GAMMA RAY LINE PRODUCTION FROM COSMIC RAY SPALLATION REACTIONS

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The gamma ray line intensities due to cosmic-ray spallation reactions in clouds, the galactic disk and accreting binary pulsars are calculated. With the most favorable plausible assumptions, only a few lines may be detectable at the level of 10^{-6} per cm^2-sec. The intensities are compared with those generated in nuclear excitation reactions.

1. Introduction. Measurements of gamma ray line intensities and energies from astrophysical sites permit the study of two types of nuclear processes: (1) Nuclear collisions by cosmic rays and other high energy particles. Possible sites for these reactions are the galactic disk (Ramaty et al. 1979), interstellar clouds, supernovae in clouds, accreting sources such as beaming pulsars in close binary systems, and active galactic nuclei, with high-energy beams interacting in the accretion disk. (2) Recent nucleosynthesis (i.e. build-up of nuclei) in supernova and nova precursors, as well as during their explosive phase (Clayton, 1973, Arnett, 1978, Mahoney et al. 1982, Clayton, 1984). The ^{26}Al line has already been observed at a flux level of 5×10^{-4}/cm^2-sec. rad (Mahoney et al. 1984 and Share et al. 1985). The latter line is probably due to nucleosynthesis in novae (Clayton, 1984).

In nuclear collisions, there are three processes that give rise to gamma ray lines: (1) Quasi-elastic collisions at low energies that generate excited nuclei. The relevant cross sections for these reactions have been reviewed by Ramaty et al. (1979). The main uncertainty here is the abundance of the low energy nuclei (near 10 MeV). (2) Nuclear spallation reactions, with the spallation products in various excited states, that de-excite promptly by gamma-ray line emission. Here the uncertainty is due to lack of information of the population of the various excited states. (3) Gamma rays produced upon the decay of various radioactive nuclides generated in nuclear spallation reactions. The associated gamma-ray energies and emission probabilities for the latter case are sufficiently well known. In this paper we shall concentrate on processes (2) and (3).

In Section 2, we calculate the spallation yields and the relative gamma ray line intensities. In Section 3, we apply these calculations to the interstellar clouds, the galactic disk, and to pulsars in an accreting system. In Section 4, the conclusions are presented, and the detectability with the GRO/OSSE detector is discussed.

2. The Spallation Yields and Relative Gamma Ray Intensities. The rate at which a nuclide of type j is created per unit volume in the interstellar medium from proton interactions (for protons in a given energy interval) is:

$$R_j \text{ (nuclides/cm}^3\text{ sec)} = 10^{-27} J \, n_H \, F_j \qquad (1)$$

Here 10^{-27} is the conversion factor from mb to cm^2, J = cosmic ray protons/cm^2-sec, in a given energy interval. (We assume that the contribution of nuclei heavier than protons results in a second-order correction, though at energies of a couple of MeV/u, the contribution of alpha-induced reactions is important.) n_H is the number of hydrogen atoms in the medium, per cm^3, and

$$F_j = \sum_i \sigma_{ji} f_i, \qquad (2)$$

where σ_{ji} is the cross section for protons with nuclide i, in units of mb yielding nuclide j, and f_i is the abundance of i per H atom in the collision medium.

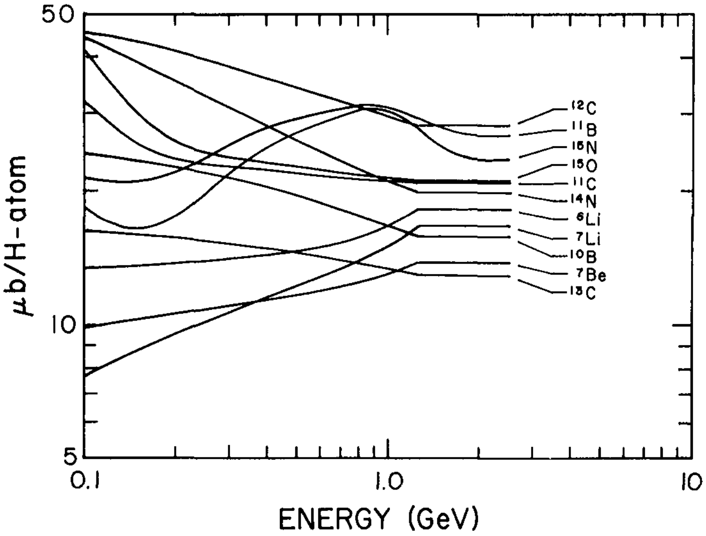

Fig. 1. The energy dependence of F_j, the production rate function for the nuclides whose secondary yields are largest.

Fig. 1 shows the values of F_j as a function of cosmic ray proton energy E, using the elemental and isotopic abundances of Cameron (1982). Assuming that most of the prompt de-excitations pass to the ground state via the first excited state, the most prominent lines induced by high energy cosmic ray protons would be 4.44 MeV from ^{12}C, 2.12 MeV from ^{11}B, 5.27 MeV from ^{15}N, 5.18 MeV from ^{15}O. In addition, the radioactive decay of ^{15}O and ^{11}C yields positrons. Fig. 2 shows the F_j values of other abundant products. Some of these F_j values are low at low energies, providing a test for the presence or absence of low-energy cosmic rays.

The rate of gamma ray line emission from a volume V is $R_j Vk$, where k is the gamma ray multiplicity from the formation of nuclide j. The gamma ray line flux from nuclide j at earth is:

$$\frac{R_j Vk}{4\pi d^2} \quad (\text{per } cm^2\text{-sec}), \qquad (3)$$

where d is the distance from the gamma ray source to earth.

