THE DYNAMICS OF THE RAPID NEUTRON CAPTURE PROCESS

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ABSTRACT

Previous studies of the rapid neutron capture mechanism of nucleosynthesis ("r" process) have been carried out with the assumption of constant temperature and density during the reactions. The "dynamics" of such a process thus consists essentially of the beta decay of neutron-rich isotopes in local statistical equilibrium for a given Z. We are attempting to improve the treatment of this process. We employ a nuclear reaction network containing six thousand nuclei whose neutron capture cross sections, neutron binding energies, beta decay rates, and delayed neutron branching ratios are calculated from nuclear systematics based upon a mass formula. We find beta decay rates much larger than in the work of Seeger, Fowler, and Clayton[1]. In a previous investigation[2], it was demonstrated that charged particle reactions in an expanding neutron-rich supernova envelope are likely to form ^{78}Ni seed nuclei. We are following the rapid neutron capture from this seed nucleus for various expanding supernova envelope adiabats. We have found that neutron captures do not proceed rapidly until the temperature falls to about 1.5×10^{9} °K. Virtually all of the neutrons have been captured by the time the temperature falls to 6×10^{8} °K. Delayed neutron effects tend to produce a small odd-even abundance effect in the final material, consistent with observed abundances. The influence of cooling and expansion of the material on the final abundances is demonstrated to be substantial for our choice of temperature and density conditions. Calculations are continuing in order to determine the initial conditions giving the best fits to the general r-process abundance curve.

1. INTRODUCTION

Following the compilation by Suess and Urey[3] of their table of abundances of the elements in the solar system, it was possible to analyze these to determine the nuclear processes which had contributed to nucleosynthesis. One of the processes thus defined was rapid neutron capture, in which neutron captures occur rapidly compared to the beta decay half-lives of nuclei near the valley of beta stability. Subsequent to the neutron capture buildup, the capture products approach the valley of beta stability by a series of beta decays. This process has been called the r-process by Burbidge, Burbidge, Fowler and Hoyle[4].

This rapid neutron capture process has previously been studied by quasi-static methods only. In these calculations, a specific temperature and neutron density are assumed and a steady flow path on the neutron-rich side of the valley of beta stability is then estimated. The process is approximated by assuming that for a fixed value of Z, neutron capture has proceeded until a statistical equilibrium is established along the Z-chain with respect to neutron capture and photoneutron reactions. These nuclei then wait at their equilibrium positions until beta decay takes place, following which further neutron capture occurs until the nuclei once again come into nuclear statistical equilibrium with respect to neutrons at a new "waiting point". For such a steady flow situation, the expected abundances of the final neutron capture products are proportional to the beta decay half-lives of the nuclei at the waiting points.

A proper dynamical study of the rapid neutron capture process must be based on the conditions expected in those types of supernovae for which hydrodynamic calculations predict a neutron-rich environment in which the process can occur. In practice this means that a neutron-rich fluid will be ejected and will expand approximately along an adiabat at a rate characteristic of a hydrodynamic time scale. The expanding material will form some seed nuclei, the character of which will depend upon the neutron-to-proton ratio in the material. These seed nuclei will then capture neutrons at rates which depend on the temperature and density conditions along the expanding adiabat. We discuss various features of this dynamical process in the following sections.

2. OLDER STUDIES OF THE RAPID NEUTRON CAPTURE PROCESS

In their original treatment of the r-process, Burbidge, Burbidge, Fowler and Hoyle[4)] used a conventional von Weizacker mass formula without shell corrections, although they attempted to make corrections for shell effects in their calculations. Their estimates of beta decay half-lives were based upon a consideration of only the decay of the ground state of the parent nucleus to the ground state of the daughter nucleus, or to a low lying state of the daughter nucleus.

Conventional mass formulas generally predict too small neutron binding energies far off the valley of beta stability. This results from the fact that the only form of the nuclear symmetry energy contained in these formulas is the volume symmetry energy, and only the leading parabolic term in its expansion is utilized. For the range of neutron-rich nuclei of pertinance to the r-process, however, higher order symmetry terms are very important in the determination of the neutron binding energies and beta decay energies. These terms include the surface symmetry term and the next volume symmetry term, which is of the form I^4A where $I = (A-2Z)/A$. Indeed, in our own current study of the r-process, we have found it necessary to go one step further: we include a higher order surface symmetry term, of the form $I^4A^{2/3}$, and a still higher order volume symmetry term, of the form I^6A.[5)] These symmetry terms give higher neutron binding energies at a given distance from the valley of beta stability; hence, for a specified temperature and neutron flux, the capture path for the r-process lies farther away from the valley of beta stability.

The assumption of beta decay only between ground states grossly underestimates the rapidity of the beta decays of very neutron-rich nuclei, where the decay energies may lie in the range 10 to 15 MeV. At these energies, beta decay from the ground state of the parent nucleus to a very large number of excited states of the daughter nucleus is then possible. A step in the right direction was taken in the subsequent study of the r-process by Seeger, Fowler and Clayton[1)]. These authors assumed that the daughter nuclei had a uniform spacing of excited states with a value characteristic of the first MeV of excitation, and they assumed that the beta decay could take place to one out of three of these excited states. However, this still grossly overestimates the half-life of the beta decay process. The number of excited states per unit energy interval increases at low energies proportionately to exp(constant E), while at higher energies it increases as exp(constant $E^{1/2}$). Thus it may be seen that enormously more excited states are available for the beta decay than were assumed by Seeger, Fowler and Clayton.

One cannot, however, calculate the total beta decay transition probability simply by adding up the decays to the individual daughter states assuming some average transition matrix element. The wave functions of the higher excited states are exceedingly complicated, hence the beta decay matrix elements to an individual state will become progressively smaller with increasing excitation energy. One expects the beta strength function, proportional to (ft) times the level density, to approach an approximately constant value. The beta decay matrix elements for the transitions between the ground state of the parent nucleus and the low lying states of the daughter nucleus are already considerably reduced compared to what they would be if the various states involved were good single-particle states. In our own work we have therefore estimated beta decay rates by assuming that the transition matrix element to the first one hundred levels in the daughter nucleus has an average (ft) value characteristic of normal allowed beta decays. We have further assumed that above the one-hundredth level there is a constant beta strength function per unit energy interval in the daughter nucleus, with the beta strength function being equal to the value attained in the daughter nucleus in the vicinity of the one-hundredth excited state.

The dramatic difference brought about by these different assumptions is evidenced by the fact that while the beta decay half-lives used by Seeger, Fowler and Clayton for the most part lay in the range 10^{-1} to 10 seconds, our own estimates of beta decay half-lives tend to lie in the range 10^{-4} to 10^{-3} seconds. We should point out that part of this difference arises from the fact that our neutron fluxes are considerably higher than those used by Seeger, Fowler and Clayton; hence the nuclei at the "waiting points" typically have larger beta decay energies.

