PROCEEDINGS OF SCIENCE

Magnetic-field influence on beta-processes in core-collapse supernova

Alexandra Dobrynina[a,b,*] **and Igor Ognev**[a]

[a] *Department of Theoretical Physics, P. G. Demidov Yaroslavl State University, Sovietskaya 14, 150003 Yaroslavl, Russia*

[b] *II. Institute for Theoretical Physics, University of Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany*

E-mail: dobrynina@uniayr.ac.ru, ognev@uniyar.ac.ru

Neutrinos play a significant and sometimes even dominant role in all phases of the supernova explosion. The most important neutrino processes in a core-collapse supernova are beta-processes, which are responsible for the energy exchange between neutrinos and the matter and change a chemical composition of a medium. We investigate an influence of a magnetic field on beta-processes under conditions of a supernova matter. For any magnetic field strength discussed in applications to astrophysical objects we obtain simple analytical expressions for reaction rates of beta-processes. In our analysis we use results of one-dimensional simulations of a supernova explosion performed with the PROMETHEUS-VERTEX code. We found that, the magnetic field with the strength $B \sim 10^{15}$ G suppresses the neutron production on several percents in comparison with the unmagnetized case. The obtained analytical expressions can be also applied for postmerger accretion discs.

**** The European Physical Society Conference on High Energy Physics (EPS-HEP2021), ****
**** 26-30 July 2021 ****
**** Online conference, jointly organized by Universität Hamburg and the research center DESY ****

[*]Speaker

PoS(EPS-HEP2021)048

1. Introduction

Supernovae are the most powerful neutrino source in the cosmos. These elementary particles play an important role in evolution for stars with masses $M_{\rm star} \gtrsim 10\, M_\odot$. The beta-processes (direct URCA-processes), $p + e^- \leftrightarrow n + \nu_e$, $n + e^+ \leftrightarrow p + \bar{\nu}_e$, are the dominant neutrino processes in the supernova matter. They provide an energy exchange between neutrinos and the matter and change of the number densities of protons and neutrons.

Despite the significant progress in modeling of core-collapse supernova, a successful supernova explosion still remains a puzzle of theoretical astrophysics. There are some alternatives how to revive the stalled shock wave or launch an explosion by other way. The magnetic field is one of the most important considered alternatives, see, for example, [1]-[3].

Moreover, the magnetic field also modify neutrino processes, not only SN dynamics. Investigations of magnetic field influence on beta-processes have a long history, see [4] and references in it. In our analysis, we remove restrictions on the magnetic field strength and consider the realistic magnetic fields reachable in astrophysical objects. For such magnetic fields, we obtain simple analytical expressions for reaction rates of beta-processes and analyze an effect of the magnetic field on the them.

2. Results

We consider that an electron-positron plasma existing in SN matter is ultra-relativistic. In addition, we suppose that nucleons are non-degenerate and electron-positron plasma is moderately degenerate. These conditions are well satisfied outside the radius of the proto-neutron star (PNS). We also assume that neutrinos propagate almost spherically symmetric in supernova. Under these conditions, the distribution functions of electrons, positrons, neutrinos and antineutrino can be approximated by the so-called "α-fit" [6].

Therefore, we have obtained the reaction rates of beta-processes in the presence of a magnetic field [7]:

$$
\begin{aligned}
\mathit{\Gamma}_{p+e^-\to n+\nu_e} &= G^2 N_p N_0\, \varepsilon_1^2\, s^s\, \Gamma^{-1}(s) &(1)\\
&\times\big[I_{s-1,s}(\varepsilon_1,b) - n_\nu\, I_{s+\alpha-4,s+\gamma\alpha}(\varepsilon_1,b) + g_{va}\cos\beta\,\chi_1\, n_\nu\, J_{s+\alpha-4,s+\gamma\alpha}(\varepsilon_1,b)\big],\\
\mathit{\Gamma}_{n+\nu_e\to p+e^-} &= G^2 N_n N_0\, \varepsilon_1^2\, e^{-\tau}\, s^s\, \Gamma^{-1}(s) &(2)\\
&\times\big[n_\nu\, I_{s+\alpha-4,s+\gamma\alpha-\gamma_t}(\varepsilon_1,b) - g_{va}\cos\beta\,\chi_1\, n_\nu\, J_{s+\alpha-4,s+\gamma\alpha-\gamma_t}(\varepsilon_1,b)\big],\\
\mathit{\Gamma}_{n+e^+\to p+\bar{\nu}_e} &= G^2 N_n \bar{N}_0\, \bar{\varepsilon}_1^2\, \bar{s}^{\bar{s}}\, \Gamma^{-1}(\bar{s}) &(3)\\
&\times\big[I_{\bar{s}-1,\bar{s}}(\bar{\varepsilon},b) - \bar{n}_\nu\, I_{\bar{s}+\bar{\alpha}-4,\bar{s}+\bar{\gamma}\bar{\alpha}}(\bar{\varepsilon},b) + g_{va}\cos\beta\,\bar{\chi}_1\, \bar{n}_\nu\, J_{\bar{s}+\bar{\alpha}-4,\bar{s}+\bar{\gamma}\bar{\alpha}}(\bar{\varepsilon},b)\big],\\
\mathit{\Gamma}_{p+\bar{\nu}_e\to n+e^+} &= G^2 N_p \bar{N}_0\, \bar{\varepsilon}_1^2\, e^{\tau}\, \bar{s}^{\bar{s}}\, \Gamma^{-1}(\bar{s}) &(4)\\
&\times\big[\bar{n}_\nu\, I_{\bar{s}+\bar{\alpha}-4,\bar{s}+\bar{\gamma}\bar{\alpha}-\bar{\gamma}_t}(\bar{\varepsilon},b) - g_{va}\cos\beta\,\bar{\chi}_1\, \bar{n}_\nu\, J_{\bar{s}+\bar{\alpha}-4,\bar{s}+\bar{\gamma}\bar{\alpha}-\bar{\gamma}_t}(\bar{\varepsilon},b)\big],
\end{aligned}
$$

Here, $G^2 = (g_v^2 + 3g_a^2)/(2\pi)\cos^2\theta_c\, G_F^2$, $g_{va} = (g_a^2 - g_v^2)/(3g_a^2 + g_v^2)$, g_v and g_a are the vector and axial constants, θ_c is the Cabibbo angle, G_F is the Fermi constant, $\Gamma(x,y)$ is the incomplete Gamma-function, $\Gamma(x) = \Gamma(x,0)$, $b = B/B_e$ is the reduced magnetic field strength written in terms of critical Schwinger value, $B_e = m_e^2/e \simeq 4.41\times 10^{13}$ G, N_0 is the unmagnetized number densities of electrons, N_n and N_p are the neutron and proton number densities. It is convenient to define the ratios of the average electron energy to the neutrino one $\gamma = \varepsilon_1/\omega_1$, $\gamma_t = \varepsilon_1/T$ and $\tau = \mu_e/T$. It is useful also to introduce first neutrino angular momentum χ_1, pinching parameters for neutrinos α and electrons s, cosine of angle between magnetic field strength and radial direction $\cos\beta$ and reduced neutrino number density n_ν. All quantities with the bar-symbol correspond to positrons or antineutrinos.

The magnetic-field dependence enters in Eqs.(1)-(4) only through the functions:

$$I_{k,\varkappa}(\varepsilon_1, b) = \varkappa^{-k-3}\,\Gamma(k+3, \varkappa\, z_b) + \varkappa^{-k-1}\,\frac{b\, m_e^2}{2\varepsilon_1^2}\Big[\Gamma(k+1) - \Gamma(k+1, \varkappa\, z_b)\Big], \tag{5}$$

$$J_{k,\varkappa}(\varepsilon_1, b) = \varkappa^{-k-1}\,\frac{b\, m_e^2}{2\varepsilon_1^2}\,\Gamma(k+1), \tag{6}$$

where $z_b = (m_e/\varepsilon_1)\sqrt{1+2b}$.

We used results of the SN simulations performed with the PROMETHEUS-VERTEX code [5][1]. In this analysis, the SN progenitor mass is equal to 27 $M_\odot$ and the final neutron star has a baryonic mass 1.76 $M_\odot$.

