Neutrino physics: Theory and experiment (SS2021)
Neutrino sources and neutrino detectors

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1. Lecture 2: Neutrino sources and neutrino detectors

This lecture gives an overview of the neutrino sources some of which will be discussed in depth in upcoming lectures. We will also discuss general aspects in the detection of neutrinos including details on some of the most employed technologies.

1.1. Neutrino sources

Generally neutrino sources can be divided in two categories: **natural and man-made** sources. Natural sources (neutrinos from the Sun or from natural radioactivity) have the advantage of being directly available without the need of building a neutrino-production 'machine'. On the other hand we have no control on their spectrum of flux.

1.1.1. Natural sources

- **Cosmological neutrinos**: Neutrinos which decoupled from thermodynamical equilibrium in the early Universe after the Big Bang. They have very low energies of $\sim 10^{-4}$ (see figure 1) and haven't been detected yet.

- **Solar neutrinos**: Neutrinos produced in the exothermic thermonuclear fusion in the center of the Sun. The net reaction is:

$$4\text{p} \rightarrow \, ^4\text{He} + 2e^+ + 2\nu_e. \tag{1}$$

- **Supernova neutrinos**: Neutrinos are produced in the core-collapse of a supernova explosion. The explosion happens for massive stars at the end of their life. During the collapse, there is first an implosion in which ν_e are produced (in the so-called neutronization process):

$$e^- + p \rightarrow n + \nu_e. \tag{2}$$

  Most of the neutrinos ($\sim$ 90%) are however emitted in a later stage via thermal pair production:

$$e^- + e^- \rightarrow \nu_\alpha + \overline{\nu}_\alpha \;\; \text{with } \alpha = e, \mu, \tau \tag{3}$$

  which cools down the supernova core.

- **Geoneutrinos**: This name is given to the neutrinos originating from ^{238}U, ^{232}Th and ^{40}K decays in the crust or mantle of the Earth. These isotopes are called primordial as they have very long half-lives (10^8 or 10^9 years) and existed in their current form before the Earth was formed.

- **Natural radioactivity**: Similar to the class above, neutrinos are produced in any naturally occurring $\beta^\pm$- decay.

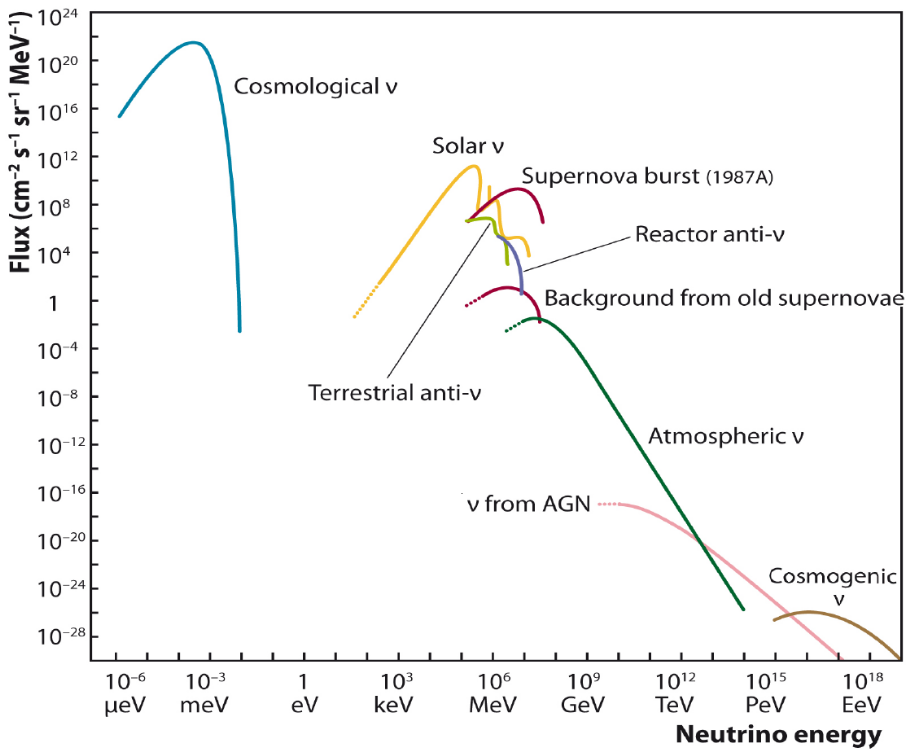

Figure 1. Spectral shape of various neutrino sources. Figure from [1].

