Influence of magnetic field on beta-processes in neutrino-driven supernova explosion

Alexandra Dobrynina
P. G. Demidov Yaroslavl State University, Russia

in collaboration with Igor Ognev

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Introduction

- Core-collapse supernova is the final stage of evolution for stars with masses

$$M_{\rm star} \gtrsim 10\, M_\odot$$

- SN matter is opaque for neutrinos $\Rightarrow$ neutrino interaction with SN matter is important ingredient of core-collapse supernova models
- β-processes are dominant neutrino processes in the SN matter:

$$\begin{aligned} 1 &: \ p + e^- \to n + \nu_e \\ 2 &: \ n + \nu_e \to p + e^- \\ 3 &: \ n + e^+ \to p + \bar{\nu}_e \\ 4 &: \ p + \bar{\nu}_e \to n + e^+ \end{aligned}$$

Supernova with magnetic field

- Magnetars (SGRs and AXPs) with $B \sim 10^{15}$ Gauss

  [S. A. Olausen and V. M. Kaspi, Astrophys. J. Suppl. 212, 6 (2014)]
- Magnetohydrodynamical (MHD) simulations of collapse of SN core:
  $B \sim (10^9 - 10^{10})$ G at pre-supernova stage $\Rightarrow$
  $B \sim (10^{12} - 10^{13})$ G at post-bounce stage

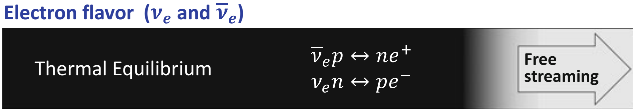
  [A. Heger et al, ApJ 626, 350 (2005);
  M. Obergaulinger et al, MNRAS 445, 3169 (2014)]
- SN magnetorotational model $\Rightarrow B \sim (10^{14} - 10^{15})$ Gauss

  [G. S. Bisnovatyi-Kogan, Sov. Astron. 14, 652 (1971);
  G. S. Bisnovatyi-Kogan et al, Atom. Nucl. 81, 266 (2018)]

β-processes in magnetic field

- Magnetic field can influence not only supernova dynamics, but also modify the neutrino processes
- Investigations of the magnetic field influence on β-processes have a long history
  - L.I. Korovina, Izv. Vyssh. Uchebn. Zaved., Fiz. 6, 86 (1964)
  - L. Fassio-Canuto, Phys. Rev. 187, 2141 (1969)
  - A.I. Studenikin, Sov. J. Nucl. Phys. 49, 1031 (1989)
  - L.B. Leinson and A. Perez, JHEP 9809, 020 (1998)
  - A.A. Gvozdev and I.S. Ognev, JETP Lett. 69, 365 (1999)
  - D.A. Baiko and D.G. Yakovlev, Astron. Astrophys. 342, 192 (1999)
  - D.G. Yakovlev et al, Phys. Rept. 354, 1 (2001)
  - H. Duan and Y.Z. Qian, Phys. Rev. D 72, 023005 (2005)
  - V.L. Kauts et al, Phys. Atom. Nucl. 69, 1453 (2006)
  - ...
- I.S. Ognev, JETP 123, 643 (2016): influence of magnetic field on β-processes in transparent for neutrino matter $\Rightarrow$ extend to partially transparent matter

Region of neutrino interaction with matter for β-processes



[G. Raffelt, arXiv:1201.1637]

Analysis of results of 1D PROMETHEUS-VERTEX simulations

[L. Huedepohl, PhD thesis, Technische Univ. (2014)]

Let us put the following conditions on the SN matter:

- Nucleons are non-degenerate: $R \gtrsim R_{PNS}$, R_{PNS} is the proto-neutron star radius
- $e^- e^+$-plasma is moderately degenerate: $\mu_e / T \lesssim 10 \Rightarrow R \gtrsim 16$ km
- $e^- e^+$-plasma is ultra-relativistic: $T \gg m_e \Rightarrow R \lesssim 500$ km
- SN explosion is spherically symmetric $\Rightarrow$ neutrinos propagate along a radial direction of the SN

$$16 \text{ km} \lesssim R \lesssim 500 \text{ km}$$

Distribution functions of $e^-, e^+, \nu_e, \bar{\nu}_e$ can be approximated by "α-fit":

[M.T. Keil et al, Astrophys. J. 590, 971 (2003)]

$$\omega^2 f(\omega) \sim \left(\frac{\omega}{\omega_1}\right)^{\alpha - 1} e^{-\alpha\, \omega / \omega_1}$$

ω_1 is an average energy and α is a numerical parameter

Analytical results

- Reaction rates of beta-processes Γ, energy Q and momentum $\mathcal{F}$ transferred from neutrinos and antineutrinos to the matter
- For reaction rates, we have

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

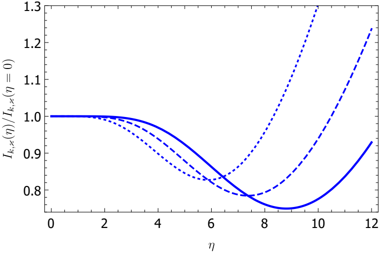
- 4 matter parameters + 10 neutrino parameters + magnetic field strength + angle between magnetic-field vector and star radial direction
- PROMETHEUS-VERTEX code developed by H.-T. Janka and his collaborators: $M_{progenitor} = 27\ M_\odot$, $M_{PNS} = 1.76\ M_\odot$
- All parameters reduce to t + R + b + $\cos\beta$

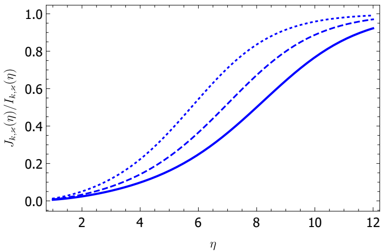
Magnetic field

- Magnetic field strength is included only in functions $I_{k,\varkappa}$ and $J_{k,\varkappa}$
- Significant modification of $I_{k,\varkappa}$ and $J_{k,\varkappa}$ at $B \gg B_e = m_e^2/e = 4.41 \times 10^{13}$ Gauss
- Dependence on magnetic field is defined by

$$\eta = \varkappa \frac{m_e}{\varepsilon_1} \sqrt{\frac{2B}{B_e}}$$

- The increase of average energy of $e^- e^+$-plasma reduces the parameter η
- Parameter η increases with a growth of the magnetic field B and the degeneracy of leptons $\varkappa$
- Properties of $I_{k,\varkappa}$ and $J_{k,\varkappa}$



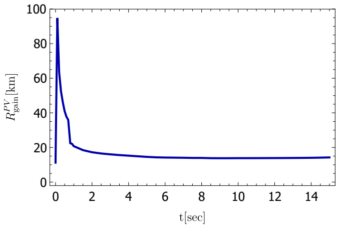


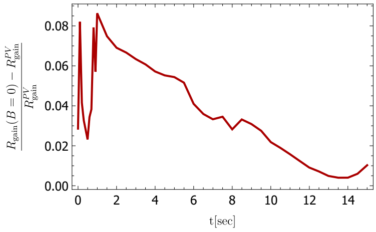
Dotted line: $k = 3$. Dashed line: $k = 4$. Solid line: $k = 5$.