3. THEORIES OF SUPERNOVAE

The first serious numerical hydrodynamic study of a supernova explosion was carried out by Colgate and White[6]. The basic mechanism involved in their study was the collapse of a stellar core to nuclear densities, followed by the transport of released gravitational potential energy away from the core by neutrinos and antineutrinos. These particles were found to heat the infalling matter sufficiently to create a shock wave, leading to an expansion of the outer part of the infalling material in a strong supernova shock wave which blows the remainder of the star off into space. In such a process it might be expected that a few tenths of a solar mass would be compressed to high enough densities to create a very neutron-rich fluid which, upon expansion into space, would result in the mixing of the products of the rapid neutron capture process with the interstellar medium. This was a little embarrassing with regard to nucleosynthesis, since it appeared that considerably too much production of r-process nuclei would take place[2,7].

At the present time there is grave doubt that any significant amount of mass ejection can occur by this neutrino-antineutrino transport process. Studies by Arnett[8] indicated that for cores of mass $M > 4M_{\odot}$, no explosion would take place. Recent numerical hydrodynamical studies of a supernova implosion by Wilson[9], in which the neutrino and antineutrino transport was treated somewhat more correctly, failed to give any expulsion of material. There is thus considerable reason to doubt that the formation of any significant amount of r-process elements will occur in this type of supernova event.

Meanwhile, as a result of studies by Arnett[10], it appears that a wide range of supernovae may result from thermonuclear explosions. In these cases, a star does not succeed in initiating carbon or oxygen-burning processes during the normal course of its evolution. Instead, it forms a highly degenerate core which begins to contract rapidly as a result of neutrino losses, so that when the ignition of carbon or oxygen thermonuclear reactions occurs, the thermal runaway burns the carbon and oxygen thermonuclear fuels explosively and triggers the formation of a detonation wave in the core of the star. This blows the star completely apart, dispersing all of the material into space. The thermonuclear reactions which occur during this explosive process reproduce the abundances of nuclei in the vicinity of the iron nuclear statistical equilibrium peak very well[11]. At no time during the contraction of the core does the density ever become high enough for appreciable electron capture to have occurred to provide a large abundance of free neutrons; hence it is not expected that these explosive supernovae events will make any significant contribution to the r-process.

More massive stars are now expected to implode almost completely, presumably forming black holes, with possible thermonuclear expulsion of the outer layers, but without the expulsion of any of the imploding material. Thus these also cannot be the site of r-process element formation.

Nevertheless, the identification of the pulsars with rotating neutron stars indicates that some supernovae occur in which compression of matter to nuclear densities takes place. These probably result from lower mass stars in which the contraction of the carbon core to highly degenerate densities occurs more slowly. Under these conditions, the thermonuclear ignition of the carbon reactions may fail to raise the electron degeneracy, thus preventing a detonation wave from forming. It is possible that cooling by rapid electron capture will also reimplode expanding material.

The formation of a neutron star certainly appears to be a necessary prerequisite to the formation of a fluid sufficiently neutron-rich to be a possible source of r-process nuclei. However, it is also necessary to find a mechanism by which some of the neutron-rich fluid can be ejected from the star after its compression to these enormously high densities has taken place. If the neutrino-antineutrino energy transport mechanism is ineffective, then it is not possible to envisage any large amount of neutron-rich material being ejected in the process.

An interesting possible mechanism has recently been discussed by LeBlanc and Wilson[12]. They have carried out a two-dimensional hydrodynamic calculation of the collapse of a star, allowing for the presence both of rotation and magnetic fields in the interior. They found that an initially co-rotating star developed differential rotation after the collapse had taken place. Consequently, the rotational shear in the inner part of the resulting disk wrapped the magnetic field lines into a very tight spiral, creating an enormous magnetic energy close to the central axis of the collapsed star. The excess magnetic pressure then caused an expansion of the material along the axis, which, owing to the resulting buoyancy of the material with respect to the local neighborhood, causes the ejection of a jet of material along the axis of the configuration. LeBlanc and Wilson have estimated that this jet contains about 10^{-2} solar masses of material, which has been compressed to a sufficiently high density for it to be very neutron-rich. This estimate is in reasonable agreement with an estimate made by two of us[13)]; we find that the amount of r-process material which must be ejected, when a neutron star is formed, to account for the abundances of r-process material in the solar system is $\sim 6 \times 10^{-3}$ solar masses per explosion.

Thus the present astrophysical outlook is that r-process nucleosynthesis will result from the compression of more or less normal material to a range of relatively high densities, at which varying amounts of electron capture will take place, so that a variety of neutron-to-proton ratios will be produced in the compressed material. This material will then expand roughly along an adiabat on a hydrodynamic time scale. The physics which has to be investigated is thus the behavior of the material after such compression, as it expands along the approximate adiabat and is ejected into interstellar space.

4. THE FORMATION OF SEED NUCLEI

We have recently carried out a variety of investigations related to the question of the formation of seed nuclei. The first set of investigations was carried out by Truran, Arnett, Tsuruta, and Cameron[2)]. This work was based on the model of a neutrino-antineutrino energy-transport supernova, but the details of the ejection mechanism are not particularly significant insofar as the subsequent physics is concerned: the mechanism suggested by LeBlanc and Wilson[12)] would serve just as well as input data for these calculations. In this study, a largely neutron material was followed as it expanded along an adiabat. It was found that, provided the electrons remained degenerate during the early stages of the expansion, neutrons would remain in excess abundance over protons; further, an equilibrium ratio between neutrons and protons was maintained by weak interactions until the temperature fell to about 2×10^{10} °K.

At this point, the model calculations suggested that a neutron-to-proton ratio of about 8 would be established. At temperatures below 2×10^{10} °K, the densities were still high enough for the protons to combine with neutrons, first to form ^{4}He, and subsequently to build up into heavy elements during the expansion. At the highest densities considered, the most abundant seed nucleus was found to be ^{78}Ni. This is a nucleus having a doubly-closed shell of 28 protons and 50 neutrons. Its dominant abundance in equilibrium under these conditions follows in part from the special stability associated with the closed shells and in part from the very large neutron excess in the medium.

The equilibrium abundances of nuclei at a temperature $T = 4 \times 10^{9}$ °K for an expansion adiabat defined by $\rho = 7 \times 10^{4}\ T_9^{\ 3}$ (T_9 is the temperature in billions of degrees Kelvin), is shown in Figure 1. The three most abundant nuclei ^{78}Ni, ^{79}Cu and ^{80}Zn respectively, are all characterized by a "magic number" of neutrons (N= 50). The total ratio of neutrons to protons was taken to be N/Z = 8 for this material. The free neutron number density is enormous under these conditions, $n_n = 1.88 \times 10^{30}\ cm^{-3}$.

More recently, two of us (Delano and Cameron[14)]) have looked in more detail at reactions involving light nuclei in an expanding medium. We have found that there are a number of reactions involving light nuclei which can take place parallel to the triple alpha reaction in the formation of heavier nuclei; the reaction $2\,^{4}He + n \rightarrow\ ^{9}Be\ (\alpha,n)\ ^{12}C$ is particularly important. These reactions bridge the gap between helium and carbon more rapidly than the triple-alpha reaction, thus assuring that the heavy nuclei seeds can be built up during the expansion phase of the neutronized material.