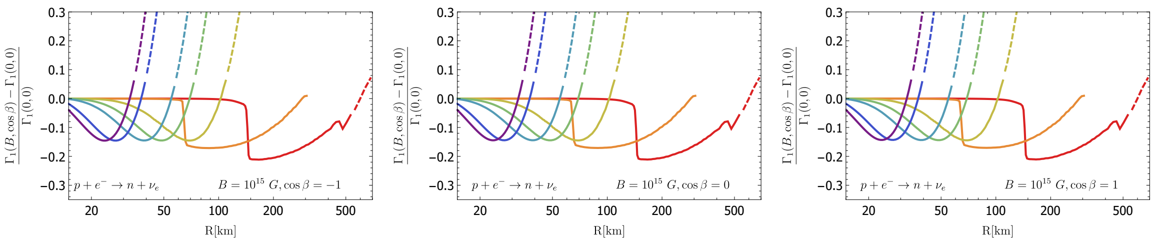

Figure 1: The deviation of the reaction rate of electron capture by proton, calculated in the magnetic field, relative to the unmagnetized case in dependence on the distance R from the PNS center for several values of the time t after a bounce and different directions of the magnetic field ($\cos\beta = -1, 0, 1$). The dashed parts of the lines correspond to supernova regions where the electron-positron plasma is no longer ultrarelativistic. *Red lines:* $t = 0.1$ sec; *orange:* $t = 0.5$ sec; *yellow:* $t = 1.5$ sec; *green:* $t = 4$ sec; *cyan:* $t = 5.5$ sec; *blue:* $t = 10$ sec; *violet:* $t = 13$ sec.

The reaction rates (1)-(4) of each individual β-processes separately suppressed by magnetic field, and this suppression can reach few tens percents at maximum, for example, see Fig. 1. This suppression is an order of magnitude large then numerical results for total rate of the proton-to-neutron transition, occurring in the sum of all β-processes, which are presented in Fig. 2. A cancellation of such significant magnetic-field impact on individual processes is a result of summation of contributions caused by magnetic field in each process with different signs, which leads to substantial reduction in total rates.

As seen in Fig. 2, the influence of the magnetic field on total rate of sum of all β-processes becomes more pronounced just after a bounce in region of the stalled shock wave and in a more later time, when the supernova has already cooled down through the neutrino emission. Moreover,

[1] https://wwwmpa.mpa-garching.mpg.de/ccsnarchive/archive.html

PoS(EPS-HEP2021)048

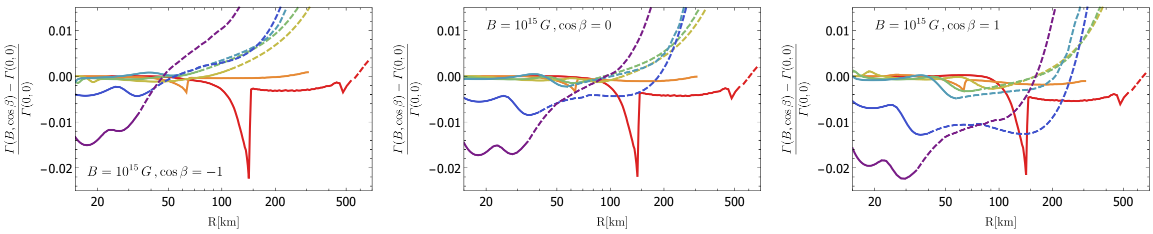

Figure 2: The deviation of the total rate of the proton-to-neutron transition, calculated in the magnetic field, relative to the unmagnetized case in dependence on the distance R from the PNS center for several values of the time t after a bounce and different directions of the magnetic field ($\cos\beta = -1, 0, 1$). The legend is the same as before.

the magnetic field suppresses the neutron production on several percents in comparison with the unmagnetized case.

3. Conclusions

Analytical expressions for reaction rates of beta-processes and other quantities are obtained. As numerical analyses shown, the magnetic-field influence on the chemical composition of a matter is more pronounced just after a bounce in a region of the stalled shock wave, and in a more later time, when supernova has already cooled down through the neutrino emission. The presence of magnetic field results into a decrease of the reaction rates responsible for the matter chemical composition and, as a consequence, a neutron production is suppressed by the magnetic field.

4. Acknowledgments

The work is supported by the RSF (Grant No. 18-72-10070). We are thankful to H.-T. Janka and his collaborators for providing us with the data of the supernova explosions and for helpful discussions. A.D. acknowledges the support by the Alexander von Humboldt foundation.

References

[1] A. Heger, S. E. Woosley and H. C. Spruit, *Astrophys. J.* **626** (2005) 350.

[2] G. S. Bisnovatyi-Kogan, S. G. Moiseenko and N. V. Ardelyan, *Phys. Atom. Nucl.* **81** (2018) 266.

[3] M. Obergaulinger, O. Just and M. A. Aloy, *J. Phys. G* **45** (2018) 084001.

[4] I. S. Ognev, *J. Exp. Theor. Phys.* **123** (2016) 643.

[5] L. Hüdepohl, PhD thesis, Technische Universität München, 2014.

[6] M. T. Keil, G. G. Raffelt and H. T. Janka, *Astrophys. J.* **590** (2003) 971.

[7] A. Dobrynina and I. Ognev, *Phys. Rev. D* **101** (2020) 083003.