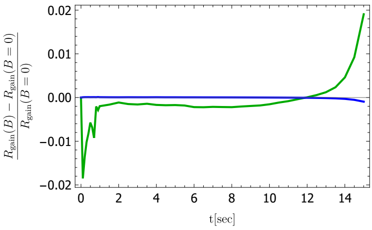
Test of results

$R_{gain}(B)$: gain radius from analytical equations, $Q_{total} = \sum_i Q^{(i)} = 0$

R^{PV}_{gain}: gain radius from PROMETHEUS-VERTEX simulations

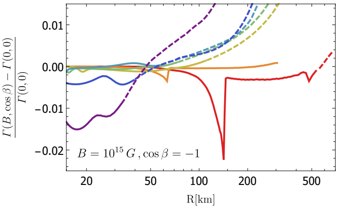


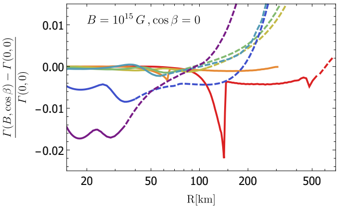


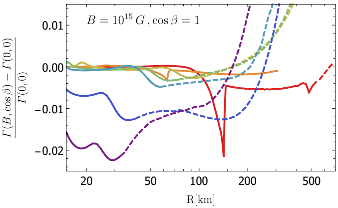


Blue line: $B = 10^{15}$ G
Green line: $B = 10^{16}$ G

$$\text{Total reaction rate } \Gamma_{p\to n}(B,\cos\beta) = \sum_{i=1}^{4} \Gamma^{(i)}_{p\to n}(B,\cos\beta)$$



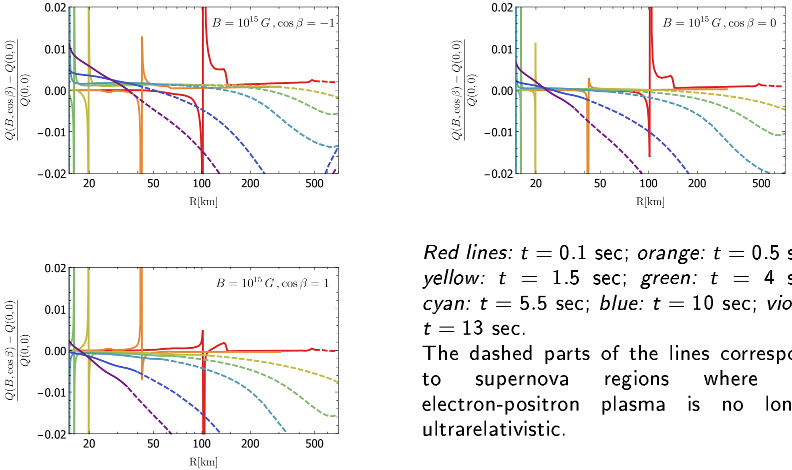




Red lines: $t = 0.1$ sec; *orange:* $t = 0.5$ sec; *yellow:* $t = 1.5$ sec; *green:* $t = 4$ sec; *cyan:* $t = 5.5$ sec; *blue:* $t = 10$ sec; *violet:* $t = 13$ sec.

The dashed parts of the lines correspond to supernova regions where the electron-positron plasma is no longer ultrarelativistic.

Total energy $Q(B, \cos\beta) = \sum_{i=1}^{4} Q^{(i)}(B, \cos\beta)$



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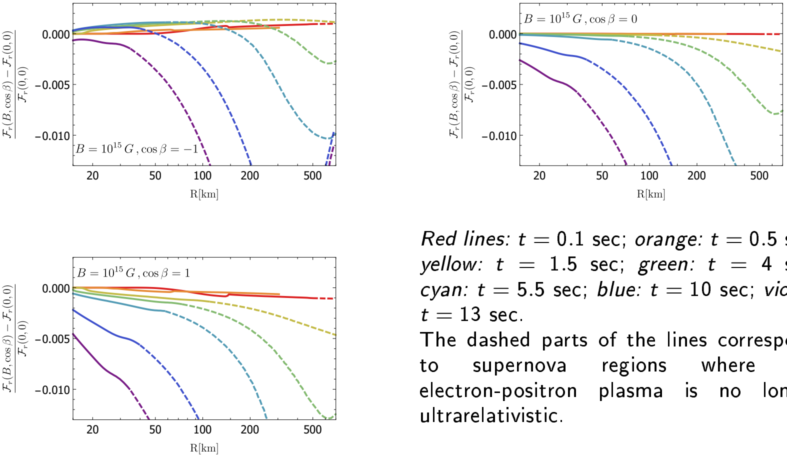
Total radial momentum $\mathcal{F}_r(B,\cos\beta) = \sum_{i=1}^{4} \mathcal{F}_r^{(i)}(B,\cos\beta)$



