Exp. Methods in Astroparticle Physics (SS 2020) - Problem sheet 12

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Deadline for this sheet: Thu, 16.07.2020

Direct determination of the electron neutrino effective mass

12.1 Tritium-based experiments *4 Points*

a) Define the phase space term of the neutrino and derive the effective electron anti-neutrino mass.

b) Extract the fraction of events which occur in a tritium spectrum in an energy range around $10\,\mathrm{eV}$ below the endpoint of the spectrum. *Utilize the shape of the phase space factor.*

c) The KATRIN experiment uses a MAC-E filter (shown in Figure 1) to select electrons above a given energy threshold. Describe the concept of a MAC-E filter, why the transport of electrons can be considered adiabatic, and how the energy resolution is defined.

d) KATRIN also uses a Windowless Gaseous Tritium Source (WGTS) which provides about 10^{11} decays/s. What is the amount of tritium which is constantly present in the source? For the PTOLEMY experiment, a tritium source of about $100\,\mathrm{g}$ is foreseen. Calculate the corresponding activity and the number of events in the last $10\,\mathrm{eV}$ below the endpoint.

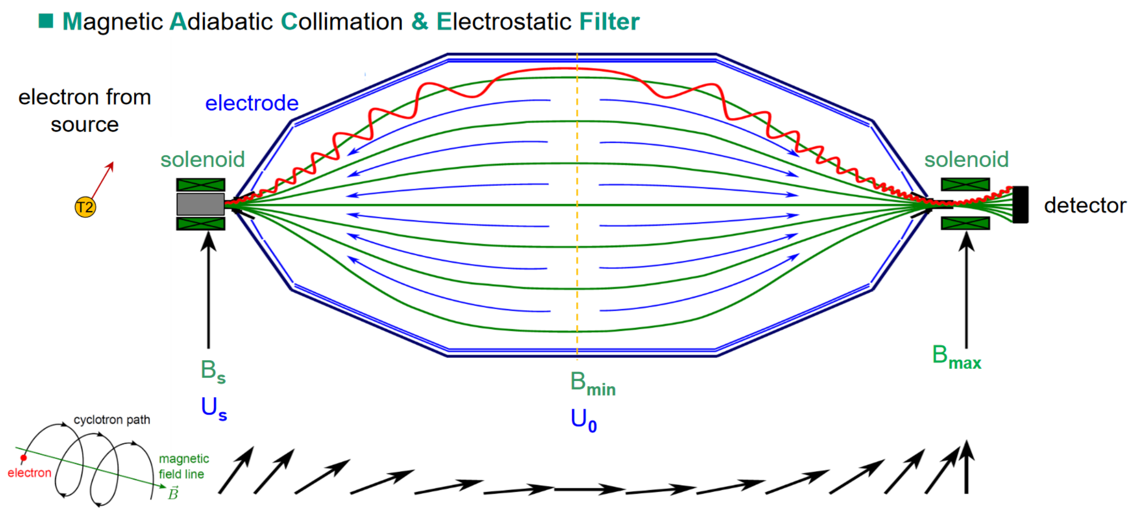
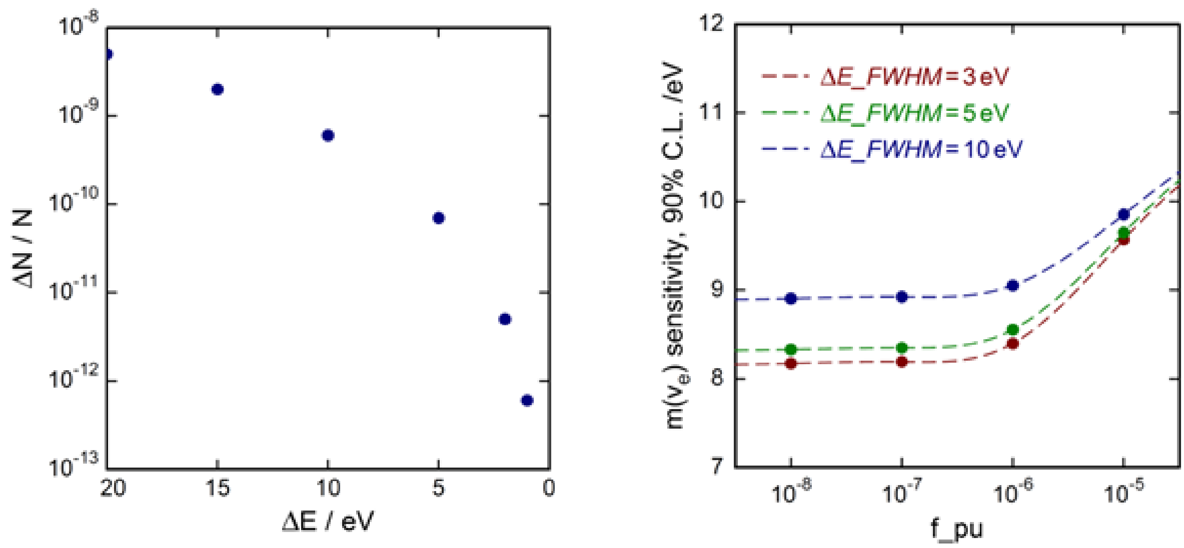


Figure 1: Magnetic Adiabatic Collimation & Electrostatic (MAC-E) Filter of the KATRIN experiment.