At extremely low densities, when very little neutron excess is produced, the most abundant nucleus under conditions of nuclear statistical equilibrium can be expected to be ^{56}Fe. However, at somewhat higher densities, the most abundant nucleus under conditions of nuclear statistical equilibrium shifts to a nickel isotope somewhat more massive than mass number 56. At the highest densities of interest, the dominant seed nucleus is ^{78}Ni. Thus, the astrophysical context to which the rapid neutron capture calculations should be related is the expansion of a neutron-rich fluid containing a seed nucleus composed of an isotope of iron or nickel with a mass number depending upon the degree of neutron enrichment.

5. EQUILIBRIUM FLOWS

As we have discussed in a previous section, a "steady" flow path can be roughly defined for a particular choice of both the temperature and the free neutron number density. The assumption that nuclear statistical equilibrium is achieved and maintained along a given isotope chain allows one to write the following expression for the ratio of the abundance of isotope (A + 1) to isotope A

$$\ln \frac{n(Z,A+1)}{n(Z,A)} = \ln \frac{w(Z,A+1)}{w(Z,A)} + \ln n_n - 78.45 - \frac{3}{2} \ln T_9 + \frac{11.61}{T_9} Q_n(Z,A+1)$$

where $Q_n(Z,A+1)$ is the binding energy of the last neutron in the nucleus (Z,A+1) and w(Z,A) and w(Z,A+1) are the appropriate nuclear partition functions. For a specified temperature and free neutron number density, n_n, the most abundant isotope in equilibrium can be determined from the above relation for each Z-chain.

The neutron binding energies for very neutron-rich nuclei must be determined by a mass formula extrapolation. In these calculations we have employed the predictions of the mass formula of Truran, Cameron and Hilf[5)]. As the individual neutron and proton shell corrections determined in this mass formula exhibit a rather smooth and physically understandable variation with mass number, we believe that extrapolations into the neutron-rich regions far from the valley of beta stability may be somewhat more reliable.

The "flow paths" defined by the positions of these peak nuclei in equilibrium are illustrated in Figure 2 for a temperature $T = 2 \times 10^9\ {}^oK$ and two expansion adiabats:

$$\rho = 5 \times 10^4\ T_9^{\ 3}$$

$$\rho = 5 \times 10^2\ T_9^{\ 3}$$

The free neutron density is taken to comprise 80 percent of the mass. The experimentally determined valley of beta stability and the neutron drip line predicted by the mass formula of Truran, Cameron and Hilf are also indicated. For both adiabats, the flow paths follow the neutron drip line rather closely in the light element region. For the heavier nuclei, the flow paths do not approach the position of the drip line at this temperature, except at closed neutron shells. The position of the major r-process peaks at A $\simeq$ 130 and A $\simeq$ 195 are also indicated in this figure, as is that of the lesser peak in the rare earth region.

It is important to note that the positions of the neutron closed shells at neutron numbers N = 82 and 126 shown in this figure are not consistent with the production of the dominant r-process peaks following a sequence of beta decays. In both instances, a buildup of something more than 5 mass units is required relative to equilibrium at $T = 2 \times 10^9$ °K. This feature of the flow paths is appreciably adjusted by variations in the temperature, as is clear from the results shown in Figure 3. Here the flow paths defined by the positions of the peak nuclei in equilibrium for each Z-chain are shown for the adiabat $\rho = 5 \times 10^3\ T_9^{\ 3}$ for temperatures T_9 = 1, 3 and 5. At the highest temperature, the closed shell feature at N = 126 does extend beyond mass number A = 195 but the fast capture peak at A = 130 is still not explained. Furthermore, our dynamic studies indicate that, for the adiabats we have considered, equilibrium is rather well maintained for each isotope chain down to temperatures $T < 2 \times 10^9$ °K in the expansion. The formation of the rapid capture peaks in the vicinity of mass numbers A = 130 and 195, in fact, takes place as a result of the "freezing" characteristics of this neutron capture process. We shall consider this problem in detail in the next section.

The important role played by these closed shell features is further emphasized by a consideration of the average beta decay half-lives for each Z-chain. The mean chain half-life is plotted as a function of proton number in Figure 4 for the adiabat $\rho = 5 \times 10^3 T_9^{\ 3}$ at a temperature of 2×10^9 °K. The longest mean half-lives, approaching 10^{-2} seconds, are those corresponding to Z-chains for which the most abundant isotope contains a magic number of neutrons (N = 82 or 126). As these nuclei at the neutron closed shell positions are the last to undergo beta decay, it is clear that the flow back toward the valley of beta stability takes place rather late in the expansion of the supernova material. This again suggests that the formation of the r-process peaks at mass numbers A $\simeq$ 130 and 195 will be sensitive to the details of the late stages of expansion.

6. GENERAL TRENDS FOR R-PROCESS DYNAMICS

In order to understand some of the dynamic features of the rapid neutron capture process under changing conditions of temperature and density, three salient properties of the network must be emphasized.

First: Along a Z-chain, the neutron binding energy of each isotope, on the average, decreases as one moves from the valley of beta stability to the neutron drip line. With neutrons maintaining an approximate equilibrium along each Z-chain, this has the following consequences: a) decreasing temperatures will tend to shift the flow path toward the drip line; b) decreasing densities will tend to shift the flow path towards the valley of beta stability; c) the depletion of neutrons tends to shift the flow path towards the valley of beta stability.

Second: Along a Z-chain, the total beta decay half-life of each isotope, on the average, decreases as one moves from the valley of beta stability to the neutron drip line. Consequently, flow paths which lie far off the valley of beta stability will conduct material up the network (beta decay to successively higher proton numbers) at a much faster rate than flow paths lying close to the valley of beta stability.

Third: Along a Z-chain, beta decay with the delayed emission of up to three neutrons increasingly tends to become the dominant mode of decay for each isotope as one moves from the valley of beta stability to the neutron drip line. This means that beta decays will not proceed along isobar lines far from the valley; instead there will be a "fall back" to lower mass numbers.

Because of the abrupt decrease of neutron binding energies at neutron closed shell positions, these general features are less applicable to a description of the dynamic features near these positions.

7. TEMPERATURE AND DENSITY PROFILES AND SOME PRELIMINARY RESULTS FOR THE R-PROCESS

The temperature relaxation for the expanding r-process gas was adopted from the supernova calculations of Arnett[8,15]. It is

$$T_9 = 4 \times \left(\frac{0.03}{0.03 + \text{time}}\right)^{0.852}$$

For a variety of adiabats in the range,

$$4 \times 10^2\ T_9^{\ 3} \leq \rho \leq 5 \times 10^4\ T_9^{\ 3} \quad ,$$

this profile is such that the temperature falls from $T_9 = 4$ to $T_9 = 2$ in 3.8×10^{-2} sec and from $T_9 = 2$ to $T_9 = 1$ in about a tenth of a second.

