Nuclear Statistical Equilibrium neutrino spectrum

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The spectral emission of neutrinos from a plasma in nuclear statistical equilibrium (NSE) is investigated. Particular attention is paid to the possible emission of high energy (>10 MeV) neutrinos or antineutrinos. A newly developed numerical approach for describing the abundances of nuclei in NSE is presented. Neutrino emission spectra, resulting from general Fuller, Fowler, Newman (FFN) conditions, are analyzed. Regions of T-ρ-Y_e space favoring detectability are selected. The importance of critical Y_e values with zero net rate of neutronization (˙Y_e) is discussed. Results are provided for the processing of matter under conditions typical for thermonuclear and core-collapse supernovae, pre-supernova stars, and neutron star mergers.

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I. INTRODUCTION

Neutrino cooling is of paramount importance in the modern astrophysics 1  2 3. It governs late stages of stellar evolution, especially massive stars (>8-10 M☉) 1  2, red giant cores 6, white dwarfs 7, core-collapse supernovae 8  9  10  11  12  13 and (proto)neutron stars  14. Neutrino emission is important in mergers involving neutron star  15  16, 17  18  19, the dense accretion disks of Gamma Ray Bursts (GRB) models 20  21  22, type Ia supernovae 23 and X-ray flashes 24.

Usually, neutrinos carry away energy, and only the total neutrino emissivity, i.e. amount of energy carried out by neutrinos is of interest. The neutronization induced by the net ν_e − ¯ν_e flux is crucial for understanding of the nucleosynthesis. Therefore previous research on NSE neutrino emission 25 focused on: (1) ν_e − ¯ν_e particle emission rates and (2) total ν_e + ¯ν_e energy carried out by the neutrinos. We would like to extend this analysis to cover spectral/flavor properties of the NSE neutrino flux.

In known research a detailed treatment of the neutrino emission is done for core-collapse simulations 26  27. On the other hand, it is frequently neglected for other astrophysical objects (e.g. Ia supernovae). Nowadays more interest is dedicated towards spectral properties of the neutrino flux. The neutrino energy is important for core-collapse supernovae, for the neutrino-induced nucleosynthesis (ν-process, 28  29  30), neutrino oscillations, and for the detection of neutrinos in terrestrial experiments. The last area is poorly explored. The neutrino spectrum for neutrino cooling processes rarely is treated in rigorous way. Typical procedure is to use more or less justified analytic forms for the neutrino energy spectrum. There are parameters that are found from known neutrino emissivity and the average neutrino energy. In this paper we continue our former investigation 31  32 to find spectral properties for important neutrino emission processes, we proceed now to processes involving weak nuclear β transitions.

Neutrino cooling processes can be separated into two classes. There are (1) thermal processes including e^− e^+ pair annihilation, massive in-medium photon & plasmon decay and neutrino photoproduction, and (2) weak nuclear processes (i.e. β± decays and e^± captures). We would like to point out that for all thermal processes (pair, plasma, photoproduction, bremsstrahlung, neutrino de-excitation of the nuclei) the neutronization rate vanishes, i.e. the change of the proton/neutron ratio is due exclusively to weak nuclear processes. Class (1) produces all flavors while (2) only ν_e and ¯ν_e. However, neutrino oscillations can mix flavors. Information on thermal and weak components might be destroyed. It happens somewhere between emission and interaction/detection.

We assume that matter is transparent to neutrinos. Therefore, weak nuclear processes often tend to dominate neutrino emission of hot and very dense plasma. In particular, electron captures by both protons and heavy nuclei are progressively more intense. With growing density, the Fermi energy E_F ≃ μ_e can become larger than the capture threshold (Q-value), for increasing number of nuclear species. High temperature additionally enhances emission. Many of the nuclei remain in the thermally excited states. Matrix elements for these weak transitions are often large. For temperatures above ∼0.5 MeV, a significant fraction of equilibrium positrons builds up. This causes a strong ¯ν_e flux due to e^+ captures, particularly on free neutrons.

