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POSITRON ANNIHILATION IN SOLAR FLARES

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POSITRON ANNIHILATION IN SOLAR FLARES

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The gamma-ray line at 0.51 MeV originates from the annihilation of positrons. When a fraction of the positrons annihilate from bound states of positronium, the 0.51-MeV line is accompanied by a continuum of 3-gamma annihilation radiation at energies up to 0.51 MeV. We present accurate calculations of the rates of free annihilation and positronium formation in a solar flare plasma, and we also discuss positronium formation by charge exchange. The observability of the 3-gamma annihilation is increased by the inherent delay in the production and slowing down time of the positrons. We conclude that such radiation could be detected at times late in solar gamma-ray events when the continuum and prompt line emissions have essentially disappeared.

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POSITRON ANNIHILATION IN SOLAR FLARES

1. Introduction. Gamma-ray line emission at an energy of approximately 0.51 MeV was observed by Chupp et al. (1973) from the 1972 August 4 and August 7 solar flares. This line is believed to be due to the annihilation of positrons which result mainly from the decay of π^+ mesons and radioactive nuclei produced in nuclear reactions of flare accelerated particles with constituents of the solar atmosphere (Lingenfelter and Ramaty 1967; Ramaty, Kozlovsky, and Lingenfelter 1975). In addition to positron annihilation radiation, line emissions were also observed at 4.4 MeV and $\sim$ 6.2 MeV from the August 4 flare, and at 2.2 MeV from both the August 4 and 7 flares (Chupp et al. 1975).

In the present paper we discuss the various processes that affect the annihilation of positrons. In particular, since a large fraction of the positrons may annihilate from bound states of positronium, we investigate the question of whether positronium annihilation radiation is observable from solar flares.

2. The Fate of Positrons in Solar Flares. Positrons in solar flares result from the decay of π^+ mesons and various radioactive nuclei produced by nuclear reactions of accelerated charged particles with the ambient solar atmosphere. The half lives of these positron emitters range from values less than 1 second to about 20 minutes, and they produce positrons of energies from several hundred keV to about 100 MeV.

There is a finite probability ($\sim$ 10%, e.g. Wang and Ramaty 1975) for relativistic positrons to annihilate in flight. However, because of the Doppler effect, these annihilations do not contribute to observable 0.51-MeV line emission. The positrons which do not annihilate in flight either escape from the Sun or decelerate to thermal energies due to interactions with ambient matter and magnetic fields.

Thermal positrons either annihilate freely and produce two 0.51-MeV gamma rays per positron, or form positronium; 25% of the positronium is formed in the singlet spin state and 75% in the triplet state. Positronium in the singlet state has a mean life of 1.2×10^{-10} seconds and decays into two 0.51-MeV gamma rays. Positronium in the triplet state has a mean life of 1.4×10^{-7} seconds, and if left undisturbed for a period much longer than its mean life, it decays into 3 gamma rays of energies less than 0.51 MeV. Collisions with the ambient medium dissociate triplet positronium if the density of the ambient medium is larger than a few times 10^{14} cm^{-3}. These collisions can also cause spin-flip transitions from the triplet to the singlet state. The fate of positrons in solar flares is graphically illustrated in Figure 1.

Depending on the state of ionization of the ambient medium, positronium formation proceeds either by radiative recombination with free electrons or by charge exchange with atoms and ions. At temperatures greater than a few times 10^5 K radiative recombination dominates. In Figure 2 we show the rate coefficient ($\langle\sigma v\rangle$) for positronium formation by radiative recombination in a hydrogen plasma as a function of its temperature. The results of a calculation by Nieminen (1967), which does not include folding the rate coefficient into the expected Maxwell-Boltzman distribution, are shown for comparison. The difference arises solely from the lack of such appropriate averaging. Also shown in this figure is the rate coefficient for free annihilation corrected for Coulomb interactions. The details of these calculations will be published elsewhere.

