Reports

Short-Lived s-Process Gamma-Ray Lines in Type II Supernovae

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The nuclear abundances in the helium-burning shells of presupernova stellar models are calculated. For stars of over 20 solar masses the $^{22}Ne(\alpha,n)^{25}Mg$ reaction produces enough neutrons on a sufficiently short time scale for the s-process to produce ^{59}Fe (half-life = 45 days) and ^{60}Co (half-life = 5.3 years). These isotopes are expected to survive the passage of the shock, and gamma rays from their decays should be detectable from most galactic type II supernovae with the NASA Gamma Ray Observatory. Because of its great distance and low metallicity, these lines are not expected to be observable from supernova 1987A.

JUST AS SPECTRAL LINES FROM ATOMIC transitions provide "fingerprints" identifying the atoms responsible, so the gamma rays from the decays of nuclear excited states identify specific isotopes. Nuclear reactions in stars synthesize unstable nuclei whose β-decays leave the daughter nuclei in excited states. The detection by modern gamma-ray telescopes of the resulting deexcitations is expected to provide information on the important nuclear reactions in stellar evolution.

Interest in the gamma-ray lines from type II supernovae has focused on the nuclei produced during the explosion, especially those produced abundantly in the central regions such as ^{56}Ni (*1*). Here, I consider the gamma-ray lines from some unstable nuclei that survive from the star's presupernova evolution. They have much lower abundances but quite rapid decay rates, leading to high gamma-ray fluxes over a short period of time.

Conditions in the helium-burning shells of such stars (with temperatures $0.2 < T_9 < 0.5$, where the subscript indicates units of 10^9 K) favor the $^{22}Ne(\alpha,n)^{25}Mg$ neutron source for neutron captures on ^{56}Fe by the s-process (slow neutron capture). Since ^{22}Ne and ^{25}Mg are both themselves neutron poisons, neutron captures on ^{56}Fe are not expected to produce nuclei with atomic mass number $A > 70$ (*2*). In this mass range there are three nuclei with half-lives long enough to survive until the supernova envelope becomes transparent to gamma rays after ~200 days (*3, 4*), but short enough to emit high fluxes: ^{59}Fe, ^{60}Co, and ^{65}Zn, whose gamma-ray lines are shown in Table 1.

The small abundance of these s-process nuclei in the helium burning zone is also partly offset by the fact that above the actual burning zone lies an extensive [~1 to 2 $M_\odot$ (solar masses)] convective region, which under the circumstances considered here may be assumed to have the same composition as that calculated for the burning zone.

In my calculation, the temperature and density of the helium-burning zone was taken from the most recent published models of 15 and 25 $M_\odot$ stars at the start of the collapse before the explosion (*5*), as was the mass of the convective region. The nucleosynthesis is treated in a single-zone approximation (*6*) by which the initial composition is burned at a constant temperature and density for an effective helium-burning time t_{eff} (*7*). The resulting composition is mixed into the convective zone, in which no nucleosynthesis (other than β-decays of unstable species) occurs. This approximation should be valid so long as the convective time scale [calculated from mixing-length theory (*8*)] is much shorter than the nuclear burning time scale. Under stellar helium-burning conditions it becomes invalid for $T_9 \geq 0.5$, corresponding in the Woosley-Weaver models to masses above ~25 $M_\odot$. I also performed calculations at intermediate masses, with temperatures and densities interpolated between the 15 and 25 $M_\odot$ values.

The initial composition for helium burning was that left by CNO-cycle hydrogen burning in a population I star, with the ^{14}N converted to ^{22}Ne by low-temperature helium burning: the fractional abundances by mass are then $X(^4He) = 0.98$, $X(^{22}Ne) = 0.02$, and $X(^{56}Fe) = 1.12 \times 10^{-3}$. The iron peak nuclei were assumed to be distributed between ^{56}Fe, ^{57}Fe, ^{58}Fe, and ^{59}Co in solar system proportions. A charged particle reaction network was set up for helium burning, containing the important reactions involving ^4He, ^{12}C, ^{16}O, ^{22}Ne, ^{24}Mg, ^{25}Mg, and ^{26}Mg; the most recent reaction rates (*9*) were used. This network was solved by a finite difference method, and free neutron abundances were calculated at each time step for the resulting composition. Neutron captures on the nuclei between ^{56}Fe and ^{65}Zn were then calculated by means of the analytic s-process solution of Clayton *et al.* (*10*), modified to take account of branches at ^{59}Fe, ^{60}Co, and ^{63}Ni. Neutron capture cross sections were taken from the most recent sources (*11*). Enhanced β-decay rates at helium-burning temperatures and densities were interpolated from those of (*12*). The one free parameter, the effective burning time t_{eff}, was fixed by burning until the preexplosion helium abundances (*5*) were reproduced. I found that the subsequent passage of the supernova shock has negligible effects on the s-process abundances (*13*).