Figure 1 is an overview of neutrino sources in which their flux and spectral shape is shown.

- **Atmospheric neutrinos**: protons hit constantly the upper atmosphere and create particle showers (cosmic ray showers) including π's and μ's. These particles decay producing atmospheric neutrinos. Cosmic rays have a very large range of energies and therefore also the resulting neutrinos have energies from sub-GeV up to PeV (10^{15} eV).

- **High energy ν's from astrophysical sources**: Astrophysical objects, as for instance active galactic nuclei (AGNs), can accelerate particles to extremely high energies. Accelerated cosmic-ray protons interact with the interstellar medium:
$$p + p \rightarrow \pi^0, \pi^\pm, K^\pm ... \tag{4}$$
producing pions, kaons or other particles with then decay producing neutrinos.

1.1.2. Man-made sources

There are two main sources of man-made neutrinos: from reactors and from particle accelerators.

- **Reactor neutrinos**: Neutrinos are emitted in the β^--decay of neutron-rich fragments in the fission of uranium and plutonium.

$$^{235}\mathrm{U} + n \rightarrow X_1 + X_2 + 2n \tag{5}$$

In average, 6 $\overline{\nu}_e$ are emitted per fission from the decay of X_1 and X_2.

- **Neutrinos from accelerators**: in particle accelerators typically protons are collided into a target (Be, Al, graphite, carbon). In these reactions π's and K's are emitted and neutrinos appear in their corresponding decays.

1.2. Neutrino detection

Neutrinos can be identified by measuring charged particles produced in their interactions with matter. These interactions can be classified into neutral current and charged current.

- **Charged current**: in these interactions, the lepton partner of the neutrino appears, as for instance in:

$$\nu_e + n \rightarrow e^- + p \tag{6}$$

$$\overline{\nu}_e + p \rightarrow e^+ + n. \tag{7}$$

The reactions happen over the exchange of $W^{\pm}$ bosons of $m(W) \sim 80\,\mathrm{GeV}$ mass.

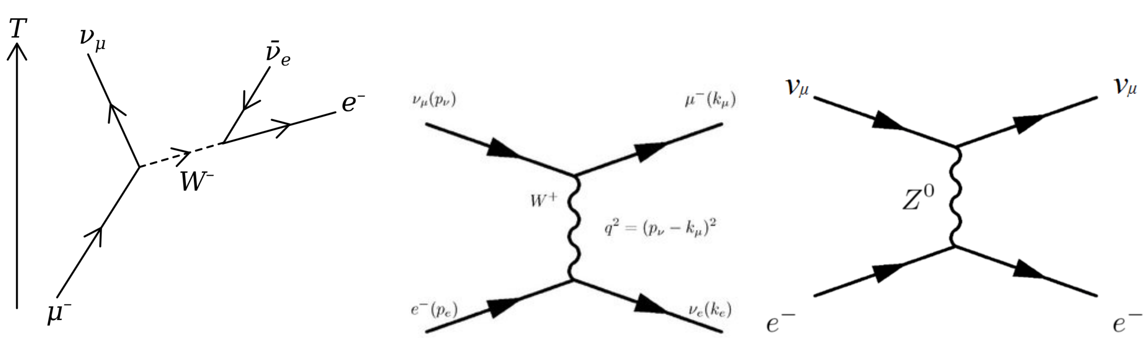

Figure 2. Diagrams for the muon decay (left), the muon scattering on electrons (middle) and the neutral current scattering of ν_μ on electrons (right).

- **Neutral current**: The electroweak theory from Glashow, Weinberg & Salam predicted the existence of neutral current interaction. In 1973, those reactions were discovered in the Gargamelle experiment (bubble chamber) at CERN.

$$\nu_\mu + N \rightarrow \nu_\mu + hadrons. \tag{8}$$

Neutral current reactions take place over the exchange of Z^0 bosons of $m(Z) \sim 90\,\mathrm{GeV}$ mass (see figure 2).

