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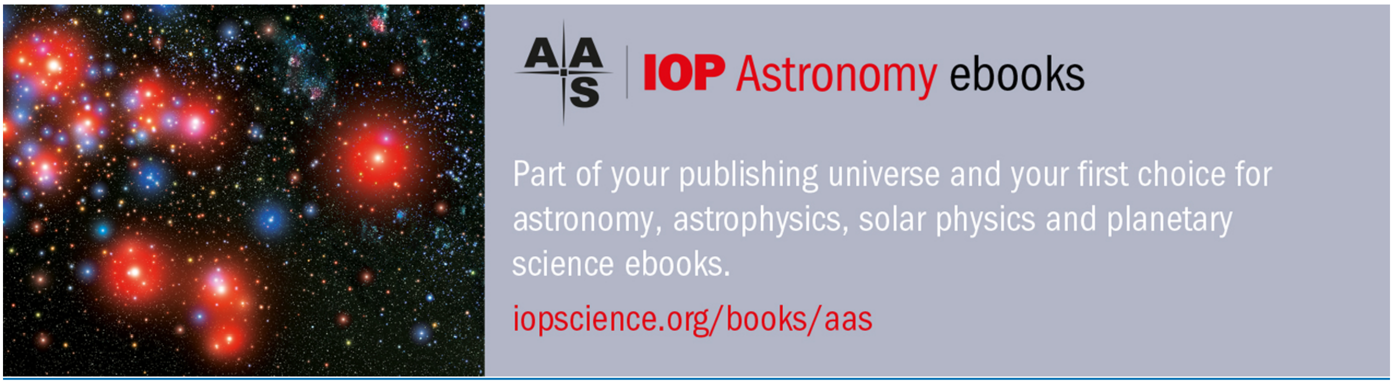

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Supernova neutrino–nucleus astrophysics

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Abstract

In this brief review we explore the role of neutrino–nucleus interactions in core-collapse supernovae and discuss open questions. In addition implications of neutrino mass and mixings in such environments are summarized.

1. Open questions for neutrino interactions in core-collapse supernovae

We do not as yet understand how supernovae explode or even whether explosion is a common outcome of a core-collapse event. The current ‘nuclear physicist’s paradigm’ (that is, leaving out rotation and magnetic fields) for explosions is as follows: a massive star evolves on a timescale of millions of years and forms a Chandrasekhar mass core composed of iron peak nuclei. The weak interaction dominates the evolution of an object like this and neutrino emission from core carbon/oxygen burning onward efficiently removes entropy from the star, ultimately causing the iron core to have a very low entropy per baryon. As a result, the core is supported by relativistically degenerate electrons and this fact has immediate implications: the core will go dynamically unstable and will collapse at a near free fall rate on a very low adiabat until the nuclei and nucleons merge at nuclear density. A shock wave is generated at this point, essentially at the edge of an inner homologous core which is a sort of instantaneous Chandrasekhar mass. During the collapse, the electron Fermi energy rises as the volume of the core decreases. This drives copious electron capture on protons, lowering the fraction of electrons per baryon, Y_e, and, hence, lowering the instantaneous Chandrasekhar mass. The protons which are the targets for electron capture are mostly inside large nuclei on account of the low entropy. The physics of this process is discussed in detail in [1].

At issue is the fate of this ‘bounce’ shock (see, e.g. [2]). The mere fact that nucleons are bound in nuclei by some 8 MeV on average implies that this initial shock will be ‘dead on arrival.’ As the shock transits material beyond the inner core, most of its kinetic energy is dissipated in the photo-dissociation of nuclei. The shock quickly (∼100 ms) evolves to become a standing accretion shock.

This process has to happen for two reasons: (1) a strong shock will have a large (by nuclear physics standards) jump in entropy across it (∼factor of 10 in this case) and (2) the

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temperature is high enough that all the material is in nuclear statistical equilibrium. All nuclei will be ‘melted’ if the entropy is increased by more than three or four units of Boltzmann’s constant per baryon.