Starting with free neutrons and ^{78}Ni seed nuclei with number density ratios in the range

$$50 \leq \frac{n}{^{78}\mathrm{Ni}} \leq 130 \quad ,$$

the r-process was studied for the above temperature and density conditions.

At the initial temperature of $T_9 = 4$, the flow (beta decays) of material up the Z-chains progresses slowly. As the temperature falls, the flow path begins to shift toward the drip line and hence enters the region of increasingly rapid beta decays. This is in evidence in Figures 5, 6, and 7, where the total beta decay rate per nucleus is plotted against temperature for different adiabats and different initial ratios of neutrons to seed nuclei. Up until the depletion of the neutrons, these plots indicate that the total beta decay rates, and hence the speed with which material flows up the Z-chains, increases roughly monotonically as the temperature decreases.

In all of the model calculations we have performed to date there has been one recurring feature which persists until the neutrons begin to be depleted. This is the formation of two strong abundance peaks, one at mass number $A = 124$, and one at $A = 190$. The reason is not hard to discover. The $A = 124$ nucleus lies on the $N = 82$ closed neutron shell position and the $A = 190$ nucleus lies on the $N = 126$ closed neutron shell position.

The equilibrium flow paths, displayed in Figures 2 and 3, show that for a broad range of temperatures and densities ($1.1 \leq T_9 \leq 5$ and $4 \times 10^3 \leq \rho \leq 4 \times 10^5$) all material is essentially constrained to flow along these closed neutron shell positions. Beta decaying up the Z-chains along the neutron positions $N = 82$ and $N = 126$, material accumulates when it reaches proton number $Z = 42$ (along $N = 82$) and $Z = 64$ (along $N = 126$). Referring to Figure 4, it will be seen that at

$T_9 = 2$ these two proton numbers correspond to the two slowest beta emitters in the occupied region of the network. Consequently ^{124}Mo and ^{190}Gd have the effect of mass traps in this network.

The dynamics of the r-process is then the following: first, neutron captures on ^{78}Ni seed nuclei, and subsequent beta decays, lead to the formation of the first peak at A = 124, and then, as more and more material piles up at A = 124, it slowly beta decays, leading to the buildup of the second peak at A = 190. By the time the second peak has formed, about 90% of the free neutrons have been captured, and virtually all the nuclei in the network are becoming trapped at ^{124}Mo or ^{190}Gd. This may be seen in Figures 4, 5, and 6, where the sudden drops in the beta decay rates are quite pronounced. This was not due to a sudden shifting of the flow paths towards the valley of beta stability, and hence slower beta decay rates, but rather, it results solely from the fact that all the material in the network is quite rapidly winding up in the two slowest beta emitters, ^{124}Mo and ^{190}Gd.

Since presumably the two peaks at A = 124 and A = 190 are the precursors of the r-process peaks at A = 130 and A = 195, the freeze-out process of falling temperatures and neutron depletion must be critical in determining the 5 or 6 mass unit displacement needed for agreement. The depletion of the neutrons, at temperatures in the range $1.2 \leq T_9 \leq 1.6$, will tend to move the peaks toward lower mass number and toward the valley of beta stability. If the neutrons are not depleted, temperatures falling to $0.5 \leq T_9 \leq 1.1$ will move the peaks through the closed neutron shell positions towards higher mass numbers. Consequently, in order for our calculations to reproduce the two major r-process peaks, the neutrons must not be completely depleted before the temperature falls below $T_9 = 1$.

The temperature and density profiles we have been using do not appear to be capable of accomplishing this. To illustrate, attention is called to Fig.8 in which is plotted the mass fraction in each isobar at three different times in the expansion of an r-process gas. This was for an initial neutron to ^{78}Ni seed nucleus ratio of 83, and relaxation was down the adiabat $\rho = 4 \times 10^3 \, T_9{}^3$ from an initial temperature of $T = 4$. At 5.7×10^{-2} sec the temperature has fallen to $T_9 = 1.63$ and about one-third of the neutrons have been captured. The first peak at A = 124 is forming, and it is apparent that material is being held up at A = 190.

At 7.59×10^{-2} sec, in the second section of the figure, the temperature has fallen to $T_9 = 1.37$, and about 85% of the neutrons have been captured. Here A = 124 is the dominant peak but the one at A = 190 is rapidly building up from neutron captures on the beta decay products of A = 124. In the final plot, at 1.01×10^{-1} sec, the temperature has dropped to 1.15 billion degrees after the capture of 99% of the free neutrons. The peak at A = 190 has moved to A = 192, but this is due to the beta decay of A = 190 along the N = 126 closed shell. Beta decay has reduced the peak at A = 124 to the point where it is an order of magnitude less in abundance than the one in the A = 190 region.

It is clear, that in the final depletion of the neutrons and subsequent beta decay of this neutron rich material to the valley of beta stability, there will be no net movement of the peaks towards higher mass numbers.

8. NUCLEAR ENERGY GENERATION AND THE TEMPERATURE RELAXATION

We have stated that our calculations might produce the r-process element abundances if the temperature falls below $T_9 = 1$ with about 5 neutrons per peak nucleus remaining. Clearly the temperature relaxation we have been using must be speeded up at the point where the neutrons are being depleted. We could arbitrarily amend our temperature relaxation in an attempt to get the desired results, but they would obviously be more believable if the physics of the situation dictated the rate at which the gas cools.

In this regard we point out that nuclear energy generation has been absent from our calculations thus far. With several MeV per neutron capture and the release of up to 15 MeV per beta decay, rough estimates indicate that these sources are capable of generating an amount of energy per unit volume which is comparable to the energy density of the gas. In short, nuclear energy generation may contribute to somewhat higher temperatures and initially slower cooling rates in the expanding gas. But, as the neutrons are depleted, the photon energy from neutron capture will be cut off and as more material becomes trapped in the slow beta emitters at A = 124 and A = 190 the rate of energy generation from beta decay will die. Consequently, it is not unreasonable to expect a more rapid drop in the temperature at the time of the neutron depletion, if nuclear energy generation is significant.

The importance of nuclear energy generation and the possibility of having an abrupt temperature drop to below $T_9 = 1$ with four to five neutrons remaining per peak nucleus is presently under investigation. To test the idea, however, and also to demonstrate the effects of delayed neutron emission when material beta decays to the valley of beta stability, we have irradiated the two peaks at A = 124 and A = 190, with about three neutrons for each peak at a temperature of $T_9 = 0.519$ and a mass density of 6.97×10^3 gm/cm^3. We have also included two minor peaks at A = 138 and A = 146, positions which on the average had high abundances in our calculations, in order to see the effects of the freezing process on the intervening material between A = 124 and A = 190.