- In general the rate of charged current interactions is higher than the ones of neutral current interactions due to the higher cross section of the former.

$$R = \frac{\sigma(\nu_\mu + N \to \nu_\mu + N)}{\sigma(\nu_\mu + N \to \mu^+ + X)} = 0.22 \pm 0.04 \tag{9}$$

1.3. General characteristics of neutrino detectors

This section sumarizes the general characteristics of a detector to record radiation. The information is based on [2].

1.3.1. Sensitivity

The sensitivity of a detector depends on the type of radiation and its energy.

- **Cross section**: gives the probability for ionizing particles to react in the target
- **Detector mass**: neutral particles require in general larger masses as they have to interact before leaving a signal. Otherwise the detector would be transparent for such particles.
  This aspect is particularly important for neutrinos! Too small detectors would have a negligible rate of neutrinos for a certain source.
- **Detector noise**: even if ionization is produced in a detector, a minimum amount is required in order to have a usable signal. This minimum is determined by the noise of the detector.
- **Detector surrounding materials**: these can stop radiation from the outside. As an example, α's cannot cross the encapsulation of a germanium detector and are therefore not recorded.

1.3.2. Response/linearity

Typically, ionization/scintillation is proportional to the energy deposited in the detector, if the detector is large enough to contain the complete energy deposition.

- It is **proportional** to the electrical charge contained in its signal, i.e. to the integral of the pulse height (voltage) over time (see figure 3).
- If the **shape is constant** for all signal sizes, both the pulse height and the pulse area can be used as estimators of the energy.
- In reality the response varies with the particle type and its energy. This is related to the different reaction mechanisms in the detector medium.

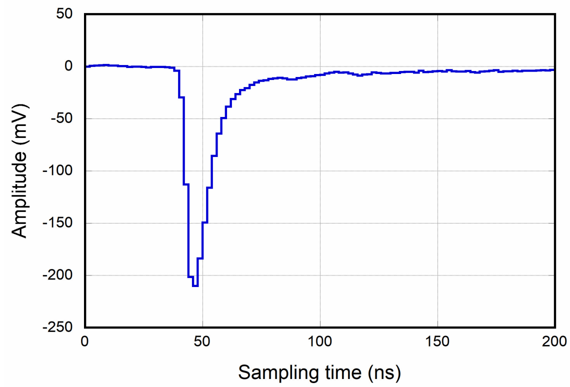

Figure 3. Example of a recorded PMT signal. Figure from [3].

1.3.3. Energy resolution

The energy resolution of a detector tells how well it can distinguish two close lying energies. Ideally, the response to a mono-energetic signal would be a **delta function**. In reality, however, a **finite width** appears usually Gaussian in shape. The width arises from fluctuations in the number of ionizations/excitations. In addition to these fluctuations due to the energy deposition process, there are further factors that can contribute like electronic noise or electronic drifts.

- The energy resolution is often given as the full width at half maximum (FWHM) of the peak or as the sigma of a Gaussian function divided by the energy:

$$Resolution = \Delta E/E \quad \text{(in \%)}. \tag{10}$$

- While a NaI scintillation detector has a typical energy resolution of 8% at 1 MeV, the resolution of a germanium ionization detector is about 0.1% for the same energy.
- The resolution is **energy dependent** improving with increasing energy. This is a consequence of the Poisson statistics of ionization and excitation. Figure 4 shows the energy resolution of a liquid xenon detector.

