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ed with 1 cm of iron and 15 cm of lead, and to many astrophysicists who informed the authors of recent astrophysical knowledge.

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Thermonclear Origin of Rare Neutron-Rich Isotopes*

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Many rare neutron-rich isotopes in the range $16 \leq Z \lesssim 34$ can be synthesized from seed nuclei exposed to explosive carbon burning. This process, which involves no new astrophysical parameters, can solve most of the outstanding problems in the thermonuclear synthesis of elements in the range $Z \lesssim 34$.

For a theory of the origin of the atomic nuclei to be satisfactory, it must account quantitatively for the abundances of all of the stable nuclei, not just the more abundant ones. The explosive burning of oxygen and silicon nuclear fuel during rapid hydrodynamic ejection from stars produces the nuclei between silicon and nickel with convincing success[1] except for the relatively rare neutron-rich species ^{36}S, ^{40}Ar, ^{40}K, ^{43,46,48}Ca, ^{45}Sc, ^{47,50}Ti, ^{50}V, ^{54}Cr, ^{58}Fe, and ^{64}Ni. We are thus led to seek within the general picture of exploding stellar shells a naturally occurring circumstance for the synthesis of these nuclei from sources other than the primary fuels. We have discovered that a very promising site for this synthesis is in the shells that explosively burn carbon as a primary fuel, resulting in the primary products ^{20}Ne, ^{23}Na, ^{24,25,26}Mg, and ^{27}Al. During this nuclear combustion a brief but intense flux of neutrons and protons[2] converts already existing trace amounts (hereafter called *seed nuclei*) of the more common isotopes, primarily ^{32}S, ^{36}Ar, ^{40}Ca, and ^{56}Fe, into neutron-rich species with approximately the proper yield to account for many of the rare species. This process naturally accompanies the carbon combustion and thus requires no *ad hoc* hypotheses.

Quantitatively our calculations are based on the following reasoning. The previous theronuclear evolution of the star through hydrogen and helium burning has resulted in a stellar shell of ^{12}C and ^{16}O in roughly equal amounts. Heavier nuclear species, such as ^{40}Ca, exist at that time only by virtue of their inclusion in the original material of the star. For example, we expect ^{40}Ca to be present with the mass fraction $X_\odot(^{40}\text{Ca}) = 8.11 \times 10^{-5}$ characterizing its natural abundance in the sun.[3] If this shell is now ejected in such a way that the explosive burning of carbon produces ^{20}Ne, ^{23}Na, and ^{24,25,26}Mg in their observed abundance ratio, it happens that about 5% of the mass is converted to ^{24}Mg. Since we expect this to be the natural source of ^{24}Mg, it follows that a mass of about 20 times the natural mass of ^{24}Mg in the galaxy has been processed by explosive carbon burning events. Per gram of ^{24}Mg produced, therefore, $20X_{\odot}(^{40}\text{Ca}) = 1.62 \times 10^{-3}$ g of ^{40}Ca have been exposed to the neutron and proton flux characterizing the explosive event. The same type of reasoning yields the amount of other heavy seed nuclei that have been exposed to the same irradiations. Our finding is, in short, that these irradiations of the seed nuclei produce most of the rare neutron-rich species in approximately the yield required to qualify as their source.

In the massive stars probably responsible for most nucleosynthesis, the carbon-burning shell of the hydrostatic presupernova star has a mass density[4] near $\rho = 10^5$ g cm^{-3}. We therefore take this density to characterize the initial conditions for the explosion, which is initiated when the carbon is heated quickly to temperatures near 2×10^9 °K. At these temperatures a substantial fraction of the carbon burns quickly (times of order 0.1 sec), but the burning is truncated by an equally rapid dynamic expansion and cooling of the gas. To follow the nuclear reactions in the absence of a complete hydrodynamic model, we assumed that the density decreases in the explosion as $\rho = \rho_0 \exp(-t/\tau)$, where $\tau = (24\pi G\rho)^{-1/2} = 446\rho^{-1/2}$ sec.[1] These are conditions which synthesize ^{20}Ne, ^{23}Na, ^{24,25,26}Mg, and ^{27}Al from the carbon with the proper relative yields.