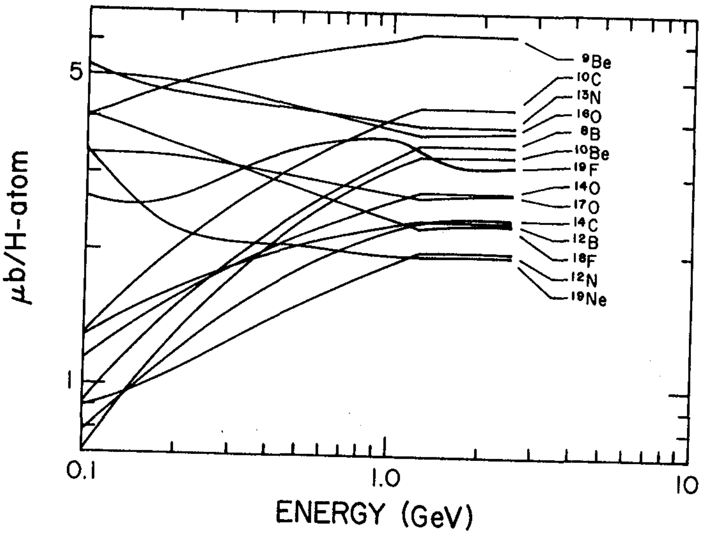

Fig. 2. The energy dependence of F_j for less abundant product nuclei.

3. The Cosmic-Ray Induced Gamma Ray Flux from Clouds, the Galactic Disk and from Accreting Pulsars. The flux from a large cloud is calculated, using the properties discussed by Issa et al. (1981) i.e. we assume a cloud mass of about 10^5 solar masses, or 10^{62} hydrogen atoms. A distance of 400 pc is assumed. If one adopts Cameron's abundances for the calculations, F=0.03 for the ^{12}C 4.44 MeV line. J, for the local interstellar cosmic ray intensity is about 10/cm^2-sec. With the most conservative assumptions, the flux of the 4.4 MeV carbon line is about $2x10^{-9}$ γ/cm^2-sec. However, Issa et al. (1981) noted that the cosmic ray flux is higher by a factor of 5, especially in clouds associated with O-B stars, where frequent supernovae occur. Furthermore, such C-B regions should have nucleosynthetic enhancement of elements heavier than helium. Adopting a factor of 5 for this enhancement the flux is $5x10^{-8}$. Reeves (1978), based on the general abundances of isotopes of B, has concluded that there is a very large flux of low-energy particles. A large low-energy cosmic ray flux coupled to the large low-energy cross sections would further increase the 4.4 MeV gamma ray flux from a large cloud by an order of magnitude, to values near 5×10^{-7}/cm^2-sec. With a large proton flux between 5 and 30 MeV, such as considered by Ramaty et al. (1979), the contribution of nuclear excitations to the gamma ray line flux becomes dominant; the 4.4 MeV gamma ray line flux could then be boosted further by a factor of about 10.

With the "optimistic" latter assumptions, the flux from the galactic disk (near 4 MeV) due to spallation is about 3×10^{-6}/cm^2-sec, and with nuclear excitation included, about $3x10^{-5}$/cm^2-sec (Ramaty et al. 1979). The gamma ray background from the galactic disk (due largely to bremsstrahlung) is about 10^{-4} photons/cm^2-sec MeV at 4 MeV and about 10^{-2} at 1 MeV (O'Neill et al. 1983). This background renders the lines from the galactic disk (near 4 MeV) difficult to observe if the fluxes are less than 10^{-5}/cm^2-sec, unless the line is narrow (i.e. if the recoil nuclei are produced in grains and come to rest therein) and the instrument has an excellent resolution (about 5 keV).

Consider a pulsar beam incident on an accretion disk that is sufficiently thick for most particles to collide. Adopting (a) Cameron's (1982) abundances for the accretion disk material, (b) power input of 10^{37} ergs/sec per decade of energy interval, and (c) a distance of 1 kpc, we estimate a flux of about 10^{-6} f/cm²-sec for the 4.4 MeV ^{12}C spallation-induced gamma rays. (The flux is about 10 times larger if low-energy nuclear excitation reactions are considered.) Here f is the gamma ray suppression factor due to opacity of the accretion disk; f<1.

Table 1 summarizes the 4.4 MeV ^{12}C fluxes from the sources discussed above. The 5.1-5.3 MeV fluxes of ^{15}O, ^{15}N, ^{14}N are nearly as abundant.

Table 1. The 4.4 MeV ^{12}C Flux (cm^{-2} sec^{-1}) from Various Sources

Dominant Reaction	Large cloud[a]	Inner Galactic Disk	Accreting Pulsar[a]
Spallation	5×10^{-7}	3×10^{-6}	10^{-6} f
Excitation[b]	5×10^{-6}	3×10^{-5}	10^{-5} f

[a] The assumed proton fluxes and properties of these sources are given in the text.

[b] Excitation dominates over spallation if low-energy cosmic rays dominate.

4. Conclusions.

Gamma ray lines due to nuclear spallation reactions should be detectable with a detector that has a threshold of 10^{-6}/cm²-sec from sources like the galactic disk (if the low-energy 20-50 MeV cosmic ray flux is high) and from pulsars and active galactic nuclei that beam into accretion disks. The above detection threshold is about 10 times lower than that of GRO/OSSE. However, if the flux between 5-30 MeV is high, as suggested by Reeves et al. (1978) and Ramaty et al. (1979), nuclear excitation lines will be observable from the above sites (with the GRO/OSSE detector) as well as from supernova remnants in clouds (Morfill et al. 1981).

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