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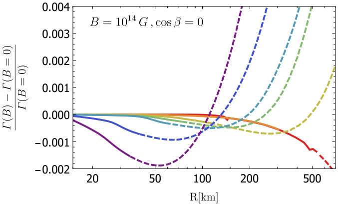
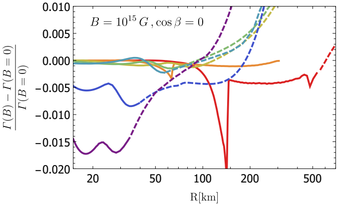
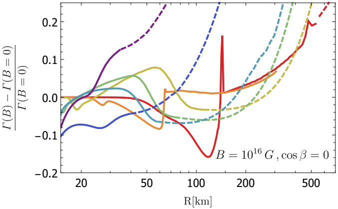
Conclusions

- Simple analytical expressions for reaction rates of beta-processes as well as energy and momentum transferred from neutrinos and antineutrinos to the matter are obtained for an arbitrary strength of magnetic field in SN conditions
- The influence of magnetic field on Γ, Q and $\mathcal{F}$ increase with growth of the lepton degeneracy while the increase of the averaged energy of electron-positron plasma reduce it
- Using of results of SN simulations allows to reduce a vast amount of necessary parameters to four and perform an analysis of magnetic field influence on quantities specified
- Modifications of the macroscopic quantities by the magnetic field with the strength $B \sim 10^{15}$ G are of a few percents only $\Rightarrow$ magnetic-field effects can be safely neglected, considering neutrino interaction and propagation in a supernova matter

Total reaction rate $\Gamma_{p\to n}(B, \cos\beta) = \sum_{i=1}^{4} \Gamma^{(i)}_{p\to n}(B, \cos\beta)$ for several fixed values of magnetic field







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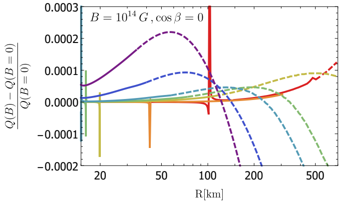

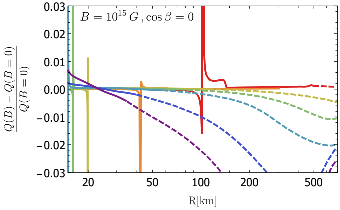

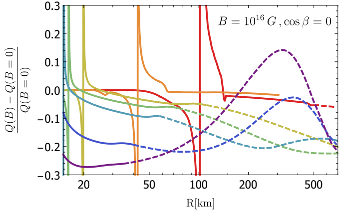

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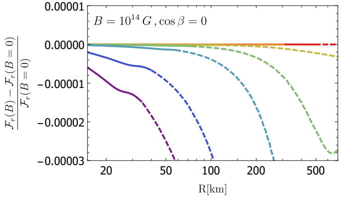

