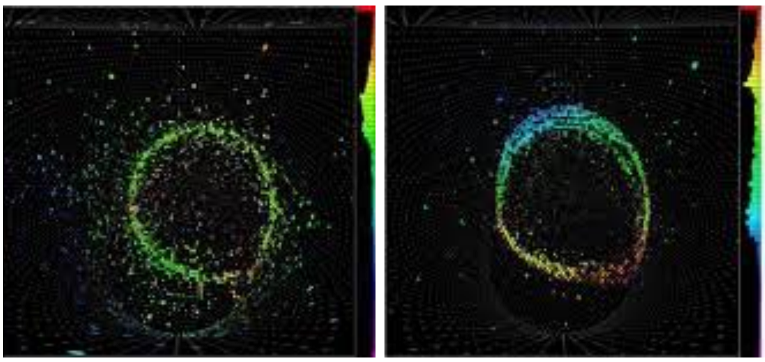
Neutrino Physics: Experimental Part
Exercises

1. **The T2K experiment:**

   Identification of events in Super-Kamiokande

   Super-Kamiokande is the far detector of the T2K experiment. The detector, located in the Kamioka mine in Japan in a depth of 1000 m (2700 m.w.e.), consists of 50 kt of pure water, which is monitored by about 11200 PMTs (20-inch diameter) at the detector walls. The PMTs measure the Cherenkov light emitted by fast charged particles in the water created by neutrino interactions.

   (a) electron (b) muon

   Figure 1: Cherenkov rings of two events in Super Kamiokande.

   (a) The Cherenkov cones of electrons and muons are recorded as rings at the position of the detector walls. How can the rings produced by electrons be distinguished from the rings produced by muons? Use Fig.1 to justify your explanation.
   (b) How do you think the energy of the particle is measured?
   (c) What about tau neutrinos?
   (d) Can one measure the direction of the particle? How?

CP violation in neutrino oscilations

Few days ago T2K published an important result about the CP violation in the lepton sector. For the first time, the value of δ_{CP} was constrained by a neutrino oscillation experiment. Please read and be prepared to discuss the paper: Nature **580**, 339–344(2020)

We will discuss the following questions, please try to prepare answers beforehand:

(a) Explain briefly the working principle of the T2K experiment

(b) What type of neutrinos are produced in J-Park? Which are the oscillation modes studied? Why?

(c) Explain Fig. 1 of the paper.

(d) What do we learn from Fig. 2 of the paper.

(e) What is the main result of the paper? What is the difference with the previous results from T2K?

(f) Why is this result so important? What does it mean for the lepton sector?

2. **Sources of the different types of neutrinos**

We usually refer to the neutrinos according to their source of production: solar neutrinos or atmospheric neutrinos for example. In the table below you can find the different sources of neutrinos together with the type of neutrinos that they produce.

Source	Type of ν	Mean E [MeV]
Reactors	$\overline{\nu}_e$	~ 1
Accelerators	ν_e, ν_μ, $\overline{\nu}_e$,$\overline{\nu}_\mu$	~ 1000
Atmosphere	ν_e, ν_μ, $\overline{\nu}_e$,$\overline{\nu}_\mu$	~ 1000
Sun	ν_e	~ 1
Earth	$\overline{\nu}_e$	~ 1

For each source, explain how the different types of neutrinos are produced indicating the reactions and processes involved in each case.

3. **Detection of the first atmospheric neutrino**

The Cowan–Reines neutrino experiment (1956) is well known because it confirmed the existence of the neutrino. The experiment detected antineutrinos near the Savannah River nuclear reactor. F. Reines (Nobel Prize 1995) also conducted a very important and interesting experiment related to lepton physics in 1965, although no so popular, to detect what he called the **first natural neutrino** or neutrino in nature.

With the term natural neutrino F. Reines referred to those neutrinos which are naturally produced in Earth, in particular in the atmosphere. He intended to detect the first atmospheric neutrino produced by the interaction of cosmic rays.

