Methods and problems in low energy neutrino experiments (solar, reactors, geo-)

G. Ranucci

ISAPP 2011
International School on Astroparticle physics

THE NEUTRINO PHYSICS AND ASTROPHYSICS

July 26th - August 5th, 2011
Varenna - Italy
Summary of the topics

- Neutrino detection overview
- Radiochemical methodology
- Scintillation methods
- Cerenkov approach
- Low background implications in low energy neutrino search

With examples of applications taken from experiments
A many facets problematic: sources

The neutrino detection techniques encompasses several different methodology of widespread use in the general field of particles detection.

The multiplicity of the detection methods is enhanced by the plurality of experimental needs posed by the different neutrino sources of experimental interest:

- solar neutrinos
- atmospheric neutrinos
- reactor neutrinos and geo-neutrinos (anti-ν)
- accelerator neutrinos
- supernova neutrinos (not discussed here)
- ultra high energy neutrinos from astrophysical sources
A many facets problematic: experimental methods

The richness of the neutrino physics field finds almost naturally its counterpart in the variety of techniques applied or proposed by the experimentalists to cover this broad range of applications:

- Radiochemical methods
- Water cerenkov detectors
- Heavy water detectors
- Scintillation techniques
- Long string, large Water Cerenkov Detectors
- Time projection chambers
- Nuclear emulsions
Focus of this presentation

a) **Radiochemical methods** vastly applied in the solar neutrino search

b) **Water cerenkov detectors**, included the heavy water version, which provided epochal results in the atmospheric neutrino detection, and in the assessment of neutrino oscillations

c) **The scintillation detectors** which are the choice for most of the reactor and accelerator experiments, as well as fundamental instruments for the challenging real time detection of low energy solar neutrinos.

d) **Low background issues** connected to the low energy neutrino measurements
Neutrino production in the Sun

The pp chain reaction
The CNO cycle

There are different steps in which energy (and neutrinos) are produced

In our star > 99% of the energy is created in this reaction
In the Sun < 1% More important in heavier stars

Monochromatic v’s
(2 bodies in the final state)

pp
ν from:
pp
pep
7Be
8B
hep

CNO
ν from:
13N
15O
17F
Neutrino energy spectrum as predicted by the Solar Standard Model (SSM)

John Norris Bahcall
(Dec. 30, 1934 – Aug. 17, 2005)

$^7\text{Be}$: 384 keV (10%)  
862 keV (90%)  
Pep: 1.44 MeV
Solar neutrino experiments: a more than four decades long saga

Radiochemical experiments

Homestake (Cl)
Gallex/GNO (Ga)
Sage (Ga)

Real time Cherenkov experiments

Kamiokande/Super-Kamiokande
SNO

Scintillator experiments

Borexino
Radiochemical methods

The radiochemical technique exploits a detection target which, upon absorption of a neutrino, is converted into a radioactive element whose decay is afterwards counted.

Experiments of this kind: Homestake, Gallium Detectors (Gallex/GNO, SAGE)

The pioneering Homestake experiment was based on the inverse beta reaction

\[ \nu_e + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + e^- \text{ (threshold 0.814 MeV)} \]

(method proposed by Pontecorvo (1946) and later independently by Alvarez (1949))

The Gallium experiments are based on the reaction:

\[ \nu_e + ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} + e^- \text{ (threshold 0.233 MeV)} \]

(proposed by Kuzmin in 1965)
Example of radiochemical methods: The Gallium solar Neutrino Observatory (GNO) at Laboratori Nazionali del Gran Sasso

The detector is sensitive mainly to pp-neutrinos (53% of the interaction rate according to the standard solar model), with smaller contributions from $^7\text{Be} \nu$ (27%), $^8\text{B} \nu$ (12%), and CNO $\nu$ (8%).

The target consists of 101 tons of a GaCl$_3$ solution in water and HCl, containing 30.3 tons of natural gallium; this amount corresponds to $\sim 10^{29}$ $^{71}\text{Ga}$ nuclei. The solution is contained in a large tank.

$^{71}\text{Ge}$ produced by neutrinos is radioactive, and decays back by electron capture into $^{71}\text{Ga}$. The mean life of a $^{71}\text{Ge}$ nucleus is about 16 days: thus the $^{71}\text{Ge}$ accumulates in the solution, reaching equilibrium when the number of $^{71}\text{Ge}$ atoms produced by neutrino interactions is just the same as the number of the decaying ones. When this equilibrium condition is reached, about a dozen $^{71}\text{Ge}$ atoms are present inside the 103 tons gallium chloride solution (containing $\sim 10^{29}$ Ga nuclei).
GNO/Gallex Tank

- N₂ (Nitrogen) enters the tank and reacts with GaCl₃ + HCl to form GaCl₄.
- GaCl₄ then dissolves in H₂O to form GaCl₃·H₂O.

Tank capacity: 54 m³
GNO/Gallex experimental procedure

The solar neutrino flux above threshold is deduced from the number of $^{71}$Ge atoms produced using the theoretically calculated cross sections.

The $^{71}$Ge are identified through their decay after chemical separation from the target.

In summary the methodology for the measurement of the solar neutrino flux contemplates the following steps:

- The solution is exposed to solar neutrinos for about 4 weeks; at the end of this time $\sim 10^{7} \, ^{71}\text{Ge}$ nuclei are present in the solution, due to solar neutrino interactions on $^{71}\text{Ga}$.