During the collapse of the core, the infall epoch, electrons are captured on protons which for the most part reside in nuclei. The electron neutrinos produced in this process freely escape from the core at first, but later become trapped at densities exceeding 1% of nuclear matter density. Subsequently, the electron neutrinos scatter and exchange energy and approach beta equilibrium. However, the manner in which the neutrinos approach equilibrium may depend on neutrino–nucleus interaction rates. These include processes in which nuclear excitation energy is changed into neutrino energy and processes in which neutrinos give up energy to nuclei [3]. For example, it could be that the de-excitation of hot nuclei into neutrino–antineutrino pairs is the dominant source of low-energy neutrinos and the principal means by which the low-energy neutrinos are driven into equilibrium during the infall epoch. This needs to be investigated further.

The gravitational binding energy release in the collapse to nuclear density, some 1% of the core rest mass promptly and, ultimately, 10% of the rest mass, is radiated as neutrinos of all flavours. It is believed that some of this neutrino energy is transferred to thermal energy behind the otherwise stalled shock on a timescale of some hundreds of milliseconds post bounce. How the neutrino energy can be transported to and pumped into this region in and around the shock is still very much an open question. Neutrino–nucleus interactions are expected to play an important role.

Electron neutrino captures on neutrons (making protons) and electron antineutrino captures on protons (making neutrons) will proceed apace in this region. This is likely the dominant way in which energy can be transferred to the shock from the neutron star directly via neutrinos. (Convection through the neutrino sphere can be regarded as an effective increase in neutrino luminosity. Convection between the neutrino sphere and the shock is different and may be quite important for obtaining an explosion, and will be ignored here.) If the core (proto neutron star) is highly relativistic, then neutrino–antineutrino annihilation may also play a significant role in energy deposition. These charged current captures on free nucleons also determine the neutron to proton ratio in the material above the neutron star. The neutron excess of the neutron star is ‘transmitted’ to the overlaying material via neutrinos and these charged current capture processes.

Electron neutrino and antineutrino captures on heavy nuclei ahead of the shock may be important. If enough energy can be transferred to these nuclei from these processes to melt a fraction of the nuclei then the shock dynamics can be altered. This ‘pre-heating’ of the material ahead of the shock (a misnomer as the material has a large specific heat on account of the heavy nuclei and the temperature does not rise much) could help the shock by partially dissociating nuclei; and, it could hurt the shock by melting nuclei, giving a higher number density of particles and therefore producing a higher pressure. The Mach number of the shock goes roughly like the pressure ratio across the shock front and it is obvious that melting the nuclei ahead of the shock goes in the direction of evening up the pressure on both sides. Which of these effects wins is not at all clear at present. To predict the outcome with confidence we need a better handle on neutrino–nucleus interaction cross sections, among other things.

In general, the cross sections per nucleon for these processes are small compared to those for free nucleons. However, collectivity in the electron neutrino charged current channel (for nuclei with a neutron excess) and in the (all neutrino flavours) neutral current channel can result in significant cross sections that may be important. To this end one needs neutral- and charged-current neutrino–nucleus inclusive cross section for neutrino energies ranging from tens of MeV to 100 MeV or so, principally for the iron peak nuclei.

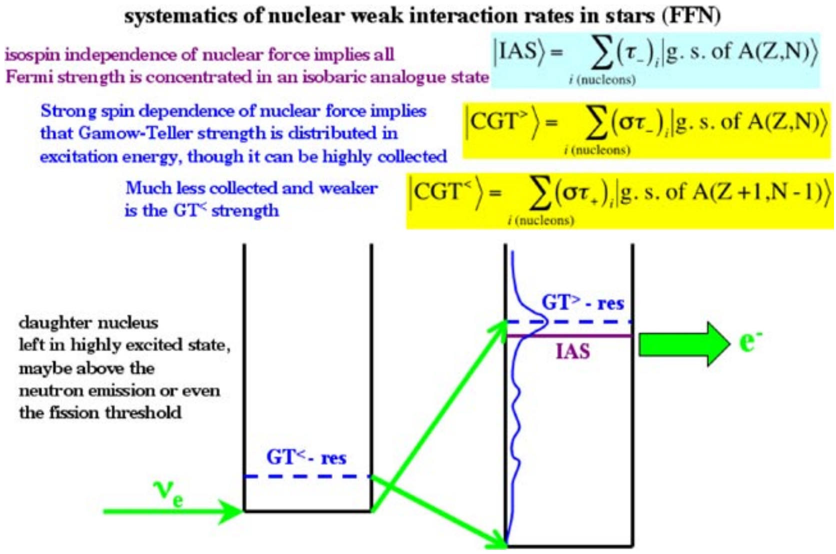

Figure 1. The systematics of the nuclear physics of neutrino capture on a neutron-rich target nucleus.