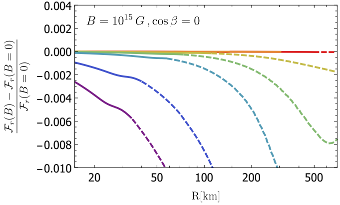

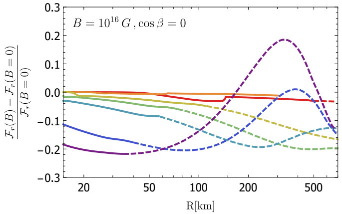

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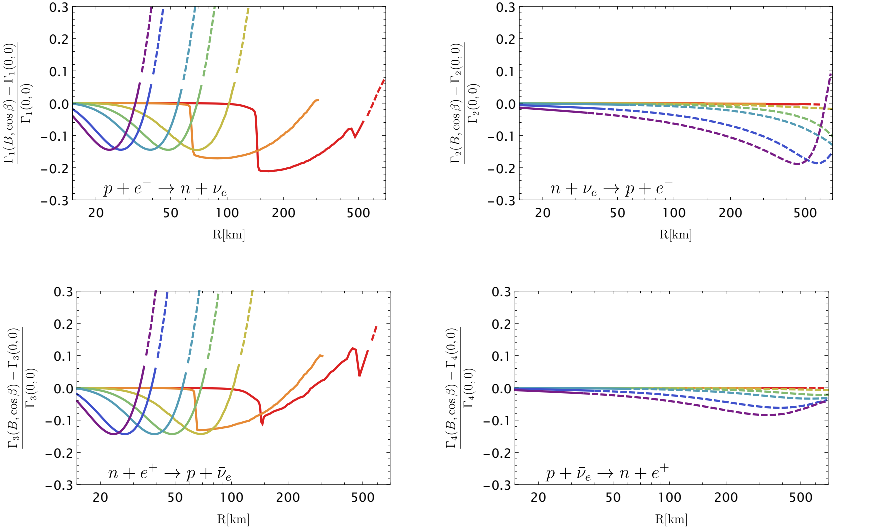
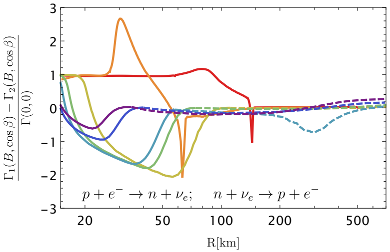
Magnetic-field influence on $\Gamma^{(i)}(B, \cos\beta)$ of individual β-processes

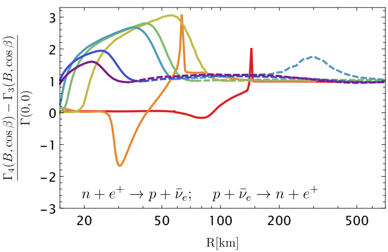
$B = 10^{15}$ G, $\cos\beta = 0$

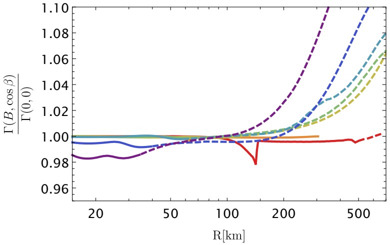


Agree with E. Roulet, JHEP (1998); D. Lai and Y. Z. Qian, ApJ (1998); H. Duan and Y. Z. Qian, Phys.Rev.D (2004); I. S. Ognev, JETP (2016).

Contributions of $\Gamma^{(i)}(B,\cos\beta)$ to the total reaction rate $\Gamma_{p\to n}(B,\cos\beta)$







$B = 10^{15}$ G, $\cos\beta = 0$

Comparison

I.S. Ognev, JETP 123, 643 (2016)

- Sum over all Landau levels
- Keep the oscillatory terms
  $\Rightarrow$ contribution from them is small in SN condition
- No nucleon magnetic moments
  $\Rightarrow \epsilon_{abs}(np) = 0$

P. Arras and D. Lai, Phys.Rev.D 60 (1999)

- Replace the sum by an integral
- Ignore the oscillatory terms
- Include nucleon magnetic moments
  $\Rightarrow \epsilon_{abs}(np)$

In limit when more than few electron Landau levels are filled and neglecting the nucleon magnetic moments, our results coincide with absorption opacity by Arras and Lai

Our results agree with D. Baiko and D. Yakovlev, A&A 342, 192 (1999); H. Duan and Y.-Z. Qian, Phys. Rev. D 72, 023005 (2005).