The neutron density during the explosion ($n_n \lesssim 10^{21}$ cm^{-3}) quickly drives the seed nuclei toward neutron-rich isotopes. Because of their low abundance, the seed nuclei are only a small perturbation on the primary explosion. Calculations with and without the heavy seed nuclei as neutron absorbers showed only a small difference in the free-neutron density. Under these conditions the event is similar to an r process[5]; for example, ^{56}Fe seed are driven quickly by successive (n,γ) reactions to ^{62}Fe and ^{64}Fe where the flow is stopped by the high rates of $^{63}\text{Fe}(\gamma,n)^{62}\text{Fe}$ and $^{65}\text{Fe}(\gamma,n)^{64}\text{Fe}$. After the explosion, the ^{62}Fe and ^{64}Fe decay to the stable nuclei ^{62}Ni and ^{64}Ni, thereby making a significant contribution to the abundance of those nuclei. Our calculations for seed nuclei of iron and greater atomic number were carried out using only neutron-capture chains opposed by photoneutron reactions, because our estimates show that near $T = 2\times10^9$ °K the proton-induced reactions for $Z \geq 26$ are generally too slow, because of the Coulomb barrier, to be effective. In the highest temperature ($T = 2.15\times10^9$ °K) and proton density calculation we have made in this survey, we estimate that about 10% of the Fe seed may undergo (p,n) reactions to form Co nuclei, in which case the (p,n) cross section is beginning to have an important role in the yield of ^{65}Cu and ^{67}Zn (see Table I). In the sulfur-calcium region, however, (p,γ) and (p,n) reactions, although slower than (n,γ) reactions, play a much more important charge-increasing role. We constructed a computer code which calculates the rate of change of the abundances of the seed nuclei in terms of the free densities of neutrons and protons and integrates those equations through the explosion. The network to follow the fate of the S, Ar, and Ca seed nuclei involves as many as 91 nuclear species in the region $14 \leq Z \leq 24$ including the isotopes ^{28}Si through ^{35}Si, ^{31}P through ^{36}P, ^{32}S through ^{37}S, ^{35}Cl through ^{46}Cl, ^{36}Ar through ^{47}Ar, ^{39}K through ^{50}K, ^{40}Ca through ^{51}Ca, ^{43}Sc through ^{50}Sc, ^{45}Ti through ^{51}Ti, ^{47}V through ^{51}V, and ^{49}Cr through ^{51}Cr. The limits to this network were chosen from considerations of neutron separation energies and of (p,n) and (p,γ) reaction rates for nuclei of increasing Z. The validity of the network boundaries was checked by a consistency analysis of the computed results. We used nuclear information from a variety of sources, both experimental and semiempirical. The details will be given in a full paper describing the research.

The results of one calculation are shown in Table I. The carbon has exploded at the initial peak temperature $T = 2.15\times10^9$ °K and initial peak density $\rho = 10^5$ g cm^{-3} and expanded with hydrodynamic time scale $\tau \approx 1$ sec. The first row shows that a primary product of carbon burning, ^{24}Mg, constitutes 10% of the mass after this explosion, and that this mass fraction is 180 times greater than the mass fraction of ^{24}Mg in the sun. The entire galactic content of ^{24}Mg is thus produced if $\frac{1}{180}$ of the galactic mass has emerged from an event like this one. The other rows show the mass fractions X produced in the explosion, the seed nuclei from which they were primarily synthesized, and the ratio $X/X_{\odot}$ of that mass fraction to the mass fraction of that species in the sun. For a value $X/X_{\odot} = 180$, as occurs for ^{36}S, the species is synthesized with exactly the same relative overabundance as ^{24}Mg, and thus is synthesized in the proper absolute yield if ^{24}Mg is. The final column $(X/X_{\odot})/(X/X_{\odot})_{^{24}\text{Mg}}$ gives the species yield relative to its observed solar abundance on the

TABLE I. The production of rare neutron-rich isotopes from seed nuclei. The last column is essentially the ratio of predicted to observed abundance. The explosive-nucleosynthesis calculations were begun at $T = 2.15\times 10^9$ °K and $\rho = 10^5$ g cm^{-3}.

Nuclear Product	Primary Seed	Yield X (mass fraction)	$\frac{X}{X_\odot}$	$\frac{X/X_\odot}{(X/X_\odot)_{^{24}Mg}}$
^{24}Mg	C-burn	0.10	180	1.0
^{36}S	^{32}S, ^{36}Ar	1.3×10^{-5}	180	1.0
^{40}Ar	^{36}Ar, ^{32}S	3.4×10^{-6}	300	1.7
^{40}K	^{36}Ar, ^{32}S	1.4×10^{-6}	290	1.6
^{43}Ca	^{36}Ar	5.1×10^{-6}	39	0.22
^{46}Ca	^{36}Ar, ^{40}Ca	2.3×10^{-6}	730	4.1
^{48}Ca	^{40}Ca	2.0×10^{-5}	110	0.61
^{45}Sc	^{36}Ar	4.0×10^{-6}	95	0.53
^{47}Ti	^{40}Ca, ^{36}Ar	1.9×10^{-5}	86	0.48
^{49}Ti	^{40}Ca	5.1×10^{-5}	290	1.6
^{50}Ti	^{40}Ca	1.2×10^{-5}	68	0.38
^{50}V	^{40}Ca	2.3×10^{-7}	72	0.40
^{62}Ni	^{56}Fe	1.1×10^{-3}	380	2.1
^{64}Ni	^{56}Fe	3.9×10^{-4}	430	2.4
^{65}Cu	0.1 Fe(p,n)	1.4×10^{-4}	270	1.5
^{67}Zn	0.1 Fe(p,n)	2.3×10^{-5}	200	1.1
^{68}Zn	$^{58,60}Ni$	7.3×10^{-5}	130	0.72
^{70}Zn	$^{58,60}Ni$	8.9×10^{-6}	320	1.8
^{71}Ga	0.1 Ni(p,n)	6.9×10^{-6}	190	1.05
^{73}Ge	0.1 Ni(p,n)	2.0×10^{-6}	100	0.56
^{76}Ge	Zn	1.9×10^{-6}	92	0.51