Results from a calculation in a star of mass 20 $M_\odot$ (estimated by interpolation) are shown in Table 2. Results for ^{59}Fe and ^{60}Co as a function of mass (parametrized by burning temperature) are shown in Fig. 1 and may be explained with reference to the s-process paths in Fig. 2. Production of ^{65}Zn was found to be negligible in all circumstances.

I note first that the explosion occurs when helium burning is at a very early stage, when only a few percent of the initial helium has been consumed (*5*). At low temperatures (masses close to 15 $M_\odot$) the $^{22}Ne(\alpha,n)^{25}Mg$ reaction proceeds too slowly to be a neutron source, and s-processing is negligible. However, the $^{22}Ne(\alpha,n)$ reaction rate increases much faster with temperature than the rate of the triple-alpha reaction. Therefore, for $T_9 > 0.3$ (masses $\geq$ 20 $M_\odot$) neutrons are produced rapidly enough for ^{56}Fe to be s-processed to mass numbers 59 and 60 within the time t_{eff}.

Production of ^{59}Fe at higher temperatures is roughly constant, because s-processing never proceeds to much higher mass numbers even if all the ^{22}Ne is consumed, owing to the presence of neutron poisons (*2*). However, production of ^{59}Co goes through a sharp peak around $T_9 = 0.35$ and decreases for higher temperatures (Fig. 1). This behavior is due to the branch at ^{59}Fe (Fig. 2). As the temperature increases, and with it the free neutron abundance from more rapid burning of ^{22}Ne, the time scale for neutron captures becomes shorter than the ^{59}Fe β-decay lifetime. Material no longer passes into the branch through ^{59}Co and ^{60}Co, but instead undergoes further neutron

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Fig. 1. Abundances by mass fraction of ^{59}Fe and ^{60}Co produced as a function of helium-burning temperature. Arrows at top denote the helium-burning temperatures of the 15 and 25 $M_\odot$ presupernova models (*5*). Arrow at the side represents the abundances of ^{59}Fe and ^{60}Co that are marginally detectable at a distance of 10 kpc by GRO ($\phi_{min} = 5 \times 10^{-5}$ cm^{-2} sec^{-1}) assuming that they exist throughout a convective zone of mass $M = 2\ M_\odot$, and that ^{59}Fe has decayed for 200 days prior to detection. It is coincidental that this minimum detectable abundance is the same for both species.

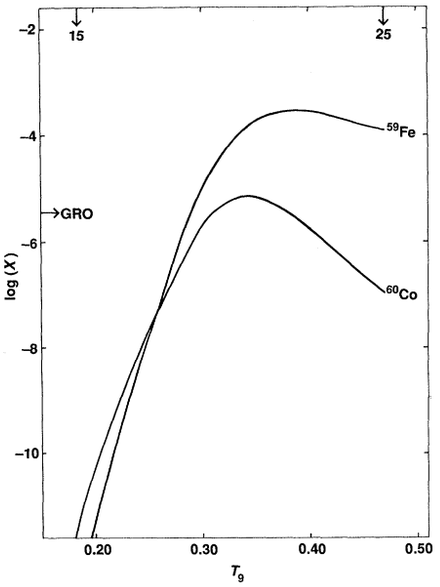
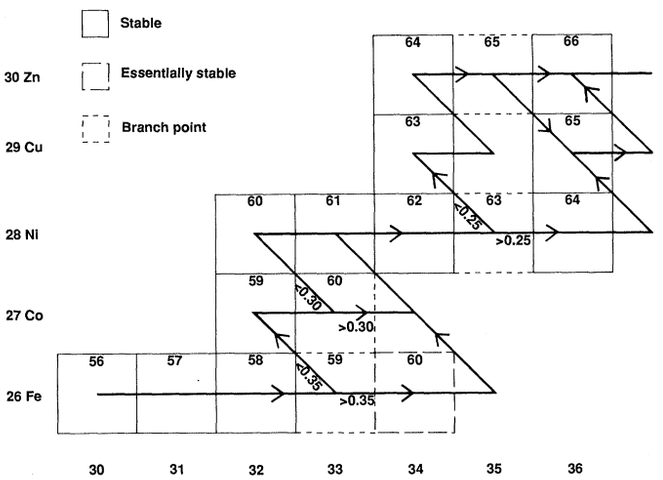


Fig. 2. Paths followed during s-processing by material initially in ^{56}Fe. Nuclei with half-lives much greater than the neutron capture time scale are regarded as effectively stable. Branches in the path are labeled by the temperature range where they predominate for the run of temperatures and densities in the Woosley-Weaver models (*5*).



captures to ^{60}Fe and ^{61}Fe. This sensitivity to the temperature makes ^{60}Co potentially a very good indicator of mass close to 20 $M_\odot$.