Figure 9 displays the mass fraction in an isobar as a function of mass number at three different times in the irradiation. The first plot at 0.0 sec shows the initial abundance peaks to be subjected to neutron capture. The second plot at 10^{-9} sec shows these peaks after the capture of virtually all the neutrons. The A = 124 mass peak has been pushed to A = 130, where it should be, but the A = 190 peak has been driven to A = 206, 11 mass units beyond where it should be. At this point all the nuclei are very neutron-rich and are just beginning to beta decay to the valley of beta stability. In the last plot, at 4.5×10^{-3} sec, beta decay to the valley is about two-thirds complete and several effects are quite noticeable.

First, the peaks at A = 130 and A = 206 have fallen back to A = 128 and A = 204, respectively. This is due mostly to delayed neutron emission, but photoneutron reactions may be partially responsible. Second, we have formed the r-process peak at A = 164. This peak has been a recurrent feature in the beta decay, with delayed neutron emission, of material to the valley of beta stability. It does not appear to be a sensitive function of the way in which material between mass numbers A = 124 and A = 150 is distributed. As long as some material exists in this region it always seem to be formed into this broad shallow peak as the valley is approached. The third point worth mentioning is the smoothness of the final mass fraction curve and the rather uniform small odd-even differences. This is consistent with the qualitative features of the r-process abundance curves. Our results suggest that it is due almost entirely to the smearing out effects of delayed neutron emission.

9. DISCUSSION

The present studies are obviously still preparatory to a full investigation of the dynamics of the r-process. It is clear that a final study will require an improved treatment of several features of the process:

1. It will be necessary to investigate the behavior of a variety of true adiabats at a range of expansion rates. The calculation for a given adiabat must consistently determine the initial neutron-proton ratio and the abundance distribution of seed nuclei formed in nuclear statistical equilibrium, and the changes in internal energy due to nuclear reactions must be calculated.

2. While we are resonably satisfied with the predictions of the mass formula utilized in this work, the same is not true of the calculated beta decay rates. An improved treatment of the beta strength functions is needed.

3. The effects of fission have so far been neglected. It will be necessary to estimate both the points of termination of neutron capture by neutron-induced fission, and the effects of fission competition with beta decay. The latter point is especially important for the problem of determing whether r-process products can decay into the superheavy island of stability.

The present calculations have shown an approximate, but not detailed, agreement between calculated and observed r-process abundances. One encouraging result of the calculations is the demonstration that the final frozen r-process abundances have a reduced odd-even fluctuation as a result of multiple delayed neutron emission, in accord with observation.

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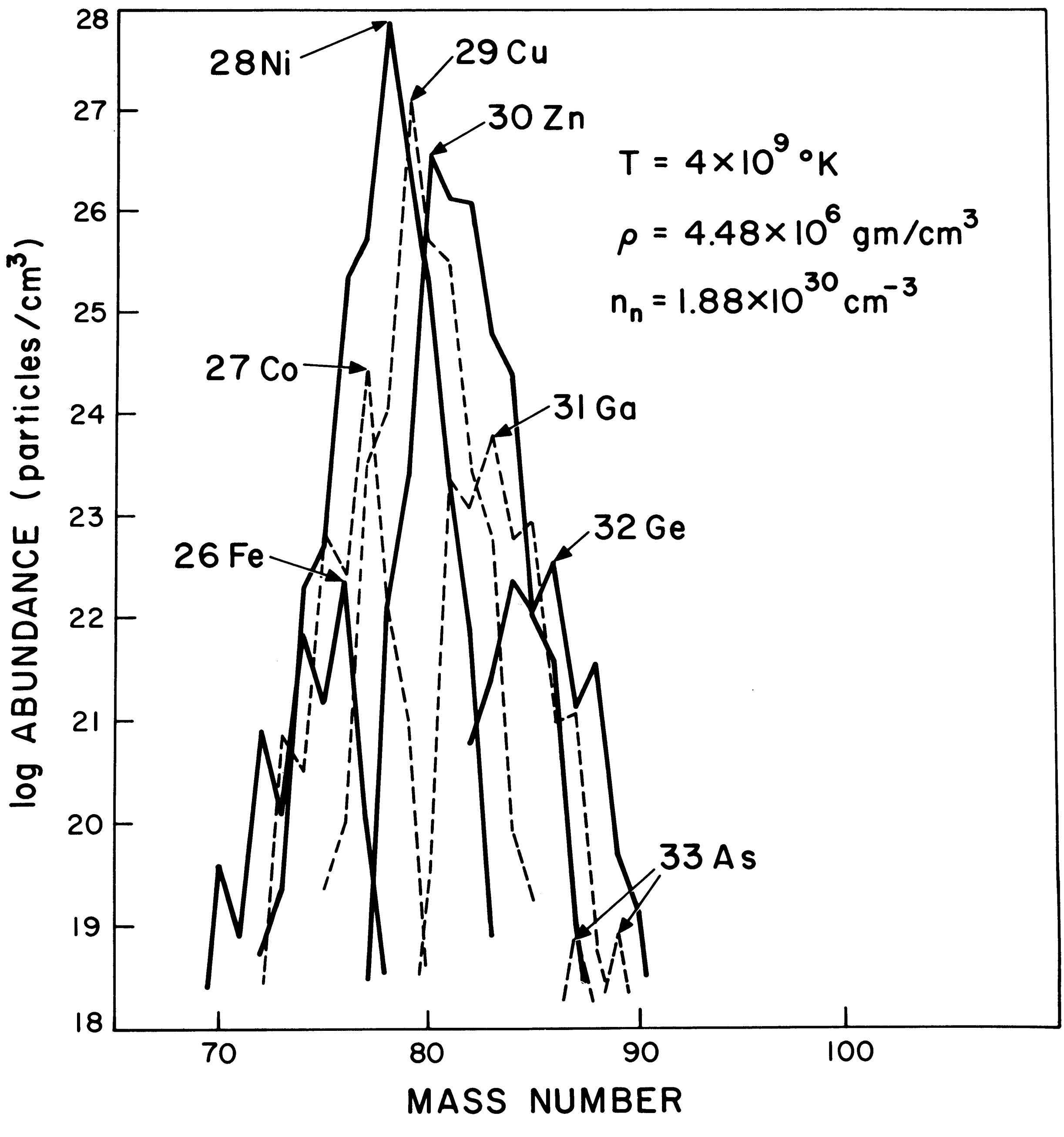

Fig. 1 The abundances of nuclear species in nuclear statistical equilibrium in matter with a large neutron excess, peaked at ^{78}Ni.