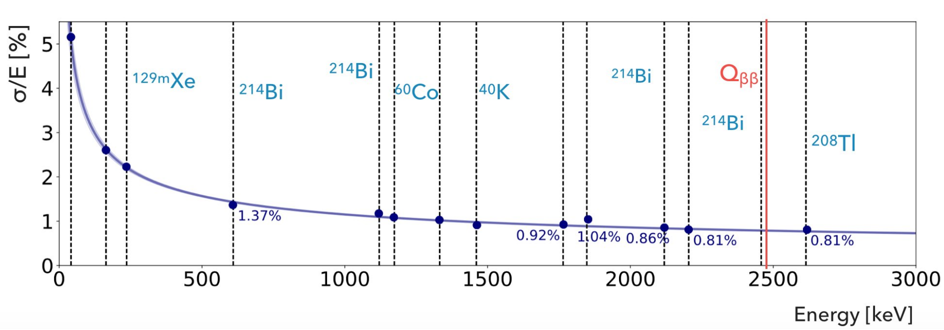

Figure 4. Energy resolution of the XENON1T experiment as function of energy. Data from [4].

1.3.4. Response function

It is given by the different interactions of the radiation as well as the detector design and geometry. An example is shown in figure 5. γ-rays interact with the medium via Compton scattering and photo-absorption, however depending on their energy and on the detector, the response varies.

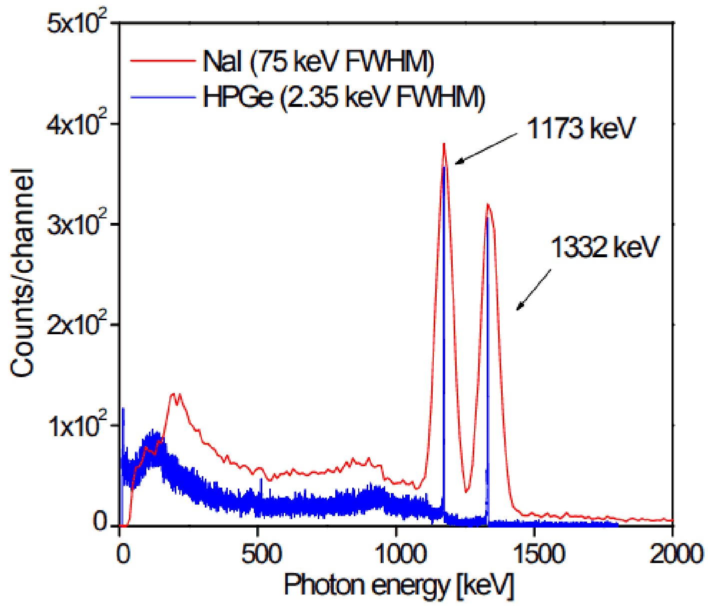

Figure 5. Response of a high purity germanium detector (HPGe) and a sodium iondine (NaI) to γ-rays from a ^{60}Co source. Figure from https://www.nuclear-power.net

1.3.5. Response time & dead time

The response time is the time required to form the signal after the arrival of the radiation.

- **Rising flank**: should be as vertical as possible to reconstruct the interaction time
- **Duration**: during the pulse time a second event cannot be acquired $\rightarrow$ pile-up on the first
- **Dead time**: give the amount of time in which a detector is blind due to the presence of another signal. This can be due to the length of the pulse or due to the electronics in the read-out chain

1.3.6. Efficiency

The **total efficiency** of a detector is defined as the fraction of events detected over the number of events emitted by the source.

$$\varepsilon_{TOT} = \frac{Events\ registered}{Events\ emitted}. \tag{11}$$

Both the geometrical solid angle and the probability of a particle to interact are included in the total efficiency

$$\varepsilon_{TOT} = \varepsilon_{geo} \cdot \varepsilon_{int}, \tag{12}$$

which is nowadays calculated via Monte Carlo simulations.

In addition, there is also an **intrinsic efficiency** which is the number of events registered over the number of events hitting the detector. This is specially relevant for events at the energy threshold of an experiment. Although some particles deposit a small amount of energy in a detector, they might not be recorded because the signal is too small.

1.4. Water Cherenkov detectors

Water Cherenkov detectors have been successfully used in neutrino physics as they have various important advantages compared to other detector types. Large target masses can be build rather easily (cheap detector material), they have a fast response to incoming radiation (within ns) and they have particle directionality and identification capabilities.

1.4.1. Cherenkov effect

When a charged particle travels through a medium with a speed $v_{particle} = \beta c$ greater than that of light in the medium, Cherenkov radiation is emitted

$$v_{particle} > c/n, \tag{13}$$

where n is the index of refraction of the medium and c the speed of light in vacuum.