I next consider the detectability of the resulting gamma-ray lines. If a nucleus of mass A with lifetime τ is found with an abundance X in a stellar zone of mass M (in units of solar mass), it can easily be shown that a gamma-ray line of multiplicity g can be detected after time t if

$$\frac{gMX}{\tau A} \exp(-t/\tau) \geq 10^{-13}\, \phi_{min}\, r^2 \qquad (1)$$

where ϕ_{min} is the minimum detectable flux in photons per square centimeter per second and r is the distance in kiloparsecs. For the best current detectors (*14*) $\phi_{min} \approx 10^{-4}$, falling to $\sim 5 \times 10^{-5}$ when the Gamma Ray Observatory (GRO) is launched in 1991 (*15*).

In Fig. 1 I show the ^{59}Fe and ^{60}Co abundances necessary for detection by GRO at 10 kpc, assuming $\phi_{min} \sim 5 \times 10^{-5}$ and $M \sim 2\ M_\odot$. The 10 kpc range should include most galactic supernovae. If the supernovae have the right masses, the lines from both species should be visible. In the case of ^{59}Fe the flux decays rapidly because of the short half-life; my estimate of the detectable abundance assumes that the supernova becomes transparent to gamma rays after $t \approx 200$ days. The ^{59}Fe lines from a 20 to 25 $M_\odot$ supernova should thereafter remain detectable for a further ~200 days according to Eq. 1. The ^{60}Co lines should remain visible for some years after the explosion. The visibility of the lines may be reduced by high levels of the gamma-ray continuum caused by scattering of photons from ^{56}Ni and ^{56}Co decay. However a calculation of the continuum for a 15 $M_\odot$ star (*4*) suggests that the ^{59}Fe lines are strong enough to be distinguished (given the GRO energy resolution ~50 keV), whereas the weaker ^{60}Co lines will survive long enough to become visible after decay of the ^{56}Co has caused the continuum intensity to fall off on a time scale ~1 year.

Table 1. Prospective s-process gamma-ray lines.

Nucleus	Half-life	Line energy (MeV)	Multiplicity (%)
^{59}Fe	44.6 days	1.099	57
		1.292	43
^{60}Co	5.3 years	1.173	100
		1.332	100
^{65}Zn	244 days	1.116	51

Table 2. Results of s-process calculation in a 20 $M_\odot$ star. Notation: $A(B) = A \times 10^B$. Abundances are expressed as mass fraction. The quantity τ is a measure of the neutron exposure of the heavy elements:

$$\tau = v_T \int_0^{t_{eff}} N_n\, dt$$

where N_n is the neutron number density and v_T the thermal mean velocity.

Run parameters:	
T_9	0.33
Density (g cm^{-3})	8.15(2)
M ($M_\odot$)	1.6
t_{eff} (sec)	3.65(6)
τ (cm^{-2})	6.52(25)
Abundances:	
^{1}n	1.157(−16)
^{4}He	9.004(−1)
^{22}Ne	1.661(−2)
^{56}Fe	4.778(−4)
^{57}Fe	2.236(−4)
^{58}Fe	3.309(−4)
^{59}Fe	8.304(−5)
^{59}Co	1.555(−5)
^{60}Co	5.978(−6)
^{65}Zn	3.609(−12)

If Eq. 1 is applied to supernova 1987A ($r = 50$ kpc) it would appear that the ^{59}Fe lines might be marginally detectable if the supernova mass was 20 to 25 $M_\odot$, the flux from the 1.099-MeV line at 200 days being as high as 1.9×10^{-4} cm^{-2} sec^{-1}. However, because the Large Magellanic Cloud has only 1/3 of solar metallicity (*16*) the ^{56}Fe abundance would be 1/3 of that assumed here, and all s-process abundances will be reduced by this factor.

