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# $^{26}$Al - A GALACTIC SOURCE OF GAMMA RAY-LINE EMISSION

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ABSTRACT

A detectable gamma-ray line at 1.809 MeV results from the decay of $^{26}$Al in the interstellar medium if this isotope is synthesized in supernovae with abundance $\sim 10^{-3}$ relative to $^{26}$Mg. The expected intensity from the direction of the galactic center is $\sim 10^{-4}$ photons cm$^{-2}$sec$^{-1}$rad$^{-1}$, and the line width is <3 keV. This intensity is comparable to the intensities of the other strongest gamma-ray lines resulting from processes of nucleosynthesis at 0.847 MeV from $^{56}$Fe, 1.156 MeV from $^{44}$Ca, and 1.173 and 1.332 MeV from $^{60}$Ni. But the width of the line from $^{26}$Al decay is an order of magnitude smaller than that of either the 0.847 or the 1.156 MeV lines and hence this line should be much more easily observable with high resolution detectors.

Subject headings--gamma rays - nucleosynthesis.

The purpose of the present Letter is to point out that observable gamma-ray line emission is produced from the beta decay of $^{26}Al$ in the interstellar medium. $^{26}Al$ decays with a half life of $7.4 \times 10^5$ yrs by positron emission or electron capture into excited states of $^{26}Mg$ with ensuing line emission at 1.809 MeV (100%) and 1.130 Mev (4%). The isomeric state of $^{26}Al$ with a half life 6.4 seconds, however, beta decays directly to the ground state of $^{26}Mg$ and hence does not produce prompt gamma rays. But excitation of $^{26}Al$ to its isomeric state is extremely unlikely in the interstellar medium. For details of the nuclear data see Endt and van der Leun (1973) and Nuclear Data Group (1973).

$^{26}Al$ is believed to be produced by explosive carbon burning in supernovae (Arnett 1969) with a yield relative to $^{26}Mg$ of about $10^{-3}$ (Schramm 1971 and private communication 1976). The importance of the decay process $^{26}Al \rightarrow ^{26}Mg$ as a source of line emission can be assessed by comparing it with the other decay chains resulting from nucleosynthesis, which Clayton (1973) suggests should produce the most intense gamma ray lines: $^{56}Ni \rightarrow ^{56}Co \rightarrow ^{56}Fe$, $^{44}Ti \rightarrow ^{44}Sc \rightarrow ^{44}Ca$ and $^{60}Fe \rightarrow ^{60}Co \rightarrow ^{60}Ni$. These chains, with their relevant half lives, yields per supernova, photon energies, and photons per disintegration are listed in Table 1. The yields of $^{56}Ni$, $^{44}Ti$ and $^{60}Fe$ per supernova are consistent with the solar system abundances (Cameron 1973) of the final decay products of these isotopes

($^{56}Fe$, $^{44}Ca$ and $^{60}Ni$), and with the assumption that 1% of the $^{60}Ni$ originates from $^{60}Fe$. (This value is the minimum contribution of $^{60}Fe$ to $^{60}Ni$ estimated by Clayton 1973.)

The half lives of the radioactive isotopes are of crucial importance for the detectability of the lines. Because nucleosynthesis takes place in dense material, gamma ray lines can be observed only if significant expansion occurs before the decay of the nuclei, so that the overlying matter is optically thin to the emitted photons. For gamma rays from the long-lived isotopes $^{26}Al$, $^{44}Ti$ and $^{60}Fe$, the emitting region is definitely transparent. For the lines of $^{56}Co$ one expects that the medium could just become transparent in 77 days provided that in the supernova explosion, $\sim$one solar mass is ejected with a velocity of about $10^4$ km/sec. But for gamma rays from the short-lived isotopes $^{56}Ni$ (6.1 days) and $^{48}V$(16 days), which were previously suggested as potential line sources, the emitting region is opaque, and hence lines from these isotopes are not included in Table 1.

The half life of the isotope also effectively determines the width of the lines. For times of the order of the half lives of $^{44}Ti$ and $^{56}Co$ we expect expansion velocities of about 6000 km/sec (Chevalier 1977), and hence line widths (FWHM) of about 40 keV at an MeV. On the other hand, for the lines of $^{26}Al$ and $^{60}Fe$, expansion velocities after $10^5$ yrs should be only tens of km/sec so that galactic rotation velocities are more appropriate giving a FWHM <3 keV.

We proceed now to estimate the fluxes of the lines listed in Table 1 from various astrophysical sites. Because of its short lifetime it is unlikely that the decay chain $^{56}Ni \rightarrow ^{56}Co \rightarrow ^{56}Fe$ can be observed from a galactic supernova. The Virgo cluster, however, with 2500 galaxies (Allen 1973) and an average supernova rate of 1 every 50 years per galaxy (Tammann 1974) presents an essentially continuous source of $^{56}Co$ decay lines. For a distance of 19 Mpc the flux of the 0.847 MeV line is about $10^{-4}f$ photons $cm^{-2}sec^{-1}$, where f is the fraction of the line photons which escape from the supernova. Clayton et al. (1969) have estimated that f could be close to unity, but clearly the value of this parameter depends strongly on the total ejected mass, on the radial dependence of the composition, and on the velocity of the ejecta. The ejection velocity could be determined from the width of the line; for 6000 km/sec it would be about 35 keV.

