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A NEW SITE FOR THE ASTROPHYSICAL GAMMA-PROCESS

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ABSTRACT

A leading model for the origin of rare proton-rich isotopes (p-isotopes) involves the transmutation of heavy elements into lighter p-isotopes via a series of (γ, n), (γ, p) and (γ, α) reactions. Such a model, called the gamma-process, is quite successful in reproducing the abundance pattern of many rare p-isotopes if one assumes that a distribution of near-solar seeds is exposed to the thermodynamic conditions that occur naturally in the neon-oxygen layers of massive stars ($M > 10$–$12\ M_\odot$) experiencing Type II supernova explosions. However, a failure of this model is the inability to reproduce the abundance pattern of the light p-isotopes ^{78}Kr, ^{92}Mo, ^{94}Mo, ^{96}Ru, and ^{98}Ru due to a lack of sufficient seeds with $A \geq 96$. We propose that the requisite thermodynamic conditions may also occur in Type Ia or certain subclasses of Type II supernovae, where a carbon-oxygen white dwarf explodes by deflagration or detonation. For such cases, the abundance pattern of all p-nuclei, including the light p-nuclei, is well reproduced. We also note the production of several possible p-isotope cosmochronometers ^{53}Mn ($\tau_{1/2}$: 3.7×10^6 yr), ^{92}Nb ($\tau_{1/2}$: $36. \times 10^6$ yr), ^{97}Tc ($\tau_{1/2}$: 2.6×10^6 yr) and ^{146}Sm ($\tau_{1/2}$: $103. \times 10^6$ yr).

Subject headings: abundances — nuclear reactions — stars: supernovae

The origin of the proton-rich isotopes of the heavy elements in nature has been studied for over 30 years (Burbidge et al. 1957; Cameron 1957; Audouze & Truran 1975; Arnould 1976; Woosley & Howard 1978; Rayet, Prantzos, & Arnould 1990; and Woosley & Howard 1990). Specifically, the p-isotopes are those stable nuclear isotopes with mass number $A \geq 74$ that lie on the proton-rich side of the valley of beta-stability and are bypassed by the neutron capture chains (r- and s-processes) that are thought responsible for producing the bulk of the heavy elements. A leading model for the origin of the p-isotopes involves transmuting heavy elements into lighter p-isotopes via a series of nuclear photodisintegrations involving (γ, n), (γ, p), and (γ, α) reactions (Woosley & Howard 1978; Rayet et al. 1990; and Woosley & Howard 1990). Such a model, called the gamma-process, is quite successful in reproducing the bulk of the p-isotopes if one assumes a seed distribution of heavy nuclei resulting from mild prior s-processing, peak temperatures in the range $2.0 \leq T_9 \leq 3.0$ and a hydrodynamical expansion time scale of order 1 s. The requisite thermodynamic conditions occur quite naturally in the neon-oxygen layers of massive stars ($M > 10$–$12\ M_\odot$) during Type II supernovae explosions. However, a major failure of this model is that the solar system abundance pattern of some light p-isotopes (in particular ^{78}Kr, ^{92}Mo, ^{94}Mo, ^{96}Ru, and ^{98}Ru) is not well reproduced due to a lack of sufficient seeds with $A \geq 96$. Enhancing the heavy elements with prior s-processing during core helium burning provides insufficient seeds because the peak of such an s-process distribution is only near $A = 80$ (Lamb, Iben, & Howard 1976; and Prantzos, Arnould, & Arcoragi 1987). Proton captures play no role in this model because in the neon-oxygen–rich layer the proton mass density is too low to induce captures on the relevant time scales. However, neutron captures may slightly modify the distribution (see Rayet et al. 1990).