In contrast to thermal processes, determined entirely (including energy spectrum) by the local thermodynamic properties of matter (e.g. temperature kT and electron
chemical potential $\mu_e$), weak nuclear processes depend also on abundances of nuclei. This renders the task of calculating neutrino spectrum difficult to achieve. This is especially true for evolutionary advanced objects\(^1\). All that we can say for rapidly evolving object, is that the neutrino spectrum emitted from plasma is of the form:

$$\phi(\mathcal{E}_\nu) = \sum_k X_k(t) \psi_k(\mathcal{E}_\nu, kT, \mu_e) \frac{\rho}{m_p A_k},$$

(1)

Here $\psi_k$ represent (assumed known, from theory or experiment) spectral shape of single nuclei neutrino emission, and $X_k(t)$ set of usually unknown and rapidly varying abundances. Tracking of the required required number of a few hundred abundances is possible at most in simplest one-dimensional models, to our knowledge.

Fortunately, if the temperature becomes high enough, nuclei begin to „melt” due to photo-disintegrations. Nuclei re-arrange due to strong interactions into the most probable state favored by the thermodynamics\(33\). This is the Nuclear Statistical Equilibrium (thereafter NSE) approximation\(34\). The timescale required to achieve NSE is temperature-dependent\(35\). It can be approximated as\(37\):

$$\tau_{\text{NSE}} \sim \rho^{0.2} e^{179.7/T_9 - 40.5}$$

(2)

where $\rho$ is the density in $g/cm^3$, $T_9 = T/10^9 K$ and $T$ is the temperature in K. Eq. (2) provides one of the most important constraints limiting the use of the NSE approach. We assume implicitly in (2) that $Y_e = 0.5$\(35, 36\). Therefore in a plasma with the value of $Y_e$ which is far from 0.5 caution is required. Both under- an over-estimate is possible. The timescale is of the order of the age of the universe, $\tau_{\text{NSE}} \sim 10^9$ years, for $kT = 0.2$ MeV and $\tau_{\text{NSE}} \sim 10^{-9}$ seconds for $kT = 1$ MeV. In the core of a typical pre-supernova star with $\rho = 10^9 g/cm^3$ and $kT = 0.32$ MeV we have $\tau_{\text{NSE}} \approx 2$ days. A typical duration of the Si burning stages depends on stellar mass and varies from few hours to 3 weeks. During the thermonuclear explosion of type Ia supernova in the flame region temperatures grow up to $kT = 0.4 \ldots 0.6$ MeV, the timescale $\tau_{\text{NSE}} \approx 5$ milliseconds, and the explosion time is of the order of 1 second.

The weak transmutation rate between protons and neutrons is denoted by $\dot{Y}_e$,

$$\dot{Y}_e = \frac{dY_e(t)}{dt} = \lambda_{\nu_e} - \lambda_{\bar{\nu}_e},$$

(3)

where:

$$\lambda_{\nu} = \sum_k \lambda_{\nu}^{(k)} X_k / A_k, \quad \lambda_{\nu}^{(k)} = \int_0^\infty \psi_k(\mathcal{E}_\nu) d\mathcal{E}_\nu.$$
cf. e.g. [27, 47]. Unfortunately, in the case of multi-peaked neutrino spectrum this approach simply does not work, cf. Fig. 1 and related comments in [47]. The antineutrino spectrum is computed only for free neutrons, in applications known to the author.

The spectrum of neutrinos emitted from single nuclei in astrophysical plasma depends strongly on the temperature and the chemical potential of electrons (and positrons if $kT \sim m_e = 0.511$ MeV or larger). The temperature is large in typical evolutionary advanced astrophysical objects (pre-supernova or supernova, for example). We will study neutrino spectrum in this regime. On the contrary, for the solar interior, $kT = 1.35 \times 10^{-3}$, $\mu_e = 0$, and this makes little change with respect to laboratory experiments.

