,$$

where A is the constant, t_0 is the time when the gamma-ray lines are observed and S(t') is the time profile of the neutron production (Vestrand and Forrest, 1993). Temporal dependence of S(t') is assumed to be similar to that of the C+O line emission. Using this formula, we can obtain τ which gives the best fit for the observed time profile of the 2.223 MeV line emission. The ^{3}He/H ratio is determined from this best fit τ, if n_H is assumed.

Yohkoh measured a whole time profile of the γ-ray emission from a γ-ray flare on 6 November, 1997 (Yoshimori *et al.*, 1999, Shiozawa, 1999). We analyzed the time profiles of the 2.223 MeV line and C + O line emissions and estimated the photospheric ^{3}He/H ratio using the simplified approach. The present result were compared with the previous ones.

2 Observation and Result:

The flare occurred at 11:52 UT on 6 November, 1997. Its location, GOES class and Hα importance were S18W64, X9.0 and 2B, respectively. The γ-ray spectrometer (two BGO scintillators) aboard Yohhoh recorded strong γ-ray emission. This flare exhibited the highest γ-ray counting rate in the Yohkoh events observed so far. Three counting rate time profiles of 2.136-2.375, 4.001-7.225 and 7.225-10.160 MeV emission are shown in Fig.1. The first two time profiles roughly correspond to those of the neutron capture line and prompt C and O lines. We see that the decay time of the 2.223 MeV line emission is longer than that of the C+O line emission. The γ-ray count spectrum in 11:52:32 - 12:01:08 UT is shown in Fig.2. We see the appparent neutron capture line and prompt C and O lines superposed on the continuum. In order to derive the fluxes of these three γ-ray lines, we used the similar spectral fitting method as descrived in Murphy *et al.* (1990). We assume that the γ-ray spectrum consists of bremsstrahlung (single power law) and ten narrow and five broad lines (Gaussians). A trial incident photon spectrum is constructed and convolved with the instrumental response function. The resulting predicted count spectrum is compared with the

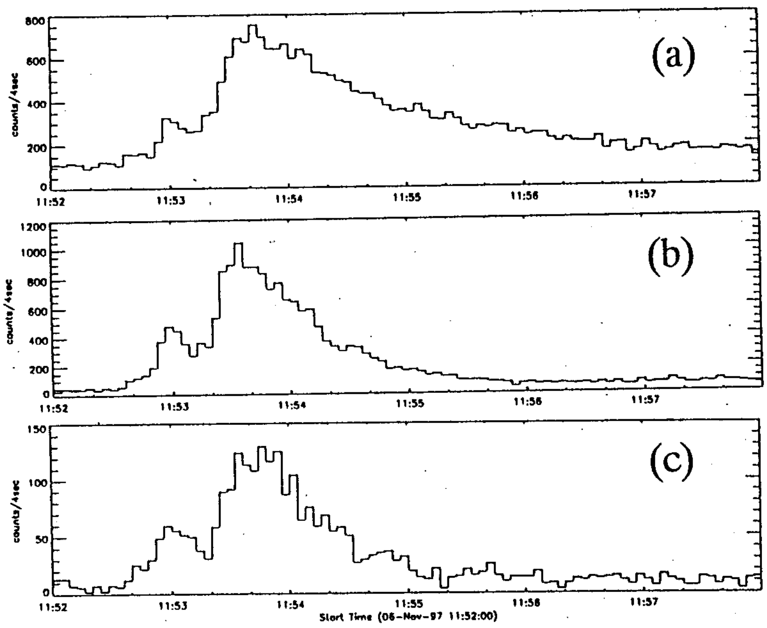

Fig.1 Time profiles of (a) 2.136-2.375, (b) 4.001-7.225 and (c) 7.225-10.160 MeV emission.

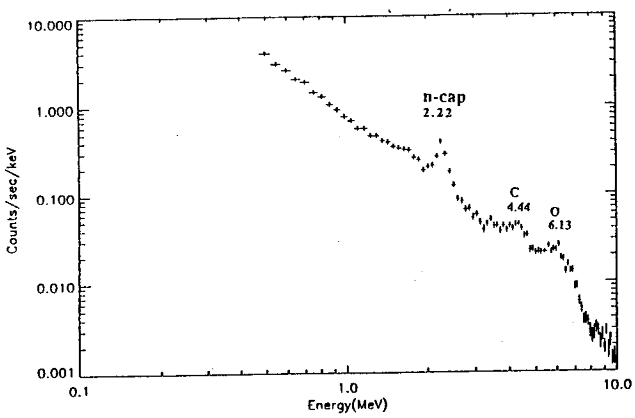

Fig.2 γ-ray count spectrum in 11:52:36-112:01:08 UT

observed one. A χ^2-square minimization algolithm is used to fit the data. In order to constrain the fits, we fixed the line center energies and widths of the lines at their theoretical values (Murphy *et al.* 1990). Free parameters in the fits are the amplitude of lines and the amplitude and exponent of the single power law.

The temporal variations of γ-ray fluxes of three lines at 2.223, 4.443 and 6.129 MeV obtained from this spectral fitting method are shown in Fig.3 (a) and (b), respectively. Here if we assume that the time profile of neutron production is proportional to that of C+O line emission and $n_H = 1.3 \times 10^{17}$ cm^{-3}, we obtain the best fit value of $\tau = 72 \pm 11$ s. It gives the photospheric $^3He/H$ ratio of $(2.3 \pm 1.4) \times 10^{-5}$.