In this *Letter* we propose that the requisite thermodynamic conditions may also occur when carbon-oxygen white dwarfs explode by deflagration or detonation. Observationally these may be Type Ia supernovae (e.g., Woosley & Weaver 1986), or perhaps Type II-L (Swartz, Wheeler, & Harkness 1991), or even Type II-p or Ic if the degenerate carbon core of an AGB star exploded before the entire hydrogen envelope was lost (Iben & Renzini 1983; Woosley 1990). A key difference in this model is that the outer layers of (some) carbon-oxygen white dwarfs (or some cores of AGB stars) will have undergone extensive s-processing during helium shell flashes (Iben 1977; Gallino et al. 1988; Käppeler, Beer, & Wisshak 1989; Käppeler et al. 1990) to provide sufficient seeds for producing the light p-nuclei. When these stars undergo explosive disruption, be it by deflagration or detonation (Khoklov 1990; Woosley & Weaver 1991), there will be a region near the surface where the burning temperature lies in the range $2.4 \lesssim T_9 \lesssim 3.2$. At these temperatures the enhanced s-process seeds are efficiently transmuted into p-isotopes (including the light isotopes) on a time scale of much less than 1 s. To examine this astrophysical site, we calculate the prior s-process nucleosynthesis during helium shell flashes and the nuclear transmutation that takes place when such mass zones are heated by the deflagration or detonation wave and compare our results with the solar system distribution of the p-isotopes.

Following Nomoto, Thielemann, & Yokoi (1984) (see also Nomoto, Thielemann, & Wheeler 1984 and Thielemann, Nomoto, & Yokoi 1986), we assume that the density at the edge of the core is near 10^7 g cm^{-3} when the burning front heats the matter to temperatures in the range $2.4 \leq T_9 \leq 3.2$. Similar conditions will exist in any Type Ia supernovae in the region just outside that where the silicon and calcium, so prominent in the spectrum, are found. We assume, as is typical

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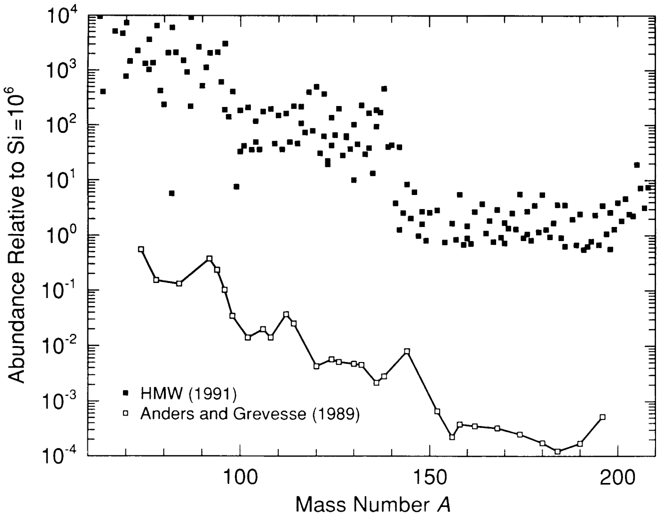

FIG. 1.—Abundance of nuclei, as a function of atomic mass A, resulting from a helium shell flash s-process exposure for a core mass of 1.3 $M_{\odot}$ (*squares*), compared to the solar system abundance (Anders & Grevesse 1989) of p-nuclei (designated by open squares and connected by solid lines). S-process abundances of less than 0.5 (relative to 10^6 for Si) have been omitted from the figure.

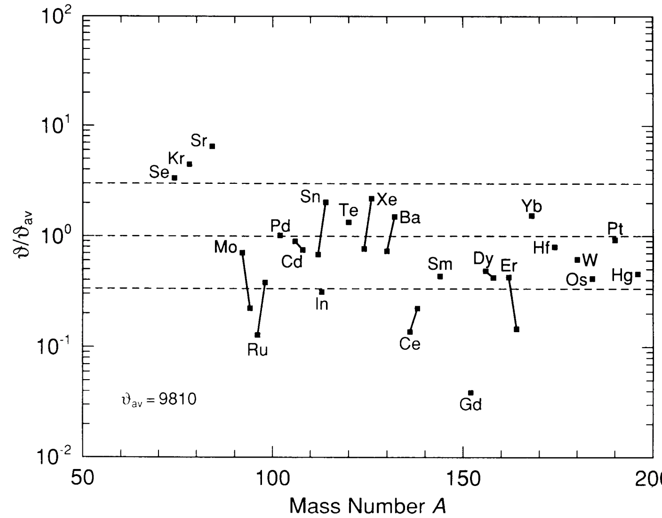

FIG. 2.—Overproduction factor, relative to the average overproduction factor, for p-isotopes as a function of atomic mass. The composite is a linear average of contributions from temperatures in the range $T_9 = 2.4$–3.2 in steps of 0.1.

in these models, that the hydrodynamical time scale for an e-fold decrease in density is approximately 0.2 s and that the temperature and density decrease adiabatically as $\rho \alpha T^3$. For the initial seed distribution of heavy elements, we take s-process enhancements resulting from helium flashes, as calculated by the method of Howard et al. (1986), for a model corresponding to a core mass of 1.3 $M_{\odot}$. For the initial composition of the carbon and neon we assume mass fractions of 0.3 and 0.7, respectively. The carbon burning provides an important source of free protons, as we will discuss later.

