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NUCLEAR GAMMA RAYS FROM ^{7}Li IN THE GALACTIC COSMIC RADIATION

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ABSTRACT

The observation of a γ-ray line feature from the direction of the galactic center by Johnson, Harnden, and Haymes is interpreted as the 478-keV nuclear de-excitation of low-energy ^{7}Li cosmic rays as they inelastically scatter from the interstellar gas. The prediction of an associated line at 432 keV is proposed as a definitive test of this idea.

This paper interprets the observed γ-ray feature from the region of the galactic center (Johnson, Harnden, and Haymes 1972) as being due to inelastic scattering of ^{7}Li nuclei in the primary cosmic radiation. In figure 1 are plotted the most abundant cosmic-ray nuclei as a function of their first excited state (for each atomic number, terrestrial isotope ratios were used for lack of more accurate cosmic-ray data). There is a general trend for the more abundant nuclei to have higher excitation levels, which is a consequence of the general principle of nucleosynthesis whereby the more stable nuclei are easier to produce and more difficult to destroy. ^{7}Li maintains a unique position on this plot; it is the most abundant cosmic-ray nuclide with an excitation energy below 1 MeV. Its abnormally high abundance is a result of its spallogenic formation, the details of which are reviewed by Reeves, Fowler, and Hoyle (1970).

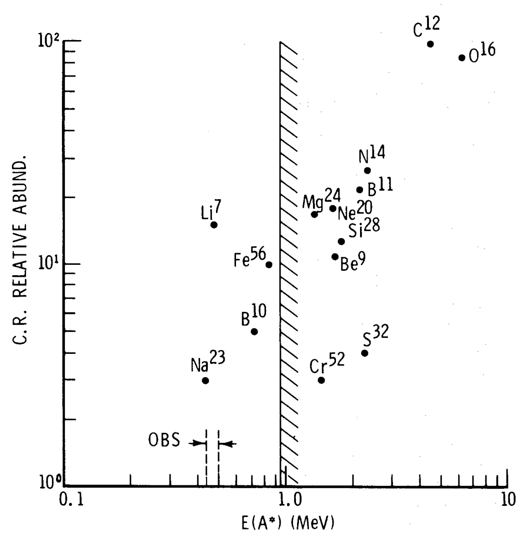

FIG. 1.—Relative abundances of cosmic-ray nuclei (Shapiro and Silberberg 1970) plotted as a function of the energy of their first excitation level. Terrestrial isotope ratios have been assumed. The energy range of the line feature observed from the galactic center region (Johnson *et al.* 1972) is indicated. No observations have been made above 0.93 MeV.

Of the nuclear interactions which may produce line γ-rays from collisions of cosmic rays with the interstellar medium, inelastic scattering has the largest cross-section. The first excitation energy of ^{7}Li, 478 keV, falls within the range of the line feature observed by Johnson *et al.* (1972), 473 $\pm$ 30 keV. The cross-section for $^7\mathrm{Li}(p, p')^7\mathrm{Li}^*$ (478 keV) rises sharply around 1 MeV to a maximum of about 240 mb in the 3–5 MeV region; it declines abruptly to 80 mb at 10 MeV and to about 10 mb at 50 MeV (Gleyvod, Heydenburg, and Naqib 1965; Locard, Austin, and Benenson 1967). For calculation purposes we will take $\bar{\sigma} = 150$ mb to characterize the average cross-section between 2 and 10 MeV per nucleon, the cosmic-ray energy range we propose as the source of the line feature. As an estimate of the cosmic-ray flux

$$\int_{2\mathrm{MeV}}^{10\mathrm{MeV}} \phi(E)dE \equiv \bar{\phi}$$

required to produce the observed feature, which Johnson *et al.* (1972) estimate as $F_\gamma = 1.8 \times 10^{-3}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, we use the fact that the flux observed at Earth by a wide-angle (24°) telescope viewing the galactic disk toward its center is of the same magnitude as if the entire galactic gas and average flux were located at a distance of about $d = 10$ kpc. The flux received is

$$F_\gamma \simeq \frac{1}{4\pi} \int_V \int_E r^{-2} n_p \phi_{^7\mathrm{Li}}(E) \sigma_{p,p'}(E) dE dV\,, \qquad (1)$$

where n_p is the number density of interstellar protons (considering for order of magnitude only proton targets) and $\phi_{^7\mathrm{Li}}(E) = 8 \times 10^{-4}\phi(E)$ is the ^{7}Li cosmic-ray flux at a given energy per nucleon and $\phi(E)$ is the cosmic-ray proton flux (Shapiro and Silberberg 1970). For our order-of-magnitude calculation this simply becomes