Let us begin with typical example of the continuum electron capture process:

$$^{7}\text{Be} + e^- \rightarrow ^7\text{Li} + \nu_e$$

We make assumptions concerning the infinite nucleus mass and we neglect various correction factors (screening, Coulomb factor). Then the $e^\pm$ capture rate is proportional to the constant matrix element multiplied by the so-called phase space factor $\Phi$:

$$\Phi_\pm = \frac{\mathcal{E}_\nu^2 (\mathcal{E}_\nu - \Delta Q) \sqrt{(\mathcal{E}_\nu - \Delta Q)^2 - m_e^2}}{1 + \exp \left[\frac{[\mathcal{E}_\nu - \Delta Q - \mu_e]}{kT}\right]} \Theta(\mathcal{E}_\nu - \Delta Q - m_e),$$

where $\mathcal{E}_\nu$ denotes the neutrino energy for $e^-$ capture and $\mathcal{E}_\nu$ is the antineutrino energy for $e^+$ capture. $\Delta Q$ is the energy difference between initial and final states (both can be excited) and $m_e$ is the electron rest mass. The chemical potential $\mu_e$ of the electron includes $m_e$, and therefore for positrons $\mu_{e^+} = -\mu_e \equiv -\mu$; $kT$ is the temperature of the electron gas.

It is worth to notice, that by expressing factor [4] by the neutrino (antineutrino) energy rather than electron (positron) energy, we have just one formula, since both signs of $\Delta Q + m_e$ are covered, and $\mathcal{E}_\nu > 0$.

The neutrino spectrum from $\beta^\pm$ decay is proportional to:

$$\Phi_\pm = \frac{\mathcal{E}_\nu^2 (\Delta Q - \mathcal{E}_\nu) \sqrt{(\mathcal{E}_\nu - \Delta Q)^2 - m_e^2}}{1 + \exp \left[\frac{[\mathcal{E}_\nu - \Delta Q + \mu_e]}{kT}\right]} \Theta(\Delta Q - m_e - \mathcal{E}_\nu)$$

Figure 1 compares neutrino spectrum given by formula [4] with the more elaborated result of [48] for solar neutrinos. Results are in good qualitative agreement. In order to get combined NSE spectrum we have to sum up all terms [48] for all relevant pairs of excited states, multiply them by the partition function and matrix elements, and then substitute into Eq. (46) with $X_k$ obtained from NSE [42]. A typical behavior of the NSE $\nu_e$ and $\nu_e$ emissivities [38, 39, 40, 41, 50, 51] as a function of $Y_e$ is presented in Fig. 3. As $Y_e$ decrease, electron neutrino flux (produced mainly in electron captures on protons and by heavy nuclei) also tends to decrease. On the other hand, a decrease in $Y_e$ cause an increase in the flux of $\bar{\nu}_e$’s. Usually antineutrino emissivity peaks due to beta decays of heavy nuclei and rise due to the positron capture on neutrons and by neutron decay, cf.

![Normalized $\nu_e$ spectrum](image-url)

**FIG. 1:** The normalized neutrino spectrum for solar $^7\text{Be}$ electron capture neutrino line, computed according to [4] (solid line) and the state-of-art result computed by Bahcall ([48], Eq. (46) ) is shown by dashed line.

The increase of density result in large $\mu_e$, and that leads to a more visible effect. This is because most of the electrons, not just a small fraction from the tail, have large energies. The neutrino spectrum (Fig. 2, lower-right panel) has a very characteristic shape in this case, with sharp edge on the high $\mathcal{E}_\nu$ end. With the increasing $\mu_e$ progressively more nuclei become unstable to the electron capture with the continuously growing capture rate. Lower-right panel in Fig. 1 shows effect of large $kT$ and $\mu$.