Figure 1 is a plot of the abundance of nuclei, as a function of atomic mass A, resulting from such an s-process exposure, compared with the solar system abundance of the p-nuclei (Anders & Grevesse 1989). The figure includes all stable nuclei resulting from the neutron exposure. Some p-isotopes or r-process nuclei have a low abundance (less than 0.5 relative to Si 10^6) due to depletion by neutron capture and are not shown in the figure. Although the σN curve for the s-only nuclei would deviate significantly from that for the solar system (see Fig. 3 of Howard et al. 1986), there are significant enhancements of nuclei out to and including ^{208}Pb. One may note the large seed–to–p-nuclei ratio ($\sim 10^3$) for the light p-nuclei, particularly for ^{92}Mo. This large ratio is not present either in a solar system distribution of seed nuclei or in a distribution resulting from s-process during core helium during in massive stars (Lamb et al. 1976; Prantzos et al. 1987). This significant enhancement of the seed nuclei in the mass region $A \geq 96$ is the key feature that can allow us to reproduce the distribution of the light mass p-nuclei.

The reaction network that we use includes all important strong interactions from ^{1}H through ^{209}Bi. For experimental rates, we take the latest results from Caughlan & Fowler (1988), and where experimental results are not available we take rates either from Woosley et al. (1978) or from Woosley & Howard (1978). All strong and electromagnetic interactions are taken into account, including $^{12}C + ^{12}C$, $^{12}C + ^{16}O$, and $^{16}O + ^{16}O$. Weak interactions are included up to mass number $A = 74$. The network for interactions above $A = 74$ is the same as that included in Woosley & Howard (1978), except that in this calculation, all possible strong interactions (including proton and neutron capture) are included. In the calculation of Woosley & Howard (1978) only photodisintegration reactions were included.

Figure 2 shows production factors for the p-isotopes compared to an equal weighting average production factor averaged over mass zones that have reached peak temperatures in the range $2.4 \leq T_9 \leq 3.2$. By production factor, we mean the ratio of the p-isotope mass fraction to its solar system mass fraction. For simplicity, contributions are weighted equally in temperature in steps of $T_9 = 0.1$ in the range $T_9 = 2.4$–3.2. Notice that the bulk of the p-isotopes are coproduced within a consistent narrow production range of about 9. In particular, ^{92}Mo, ^{94}Mo, ^{98}Ru, ^{102}Pd, ^{106}Cd, and ^{108}Cd are coproduced within a factor of 3. We arbitrarily take the view to plot the abundances as a function of an average overproduction factor, rather than normalizing to the most overproduced isotope, i.e., ^{84}Sr. Thus, we arbitrarily view that ^{74}Se, ^{78}Kr, and ^{84}Sr are *overproduced* relative to the other p-process isotopes. As we will see, these isotopes are very sensitive to the proton densities in the p-process environment, which we consider as rather uncertain.

In Table 1, we also give the relative production ratio of several possible p-process cosmochronometers, including ^{53}Mn ($\tau_{1/2}$: 3.7 × 10^6 yr), ^{92}Nb ($\tau_{1/2}$: 36. × 10^6 yr), ^{97}Tc ($\tau_{1/2}$: 2.6 × 10^6 yr) and ^{146}Sm ($\tau_{1/2}$: 103. × 10^6 yr). The presence of ^{53}Mn has been inferred in the early solar system (Birck & Allègre 1985, 1988). Recently, the presence of ^{92}Nb has been inferred in the early solar system from a study of the Toluca type IAB iron meteorite and from a fine-grained Allende inclusion (Harper et al. 1991). The possible inference of ^{97}Tc in