Another way in which these processes can be interesting is in the freeze-out nucleosynthesis that may result from this shock re-heating epoch. Again, the neutron to proton ratio will be set by the charged current captures on free nucleons, but neutrino–nucleus reactions can be important.

For example, electron neutrino capture on a neutron rich target nucleus will tend to leave the daughter nucleus in a highly excited state. The Gamow–Teller strength distribution centroid will tend to lie in the vicinity of or above the excitation energy of the first isobaric analogue state in the daughter. In figure 1 we summarize the systematics of the nuclear physics of neutrino capture on a neutron rich target nucleus. The essential point of physics is this: the Coulomb energy sets the scale for daughter nucleus excitation energy. This can be $\sim$30 MeV or more for a target (parent) like ^{208}Pb. Note that such a highly excited (massive) daughter nucleus could decay by emission of one or more neutrons, or even by fission. The decay of such neutrino-capture-produced nuclei needs to be better understood, especially as regards the branching ratio into one or more neutrons and the distribution of fission fragments with mass. This in turn may shed light on, for example, where the light p-process nuclei, like ^{96}Mo, come from.

If there is an explosion and the material overlying the neutron star is ejected, or if we had a non-explosive accretion-driven collapse event, then we could be left with conditions conducive to the formation of a neutrino-driven wind. Intense neutrino fluxes from the neutron star can deposit energy (as outlined above) in the tenuous medium above the neutron star, heating it to high entropy and driving a wind. The entropy per baryon here might be some hundreds of units of Boltzmann's constant per baryon, which is indeed high from the standpoint of nuclear physics, as nuclei beyond alpha particles would be greatly disfavoured in conditions of nuclear statistical equilibrium.

In any case, it is revealing to consider the gross energetics of the neutrino-driven wind, at least insofar as the ejection of baryonic material is concerned. The gravitational binding energy of a nucleon near the neutron star surface will be $\sim$100 MeV. To be ejected into interstellar

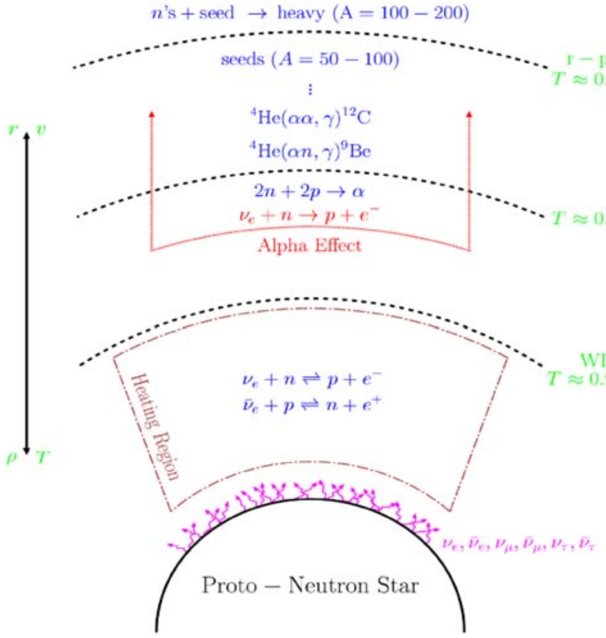

Figure 2. Outflow and nucleosynthesis history of a slow expansion neutrino-driven wind in a core-collapse supernova.

space, this baryon will have to acquire an equivalent amount of energy from heating processes, either transferred directly via weak interactions (neutrino captures or neutrino–antineutrino annihilation) or via hydrodynamic or convective transport of neutrino energy from the core (see the Mezzacappa contribution in this volume). If the energy for ejection is deposited by neutrino capture, and since average neutrino energies are some ∼10 MeV, we would require a flux of electron neutrinos and antineutrinos sufficient that each baryon ejected interacts on average some ten times with neutrinos. Given the strength of the weak interaction, it is a truly prodigious flux of neutrinos which is required.