Because of its longer half life, the decay chain $^{44}Ti \rightarrow ^{44}Sc \rightarrow ^{44}Ca$ could possibly be observed from a galactic supernova remnant. For a hypothetical remnant at the galactic center with an age equal to the $^{44}Ti$ mean life, and for Cassiopeia A with an age of 300 years, and distance of 2.8 kpc (van den Bergh and Dodd 1970), the 1.156 MeV line fluxes are about $10^{-4}$ and $4 \times 10^{-5}$ photons $cm^{-2}sec^{-1}$, respectively. For an expansion velocity of 6000 km/sec, the width of this line is about 45 keV.

While the short lived isotopes discussed above lead to essentially point sources of gamma-ray lines, the much longer lived $^{26}Al$ and $^{60}Fe$, are likely to produce diffuse emission from the interstellar medium. With a supernova rate of (30 years)$^{-1}$ (Gunn and Ostriker 1970; Seiradakis 1976) in the galactic volume of $4 \times 10^{66}$ cm$^3$, the emissivities of the 1.809 MeV line from $^{26}Al$ decay and of the $^{60}Fe$ decay lines given in Table 1 are both about $10^{-25}$photons cm$^{-3}$sec$^{-1}$. This value is comparable to the local emissivity of photons of energies greater than 100 MeV due to cosmic ray interactions with the interstellar gas of average density 1 H atom cm$^{-3}$ (e.g. Stecker 1976). If the sources of nucleosynthesis have a similar spatial distribution to that of high energy gamma-rays, then the observed flux of >100 MeV gamma-rays of $\sim 10^{-4}$photons cm$^{-2}$ sec$^{-1}$rad$^{-1}$ (Thompson et al. 1976) from the disk in the general direction of the galactic center would imply a comparable flux for both the 1.809 MeV line from $^{26}Al$ decay and from each of the $^{60}Fe$ decay lines. This flux might be somewhat smaller if unresolved pulsars contribute significantly to the observed >100 MeV gamma ray flux (Higdon and Lingenfelter 1976). In any event, a flux of $\sim 10^{-4}$photons cm$^{-2}$sec$^{-1}$rad$^{-1}$ in the 1.809 MeV line is comparable to the most intense fluxes expected from $^{56}Co$ and $^{44}Ti$ decay lines. Furthermore because of their much narrower widths (FWHM <3 keV), the 1.809 MeV line and the lines at 1.173 and 1.332 MeV should be much easier to observe with high resolution detectors.

$^{26}Al$ could also be produced by spallation processes (Schramm

1971). But, if such processes were the principal source of $^{26}Al$, other lines such as the 1.779 MeV line from $^{28}Si$ and the 1.369 MeV line from $^{24}Mg$ should be at least an order of magnitude more intense (Lingenfelter and Ramaty 1976; Ramaty et al. 1977), unless the spallation occurs only on time scales much less than $10^6$yrs.

In summary, we have shown that $^{26}Al$ is a very good candidate for producing a detectable gamma-ray line, and that this line is not only intense but also very narrow. By examining the chart of nuclides for other radioactive isotopes which could produce hitherto unnoticed gamma-ray lines following nucleosynthesis, we find that for mass numbers less than 60, the isotopes $^{22}Na$, $^{26}Al$, $^{40}K$, $^{42}Ar$, $^{44}Ti$, $^{46}Sc$, $^{54}Mn$, $^{56}Co$, $^{57}Co$, $^{58}Co$, $^{60}Co$ and $^{60}Fe$ are the only ones with sufficiently long half lives (>70) days to produce gamma rays in optically thin regions. The line at 1.275 MeV from $^{22}Na$ (2.6 y) has already been discussed by Clayton and Hoyle (1974) and by Clayton (1975), while the lines from $^{26}Al$, $^{44}Ti$, $^{56}Co$, $^{60}Co$ and $^{60}Fe$ were discussed in the present Letter and the references therein.

From the abundances of the daughter products of $^{42}Ar$ (33 y), $^{46}Sc$ (84 d), $^{54}Mn$ (313 d), $^{57}Co$ (271 d) and $^{58}Co$ (71 d), we see that gamma-ray lines from these isotopes should have intensities significantly less than those of $^{56}Co$ and $^{44}Ti$ decay lines. The solar system abundance of $^{40}K$ is sufficiently low to preclude its decay line at 1.460 MeV from becoming a serious candidate for detection. Thus the lines from decay of $^{26}$Al, $^{44}$Ti, $^{56}$Co and $^{60}$Fe are the most intense lines resulting from processes of nucleosynthesis and hence have the best prospects of detection. Among these, the line from decay of $^{26}$Al, because of its very narrow width, is a very promising candidate.

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TABLE 1

| Decay Chain | Half Life | Nuclei/Supernova | Photon Energy (MeV) | Photons/Disintegration |
|---|---|---|---|---|
| $^{56}Ni \rightarrow ^{56}Co \rightarrow ^{56}Fe$ | 77.3 d | $3 \times 10^{54}$ | 0.847 | 1 |
| | | | 1.238 | 0.70 |
| | | | 2.598 | 0.17 |
| | | | 1.771 | 0.16 |
| | | | 1.038 | 0.13 |
| $^{44}Ti \rightarrow ^{44}Sc \rightarrow ^{44}Ca$ | 47 y | $6 \times 10^{51}$ | 0.068 | 1 |
| | | | 0.078 | 1 |
| | | | 1.156 | 1 |
| $^{60}Fe \rightarrow ^{60}Co \rightarrow ^{60}Ni$ | $3 \times 10^{5}$ y | $5 \times 10^{50}$ | 0.059 | 1 |
| | | | 1.173 | 1 |
| | | | 1.1332 | 1 |
| $^{26}Al \rightarrow ^{26}Mg$ | $7.4 \times 10^{5}$ y | $4 \times 10^{50}$ | 1.809 | 1 |
| | | | 1.130 | 0.04 |