REFERENCES AND NOTES

1. D. D. Clayton, *Nature (London)* **234**, 291 (1971); in *Explosive Nucleosynthesis*, D. N. Schramm and W. D. Arnett, Eds. (Univ. of Texas Press, Austin, 1973), pp. 264–282; P. Durouchoux, in *Nucleosynthesis and Its Implications on Nuclear and Particle Physics*, J. Audouze and N. Mathieu, Eds. (Reidel, Dordrecht, 1986), pp. 331–338.
2. M. Busso and R. Gallino, *Astron. Astrophys.* **151**, 205 (1985); N. Prantzos, M. Arnould, J.-P. Arcoragi, *Astrophys. J.* **315**, 209 (1987).
3. The value of this quantity (the time scale for lifting of the envelope opacity to gamma rays) is highly uncertain for material in the He shell, although detailed calculations have been done for material originating in the star's center (*4*). It is likely to be very sensitive to the degree of presupernova mass loss. Our estimate is based on the time scale of the plateau observed in type II supernovae. It is consistent with a calculated value of ~300 days for

SN1987A assuming that the radioactive nucleus is distributed interior to the hydrogen envelope and that ~4 $M_\odot$ of mass has been lost [K. Nomoto, in *Supernova 1987A in the LMC* (Proceedings of the George Mason University Workshop, 12 to 14 October 1987), M. Kafatos, Ed. (Cambridge Univ. Press, Cambridge, U.K., in press)].
4. N. Gehrels, C. J. MacCallum, M. Leventhal, *Astrophys. J.* **320**, L19 (1987); N. Gehrels, M. Leventhal, C. J. MacCallum, *ibid.* **322**, 215 (1987); S. E. Woosley, P. A. Pinto, P. G. Martin, T. A. Weaver, *ibid.* **318**, 664 (1987).
5. S. E. Woosley and T. A. Weaver, in *Radiation Hydrodynamics in Stars and Compact Objects*, D. Mihalas and K.-H. A. Winkler, Eds. (Springer-Verlag, Berlin, 1986), pp. 91–118; *Annu. Rev. Astron. Astrophys.* **24**, 205 (1986).
6. M. J. Harris, D. L. Lambert, K. H. Hinkle, B. Gustafsson, K. Eriksson, *Astrophys. J.* **316**, 294 (1987).
7. Note that t_{eff} is comparable to the lifetime of a ^{4}He nucleus against destruction by helium burning in a single stellar layer. During the lifetime t_{shell} of the helium-burning shell many such layers are completely burned to ^{12}C and ^{16}O. Therefore $t_{eff} << t_{shell} \approx 10^6$ years. In other words, the calculation deals only with the layer that is actively burning helium at the time of the explosion.
8. D. D. Clayton, *Principles of Stellar Evolution and Nucleosynthesis* (McGraw-Hill, New York, 1968).
9. W. A. Fowler, G. R. Caughlan, B. A. Zimmerman, *Annu. Rev. Astron. Astrophys.* **13**, 69 (1975); M. J. Harris, W. A. Fowler, G. R. Caughlan, B. A. Zimmerman, *ibid.* **21**, 165 (1983); G. R. Caughlan, W. A. Fowler, M. J. Harris, B. A. Zimmerman, *At. Data Nucl. Data Tables* **32**, 197 (1985).
10. D. D. Clayton, W. A. Fowler, T. C. Hull, B. A. Zimmerman, *Ann. Phys. (N.Y.)* **12**, 121 (1961).
11. All cross sections are from Z. Y. Bao and F. Käppeler [*At. Data Nucl. Data Tables* **36**, 411 (1987)] apart from ^{59}Fe and ^{60}Co from S. E. Woosley, W. A. Fowler, J. A. Holmes, and B. A. Zimmerman, [*ibid.* **22**, 371 (1978)] and M. J. Harris [*Astrophys. Space Sci.* **77**, 357 (1981)].
12. K. Takahashi and K. Yokoi, *At. Data Nucl. Data Tables* **36**, 375 (1987).
13. Apart from the neutron-poison effect noted above, observed supernova velocities imply rather low shock temperatures [J. J. Cowan, A. G. W. Cameron, J. W. Truran, *Astrophys. J.* **265**, 429 (1983)], which, given the short time ~1 sec for which they last, are insufficient to activate the ^{22}Ne(α,n) reaction. I calculated the peak shock temperatures that the treatment of Cowan *et al.* implies for the run of temperatures and densities in the presupernova models (*5*), finding that even in the hottest and densest region of the most massive model the peak temperature $T_9 < 0.6$. A one-step solution of our s-process network was performed under these shock conditions, by which the presupernova s-process abundances were changed by <1%.
14. W. Sandie *et al.*, in *Supernova 1987A in the LMC* (Proceedings of the George Mason University Workshop, 12 to 14 October 1987), M. Kafatos, Ed. (Cambridge Univ. Press, Cambridge, U.K., in press).
15. J. Kurfess, presented at the University of Washington Physics Summer Institute on Nuclear Astrophysics, Seattle, WA, 15 July to 9 August 1985.
16. R. J. Dufour, G. A. Shields, R. J. Talbot, *Astrophys. J.* **252**, 461 (1982).
17. I am grateful to A. Sanyal and G. S. Brown of SMSRC for their assistance, to N. Gehrels for communicating his results before publication, and to the referees for their suggested improvements.