In figure 2 we show a cartoon of the outflow and nucleosynthesis history of a 'slow expansion' neutrino-driven wind. Overall, the bulk of this 'wind' is really a near hydrostatic (subsonic material transport speeds), near constant specific entropy envelope with a small total mass ($\sim 10^{-4} M_\odot$). With the approximation that the entropy is mostly carried by relativistic particles (photons and electron/positron pairs), we can relate the temperature in billions of kelvins to the radius in units of 10^6 cm and the entropy in units of 100 Boltzmann's constant per baryon, $r_6 \approx \frac{22.5}{T_9 s_{100}}$, implying that the overall mass density falls as the inverse cube of the radius. Neutrino driven wind models, where the outflow is homologous (i.e. fluid velocity is proportional to the distance), are characterized by two parameters: entropy per baryon and the expansion timescale, τ (i.e. $r = r_0\, \mathrm{e}^{t/\tau}$, where the expansion rate of the baryonic material is $\lambda_{\mathrm{exp}} \equiv 1/\tau$).

Conventional slow expansion wind models are characterized by the establishment of steady state weak equilibrium and by several alpha particle formation-related problems in the production of the r-process nuclides (see below). However, if there was a way around these alpha particle issues, then the slow expansion wind could in principle produce an r-process (though this is difficult without active-sterile matter-enhanced neutrino flavour conversion).

By contrast, rapid outflow, perhaps occasioned by a very compact proto neutron star with consequent large general relativistic effects [4, 5], can circumvent the various alpha particle/neutrino flux related problems with the r-process, but perhaps at the cost of producing either not enough r-process material or a distribution of r-process abundances, which look nothing like the ones we observe in the solar system or in ultra metal-poor halo stars.

Close in to the neutron star surface, neutrino capture reactions on free nucleons transfer energy and heat the medium to high entropy. The competition between electron antineutrino capture on protons and electron neutrino capture on neutrons sets the neutron to proton ratio. The weak freeze-out (WFO) position occurs where the rates of these isospin changing reactions fall below the expansion rate of the baryonic flow (roughly $T_9 \approx 10$). Further out where it is cooler, the bulk of charged nuclear reactions become slow compared to the expansion rate, which we can term NSE freeze-out (the crude equivalent of the alpha particle formation epoch in BBN). Still further out, neutrons can capture on the relatively few seed iron nuclei produced near NSE freeze-out.

The nucleosynthesis in the freeze-out of this ejected material might closely resemble big bang nucleosynthesis (BBN), albeit with a neutron excess instead of the proton excess which obtains in the early universe! However, unlike BBN, this near isospin mirror of BBN could produce rapid neutron capture (r-process) nucleosynthesis. Neutrons could capture on iron peak seed nuclei and yield heavy nuclei, like uranium.

All of this neutron capture will be proceeding in an environment with large fluxes of neutrinos. As we discuss below, the formation of the alpha particles in a region where the neutrino fluxes are still high can lead to a fatal problem for this scenario for the r-process. In any case, neutrino flavour transformation at the atmospheric neutrino mass-squared difference scale will likely produce an energetic spectrum of electron neutrinos. Recently, it has been shown that the electron neutrino capture-induced fission cross sections for heavy nuclei can be very large (e.g., approaching 10^{-38} cm^2 for the actinides) [6, 7]. Again, neutrino capture in this channel tends to leave the daughter nucleus in a highly excited state which, in a heavy nucleus, may be well above the fission barrier. One needs to know the branching ratios into multiple neutron emission and into fission, and if the excited daughter nucleus fissions, then we need to know the typical number of neutrons that come off.