TABLE 1

PRODUCTION RATIOS OF POSSIBLE p-PROCESS COSMOCHRONOMETERS

Cosmochronometers	Value
^{53}Mn/^{92}Mo	0.59
^{92}Nb/^{92}Mo	0.0039
^{97}Tc/^{92}Mo	0.02
^{146}Sm/^{144}Sm	0.05

the early solar system remains an exciting possibility. Whether any of these radioactive nuclides can serve as a *p*-process cosmochronometer remains to be seen. The major constraints come from the relative overproductions of ^{74}Se, ^{78}Kr, and ^{84}Sr. The presence of ^{146}Sm in the early solar system has been inferred from the study of the meteorites Allende, Ibitira, Morristown, and Acapulco (Lugmair et al. 1983; Prinzhofer, Papanastassiou, & Wasserburg 1989, 1990) and the achrondrite Bholgati Howardite (Nyquist et al. 1990).

For the thermodynamic conditions studied here, we find that the high proton abundance from carbon burning induce rapid proton capture near the $N = 50$ closed shell at the relatively high temperatures of $T_9 = 2.8$–3.1. Figure 3 gives the proton mass fraction as a function of time for the peak temperatures $T_9 = 2.6$, 2.8, and 3.0. From the carbon-burning reactions, the proton mass density is of order 1 g cm^{-3} for approximately 10 ms. Particularly interesting is the sequence of reactions that contribute to the production of ^{92}Mo. The *s*-process enhancements at the $N = 50$ closed shell are particularly significant at ^{88}Sr, ^{87}Rb, and ^{86}Kr, with lesser enhancements at ^{89}Y and ^{90}Zr. The *s*-process Mo isotopes (^{95}Mo to ^{98}Mo) are also enhanced. Proton capture reactions are important enough that approximately one-half of the ^{92}Mo is due to the reaction sequence

$$^{86}\mathrm{Kr}(p,\gamma)^{87}\mathrm{Rb}(p,\gamma)^{88}\mathrm{Sr}(p,\gamma)^{89}\mathrm{Y}(p,\gamma)$$
$$^{90}\mathrm{Zr}(p,\gamma)^{91}\mathrm{Nb}(p,\gamma)^{92}\mathrm{Mo}$$

with significant production of both ^{90}Zr and ^{92}Mo. In addition, the other half of the ^{92}Mo, as well as most of the ^{94}Mo, is produced by the (γ, n) reaction sequence

$$^{98}\mathrm{Mo}(\gamma,n)^{97}\mathrm{Mo}(\gamma,n)^{96}\mathrm{Mo}(\gamma,n)^{95}\mathrm{Mo}(\gamma,n)$$
$$^{94}\mathrm{Mo}(\gamma,n)^{93}\mathrm{Mo}(\gamma,n)^{92}\mathrm{Mo}\ .$$

Likewise, proton-capture reactions are important for the production of ^{88}Kr; that is, the sequence

$$^{74}\mathrm{Ge}(p,\gamma)^{75}\mathrm{As}(p,\gamma)^{76}\mathrm{Se}(p,\gamma)^{77}\mathrm{Br}(p,\gamma)^{78}\mathrm{Kr}\ .$$

The ^{98}Ru and ^{108}Cd are produced at peak temperatures near $T_9 \simeq 2.9$ primarily through a series of (γ, n) reactions that

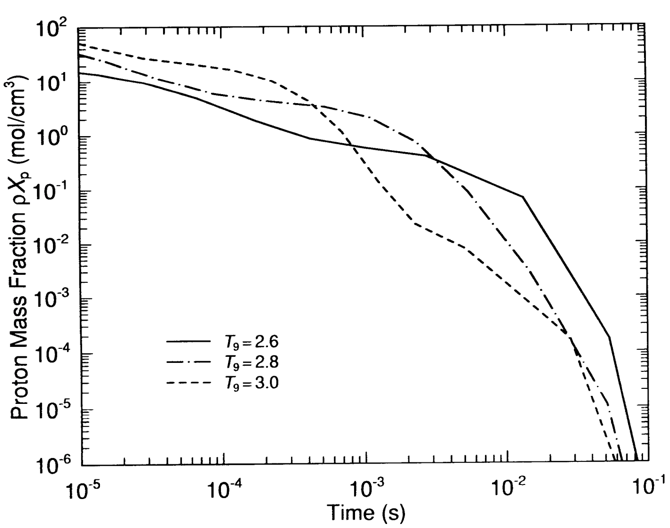

FIG. 3.—Proton mass fraction, as a function of time, for the initial temperatures of $T_9 = 2.6$, 2.8, and 3.0.