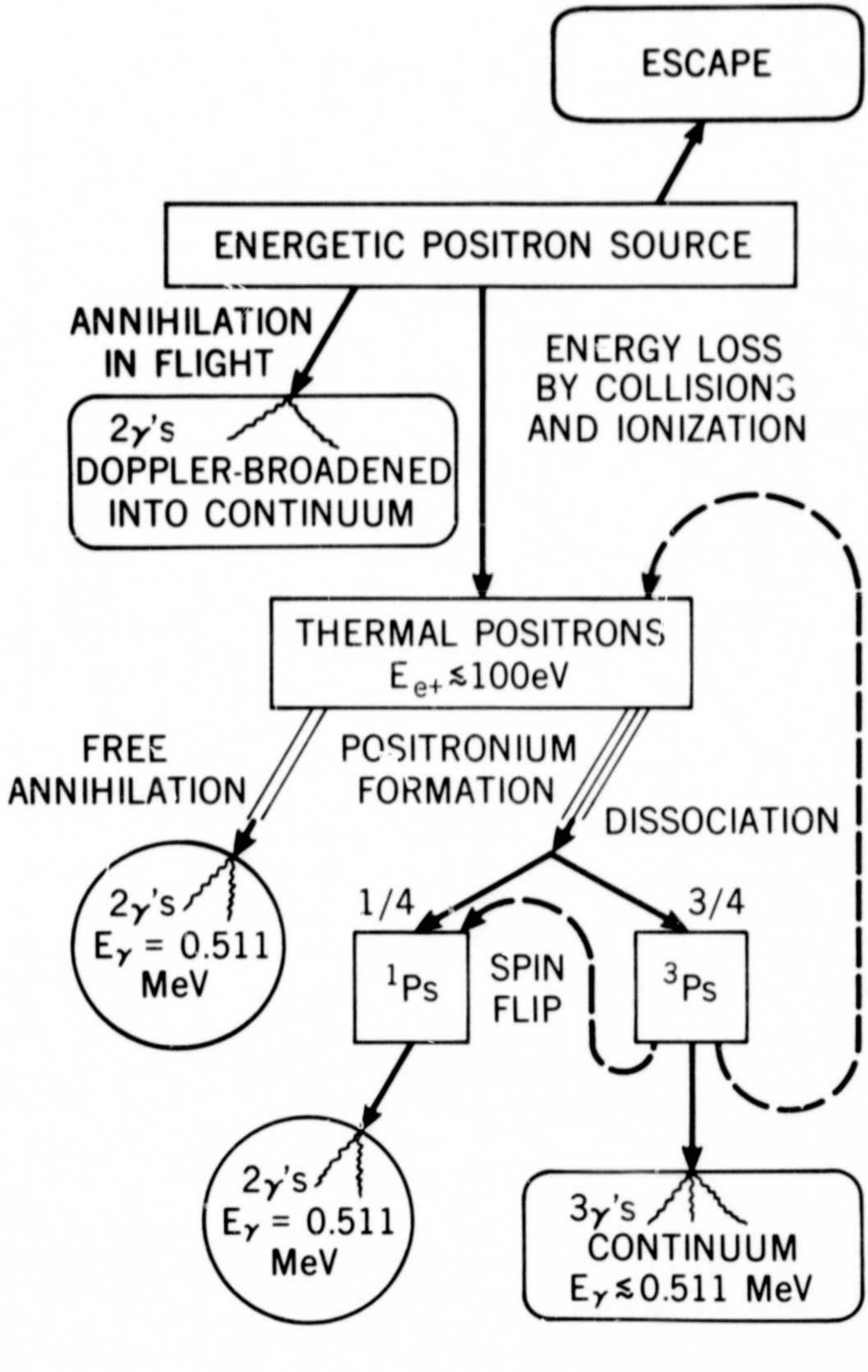

Figure 1. Fate of Positrons in a Solar Flare

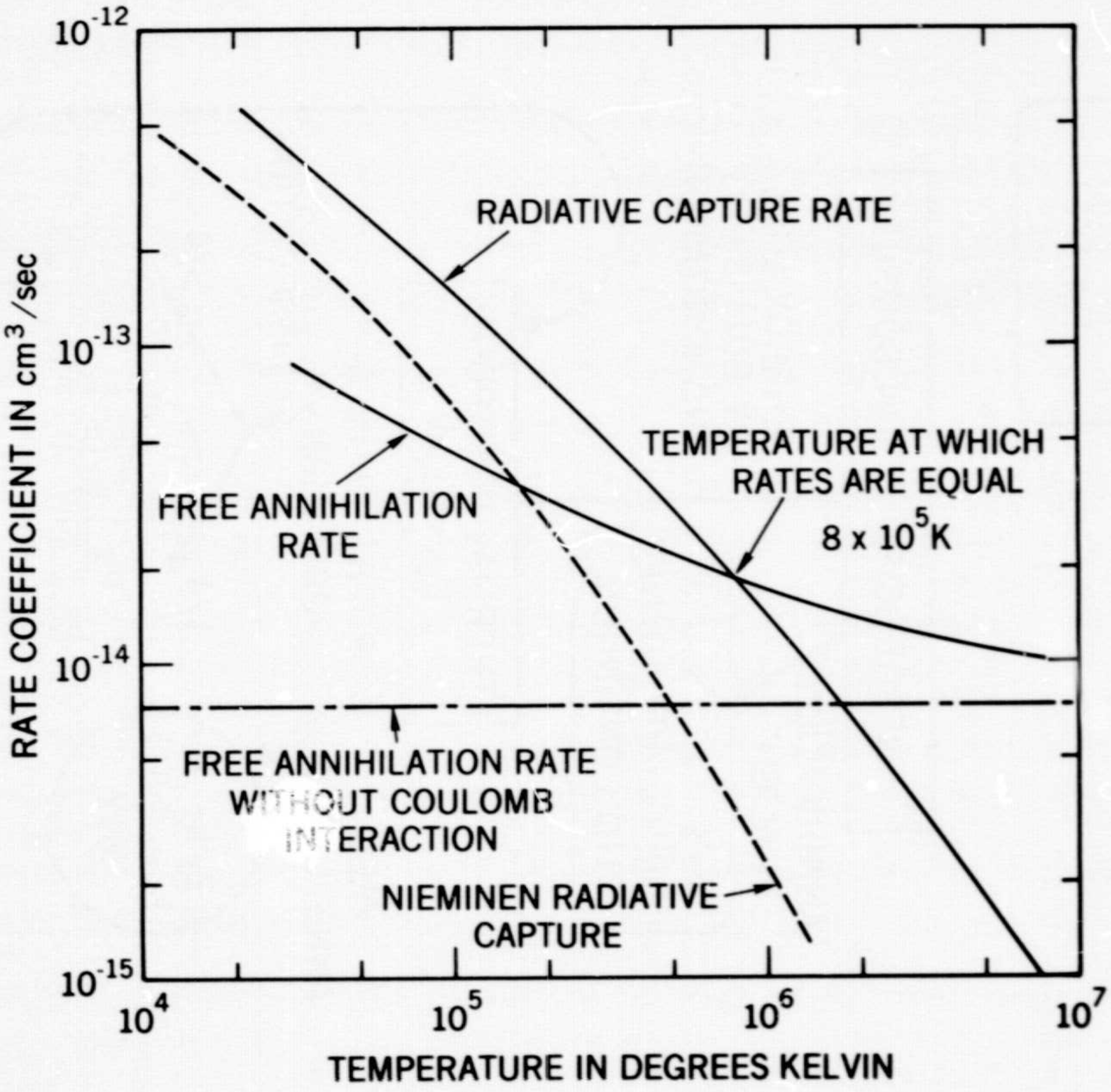

Figure 2. Radiative Recombination and Free Annihilation Rate Coefficients

As can be seen from this figure, if the temperature is greater than about 10^6 K, more than half of the positrons annihilate without forming positronium.