$$F_\gamma \simeq 8 \times 10^{-4} \frac{N_p \bar{\sigma} \bar{\phi}}{4\pi d^2}\,, \qquad (2)$$

where N_p is the total number of protons in the galactic gas. If we assume that the galactic interstellar gas comprises 2 percent of the mass of the Galaxy, we get $N_p = 3 \times 10^{66}$; and if we take $\bar{\sigma} = 150$ mb and $d = 10$ kpc, we get $F_\gamma = 1.8 \times 10^{-3}$ for

$$\bar{\phi} = 6 \times 10^4\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\,. \qquad (3)$$

We will consider several possible objections to this rather large flux between 2 and 10 MeV per nucleon. First, this flux is about a factor of 60 greater than the upper limit derived by Apparao (1968) from diffuse γ-ray observations. However, his upper limit pertains to protons in the energy range from 5 to 30 MeV. Also, uncertainties in his assumed distance to the source, the isotropy of the source, and the interstellar density, as well as the uncertainties of values used in the present calculation, could well account for the difference.

Second, the flux of equation (3) represents an energy density of over 100 eV cm^{-3} which, if maintained over a large fraction of the galactic volume, would create dynamic instabilities (Parker 1966). However, the required flux could exist in bottles of high flux regions where the ambient magnetic fields are dominated by the streaming of low-energy cosmic rays. This situation probably exists within the Gum Nebula (Ramaty *et al.* 1971) and presumably in supernova remnants and other active regions throughout the Galaxy.

Finally, Reeves *et al.* (1970) found that a flux above 30 MeV per nucleon equal to 12 cm^{-2} s^{-1} would produce (Li/H) $= 10^{-9}$ in 12×10^9 years. They point out that this number is in reasonable agreement with the observed flux at solar minimum. However, Goldstein, Fisk, and Ramaty (1970) find that the solar modulation is so strong that particles at Earth with energies of 30 MeV per nucleon are about three to four orders of magnitude less abundant than their 50–100 MeV progenitors before modulation in the interstellar medium. It seems fair to say that their paper dims the prospects for learning anything about the low-energy interstellar flux from observations near the Earth. Also, we note that if the low-energy cosmic rays form a kinetic-energy power-law spectrum, say $T^{-2.5}$, the flux $\bar{\phi}$ would exceed the flux above 30 MeV per nucleon by a factor of 60. Fowler, Reeves, and Silk (1970) also observed that the fluxes required to produce Li and B were highly inadequate to heat H I regions and suggested that if H I regions are heated by cosmic rays, it must be due to a large flux below 5 MeV. We do not want to push these considerations too hard either, because H I regions may not be typical of the high flux regions. Similar questions regarding the possibility of large fluxes of low-energy cosmic rays have been raised by Comstock, Hsieh, and Simpson (1972) from consideration of the abundances of the isotopes of hydrogen and helium in the cosmic radiation (see especially their paragraph 2, p. 704). Thus we maintain that the requirements of equation (3) are not obviously severe and, in fact, must exist if our interpretation is correct.

The production of 511-keV annihilation radiation from the Galaxy has been considered by Ramaty, Stecker, and Misra (1970). They considered the low-energy p + CNO reactions which produce positron-emitting nuclei which in turn produce the 511-keV radiation. Although the abundance of CNO in the combined cosmic radiation and interstellar medium is $\sim$25 times that of ^{7}Li, the thresholds for these reactions are considerably higher ($\geq$10 MeV) and the cross-sections are lower. Near 10 MeV, the most efficient positron-producing reaction is ^{16}O$(p, \alpha)^{13}$N which has an estimated cross-section of $\sim$40 mb. The observations of Johnson *et al.* (1972) gave no indication of 511-keV radiation with an intensity comparable to the $\sim$473-keV feature. This would imply, in terms of our model, that the low-energy cosmic-ray flux is increasing with decreasing energy down to $\sim$1 MeV so that the 2–10 MeV flux is over twice as great as the $>$10 MeV flux.