(a) Fraction of events

(b) Sensitivity

Figure 2: (a) shows the fraction of events as a function of the size of the region of interest below the endpoint of the ^{163}Ho spectrum. (b) shows the achievable sensitivity on the electron neutrino mass as a function of the unresolved pile-up fraction f_{pu} for a total count of 10^{10} events in the full spectrum and for different energy resolutions ΔE_{FWHM} of the detector.

12.2 ECHo experiment *4 Points*

An electron capture is a process in which a proton-rich nucleus absorbs an electron (usually from an inner shell). This produces an electron neutrino via $\mathrm{p} + \mathrm{e}^- \to \mathrm{n} + \nu$. In the ECHo experiment, about $10\,\mathrm{Bq}$ ^{163}Ho are enclosed in the absorber of a metallic magnetic calorimeter.

a) Given the half-life of ^{163}Ho to be $\tau = 4570\,\mathrm{a}$, calculate how many ^{163}Ho atoms need to be enclosed in a detector such that the corresponding activity is $10\,\mathrm{Bq}$.

b) Metallic magnetic calorimeters have an extremely good time resolution given the fast rise time of the thermal pulses of $\tau_{\mathrm{r}} = 100\,\mathrm{ns}$. Given an activity per pixel of $10\,\mathrm{Bq}$, what is the unresolved pile-up fraction of a single pixel?

c) In order to achieve sub-eV sensitivity on the electron neutrino mass, about 10^{14} events need to be acquired over the full range (up to $2.833\,\mathrm{keV}$). If this statistics is to be reached in one year, how many detectors, each with $10\,\mathrm{Bq}$, have to be simultaneously measured?

d) Figure 2a shows the fraction of events inside a region of interest as a function of the size of said region below the endpoint of the ^{163}Ho spectrum, in the range $[Q_{\mathrm{EC}} - \Delta E, Q_{\mathrm{EC}}]$, assuming a vanishing neutrino mass. Figure 2b shows the achievable sensitivity on the electron neutrino mass for the ECHo-1k experiment in which a total statistics of 10^{10} events will be acquired in the full spectrum. Motivate the reason which limits the investigation of neutrino masses smaller than $8\,\mathrm{eV}$.

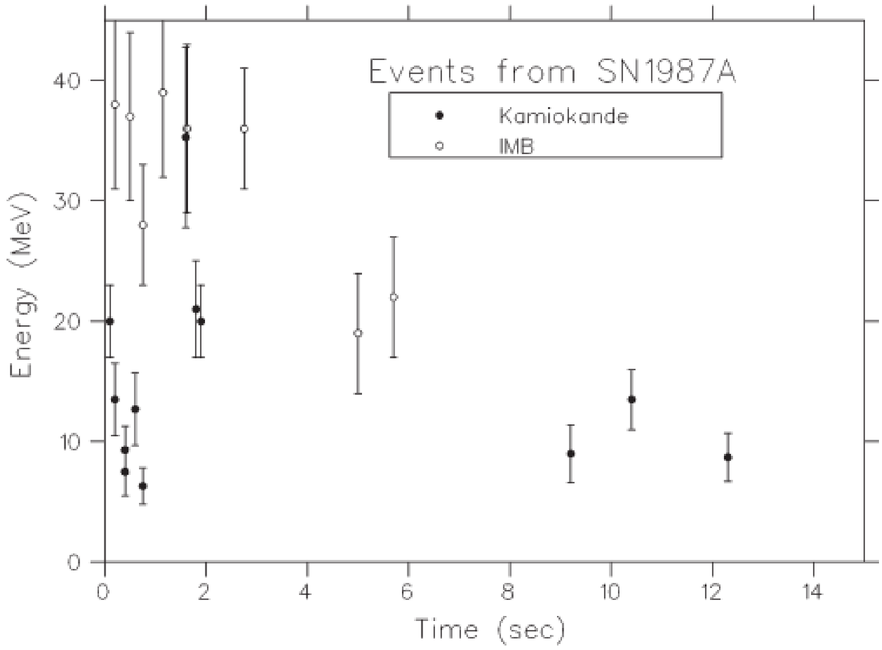


Figure 3: Events (energy versus time) detected in the Kamiokande II and IMB detectors. In the first $2\,\mathrm{s}$, there is a clear correlation of time of arrival and energy, i.e. low energy neutrinos arrive earlier than high energy neutrinos. *From: R. Boyd et. al., Science from detection of neutrinos from supernovae, Journal of Physics G: Nuclear and Particle Physics 29(11), 2003, 10.1088/0954-3899/29/11/009*

12.3 Effective neutrino mass from supernova neutrinos *2 Points*

In 1987, a supernova explosion was observed in the Magellanic cloud (SN 1987A). The neutrinos from this event were measured in three different detectors: Kamiokande II, IMB, and Baksan. From this measurement, we know that neutrinos between $10\,\mathrm{MeV}$ to $50\,\mathrm{MeV}$ arrived within a time span of $10\,\mathrm{s}$ after travelling a distance of $1.6 \times 10^{21}\,\mathrm{m}$ (see Figure 3), and $3\,\mathrm{h}$ before any light was observed. Can this information be used to determine a neutrino mass? Discuss the quantitative mass limits that could be derived from the SN 1987A. *Hint: Consider the time that particles with different energies require for a given length.*