We do not know the temperature in the annihilation region. Analyses of the time dependence of the 0.51-MeV line, showed that the positrons annihilate in a region where the density is larger than about 10^{12} cm^{-3} (Chupp et al. 1975, Wang and Ramaty 1975). It is unlikely that such dense regions can be heated to temperatures much higher than a few times 10^4 K. We note, however that the temperature of the annihilation region could be obtained best by measuring the width of the 0.51-MeV line. The full width at half maximum of this line due to thermal broadening is given by $\Delta E\gamma \simeq 1.1$ keV $T_4^{1/2}$, where T_4 is the temperature in units of 10^4 K.

Below about 10^5 K positronium formation proceeds mainly by charge exchange with neutral hydrogen. Leventhal (1973) suggested that in a very cold and low-density hydrogen gas, such as an H I region in the interstellar medium, positrons annihilate exclusively from bound states of positronium and that no free annihilation takes place.

Positronium formation by charge exchange in a hot, moderately dense, and partially ionized medium such as a solar flare, has not yet been fully investigated, mainly because of the lack of reliable cross sections. It is, nevertheless, clear that if the ambient density in the annihilation region is larger than a few times 10^{14} cm^{-3} not all positrons will annihilate from bound states of positronium. As mentioned above, from considerations of the time dependence of the 0.51-MeV line intensity, it is known that the density in the annihilation region is greater than about 10^{12} cm^{-3}.

We define the parameter f as the fraction of positrons which annihilate from the triplet state of positronium, and the quantities $N_{2\gamma}$ and $N_{3\gamma}$ as the number of photons resulting from 2-gamma and 3-gamma annihilations of thermal positrons normalized to one such positron.

$$N_{3\gamma}/N_{2\gamma} = (3/2)\ f/(1-f) \quad . \qquad (1)$$

The maximum value of f is 0.75, in which case $N_{3\gamma}/N_{2\gamma} = 4.5$. However, if only half the maximum number of annihilations proceed fr m triplet state of positronium, f = 0.375, and $N_{3\gamma}/N_{2\gamma} = 0.9$.

3. <u>Detection of Positronium Annihilation Radiation</u>. The formation of positronium atoms in solar flares could possible be observed by measuring the gamma-ray spectrum at energies just below 0.511 MeV with detectors having good energy resolution. Such measurements, however, are severely complicated by the existence of strong continuum emission due to bremsstrahlung of energetic electrons in the flare region, and by line emissions at 0.431 MeV and 0.478 MeV from the reactions $\alpha + \alpha \rightarrow {}^7Be^* + n$ and $\alpha + \alpha \rightarrow {}^7Li^* + p$ (Kozlovsky and Ramaty 1974).

The intensity of gamma rays from triplet positronium annihilation can be written as

$$\phi_t(E_\gamma) = (N_{3\gamma}/N_{2\gamma})\ \overline{\phi}_{0.51}\ P_T(E_\gamma)/0.511 \text{ photons cm}^{-2}\text{ s}^{-1}\text{ MeV}^{-1} \ , \qquad (2)$$

where $\overline{\phi}_{0.51}$ is the total observed 0.51-MeV line intensity, and $P_T(E_\gamma)$ is the probability per unit energy of finding a triplet gamma ray with a particular energy from 0 to 0.511 MeV. This function has been given by Leventhal (1973). It is normalized such that $\int_0^{0.511} dE_\gamma\ P_T(E_\gamma)/0.511 = 1$.

In the calculations below we use the observed value for the 1972 August 4 flare, $\bar{\phi}_{0.51} = 0.06$ photons cm^{-2} s^{-1} (Chupp et al. 1975), and the maximum value $N_{3\gamma}/N_{2\gamma} = 4.5$.