assumption that ^{24}Mg is entirely due to such a source. It is seen that all species listed in Table I are synthesized to within a factor of 4 of their observed abundances, and most to within a factor of 2. We regard this as a significant discovery. By suggesting that these nuclei are primarily due to nucleosynthesis during explosive carbon burning, it adds further credibility to the hypothesis that explosive nucleosynthesis is the natural source of atomic nuclei. Of the nuclei listed at the beginning of this paper, only ^{54}Cr and ^{58}Fe in the rare neutron-rich class are not synthesized with significant yield, suggesting that these two nuclei owe their origin to different circumstances altogether.

A difficult problem exists above iron, because the results depend upon the properties of neutron-rich isotopes—their (n,γ) cross sections, their neutron separation energies, their spin-statistical weights, and their (p,n) cross sections. We calculate that about 10% of the iron nuclei will undergo (p,n) reactions to cobalt during this explosion, which will be followed by neutron captures moderated by photoneutron resistance distributing the cobalt among masses 65 and 67, as shown in Table I. Cobalt is too rare to be an important seed in itself. A comparison calculation shows that at the slightly lower temperature $T = 2.05\times 10^9$ °K, the (p,n) reactions are completely ineffective, largely due to the smaller free-proton density. Much the same situation exists in the copper isotopes, and the yields of ^{71}Ga and ^{73}Ge in Table I again reflect a transmutation of 10% of nickel to copper by (p,n) reactions. Their yield is a factor of 5 smaller if Ni(p,n) is ineffective and only the Cu seed can contribute. It may happen that ^{69}Ga, ^{75}As, and ^{77}Se are also produced if the neutron separation energies differ by a few hundred keV from the values we adopted. This setting does not produce the heavy r-process nuclei, by the way, because the integrated neutron flux is not great enough and the seed-to-daughter abundance ratios are not large enough for greater atomic weight.

The yields of ^{24}Mg and of the rare neutron-rich nuclei under discussion depend upon the circumstances of the explosion, of course. We will report a fuller survey of this situation in our detailed paper. But a characteristic feature of all of these calculations is the coproduction of ^{24}Mg and the rare nuclei, even though the relative yields can differ by an order of magnitude for differing conditions. If our discovery is correct, it seems to imply that the production of the rare nuclei will impose interesting constraints on the explosive conditions.

There is in all this a very big challenge for laboratory nuclear physics. Many specific and interesting nuclear reactions play a key role in determining the final abundances of these species. Measurements relevant to thermonuclear reaction rates are badly needed, especially (1) the reaction ^{36}S$(p,\gamma)^{37}$Cl, which moderates the final yield of ^{36}S; (2) the branching ratios for (n,γ), (n,p), and (n,α) in neutron bombardment of ^{41}Ca, ^{37}Ar, and ^{33}S, which control the direction of important flows; (3) the (p,n) cross sections in very neutron-rich isotopes of Cl, Ar, K, Ca, Fe, and Ni—especially ^{43,45}Cl, ^{44,46}Ar, ^{45,47}K, ^{47}Ca, ^{62,64}Fe, and ^{68,70}Ni; (4) the (n,γ) and (p,γ) cross sections for ^{48}Ca, which moderate the final yield of ^{48}Ca; (5) the cross section for ^{49}Ti$(p,\gamma)^{50}$V which makes ^{50}V, and for ^{50}V(n,p)Ti^{50} which destroys it; (6) the radiative reactions ^{37}Cl$(p,\gamma)^{38}$Ar, ^{38}Ar$(p,\gamma)^{39}$K, ^{40}Ar$(p,\gamma)^{41}$K, ^{39}K$(n,\gamma)^{40}$K; and (7) the (n,γ) cross sections of all of the isotopes, which enter in some degree. Also of importance are the unknown neutron separation energies from the nuclei ^{45,47}Ar, ^{46,48}K, ^{63,65}Fe, ^{66,68,70}Co, ^{67,69,71}Ni, ^{70,72,74,76,78}Cu, and ^{75,77,79}Zn. A more complete discussion of these needs will appear in our full paper. The thermally averaged[6] cross sections $\langle\sigma v\rangle$ are needed primarily for temperatures between $(1.8 \text{ and } 2.5)\times 10^9\,{}^\circ$K. In the long run only careful laboratory experiments can show if explosive nucleosynthesis has provided the origins of the atomic nuclei in the manner we have outlined here. The present indications are extremely promising.

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