Anyway, possibly the most striking feature of Fig. 2 is not the shape of the spectrum but the dramatic scale change on the vertical axis. Weak rates are extremely sensitive to both $kT$ and $\mu$, mainly due to phase-space factors [4, 5].

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FIG. 2: The influence of the degeneracy (large $\mu$) and high temperatures (large $kT$) on the electron capture neutrino spectrum. Upper-left figure is for solar neutrinos (in laboratory conditions) and lower-left for cold degenerate electron gas. The upper-right figure refers to high temperature and the lower-right figure includes both degeneracy and high temperature.

FIG. 3: "(Color online)" Neutrino and antineutrino emissivities as functions of $Y_e$. Critical $Y_e$, defined as $Y_e = 0$, is seen at the crossing point of the neutrino and the antineutrino particle emission rates.

For almost all pairs ($kT$, $\rho$) we can find the value of $Y_e$ (Fig. 3) where the flux of $\nu_e$ is equal to the flux of $\bar{\nu}_e$. These threshold values are particularly interesting for the neutrino astronomy, because they might lead to the strong neutrino and antineutrino emission without further neutronization, in agreement with constraints from nucleosynthesis. The increase of the $\bar{\nu}_e$ flux (with decreasing $Y_e$) stops neutronization a little bit earlier than derived from e.g. the expansion of matter and the related decrease in rates alone. The neutronization can also stop if $Y_e$ becomes too low and positron captures/$\beta^-$ decays start to dominate. Surprisingly, these critical $Y_e$ values (defined as $Y_e$ for which $\lambda_{\nu_e} = \lambda_{\bar{\nu}_e}$, Fig. 3 and Eq. (36)) vary in a broad range (Fig. 4), reaching values close to $Y_e = 0.875$ (primordial BBN mixture of hydrogen and helium) for low densities and $kT = 0.5 \ldots 0.8$. On the other hand, for highest densities ($\rho > 10^{11}$ g/cm$^3$) and temperatures $kT = 0.8$ MeV an equilibrium sets at $Y_e = 0.2 \ldots 0.3$. It is important to notice, that due to the low accuracy of the weak rates derived from FFN tables and the variability of the NSE state with $Y_e$, Figure 4 provides only a very approximate outlook of critical values. The critical value$^4$ is also very important for NSE

$^4$ The state with $Y_e = 0$ is frequently refereed to as kinetic beta equilibrium.
TABLE I: Examples of neutrino and antineutrino spectra

| Object               | kT [MeV] | (T_9) | ρ [g/cm^3] | Y_e | Figure | Refs. |
|----------------------|----------|-------|------------|-----|--------|-------|
| BBN                  | 0.85     | 0.90  | 0.008      | 0.82| Fig. 5  | [1]   |
| Pre-SN               | 0.43     | 5.3   | 7.0 ×10^7  | 0.445| Fig. 6  | [4]   |
| SN Ia DET            | 0.53     | 6.1   | 7.8 ×10^7  | 0.5 | Fig. 7  | [80,81]|
| SN Ia DEF            | 0.52     | 6.0   | 2.0 ×10^7  | 0.5 | Fig. 8  | [80,81]|
| NS-NS merger         | 1.0      | 11.6  | 1.0 ×10^10 | 0.05| Fig. 9  | [82]  |
| -                    | 0.9      | 11.6  | 2.0 ×10^9  | 0.8 | Fig. 10 | -     |
| CC SN^a              | 1.0      | 11.6  | 1.0 ×10^12 | 0.73| Fig. 11 | [1]   |

^aNote: this example pushes our method to the limits of applicability. More realistic spectrum is different, because neutrinos are trapped and they begin to diffuse rather than escape freely.

less interesting since there are many known results

![Graph](image_url)

**Fig. 4:** "(Color online)" Critical Y_e (see Fig. 4 for explanation) for a range of considered temperatures and densities.

timescales, as "stalled" Y_e provide additional time without breaking assumption on the quasistatic Y_e evolution.