The **spectrum of the photons** emitted is continuous in a blue-UV (higher intensities at short wavelengths) regime and the photons are emitted in an electromagnetic shock wave. The coherent wavefront is conical in shape and it is emitted at a well-defined angle called **Cherenkov angle**:

$$\cos\theta_C = \frac{1}{\beta \cdot n(w)} \tag{14}$$

with respect to the trajectory of the particle (see figure 6).

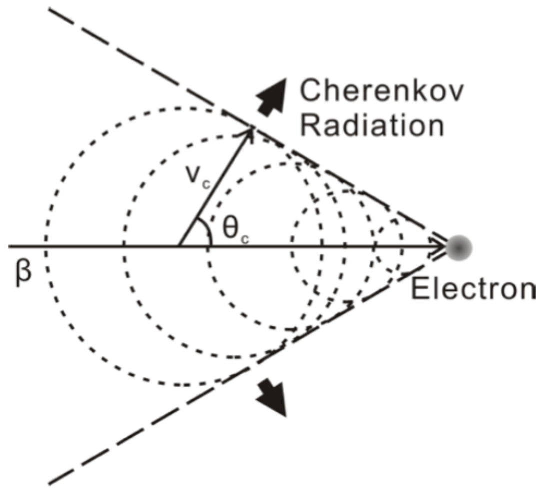

Figure 6. Schematic of Cherenkov radiation. Figure from [5].

The **energy threshold** for different particles to produce Cherenkov radiation in water can be calculated using:

$$E_{th} = \frac{n}{\sqrt{n^2 - 1}} \cdot m_0 c^2. \tag{15}$$

Using $n = 1.33$ for water, the resulting energy threshold is:

$$E_{th} = \begin{cases} 0.77\,\text{MeV} & \text{for} \quad e^{\pm} \\ 159\,\text{MeV} & \text{for} \quad \mu^{\pm} \\ 210\,\text{MeV} & \text{for} \quad \pi^{\pm} \end{cases} \tag{16}$$

1.4.2. Directionality and particle identification

- By recording the time and hit structure of photons in a water Cherenkov detector, the **direction of the incoming particle** can be reconstructed. ATTENTION: this is the direction of the charged particle! In the case of a neutrino interaction, this is not the direction of the neutrino (although it is correlated).

- Cherenkov detectors offer a certain **particle identification**: for instance electrons and muons can be separated by the shape of their rings:

  Being cosmic muons typically minimal ionizing particles, they have a homogeneous energy deposition and correspondingly an homogeneous Cherenkov ring. In contrast electrons have multiple scatters and undergo Bremsstrahlung processes leaving a diffuse ring (see figure 7).

- In some cases also π^0 particles can be identified. The γ-rays produced in its decay ($\pi^0 \to \gamma\gamma$) can be eventually separated in the angle between the both is large enough.