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Molecular-Level Control over Surface Order in Self-Assembled Monolayer Films of Thiols on Gold

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Long-chain ω-hydroxyalkanethiols [$HS(CH_2)_nOH$] coordinate to gold surfaces through the sulfur atom and produce ordered, hydrophilic monolayers in which the hydroxyl groups are exposed at the outer surface. Coadsorption of two ω-hydroxyalkanethiols of different chain lengths *n* resulted in the formation of a monolayer having a disordered surface region that was markedly less hydrophilic than the homogeneous, hydroxylic surface formed from either pure compound. By controlling the composition of the monolayer, it was also possible to control simultaneously the degree of order in the surface and its hydrophilicity. In the monolayers containing a mixture of alkanethiol components, these components apparently did not phase-segregate into macroscopic islands, but were dispersed on a molecular scale.

LONG-CHAIN ALKANETHIOLS ADSORB spontaneously from solution onto clean gold surfaces and form monolayer films (*1, 2*). These films are densely packed and highly ordered both in the plane of the monolayer and perpendicular to it (*3, 4*); the thiol coordinates to the gold surface, and the polymethylene chains pack in an all-trans conformation tilted slightly from the normal to the surface. Although gold interacts strongly with sulfur, phosphorus, and other "soft" ligands, it is inert toward most "hard" organic functionalities containing only first-row elements (*5*). This selectivity for sulfur allows us to prepare oriented organic monolayer films containing many functional groups of chemical and biological interest and to exercise a high degree of control over the structure of these films. In particular, by using adsorbates having the structure $HS(CH_2)_nX$, we can prepare monolayers presenting a more or less well-ordered array of the group X at the monolayer–air interface. If the polymethylene chain of $HS(CH_2)_nX$ is at least ten carbon atoms long, the surface properties depend primarily on the tail group X, are independent of the chain length, and are influenced only indirectly by the sulfur–gold interface. These terminally functionalized films are versatile and convenient systems with which to study the physical-organic chemistry of interfaces. A central objective of our work with these monolayer films is to discover the relations between molecular-scale structure and macroscopic physical properties of interfaces—wettability, adhesion strength, coefficient of friction—that depend strongly on short-range intermolecular forces (*6*).

We have examined the wettability by water of monolayers composed of $HS(CH_2)_{11}OH$ (abbreviated as $HSC_{11}OH$), $HS(CH_2)_{19}OH$ ($HSC_{19}OH$), and mixtures of these two compounds. Figure 1 illustrates the theory on which this group of experiments rests. If the pure compounds form well-ordered monolayers (Fig. 1, A and C), these monolayers should present a dense, hydrophilic, wettable, two-dimensional array of hydroxyl groups at the monolayer–water interface; if the monolayers are disordered, a more hydrophobic, less wettable mixture of hydroxyl and methylene groups will be exposed (Fig. 1D). In the event that monolayers of the pure compounds are highly ordered, there are two plausible structures for monolayers containing mixtures of the two components. If the components are dispersed on a molecular scale (Fig. 1B), an interesting, two-layer structure

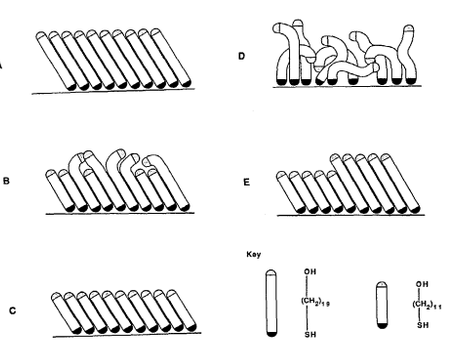

Fig. 1. Stylized illustrations of monolayer structures. Proposed structures of (**A**) pure monolayer of $HS(CH_2)_{19}OH$; (**B**) monolayer composed of 50% $HS(CH_2)_{19}OH$ and 50% $HS(CH_2)_{11}OH$; and (**C**) pure monolayer of $HS(CH_2)_{11}OH$. Structures we believe do not occur in the systems studied here are: (**D**) disordered monolayer and (**E**) monolayer containing a mixture of components and showing phase separation into islands.

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