One needs to ascertain whether or not the fission rate stemming from electron neutrino captures can be big enough to drive fission cycling in the r-process flow. This seems unlikely, however, given the large number of neutrons per fission fragment that would be required to build these fragments back to massive nuclei. To this end, we would like to know what the branch into fission for heavy nuclei and the distribution of fission fragment masses are. Capture on nuclei in the mass 195 peak, followed by fission, will likely give fragments with masses near or in the 130 peak. This may tie the abundances in these peaks together. The astronomical observations of ultra metal-poor halo stars suggest that there is a physical connection between these mass regions and the processes which produce them [8].

2. Implications of neutrino mixing in supernovae

Matter-enhanced neutrino flavour transformations, in both the active–active and active–sterile channels, can have a significant effect on the dynamics, nucleosynthesis and the neutrino signal associated with core-collapse supernova events. Here we emphasize the active–sterile channel because that is most likely to have a dramatic effect on the outcome of the stellar collapse. We ignore the rich physics that can be explored by the terresterial detection of these neutrinos [9–11]. Experimental and observational evidence for a new neutrino mass-squared difference (δm^2) scale, different from the atmospheric neutrino scale ($\delta m^2 \sim 3 \times 10^{-3}$ eV^2)

and the solar neutrino value ($\delta m^2 \sim 7 \times 10^{-5}$ eV^2) would likely provide the smoking gun for the existence of sterile neutrinos. For example, the δm^2 range being explored currently by the mini-BooNE experiment covers an important range in the $\nu_{\mu,\tau} \rightleftharpoons \nu_e$ channel, that bears on the question of whether light sterile neutrinos exist. It has recently been shown that matter-enhancement of $\nu_e \rightleftharpoons \nu_s$, $\bar{\nu}_e \rightleftharpoons \bar{\nu}_s$ in the supernova can provide an ideal environment for rapid neutron capture (r-process) nucleosynthesis and solve a fundamental problem in the slow outflow scenario r-process alluded to above.

The importance that experiments such as mini-BooNE have flow from the increase in reliability and precision in the identification and measurement of neutrino oscillation phenomena in atmospheric neutrinos [12–14] and solar neutrinos at Sudbury Neutrino Observatory [15, 16], SuperKamiokande [17], Chlorine [18] and Gallium [19–21] experiments. These experiments are so restrictive in their definition of the allowed neutrino mixing parameter space that there is ‘no room’ for mixing at an additional δm^2 scale. This result is confirmed by many independent analyses [22, 23] which also take into account the recent data from the KamLAND reactor neutrino experiment [24]. The Los Alamos liquid scintillator neutrino detection (LSND) experiment has reported an excess of $\bar{\nu}_e$-induced events above known backgrounds in a $\bar{\nu}_\mu$ beam with a statistical significance of 3–4σ [25, 26]. If this result is confirmed by mini-BooNE it represents just such evidence for vacuum neutrino oscillation at a new δm^2 scale. Discovery of such mixing would imply either CPT-violation in the neutrino sector, or the existence of a light singlet ‘sterile’ neutrino which mixes with active species. The latter explanation may signal the presence of a large and unexpected net lepton number in the universe and the existence of a light singlet complicates the extraction of a neutrino mass limit from large scale structure data. Either explanation could alter our models for core collapse supernova explosions and the origin of heavy elements in neutrino-heated supernova ejecta. Indeed, r-process abundance observations and calculations by themselves hint that the mass-squared difference range 0.1 eV^2 $< \delta m^2 <$ 100 eV^2 in the channel $\nu_{\mu,\tau} \rightleftharpoons \nu_e$ is worthy of experimental exploration.

R-process nucleosynthesis constrained to reproduce something like the solar system abundance pattern (which the ultra metal-poor, or UMP, halo star data indicates may be universal) requires a neutron-rich environment, i.e., the ratio of electrons to baryons, Y_e, should be less than one half. Arguments based on meteoritic data and the systematics of abundances in UMPs suggests that one possible site for r-process nucleosynthesis is the neutron-rich material associated with core-collapse supernovae [27, 28]. In outflow models, freeze-out from nuclear statistical equilibrium leads to the r-process nucleosynthesis. The outcome of the freeze-out process in turn is determined by the neutron to seed ratio. The neutron to seed ratio is controlled by three quantities: (i) the expansion rate; (ii) the neutron to proton ratio (or equivalently the electron fraction, Y_e) and (iii) the entropy per baryon. Of these three the neutron to proton ratio is completely determined by the neutrino–nucleon and neutrino–nucleus interactions.