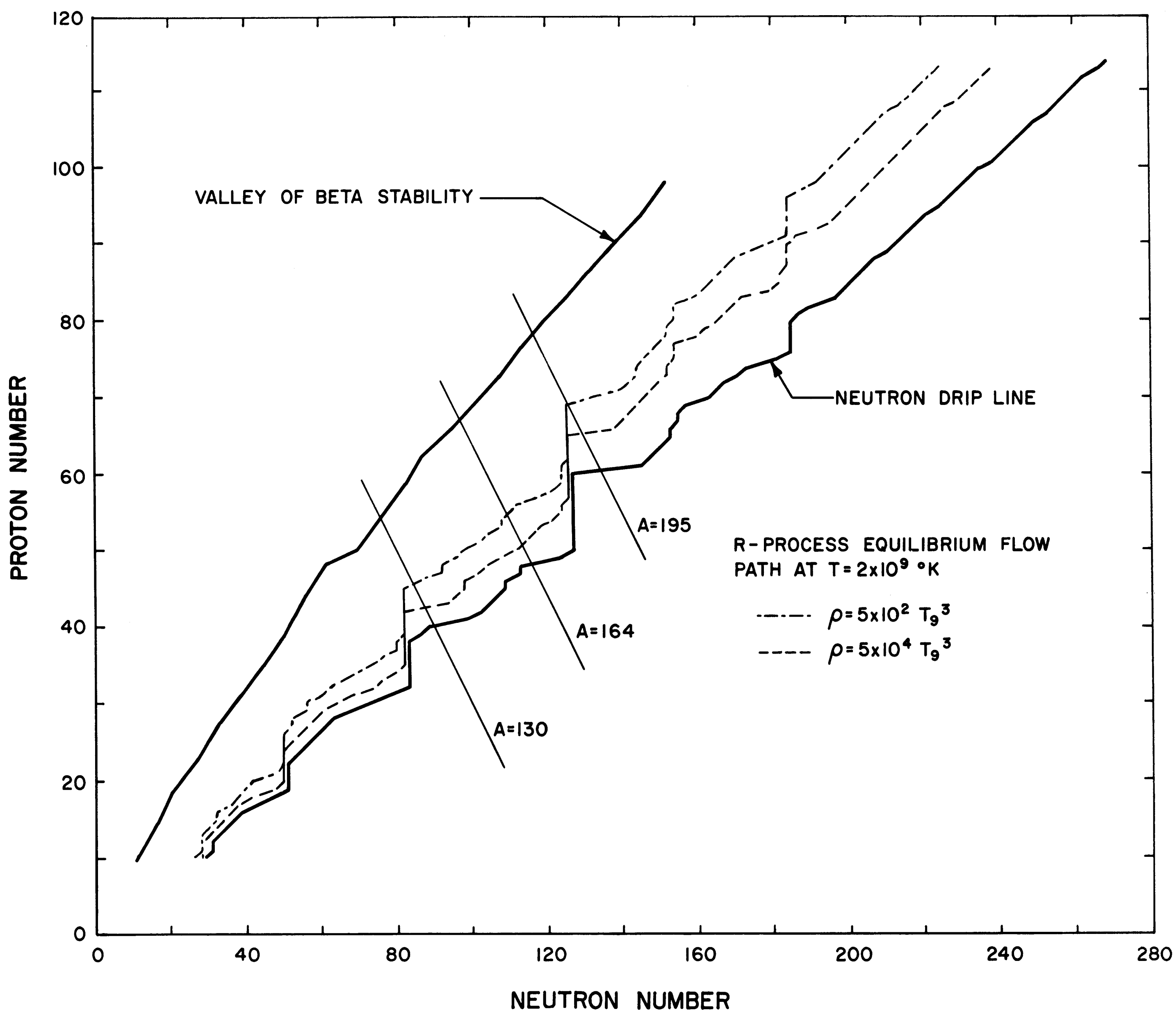

Fig. 2 R-process paths in a nuclide chart under steady flow conditions at $T_9 = 2$, for two different densities. Note that the ordinate and abscissa scales differ by a factor two.

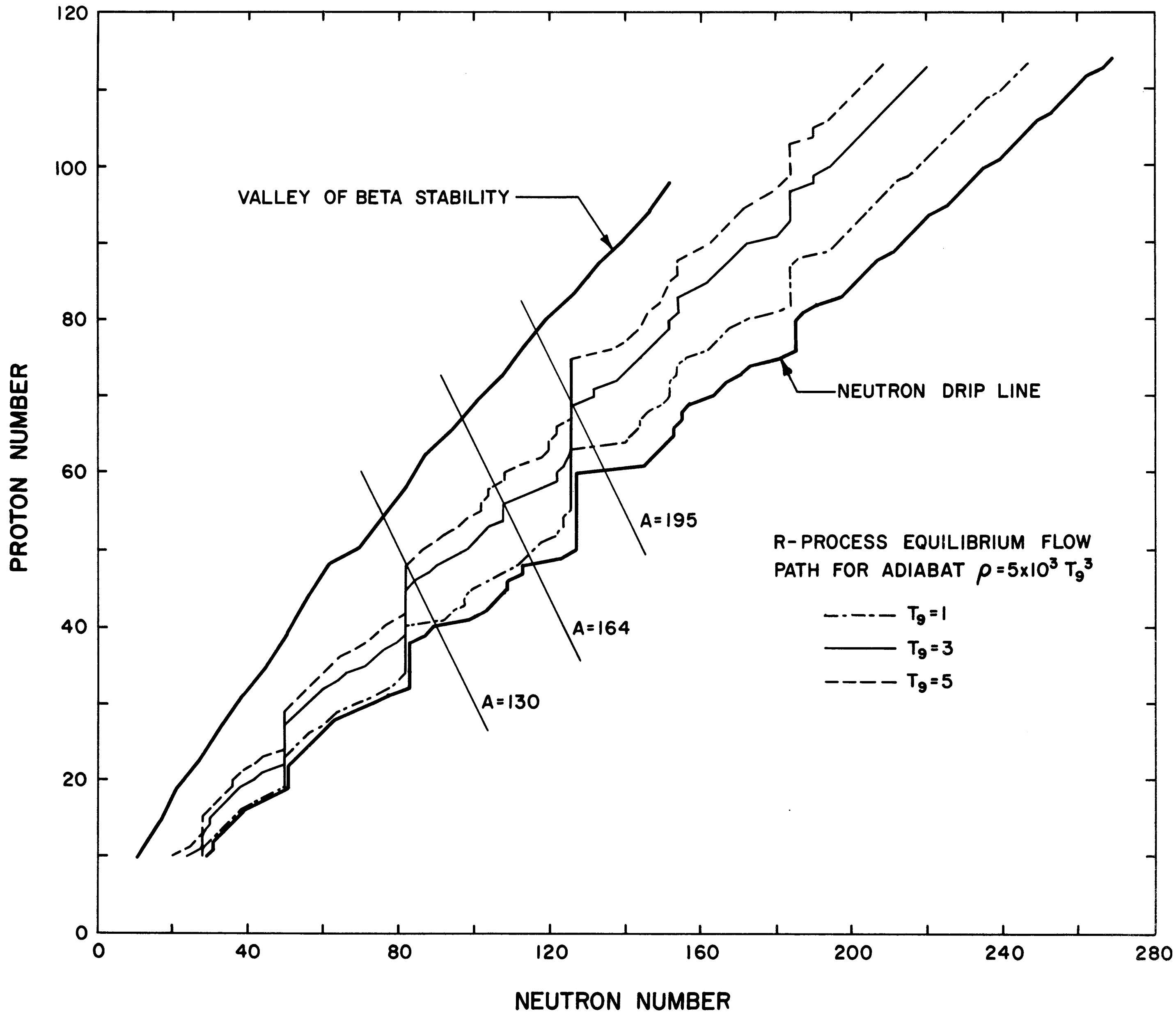

Fig. 3 R-process paths in a nuclide chart under steady flow conditions at several different stages of an adiabatic expansion. Note that the ordinate and abscissa scales differ by a factor two.