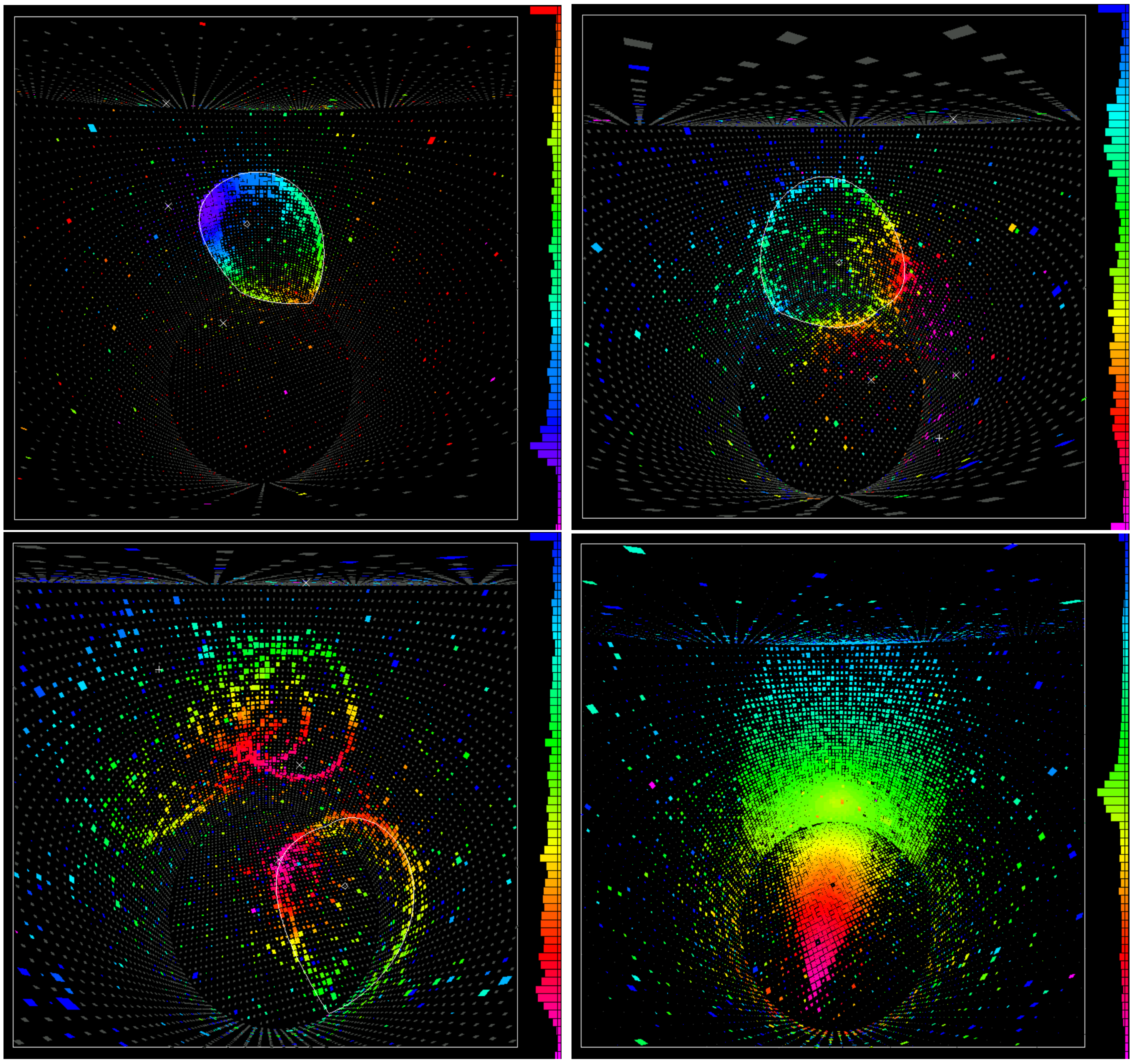

Figure 7. Cherenkov rings for 1 GeV muon (top left), for 600 MeV electron (top right), a multiparticle event (bottom left) and a through-going muon (bottom right) in the Superkamiokande detector Figure from the Superkamiokande collaboration.

Although Cherenkov detectors have great characteristics as particle detectors, there are a few **disadvantages** that have also to be taken into account:

- Below the Cherenkov threshold no radiation is emitted
- The amount of light per keV deposited energy is lower than in scintillator detectors
- The quantum efficiency of typical phtosensors is low at UV-wavelegths

1.5. Organic liquid scintillation detectors

This section describes another very extensively used technology employing organic liquids to built large scintillating detectors.

1.5.1. Scintillation mechanism

Luminescence or scintillation is a property of a medium where energy is absorbed (light or radiation) and it is emitted in the form of visible light. Typical fluorescence response times are in the order of $\tau \sim (10^{-9} - 10^{-8})\,\mathrm{s}$.

The requirements for a good scintillator are:

- A high efficiency to convert exciting energy to photons
- Transparency to its own scintillation light
- Short time constants
- Overlap of the emitted spectrum with the typical sensitivity of photosensors

Organic scintillators are made out of hydrocarbon molecules with benzene-ring structures (see figure 8, left). Six so-called π-electrons combine to a delocalized orbital with an energy level structure. Luminesce is caused by transitions from excited states in the π-orbitals to the ground state (see 8, right).