Crudely, the electron fraction in the nucleosynthesis region is given approximately by [29]

$$Y_e \simeq \frac{1}{1 + \lambda_{\bar{\nu}_e p}/\lambda_{\nu_e n}} \simeq \frac{1}{1 + T_{\bar{\nu}_e}/T_{\nu_e}}, \tag{2.1}$$

where $\lambda_{\nu_e n}$, etc are the capture rates and various neutrino temperatures are indicated by T. This expression ignores the possibility that the luminosities of neutrinos of different flavours are different and it ignores weak magnetism corrections, for example. Note that weak magnetism corrections in this case go in the direction of decreasing neutron excess and therefore increase the difficulty of obtaining a viable r-process [30]. Hence if $T_{\bar{\nu}_e} > T_{\nu_e}$, then the medium is neutron rich. Without matter-enhanced neutrino oscillations, the neutrino temperatures in some models satisfy the inequality $T_{\nu_\tau} > T_{\bar{\nu}_e} > T_{\nu_e}$. But matter effects via the MSW mechanism [32], by heating ν_e and cooling ν_τ, can reverse the direction of inequality, making the medium proton rich instead. Hence the existence of neutrino mass and mixings puts an interesting twist on the production of heavy elements in supernovae. These connections are investigated in [29] and [31]. One should also point out that in stochastic media (i.e., media with large density fluctuations) neutrino flavours would depolarize [33, 34]. Although recent solar neutrino experiments rule out such effects for the Sun [35], they may be important in supernovae [36].

It could also be (and this seems increasingly likely) that neutrino opacity sources not previously taken into account essentially wipe out the hierarchical average neutrino energy picture described above. If this is true, then all neutrino species would possess roughly the same energy spectrum. If the luminosities of the different neutrino flavours are the same, then we can draw two conclusions for this case: (1) the conditions are not neutron rich (in fact the neutron to proton ratio would be close to unity) in a slow outflow and (2) active–active matter-enhanced neutrino flavour conversion would have essentially no effect. This clearly would exacerbate the other problems with obtaining a solar system-like abundance pattern in a slow out flow neutrino-driven wind.

Other problems include, for example, the so-called alpha effect. To understand this, note that there are two kinds of neutrino reactions that can destroy the r-process scenario outlined above: (i) neutrino neutral current spallation of alpha particles [37] and (ii) formation of too many alpha particles in the presence of a strong electron neutrino flux, known as the alpha effect [38, 39]. The alpha effect comes at the epoch of alpha-particle formation: protons produced by ν_e capture on neutrons will, in turn, capture more neutrons to bind into alpha particles, reducing the number of free neutrons available to the r-process and pushing Y_e towards 0.5. Reducing the ν_e flux will resolve this problem, but we can only do so at a relatively large radius so that effective neutrino heating already can have occurred. One way to achieve this is transforming active electron neutrinos into sterile neutrinos [40, 42, 43, 45].

For active–sterile neutrino mixing in the channels $\nu_e \rightleftharpoons \nu_s$ and $\bar{\nu}_e \rightleftharpoons \bar{\nu}_s$, and for $Y_e > 1/3$, only electron neutrinos, and for $Y_e < 1/3$ only electron antineutrinos can undergo an MSW resonance [40]. If both electron neutrino and antineutrino fluxes go through a region where the isospin is in steady state weak equilibrium (i.e. the reactions $\nu_e + n \rightleftharpoons p + e^-$ and $\bar{\nu}_e + p \rightleftharpoons n + e^+$ are in steady state equilibrium with the ν_e and $\bar{\nu}_e$ fluxes), then no matter what the initial Y_e is one may expect that the system will evolve to a fixed point with $Y_e = 1/3$ ensuring a neutron rich medium [44]. Realistic calculations of the supernova wind models [40] do not bear out this assessment; although the electron antineutrinos are converted into sterile species, they are regenerated before the electron fraction and the isospin in the wind freeze-out of steady state equilibrium.