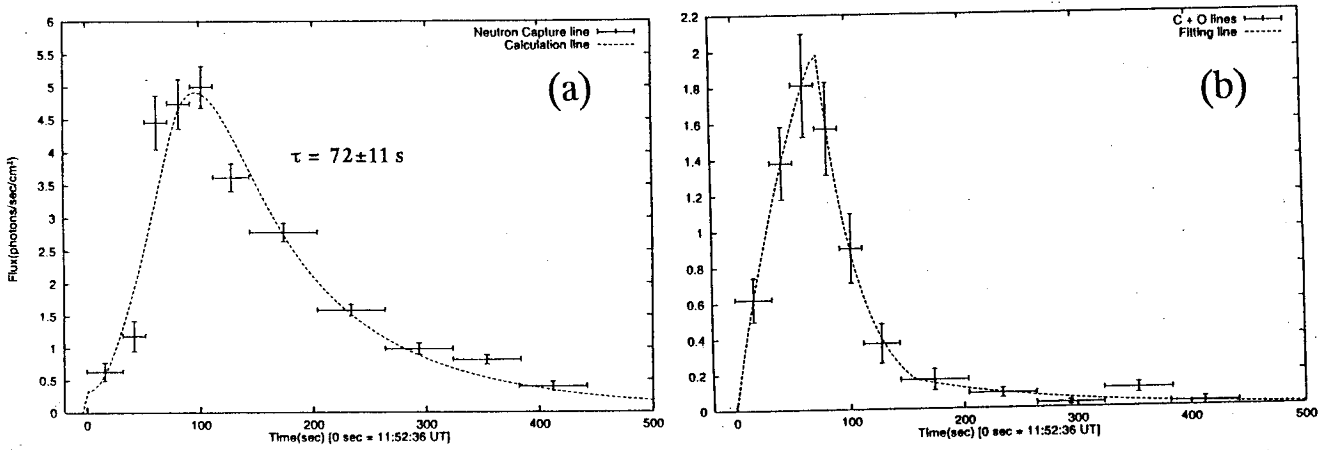

Fig.3 Temporal variations of γ-ray line fluxes. (a) neutron capture line and (b) C+O lines

3 Discussion:

We compare this result with those obtained by Prince *et al.* (1983), Hua and Lingenfelter (1987), Trottet (1994) and Murphy *et al.* (1997). These results are summarized in Table 1 along with the present one. These values are consistent within the experimental errors. Hua and Lingenfelter (1987) made the Monte Carlo calculations of the profile of 2.223 MeV line emission taking into account the photospheric ^3He abundance, energy spectrum and angular distribution of accelerated ions and using a model for the density distribution of the solar atmosphere. Their $^3He/H$ ratio was consistent with the upper limit obtained from the simplified approach (Prince *et al.*, 1983).

The decay constant of 2.223 MeV emission increases as the observing angle approaches 90° (limb). Since the present Yohkoh flare on 6 November 1997 occurred at the location W64S19, this effect is not significant. We derive a power law spectral index of spectrum of accelerated protons from a ratio of the neutron capture line to O line fluxes (Ramaty *et al.* 1996). The derived spectral index is 3.5±0.3, which roughly corresponds to the Bessel function spectrum of $\alpha T=0.02$ (Ramaty *et al.*, 1993). The neutron production occurs deeper in the photosphere as the proton spectrum becomes very hard. It leads to a short decay constant for the 2.223 MeV line emission because the neutrons are captured at the site of higher density. Hua and Lingenfelter (1987) calculated dependence of the decay constant on the proton energy spectrum. The decay constant for 2.223 MeV line emission is 90 s for $\alpha T=0.01$ and 71 s for $\alpha T=0.1$. The proton spectrum for this Yohkoh flare is not extremely hard, the decay constant is considerd to range from 70 to 90 s. The angular distribution of accelerated ions affects the temporal variation of 2.223 MeV line. According to Hua and Lingenfelter

$^3He/H$ (x 10^{-5})	Flare	Satellite
< 3.8	1982 June 3	SMM / GRS (Prince *et al.* 1983)
2.3 ± 1.2	1982 June 3	SMM / GRS (Hua and Lingenfelter, 1987)
2 - 5	1991 June 11	GRANAT / PHEBUS (Trottet *et al.*, 1993)
2.3	1991 June 4	CGRO / OSSE (Murphy *et al.*, 1997)
2.3 ± 1.4	1997 Nov 6	YOHKOH / GRS (present paper)

Table 1 ^3He to H abudance ratios derived from the time profile of 2.223 MeV line emission.

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A few data of photospheric $^3He/H$ ratio have been obtained from the γ-ray line spectroscopy. In order to advance the understanding of the $^3He/H$ problem, we need more precise gamma-ray line observations. Moreover, Share and Murphy (1997) suggested a procedure for determing the photospheric $^4He/H$ ratio from the product of the solar wind $^4He/^3H$ ratio and the photospheric $^3He/H$ ratio. The $^3He/H$ ratio is related to the $^4He/H$ ratio which is an important parameter for studies of stellar evolution and solar neutrino production. Many gamma-ray flares can be expected from CGRO, Yohkoh and HESSI observations during the 23rd solar maximum.

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