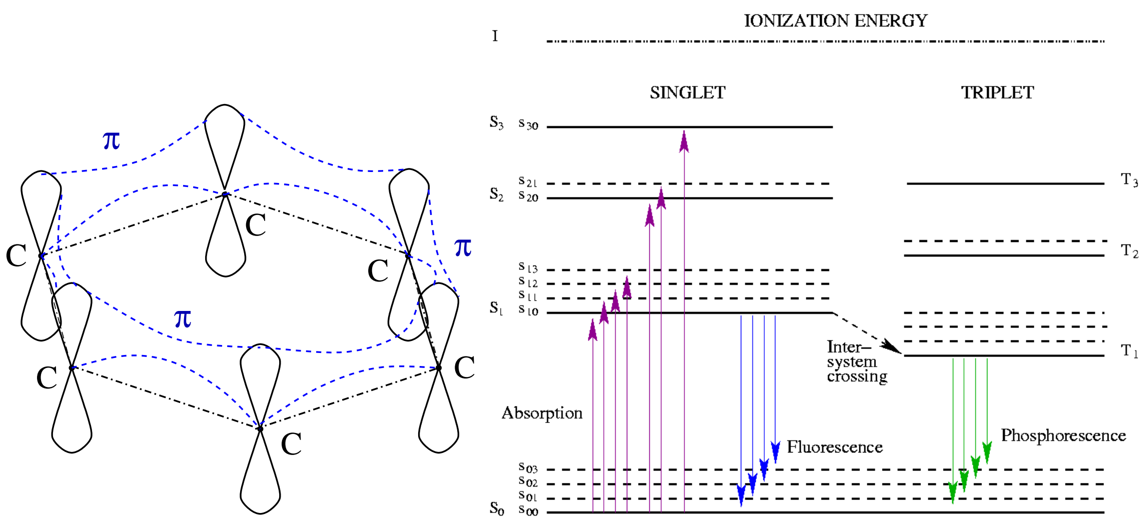

Figure 8. Left: Formation of π-orbitals in benzene. Left: energy levels pf π-orbitals in benzene. Figure from [6].

When radiation brings an electron from the ground state S_0 to a available state above it ($S_i,\ \ i > 0$), in $\sim 10^{-12}\,\mathrm{s}$ the energy is dissipated through collisions until the electron is at the state S_1.

The reaction $S_1 \rightarrow S_0$ is then responsible for the fluorescence of the material. There is also phosphorescence from the lowest lying triplet state $T_1 \rightarrow S_0$ but the lifetime of T_1 is so long that inter-crossing system reactions bring the electrons from the triplet to the singlet state.

Often the wavelength of the scintillator solvent overlaps with its own absorption. For this reason and to reach a long (meters) propagation of light without attenuation, **wavelength-shifters** are added to the organic solvent. Wavelength-shifters are organic compounds that absorb the light emitted by the solent and re-emit it at a higher wavelength. A good overlap between the solvent emission spectrum and the wavelength-shifter absorption spectrum is of great importance to achieve an efficient energy transfer.

1.5.2. Particle identification

The typical time evolution of a scintillation pulse is given by two exponential functions:

$$N = A_1 \exp\left(\frac{-t}{\tau_f}\right) + A_2 \exp\left(\frac{-t}{\tau_s}\right) \tag{17}$$

where $A_{1,2}$ are the corresponding amplitudes and $\tau_{f,s}$, the fast and slow decay constants, respectively.

The origin of these time constants is related to their corresponding processes. While the fast component arises from the transition $S_1 \to S_0$, the slow component is related to the recombination of triplet states:

$$T_1 + T_1 \to S^* + S_0. \tag{18}$$

Typical values for the fast and slow components are $\sim 5\,\text{ns}$ and $\sim 200\,\text{ns}$, respectively.

Figure 9 shows an illustration of organic liquid-scintillator pulse shapes for different particle types. The higher the dE/dx of the particle the higher is the amplitude of the slow component (due to enhanced inter-crossing system reactions).