The intensity of continuum emission from the flare of 1972 August 4, at energies near 0.51 MeV, was measured (Chupp et al. 1975) and is given by

$$\phi_C(E_\gamma) \simeq 0.4\, E_\gamma^{-3.42} \text{ photons cm}^{-2}\text{ s}^{-1}\text{ MeV}^{-1} \qquad (3)$$

We estimate the intensity of the ^{7}Li and ^{7}Be lines as follows. According to Ramaty et al. (1975), the total intensity in these lines is comparable to the intensity of the 4.4-MeV line, which was observed to be approximately 0.03 photons cm^{-2} s^{-1} for the 1972 August 4 flare (Chupp et al. 1975). Thus

$$\phi_{0.431}(E_\gamma) + \phi_{0.478}(E_\gamma) \simeq 0.03\ (\sqrt{2\pi}\sigma)^{-1}\ \{\exp[-E_\gamma - 0.431]^2/2\sigma^2 + \exp[-(E_\gamma - 0.478)^2/2\sigma^2]\} \ , \qquad (4)$$

where $\sigma \simeq 0.04$ MeV (Kozlovsky and Ramaty 1974). In equation (4) we have approximated the shapes of the $\alpha\alpha$ lines by gaussians. Such forms are valid only when the line shapes are due to thermal broadening. Since the shapes of the $\alpha\alpha$ lines are determined by nuclear kinematics, they should be calculated by a method similar to that used by Ramaty and Crannell (1975) for evaluating the shape of the 6.1-MeV line of ^{16}O. However, because the differential cross sections for the $\alpha\alpha$ reactions are not known, we postpone such a calculation for future research, and use equation (4) as a rough estimate for the present paper.

We have evaluated equations (2), (3) and (4) for the parameters given above and the results are shown in Figure 3. As mentioned above, thermal motions broaden the 0.51-MeV line ($\Delta E_\gamma \simeq 1.1$ keV $T_4^{\frac{1}{2}}$). Thermal broadening also blurs the edge of the positronium annihilation spectrum, but if the temperature is less than about 10^5 K this effect is quite negligible.

In order to assess the observability of positronium annihilation radiation, we have evaluated the number of counts due to triplet positronium annihilation, solar flare continuum, instrumental background, and $\alpha\alpha$ reactions observed by the detector of Chupp et al. (1975) in a 50 keV bin just below 0.511 MeV. Using the fact that for the 1972 August 4 flare there were 108 counts in the 0.51-MeV line, we find 404 counts for the continuum, 184 counts for the background, 38 counts for the $\alpha\alpha$ reactions, and 90 counts for triplet positronium annihilation provided that $N_{3\gamma}/N_{2\gamma}$ has its maximum value of 4.5. However, if only half the maximum number of annihilations proceed via triplet positronium, there are only 18 counts due to triplet positronium in the 0.461-MeV to 0.511-MeV energy bin.

We conclude that it will probably be quite difficult to observe positronium annihilation radiation, in the presence of a very strong solar flare continuum. The ^{7}Li and ^{7}Be lines do not present a serious problem if all annihilations proceed via positronium formation. However, if only half the positrons annihilate in this manner, positronium annihilation radiation may be indistinquishable from the ^{7}Li and ^{7}Be lines.

A more favorable condition for observing positronium annihilation radiation may arise at the late stages of solar gamma-ray events when the ratio of the 0.51-MeV line to the continuum could be much larger than that