The competition between ν_e and ν̄_e emission (Fig. 4) is usually described in terms of the balance between electron captures (mainly on protons) and β^- decay of the heavy nuclei [52]. However, for Y_e outside range of 0.35, 0.45 the most important process leading to the ν̄_e emission is the positron capture by neutrons.

III. SPECTRA UNDER ASTROPHYSICAL CONDITIONS OF INTEREST

We are able to compute approximate neutrino/antineutrino spectra for a wide range of astrophysical phenomena if the NSE timescale is short compared to dynamic and weak timescales. Main limitation of our method is the neutrino trapping. The core-collapse supernovae and related phenomena, e.g. long gamma-ray bursts, are examples of objects where neutrino trapping is essential. We can use our method for initial infall stage of the collapse only. But as long as we are in the free streaming regime this is the method of choice. We can produce much more detailed and accurate neutrino spectra (than hydrodynamic simulations itself) via postprocessing. The latter is trivial to parallelize, and allow to achieve greater accuracy.

Our method can be applied to cosmological-like [1] neutrinos (Fig. 5), the center of the pre-supernova [4] star (Fig. 6) and typical conditions during type Ia thermonuclear explosions (Fig. 7, 8). Other examples,
contribution from free nucleons can be neglected in pre-supernova case.

Another very important example of application for our method is the type Ia thermonuclear supernova. Two important regimes for thermonuclear burning in type Ia supernovae are deflagration and detonation. For deflagration we use $kT = 0.53$ MeV and $\rho = 2 \times 10^9$ g/cm$^3$. For detonation a similar temperature of $kT = 0.52$ MeV has been used, but the density has been reduced due to pre-expansion to $\rho = 7.8 \times 10^7$ g/cm$^3$. $Y_e = 0.5$ was used, but it is important to point out that small neutronization is inevitable, because the $\nu_e$ flux dominates over the flux of $\bar{\nu}_e$, cf. Fig. \ref{fig:neutrino_emission}. Neutrino emission is very sensitive to these small changes. Model y12 and n7d1r10t15c of \cite{80,81} are the sources of the values used above. For a type Ia supernovae free nucleons are among the top neutrino sources, see Figs. \ref{fig:nu_e} and \ref{fig:neutrino_emission}. Two presented cases are related to detonation and deflagration. A lower density used for detonation stage (Fig. \ref{fig:neutrino_emission}) is the result of the white dwarf pre-expansion due to the previous deflagration stage \cite{80}. The high density in Fig. \ref{fig:neutrino_emission} is connected to the initial stage of subsonic nuclear burning in the pure deflagration model of \cite{80}. Only three nuclei contribute significantly to the $\nu_e$ spectrum in both cases: $^{55}$Co, $^{56}$Ni and protons. Relative contributions and total flux are different, however. The neutrino flux per unit volume is four orders of magnitude larger for deflagration compared to detonation. Nevertheless, deflagration involve tiny volume of the white dwarf only, while the detonation wave usually traverses entire star. Integrated flux might be similar, but this is model-dependent. Antineutrino spectrum is dominated by thermal processes: pair annihilation during detonation and plasmon decay during deflagration. The total flux is much smaller than for neutrinos, and this imbalance causes $Y_e$ to decrease. Therefore results from Figs. \ref{fig:neutrino_emission} and \ref{fig:neutrino_emission} with assumed $Y_e = 0.5$, should be taken with care. For example, the NSE abundance of $^{55}$Co drops rapidly in the range $Y_e = 0.5 \ldots 0.47$. A more detailed investigation of type Ia neutrinos shows also an important contribution from free neutrons to the anti-neutrino spectrum above 2 MeV.