There is an unambiguous way to determine if the feature observed by Johnson *et al.* (1972) is due to the inelastic scattering of cosmic-ray ^{7}Li from interstellar protons. The measurements made and reviewed by Borchers and Poppe (1963) between 2 and 10 MeV and the measurements between 20 and 50 MeV by Locard *et al.* (1967) show that between 2 and 50 MeV per nucleon the cross-section for ^{7}Li$(p, n)^7$Be* (432 keV) is approximately one-third of the cross-section for ^{7}Li$(p, p')^7$Li* (478 keV). It follows that the mechanism we propose would produce a γ-ray flux at 432 keV about one-third of that at 478 keV. The observations of Johnson *et al.*, while not of sufficiently high resolution and statistical accuracy to indicate the presence of the 432-keV line, are nonetheless consistent with it. With their assistance we have replotted their data in figure 2. For comparison we show as a smooth curve the sum of a power-law background and the combined ^{7}Li-^{7}Be feature proposed in this paper. The general similarity of their data to the shape of the feature we propose is noteworthy. It will clearly be desirable in the future of γ-ray astronomy to view the galactic center with an instrument of higher sensitivity and energy resolution, inasmuch as the observation of the double peak proposed here will be necessary and probably sufficient proof of the correctness of our proposal. Variations of this flux with galactic coordinates would indicate the association of the γ-rays with regions of high cosmic-ray flux.

If the present interpretation is correct, then other nuclei with higher excitation energies should be detectable from the regions of high cosmic-ray flux and in particular ^{12}C* (4.43 MeV) and ^{16}O* (6.05 MeV) should be very prominent. These lines have been considered by Fowler *et al.* (1970) and Ramaty and Boldt (1971). The observations of Johnson *et al.* were made only up to 0.93 MeV, as indicated in figure 1. Thus far, no observations with both sufficient sensitivity and energy resolution have been made above 1 MeV, although such γ-ray telescopes exist.

Various astrophysical sources of nuclear γ-rays have recently been described (Clayton 1971 and references therein). The present paper attempts to interpret what

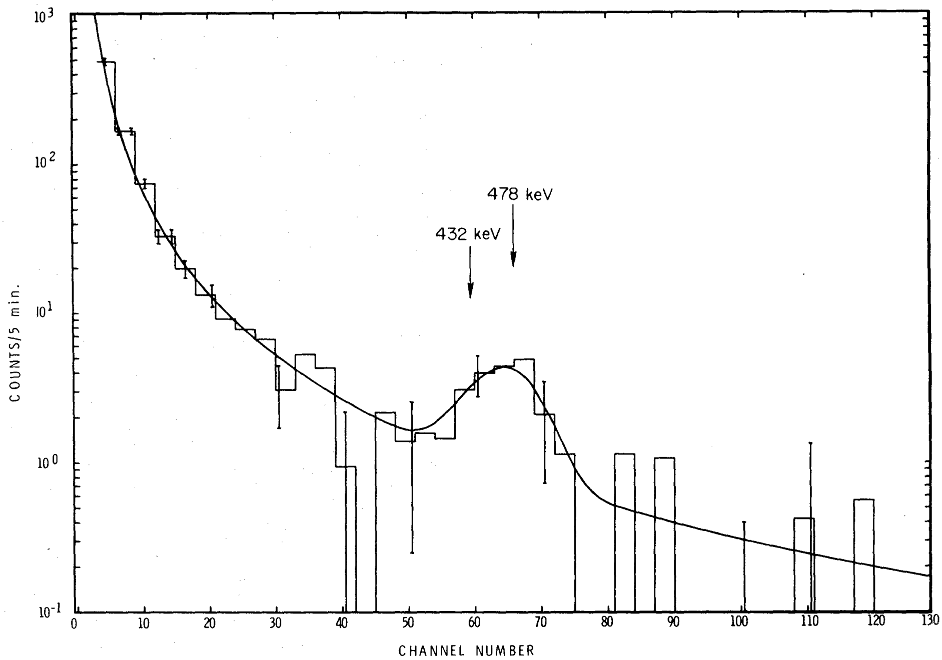

FIG. 2.—The curve shows the shape of the ^{7}Li inelastic-scattering feature superposed on a smooth power-law continuum. The profile was computed for an energy resolution equal to that of the detector used by Johnson *et al.* Because of the limited resolution, the line at 432 keV due to ^{7}Li(p, n)^{7}Be* is not physically separated from the line at 478 keV due to ^{7}Li(p, p')^{7}Li* which is three times stronger. The histograms are the data of Johnson *et al.* (1972) with their energy channels summed in groups of three adjacent channels to reduce statistical fluctuations. The consistency of their feature with the one we propose is evident.

may be the first positive measurement in the new field of observational nuclear γ-ray astronomy. If this interpretation is correct, then further observations should reveal the low-energy cosmic-ray fluxes and isotopic abundances in regions of the Galaxy which at present are unobtainable by any other means.

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