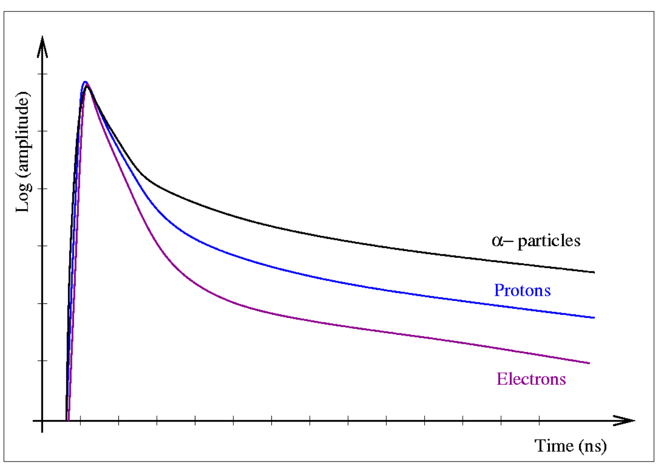

Figure 9. Schematic representation of particle pulse-shapes for different types of particles in organic scintillators. Figure from [6].

1.6. Photosensors

Nowadays there are many photosensor types being developed, however, electron tube devices (photomultipliers, PMTs) are still the most used technology. PMTs record Cherenkov or scintillation light converting it into a measurable electric current. This section gives a very brief overview of the PMT main characteristics.

Light is detected in photomultipliers via the **photoelectric effect** in which an electron is released by a photon. The probability for a photon to release an electron is given by the so-called quantum efficiency (QE). Nowadays QEs up to $(40-45)\%$ are achieved. An electric field focusses electrons from the photocathode to the first dynode (see figure 10).

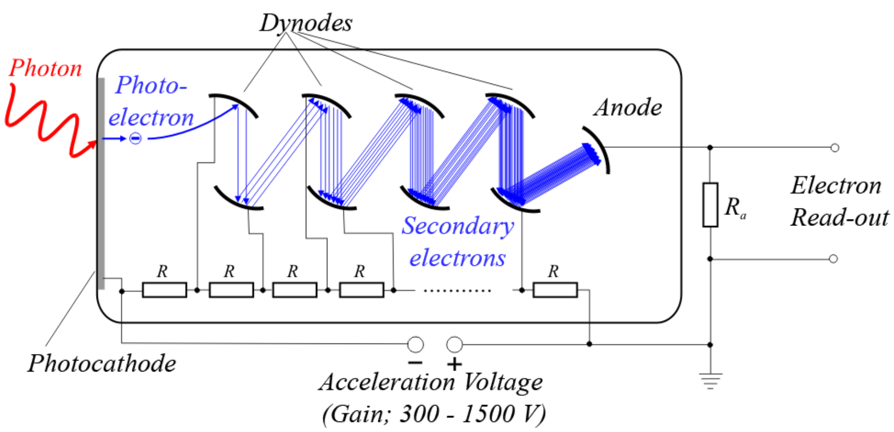

Figure 10. Working scheme of a photomultiplier. Figure from wikipedia.

A series of dynodes amplify the signal typically by a factor 10^6 producing a large electrical signal ($\sim$ a few mV) for each incident photon.

The trajectories of the electrons inside the PMT are sensitive to magnetic field and specifically to the Earth magnetic field. To keep the focussing of electrons independent of the orientation of the tube, magnetic protection (μ-metal) are often wrapped around the PMTs.

The response of photomultipliers include other features as for instance electronic noise (ideally at lower amplitudes than the single photon). An important property is the **dark count rate**: a thermionic emission of electrons in the cathode and dynodes which is ideally as low as possible. Furthermore, residual gases in the vacuum of the tubes can be ionized by the photoelectrons produced in the cathode. These ionized molecules travel back to the cathode releasing further electrons, called **afterpulses**.

1.7. Summary

In this lecture, we have briefly discussed natural and artificial sources of neutrinos as most of these will appear again in upcoming lectures. We also review the most important characteristics of detectors and then had a look in detail at two detector types: water Cherenkov and organic liquid scintillators. Finally, we are briefly summarized the properties of photomultipliers which are very widely used in large astroparticle physics detectors.

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