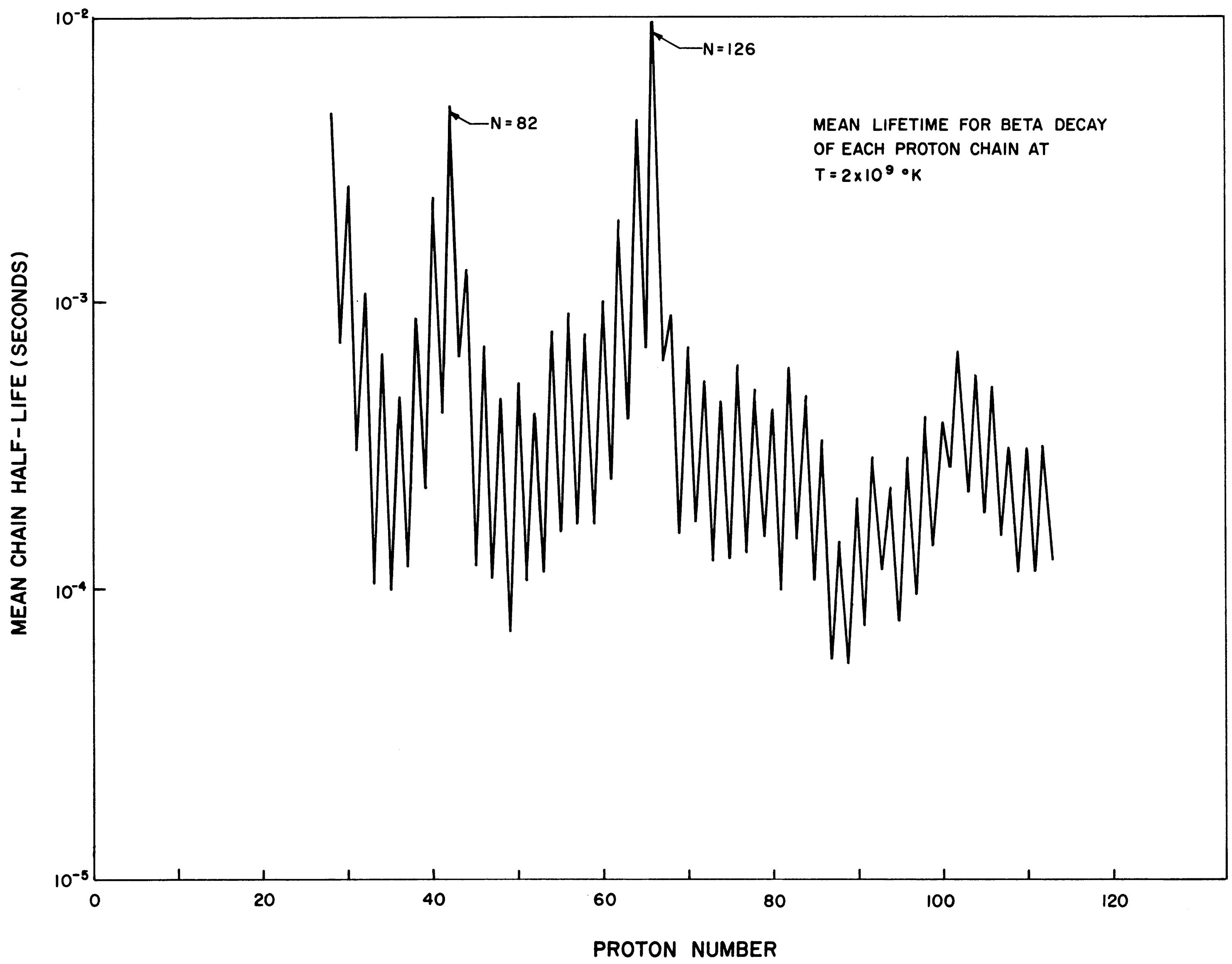

Fig. 4 The average beta decay lifetime of the nuclei with given proton number at $T_9 = 2$ and 4×10^4 gm/cm^2 with 80 percent free neutrons by mass.

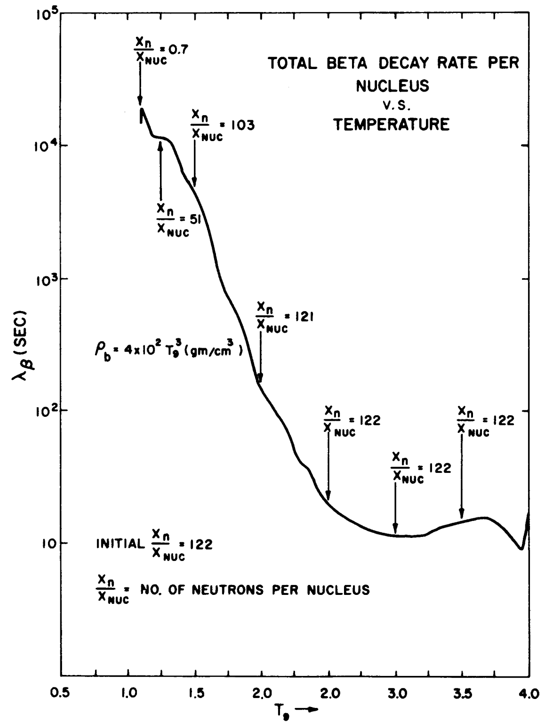

Fig. 5 Change in the total beta decay rate per nucleus during expansion of a high adiabat for an initial ratio of neutrons to ^{78}Ni nuclei of 122.

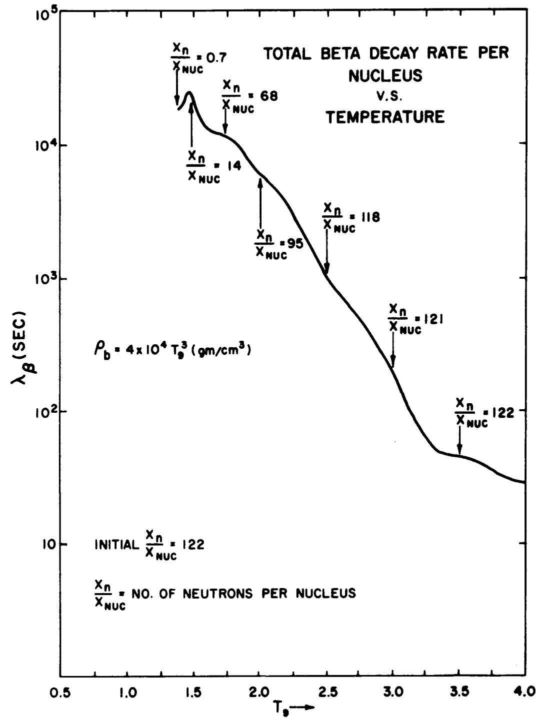

Fig. 6 Change in the total beta decay rate per nucleus during expansion of a low adiabat for an initial ratio of neutrons to ^{78}Ni nuclei of 122.

