Exercises for Neutrino Physics: Theory and Experiment

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Sheet 7: Experiment

1. **Supernovae explosion [10 Points]**

   Core-collapse supernovae are the final stage of stars with a mass above about eight solar masses. The figure shows a representation of the evolution of massive star from the onset of collapse (A) to shock formation (C), propagation of the prompt shock (D), shock stagnation and revival (E). The core collapses (B) to a proto-neutron star (PNS) within a fraction of a second. The dynamical state is shown with arrows indicating the flow of the stellar fluid. The neutron star is initially very extended and contracts to a more compact configuration while more matter accretes (D). The subsequent cooling and neutronization of the remnant is driven by the emission of neutrinos of all flavours (E).

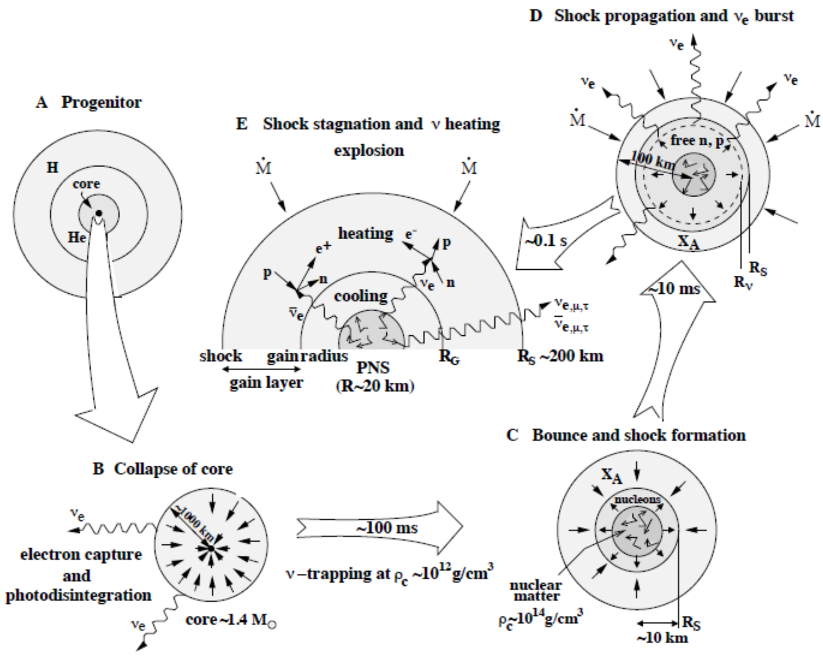

Figure 1: Representation of the evolution of a massive star. R_{s} is the shock radius, R_{gain} is the gain radius and R_ν is the neutrinosphere radius

   (a) Estimate the gravitational energy released by the core collapse, taking into account the energy of the core before and after the collapse. Take the necessary numerical data from the figure.

(b) The observed explosion energy (kinetic energy + radiation energy) is only about 10^{51} erg (kinetic $\mathcal{O}(10^{51})$ erg, radiation $\mathcal{O}(10^{49})$ erg). That is only $\sim 1\%$ of the energy and the rest of the binding energy is radiated away by neutrinos (99%). To find the neutrino flux at the time of the explosion one has to carry out an involved hydrodynamic calculation including neutrino transport. Nevertheless, an estimation is still meaningful. Calculate the total neutrino flux using the released energy found before, taking into account that the average neutrino energy is $\epsilon_\nu \approx 10\,\mathrm{MeV}$ ($1\,\mathrm{MeV} = 1.60203 \cdot 10^{-6}\,\mathrm{erg}$).

(c) If a supernova occurs at the center of the Galaxy ($d \approx 10\,\mathrm{kpc}$), what is the expected neutrino flux on Earth?

(d) Using a $20\,\mathrm{kt}$ scintillator detector ($C_{16}H_{18}$), the reaction with the largest cross section to detect neutrinos is:

$$\overline{\nu}_\mathrm{e} + p \to e^+ + n, \qquad \sigma = 93.0 \cdot 10^{-43} (E_\nu/10\,\mathrm{MeV})^2 \mathrm{cm}^2. \tag{1}$$

Detecting a supernova means detecting at least 10 neutrino events. Would it be possible to detect the supernova from c)?
Hint: Use only the protons from hydrogen for neutrino capture, $\rho = 0.985\,\mathrm{g} \cdot \mathrm{cm}^{-3}$, molecular weigh = $210.3\,\mathrm{a.m.u.}$.

(e) On 23. February 1987, a supernova (SN1987A) exploded in the Large Magellanic Cloud. The Kamiokande collaboration detected 11 neutrino events from this supernova. Why is the number of events so different to the one calculated in this problem?

2. Measurement of ν_e and $\overline{\nu}_\mathrm{e}$ from Supernovae [10 Points]

In the explosion of a supernova type II (core collapse) all types of neutrinos and antineutrinos are produced. Using a liquid scintillator detector the charged current reaction (CC) with protons is used to detect $\overline{\nu}_\mathrm{e}$ (Equation 1) but it is not the only possible reaction. The following CC reactions in carbon can be used:

$$\overline{\nu}_\mathrm{e} + {}^{12}\mathrm{C} \to {}^{12}\mathrm{B} + e^+ \qquad (Q = 17.3\,\mathrm{MeV}) \tag{2}$$
$$\nu_\mathrm{e} + {}^{12}\mathrm{C} \to {}^{12}\mathrm{N} + e^- \qquad (Q = 13.4\,\mathrm{MeV}). \tag{3}$$

In a detector of $20\,\mathrm{kt}$ an event rate of 8700, 494 and 85 events for reactions 1, 2 and 3 is expected for a supernova explosion of $8M_\odot$ in the center of our milkyway.

(a) What are the signatures of reactions 2 and 3? Take into account the decay of the daughter nuclei in the reaction. Is it possible to distinguish experimentally between these two reactions?

(b) How precise is the event rate of reaction 1? Calculate the uncertainty of the 8700 events if the relative uncertainty of the cross section is 1.5%. Mind the rules for correct rounding of errors.

(c) Calculate the error of the ν_e flux using the flux of $\overline{\nu}_\mathrm{e}$ from reaction 1 and the error of the cross section of reaction 2 taken from the experimental values given in Table 1.

Experiment	Cross section in $10^{-42}\,\mathrm{cm}^2$
KARMEN	$8.9 \pm 0.6 \pm 0.75$
LAMPF	$10.5 \pm 1.0 \pm 1.0$
LSND	$9.1 \pm 0.4 \pm 0.9$

Table 1: Measured corss sections of $\overline{\nu}_\mathrm{e} + {}^{12}\mathrm{C} \to {}^{12}\mathrm{B} + e^+$.