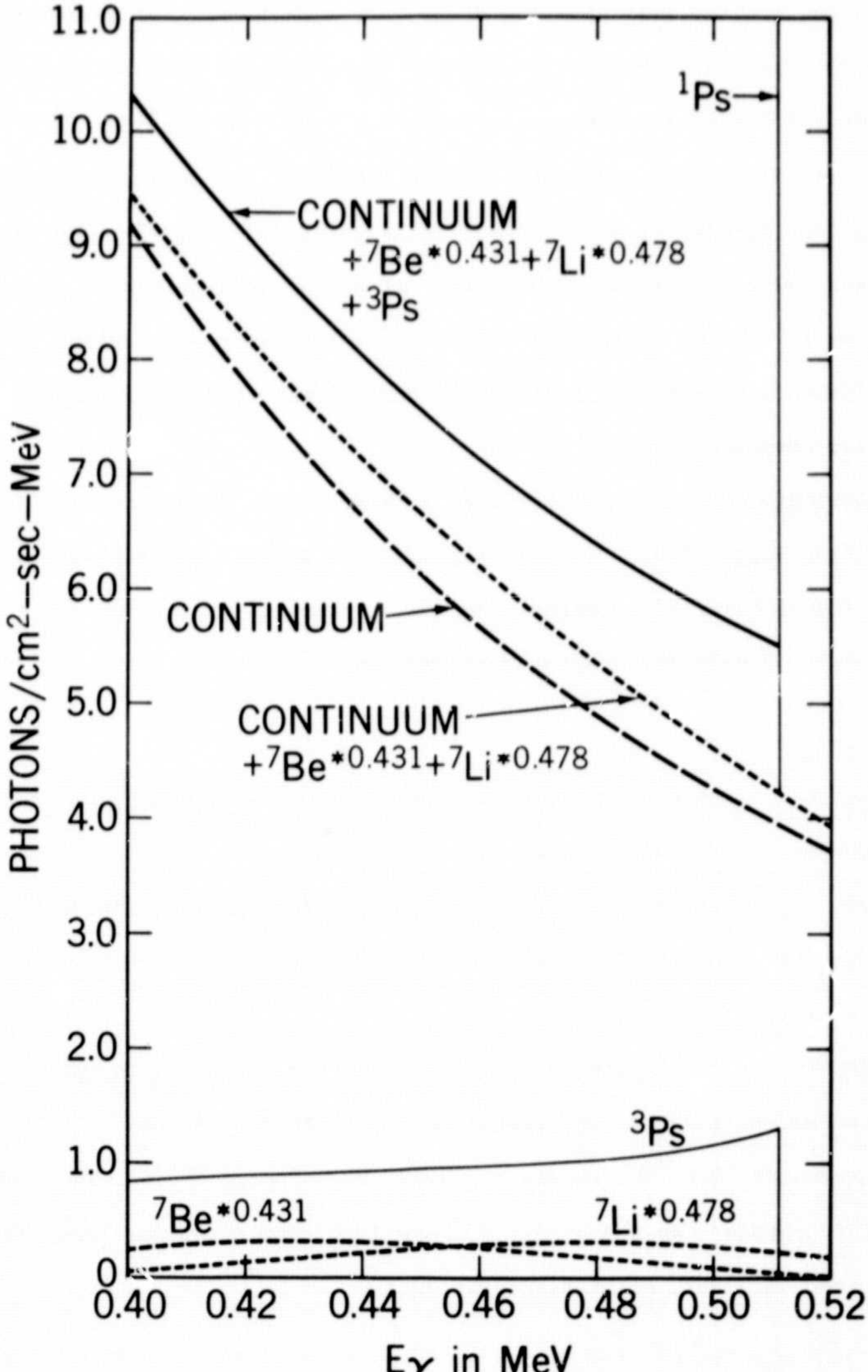

Figure 3. Spectra of the positron annihilation emission, continuum radiation, and the ^7Li and ^7Be lines.

observed for the 1972 August 4 flare. At such times, the intensity of the $\alpha\alpha$ lines is also greatly reduced. This follows from the delayed nature of positron annihilation radiation caused by the long half lives of some of the positron emitters (^{11}C and ^{13}N), and possibly also by the long slowing-down times of relativistic positrons from π^+ decay (Wang and Ramaty 1975). Thus, when the number of accelerated particles in the flare region is already diminished and hence no nuclear reactions and bremsstrahlung are produced, positronium annihilation radiation could be more easily observed.

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