He conducted a very successful experiment in South Africa and the results were presented on this paper: *Evidence for high-energy cosmic-ray neutrino interactions*.

Please read and be prepared to discuss the paper: Phys. Rev. Lett. 15 (1965) 429. Remember that to download this paper from the PRL webpage you have to be connected to the VPN of the University.

We will discuss the following questions, please try to prepare answers beforehand:

(a) The experiment was conducted in a mine. Why? What was the main background? How are the neutrino detected?

(b) What is the difference in angular distribution of the muons produced in the rock (by a neutrino interaction) and the cosmic-muons?

(c) Explain the detector set-up. Where were located the PMTs? How did they recorded the data?

(d) The scintillators were 20 MeV thick. What does it mean?.

(e) Explain the trigger settings. What is a eithtfold event?

(f) What was the conclusion of this experiment?

1. **Detection of solar neutrinos with different types of detectors**

   For the detection of solar neutrinos different detector types has been developed over the years, including radiochemical experiments with Gallium or Chlorine as target material(GALLEX/GNO, SAGE, Homestake), Cherenkov detectors using normal (Super-Kamiokande) or heavy water (SNO), as well as liquid scintillator detectors (Borexino). Compare these detector types with respect to their detection mechanism, their energy thresholds and possible sources of background. If you need, make a table for an easier comparison.

   - What are the major advantages and disadvantages in each case?
   - How do these experiments complement each other?
   - Why was SNO the only experiment able to solve the solar neutrino problem?
   - Have we learnt everything about solar neutrinos? Is it still interesting to study solar neutrinos? Why?
   - If we want to study the Sun using the information carried by solar neutrinos, which chain would provide more information? Why?
   - Future dark matter detectors, like DARWIN, will be able to observe solar neutrinos. How can the solar neutrino field benefit from the dark matter techniques? Do you think it is worth for a dark matter experiment to put some effort on this kind of searches? Why?

1. **Sensitivity to the neutrinoless double beta decay** ($0\nu\beta\beta$)
   The figure-of-merit estimation is a well established tool to directly compare $0\nu\beta\beta$ sensitivities of different experiments using common statistical methods and assumptions. It also allows for a straightforward assessment of the sensitivity as a function of different parameters, such as the fiducial mass. It does not, however, consider background uncertainties, but assumes perfect knowledge of the background rates

   Based on the figure-of-merit estimator proposed in New J. Phys. 7 (2005), we calculate the half-life sensitivity at 90% C.L. as:

$$T^{0\nu}_{1/2} = \ln 2 \frac{\epsilon \, N_A}{1.64 \, M_{\text{mol}}} \frac{\sqrt{Mt}}{\sqrt{B \Delta E}}, \tag{1}$$

   with ϵ being the total detection efficiency, N_A the Avogadro number in mol^{-1}, M_{mol} the molar mass number, M the total mass of the isotope in kg_{iso}, t the exposure time in years, B the background index in ${\text{kg}_{iso}}^{-1}\text{yr}^{-1}\text{keV}^{-1}$, and ΔE the width of the ROI in keV. The value 1.64 is the number of standard deviations corresponding to a 90% C.L.

   Calculate the expected sensitivity of several future $0\nu\beta\beta$ experiments using the information given in the table below. Assume an exposure time of 10 years for all of them.

Experiment	Iso	M [kg_{iso}]	width ROI [keV]	ϵ_{total}	B [$1/\text{kg}_{iso}$/year/keV]
Legend-1000	^{76}Ge	883	4.4	0.7	$1.59 \cdot 10^{-5}$
CUPID	^{100}Mo	253	8.4	0.68	$2.38 \cdot 10^{-4}$
NEXT-HD	^{136}Xe	991	29.26	0.32	$3.08 \cdot 10^{-5}$
DARWIN	^{136}Xe	445	46	0.68	$4.45 \cdot 10^{-5}$
nEXO	^{136}Xe	1800	46	0.68	$8.69 \cdot 10^{-6}$