Now, we study neutrino spectrum for the accretion disk formed in NS-NS merger. Needed data are taken from Fig. 1 of \cite{82}: temperature of $kT = 1.0$ MeV, $\rho = 10^{10}$ g/cm$^3$ and $Y_e = 0.05$. Similar results are expected for the neutron star - black hole mergers and other phenomena forming low $Y_e$, dense, high temperature accretion disks. The neutrino spectrum is a result of pair process and electron captures on protons. The antineutrino spectrum is heavily dominated by the neutron decay and positron captures on neutrons. The gap $0.8 < E_{\bar{\nu}_e} < 1.8$ MeV is filled by processes involving heavy nuclei. Moreover, antineutrino flux is much larger compared to the neutrino flux. The spectrum peaks at $E_{\bar{\nu}_e} \approx 5$ MeV, providing interesting candidate for the neutrino detection using the inverse $\beta$ decay.

Another example (Fig. \ref{fig:neutrino_emission}), not related to a particular astrophysical phenomena, shows the importance of thermal processes and those involving free nucleons. The antineutrino spectrum, especially the high energy end due to the positron capture is particularly important. Spectral features of this process should be interesting for future neutrino astronomy, based on gigantic $\bar{\nu}_e$ water-based detectors \cite{86,88,89,90}.

The core-collapse process is poorly described using our method, but we have provided an example for the sake of the completeness. The calculated neutrino spectrum in Fig. \ref{fig:neutrino_emission} has a complex multi-peak structure. This is in contrast to the results of the more sophisticated neutrino radiation transport results, which are always single-peaked. This can be explained by: (1) smoothing nature of the diffusive transport and (2) too small energy resolution (to few energy bins) of the transport codes used in simulations. The high energy neutrinos seen in Fig. \ref{fig:neutrino_emission} are in reality downscattered to much smaller energies. The same applies to antineutrinos. Additionally, $\nu$-$\bar{\nu}$ pairs are created in the process of collisions between neutrinos and electrons, and between pairs of neutrinos.
This leads to the energy exchange between flavors, and realistic $\nu_\tau$ spectra\footnote{Muon and tau spectra are almost identical to the thermal electron flavor spectra, except for smaller integrated flux.} are not as distinct as those from Figs. 11. Factors that block outgoing neutrinos and could shape the neutrino spectrum under such extreme conditions were omitted. Clearly, our method is not working for the core-collapse supernovae, as anticipated.

IV. CONCLUSIONS

One of our important conclusions is related to typical way of publishing data on weak nuclear processes in astrophysics. This approach dates back into year 1980, and was introduced in the famous paper \cite{38}. Tables published by the FFN become standard in modern astrophysics. Upgrades \cite{38,49,92} did not change structure of FFN tables. Unfortunately, FFN grid using mere 13x11 points is not enough to obtain precise results, as noted already by the FFN authors \cite{41}. While we understand reasons to preserve this standard for 30 years, "reverse engineering" of FFN-like tables to get spectrum, as well as complicated interpolating procedure is impractical now. If one wants to calculate the spectrum precisely, without analytical approximate formula for individual nuclei, pre-calculated tables are useless. Much more convenient is the following set of data:

1. energy and spins for ground and excited states
2. weak transition matrix elements between all relevant pairs of the excited states for the parent and daughter nuclei

Alternatively, tabulated spectrum for all $T - \rho Y_e$ pairs would be a good choice, with amount of stored data up to several megabytes. While such approach will increase amount of published numerical data by a factor of $\sim 10$, it would remove any ambiguity in the representation of the spectra.
The inspection of virtually any of the figures presented here (Figs. 5-11) clearly show the importance of both nuclear and thermal processes. The thermal emission and captures on free nucleons and nuclei should be included in consistent calculations. However, depending on the subject, all combinations of these can be found in astrophysical applications. For example, type Ia supernova simulations include NSE emission but older simulations neglect neutrino emission at all or include electron captures only. Other important regimes, core-collapse and pre-supernovae frequently neglect positron captures, particularly on neutrons. Estimates of the neutrino signal in detectors from pre-supernovae rely purely on thermal emission.

