Exercises for Experimental methods in Astroparticle Physics

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Sheet 6

1. **Solar Neutrinos**

   In the core of the Sun, energy is released by the exothermic thermonuclear fusion of four protons into Helium:

   $$4\mathrm{p} \to {}^{4}\mathrm{He} + 2e^{+} + 2\nu_{\mathrm{e}}. \tag{1}$$

   (a) Calculate the total energy released in this reaction. Note that the positrons annihilate with electrons releasing additional energy.

   (b) Each neutrino takes away an average energy of $0.3\,\mathrm{MeV}$. The remaining energy is radiated from the solar surface as electromagnetic radiation. The solar luminosity is $L_{\odot} = 3.8 \times 10^{26}\,\mathrm{W}$. How many of the above fusion reactions take place per second? How much matter is converted into energy (in $\mathrm{kg\,s^{-1}}$)?

   (c) Estimate the total flux of solar neutrinos arriving to the Earth, given the distance Sun-Earth $d = 1.49 \times 10^{8}\,\mathrm{km}$. Do oscillations change this value?

   (d) A solar neutrino experiment measures a seasonal time variation of the neutrino flux of 6.7%, i.e. the measured rate in winter is 6.7% higher than in summer. How can this variation be explained?

2. **Solar Neutrinos with Super-Kamiokande**

   To detect solar neutrinos in the water Cherenkov detector Super-Kamiokande, the following scattering reaction of neutrinos on electrons can be considered:

   $$\nu + \mathrm{e}^{-} \to \nu + \mathrm{e}^{-}. \tag{2}$$

   (a) Give an expression for the angle between the direction of the incident neutrino and the direction of the scattered electron in terms of the electron mass, electron kinetic energy and neutrino energy.

   (b) The minimal kinetic energy of the electron to be detected by Super-Kamiokande is $5.5\,\mathrm{MeV}$. With this value and the neutrino energy, given in Figure 1, calculate the maximum angle. Why is this angle important in the detection of solar neutrinos?

   (c) Discuss the main sources of background.

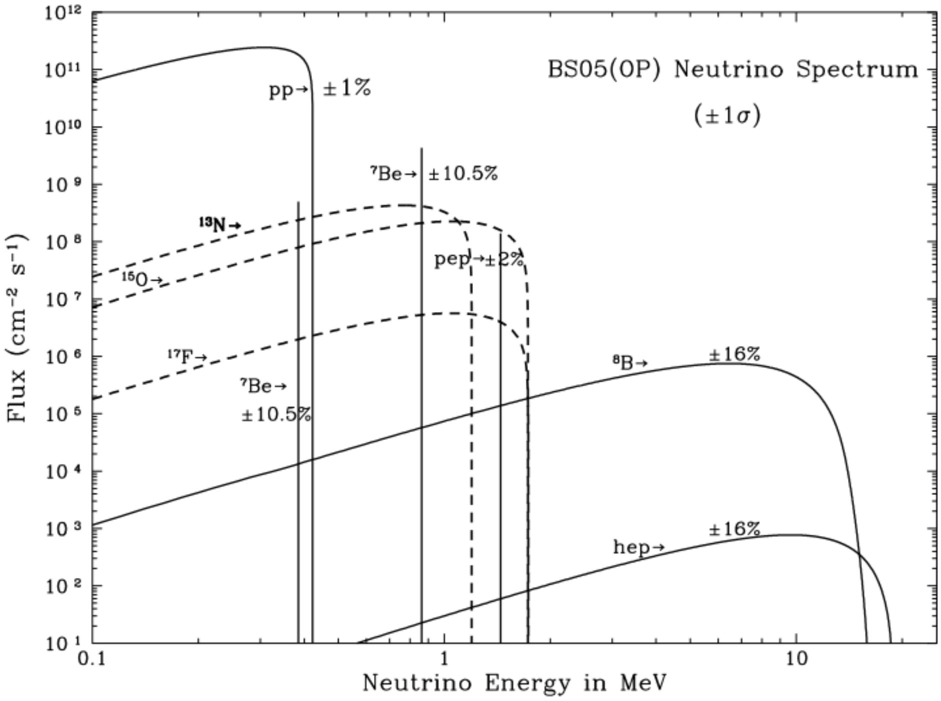

Figure 1: Solar neutrino energy spectrum
from New solar opacities, abundances, helioseismology, and neutrino fluxes - Bahcall, John N. et al. Astrophys.J. 621 (2005) L85-L88 astro-ph/0412440.

3. Gallium Neutrino Observatory (GNO) Results

Radiochemical neutrino experiments use isotopes with relatively high cross sections for inverse beta decay (i.e. neutrino capture of a proton). After some exposure time, the decay of the created unstable nuclei is measured to compute the number of neutrino events. Read about the GNO experiment in https://arxiv.org/abs/hep-ex/0504037. Then, try to answer the following questions about the GNO experiment:

(a) How are the Germanium nuclei detected?

(b) The neutrino capture rate is usually given independent from the target mass in solar neutrino units (SNU). $1\,\mathrm{SNU}$ is equal to 1 ν_e capture per 1×10^{36} $\mathrm{target\,atoms/s}$. The predicted rate for ^{71}Ge is $129\,\mathrm{SNU}$. How many ^{71}Ge atoms are produced in GNO during a 28 day solar run?

(c) Give the differential equation for the number of ^{71}Ge nuclei in the target $H_{\mathrm{Ge}}(t)$. Consider the creation with a constant production rate p and the decay of ^{71}Ge with a lifetime τ. What is the expected number of ^{71}Ge atoms in GNO at the end of a 28 day solar run?