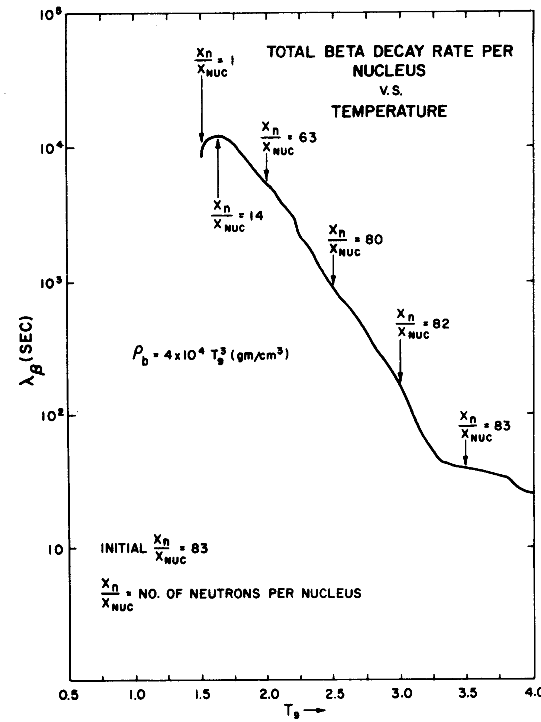

Fig. 7 Change in the total beta decay rate per nucleus during expansion of a low adiabat for an initial ratio of neutrons to ^{78}Ni nuclei of 83.

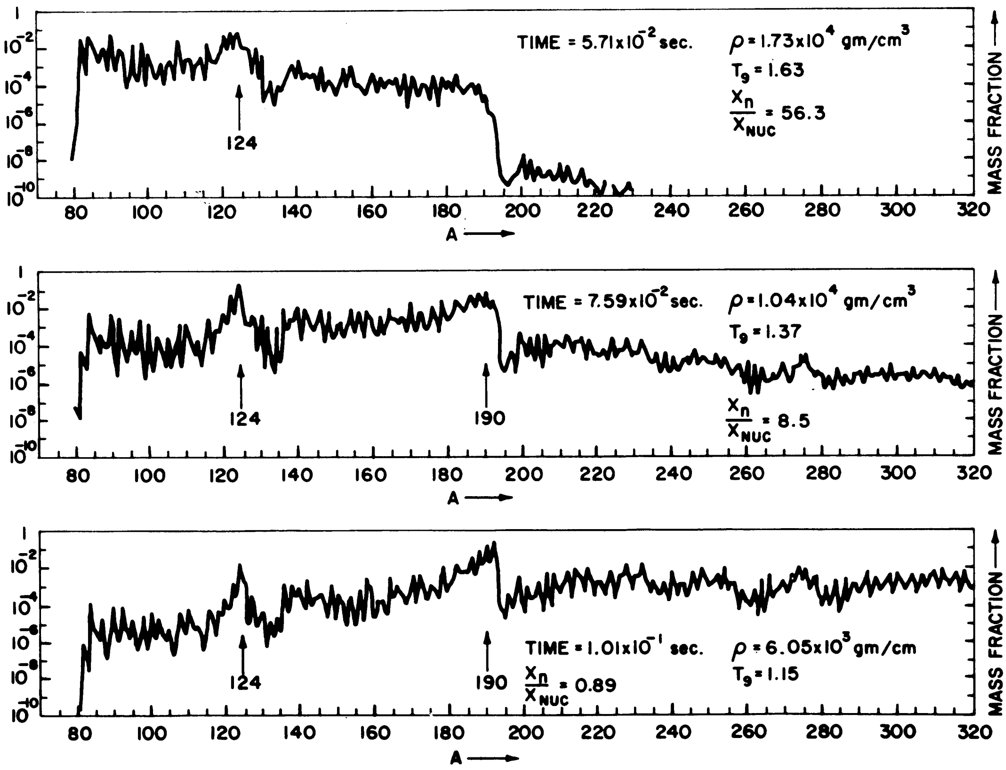

Fig. 8 Evolution of the r-process abundances during the expansion of a low adiabat.

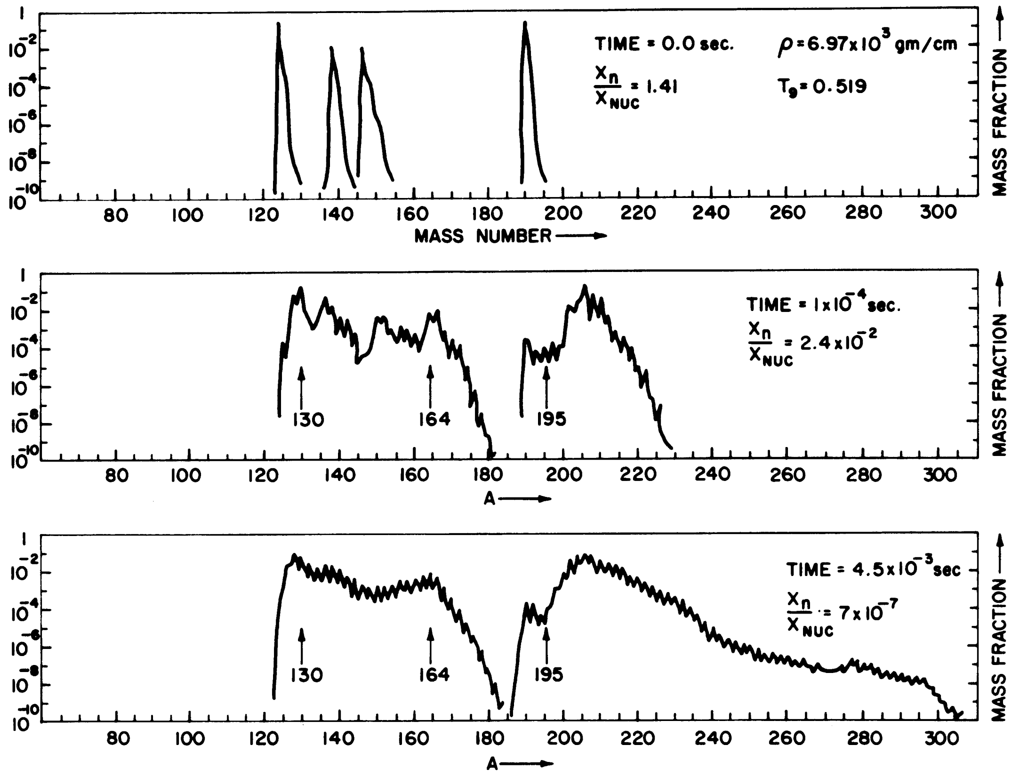

Fig. 9 R-process freezing of a selected "seed" nuclei at a low temperature.