The ultimate goal which is beyond scope of the article is to know exactly (not approximately!) the neutrino spectrum from weak nuclear processes under NSE. In the past weak rates were usually integrated and only the total neutrino flux (particles and energy) has been tabulated and presented to the public. We argue again, that this is not the best approach if one wants to calculate the neutrino spectrum. Without full input used to calculate weak rates we are unable to restore information lost in the integration. Typical (FFN-like) weak interaction tables are not sufficient. Tables of the excited states, spins and weak matrix elements for all considered nuclei will allow researchers to calculate both neutrino/antineutrino spectra and customized weak interaction rate tables.

Weak rates prepared in the FFN fashion (i.e. all published rates), even those with tabulated effective \( Q_{\text{eff}} \)-values for every grid point to get from (4) or (5) do not facilitate estimates of the neutrino spectrum. This is not surprising, because these rates were prepared for a different purpose: the neutrino energy loss and neutronization. Maximal information on the spectrum extracted from FFN-like tables can be extracted as described in the paper accompanying paper.

We re-tabulate effective \( Q_{\text{eff}} \)-values for every grid point to get from (4) or (5) the original total rate and average neutrino energy. If the total rate is not dominated by the captures we switch from (4) to (5). This approach produces significant side effects if capture and decay rates are comparable. The neutron provides good example. Due to the non-negligible contribution of \( \bar{\nu}_e \)'s from the neutron decay, the average en-
FIG. 10: "(Color online)" Neutrino (left) and antineutrino (right) spectrum emitted per unit volume under conditions of large \( Y_e \) and high temperature.

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\text{\textbf{FIG. 11:}} \quad \text{"(Color online)" Neutrino (left) and antineutrino (right) spectrum emitted per unit volume under conditions typical for the infall stage of the core-collapse.}
\]

Energies differ from that deduced from pure positron capture. Therefore the effective spectrum has a variable effective Q-value. The realistic positron (and electron as well) capture spectrum always starts with energy equal to the lowest Q-value. To sum up, the obvious next step in the research is to give up pre-calculated tables of weak rates and to re-calculate the neutrino spectrum from scratch, using nuclear data and weak matrix elements as an input.

Despite these difficulties, we obtained new results.

1. We get interpolating procedures for NSE abundances with number of convenient features: the ability to pick out of NSE selected nuclei, the computational time scaling linearly with the number of nuclides and independent of the position in \( T - \rho - Y_e \) space for full \( Y_e = 0.05 \ldots 0.95 \) range.

2. The energy spectrum, fluxes, mean energies etc. of the emitted neutrinos and antineutrinos separately for \( \nu_e \) and \( \bar{\nu}_e \).

Our analysis was meant to be general, but we can identify some possible astrophysical targets for presented methods. The NSE neutrino spectrum would be a good approximation for massive stars after Si burning and thermonuclear supernovae. A related research is under-way. Procedures developed here will be useful for the analysis of neutrino signals from X-ray flashes, neutron stars, merger events, accretion disks and some types of cosmic explosions, e.g. pair-instability supernovae.

The electron antineutrino emission due to the positron capture on neutrons provides strong and relatively high-energy flux for surprisingly large volume in \( kT - \rho - Y_e \) space. Needed thermodynamic conditions: \( kT > 0.6 \rho > 10^7 \) g/cm\(^3\) can be met in many astrophysical objects. Megaton-scale neutrino detectors will search for antineutrinos with energy \( E_{\bar{\nu}_e} > 1.8 \) MeV. The detection of strong \( \nu_e \) flux above 5 MeV produced mainly by captures on protons and heavy nuclei is standard in water Cherenkov [88, 89, 90] or liquid scintillator [88, 89, 90] detectors. Therefore further investigation of NSE neutrinos, particularly in the unexplored region of large \( 0.87 > Y_e \gg 0.55 \) should give researchers some
additional hints for the existence (or non-existence) of detectable astrophysical antineutrino sources.

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