In [40] and [45] we followed the neutrino flavour evolution equations in the wind in a manner which was self consistent with the neutrino capture reactions which set the neutron to proton ratio and, hence, Y_e. Additionally, we tracked the thermodynamic and nuclear statistical equilibrium evolution of outflowing mass elements and updated the isospin of these at each time step directly from the weak capture rates. This coupling of the neutrino evolution and self-consistent determination of the abundances is essential to accurately determine the number of neutrons available for the r-process. The results are illustrated in figures 3 and 4 for expansion timescales of $\tau = 0.3$ and $\tau = 0.9$ s, respectively. It can be concluded from these figures that there is a wide range of neutrino mass/mixing parameters (some even consistent with the LSND parameters when we take account of the dependence of the results on the uncertain entropy of the neutrino-driven wind) which vitiates the alpha effect and

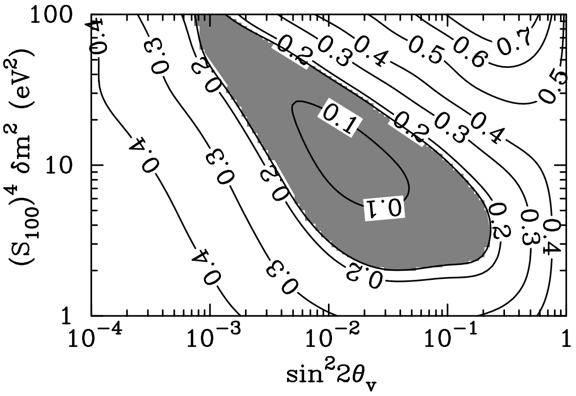

Figure 3. Contours of electron fraction for a timescale of 0.3 s in the active to sterile conversion scenerio. The shaded area yields a neutron to seed ratio of at least 100. $Y_e \sim 0.5$ in both with no flavour transformation.

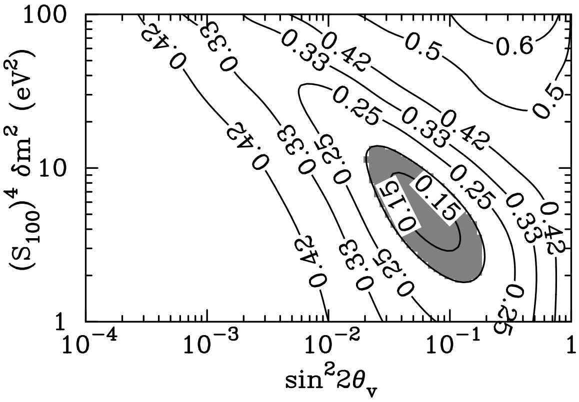

Figure 4. Same as figure 3, but with a timescale of 0.9 s.

can greatly enhance the neutron-to-seed ratio to produce favourable conditions for r-process nucleosynthesis. We note that values of the effective two-by-two active–sterile mixing angle up to an order of magnitude smaller than those probed by LSND (i.e., smaller than those probe by mini-BooNE) still give efficient flavour conversion in the hot bubble wind environment of the supernova.

In fact, the electron fractions produced in these scenarios involving matter-enhanced active–sterile neutrino flavour transformation can be extremely small, perhaps with $Y_e < 0.1$. This is intriguing. With neutron excesses this large, it is easy to get a viable r-process. Furthermore, a large enough neutron excess could cause fission-cycling in the r-process flow, where neutron-rich nuclides capture enough neutrons to become unstable against fission, and where, subsequently, the fission fragments so produced themselves quickly capture enough neutrons to build back to the nuclear mass where fission likely sets in, so that a steady state flow results. Whether or not neutrino captures or neutral current interactions could influence this flow remains unclear at present but is a focus of ongoing investigation. If the fissioning nuclides are at or above the mass $A = 195$ peak in the r-process, then the fission fragments could be expected to be in the mass range of the $A = 130$ peak. This might help explain an as yet poorly understood feature of the UMP halo star r-process data: the fact that the total abundances in these different nuclear mass peaks are about the same.

In any case, the connection between the physics of supernova dynamics and heavy element nucleosynthesis on the one hand, and the physics of neutrino mass and mixing on the other, remains a promising venue for research.

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