photodisintegrates neutrons from neighboring isotopes. However, at this temperature, the binding energies of the last neutron in these nuclei are sufficiently high (~ 10.6 MeV) that the neutron photodistintegration flow is effectively halted at these isotopes. Thus, ^{96}Ru and ^{106}Cd must be produced at higher temperatures ($T_9 = 3.0$) when the neutron photodisintegration flow can break through ^{98}Ru and ^{108}Cd. It is interesting that some ^{96}Ru and ^{106}Cd are also produced at these temperatures via proton induced reactions, specifically,

$$^{96}\mathrm{Mo}(p,\gamma)^{97}\mathrm{Tc}(p,n)^{97}\mathrm{Ru}(\gamma,n)^{96}\mathrm{Ru}$$

and

$$^{106}\mathrm{Pd}(p,\gamma)^{107}\mathrm{Ag}(p,n)^{107}\mathrm{Cd}(\gamma,n)^{106}\mathrm{Cd}\ .$$

The $^{96}\mathrm{Mo}(p,\gamma)^{97}$Tc reaction is the source for the radiogenic ^{97}Tc.

Type Ia supernovae are thought to be the source of ^{56}Fe in the solar system. From the requirement that such supernovae produce the ratio of *p*-isotopes to ^{56}Fe in solar system proportions, and with the assumption that such supernovae produce 0.5–1.0 $M_\odot$ of ^{56}Fe, our calculated overproduction factors ($\sim 10^4$) imply that the mass zones of interest comprise approximately 0.04–0.08 $M_\odot$. From the models, this seems a reasonable requirement.

The final abundances of these *p*-isotopes must be a sensitive function of temperature, proton mass fraction, and expansion time scale, as well as being sensitive to the nuclear reaction rates and the thermodynamic conditions induced by the deflagration flame. We also must assume that the helium shell flashes enrich the helium shell with *s*-process elements in the same mass zone where the deflagration flame is extinquished, when the core undergoes a supernova explosion. Detailed models are needed to verify these assumptions. Although this model appears promising as a source of *p*-isotopes, further conclusions must await a detailed study of the nuclear reaction rates and the thermodynamic conditions of the deflagration flame.

We have demonstrated with model network calculations that Type Ia supernovae provide a viable site for the gamma-process. The same thermodynamic conditions would also exist in Type II-p (Woosley 1990) and Type II-L (Swartz, Wheeler, & Harkness 1991) powered supernovae, provided that they are powered by detonation. The model overcomes some of the shortcomings of the Type II model in that it invokes the necessary photodisintegration reactions while providing for the requisite enhanced *s*-process seed and for proton induced reactions to fill in the light *p*-isotopes abundances.

Of course the possibility that the gamma-process may occur in exploding carbon cores does not preclude it from also happening in explosive neon burning in massive stars as we have described before. Both sites will contribute with the lighter *p*-nuclei, perhaps, coming mostly from the carbon deflagration supernovae: Using the present production factors (about 10,000 in roughly 0.05 $M_\odot$ of material; see Fig. 2) for a carbon deflagration and a typical production factor of 55 in about 0.3 $M_\odot$ for a Type II supernova (Prantzos et al. 1990), one finds that Type Ia supernovae, per event, might contribute 40 times more *p*-process than Type II supernovae. If one recognizes the greater relative frequency of core collapse supernovae (e.g., van den Bergh 1991), this factor is reduced to about 10. However, one must be aware of many possible sources of substantial error in this estimate: (1) the requisite combinations of temperature and prior *s*-processing may not occur in all Type Ia supernovae; (2) the production factors in Figure 2 are uncertain and vary greatly from isotope to isotope; (3) types of supernovae other than Type Ia may involve carbon deflagration (Ib, Ic, II-L, and II-p); (4) the yields for massive stars are themselves uncertain (and further depend on the mass of the star and its convective history); and (5) so too are the relative supernova rates. Our only first conclusion is that the explosion of carbon-oxygen white dwarfs (or stellar cores) may have produced an interesting portion of the *p*-process isotopes.

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