- $^{71}\text{Ge}$, present in the solution as volatile GeCl$_4$, is chemically extracted into water by pumping $\sim 3000 \, \text{m}^3$ of Nitrogen through the solution.
GNO/Gallex experimental procedure (cont'd)

- The extracted $^{71}\text{Ge}$ is converted into GeH$_4$ (Germane gas), and introduced into miniaturized proportional counters mixed with Xenon as counting gas. At the end $\sim 95-98\%$ of the $^{71}\text{Ge}$ present in the solution at the time of the extraction is in the counter; extraction and conversion efficiencies are under constant control using non radioactive germanium isotopes as carriers.

![Diagram of HD-II proportional counter]

- Decays and interactions in the counter, including $^{71}\text{Ge}$ e-capture (meanlife 16.5 days) $^{71}\text{Ge}(e^-\nu)\,^{71}\text{Ga}$, are observed for a period of 6 months, allowing the complete decay of $^{71}\text{Ge}$ and a good determination of the counter background. The charge pulses produced in the counters by decays are recorded by means of fast transient digitizer operating at 0.2 ns/chan for a depth of 400 ns.
GNO/Gallex experimental procedure (cont'd)

- Data are analyzed to obtain the most probable number of $^{71}$Ge introduced in the counter. Key issue - backgrounds minimization:
  - rigorous application of low-level-radioactivity technology in counter design and construction.
  - Rejection of the residual background through application of amplitude and shape analysis on the recorded pulses: K (10.4 keV) and L (1.2 keV) energy windows identification and rise time selection the ionization produced by the decay is point-like, so that the pulses are fast compared with most of the natural radioactivity background (producing diffuse ionization and 'slow' pulses)).
  - Counters are calibrated by an external Gd/Ce X-ray source, for amplitude and pulse shape cuts efficiency determination for each measurement. The event amplitude and shape selection reduces the mean background rate to less than 0.1 counts per day. Calibration is repeated 5 times during the 6 month counting time, to check the stability of the gain and of the resolution.
GNO/Gallex experimental procedure (cont'd)

- The final Ge production rate is obtained by a suitable maximum likelihood determination applied on the data sample after the cuts application.

- Final corrections to take into account the production rate due to so-called "side reactions", i.e. interactions in the solution generated by high energy muons from cosmic rays and by natural radioactivity.
Total Rates: Standard Model vs. Experiment
Bahcall–Serenelli 2005 [BS05(0P)]

Output (measured neutrino flux) of the Gallex/GNO and Sage experiments compared to the model prediction.
Important part of the overall methodology: global calibration with a $^{51}$Cr neutrino source.
Class of detectors based on the Cerenkov methodology

- Multi purpose detectors

- Solar neutrinos
  Kamiokande/Superkamiokande
  SNO (Heavy water version)

- Atmospheric neutrinos
  (Kamiokande/Superkamiokande)

- Accelerator neutrinos
  (Kamiokande/Superkamiokande)

- String detectors for UHE neutrinos
  AMANDA
  Baikal
  Icecube
  Antares
  Nemo
Čerenkov radiation

In a material with refractive index n, a charged particle emits photons if its velocity is greater than the local phase velocity of light.

The charged particle polarizes the atoms along its trajectory. These time dependent dipoles emit electromagnetic radiations.

If \( v < c/n \) the dipole distribution is symmetric around the particle position, and the sum of all dipoles vanishes.

If \( v > c/n \) the distribution is asymmetric and the total time dependent dipole is non null, thus radiates.
The angle is \( \cos \theta = \frac{1}{\beta n} \)

The spectrum has a dependence \( \frac{1}{\lambda^2} \)
Cerenkov light is produced in a pool reactor where the core is submerged in water.
Cerenkov/Heavy water approach: SNO (Sudbury Neutrino Observatory)

Basic idea: independent measurements of a) the flux of electron neutrinos ($\nu_e$) and b) the cumulative flux of mu- and tau-neutrinos $\nu_\mu$ and $\nu_\tau$ from the Sun. Heavy water makes this possible, allowing to determine

$$F(\nu_\mu \text{ and } \nu_\tau) = F(\nu_x) - F(\nu_e)$$

SNO can measure these fluxes via the different ways in which neutrinos will interact with the heavy water:

i. **Charged Current Reaction**

$$\nu_e + d \rightarrow p + p + e^-$$

As the neutrino approaches the deuterium nucleus, a $W$ boson is exchanged, changing the neutron in deuterium to a proton, and the neutrino to an electron.

Essentially all the neutrino energy is transferred to the electron.
Cerenkov/Heavy water approach: charge current reaction in SNO

Due to the large energy of the incident neutrinos, the electron will be so energetic that it will be ejected at light speed, which is actually faster than the speed of light in water. This causes the optical equivalent of a "sonic boom", where a "shock wave of light" is emitted as the electron slows down. This light flash, called Cerenkov radiation, is detected by the photomultiplier tubes (PMTs); the amount of light is proportional to the incident neutrino energy.

From the PMT hit patterns the energies of the neutrinos can be determined and an angular distribution measured. The spectrum of neutrino energies will show a distortion from the theoretical shape if neutrino oscillations are occurring.

(The Standard Solar Model predicts about 30 charged current events per day in SNO)
Cerenkov/Heavy water approach: neutral current reaction in SNO

ii. Neutral Current Reaction

\[ \nu_x + d \rightarrow p + n + \nu_x \]

In this reaction a neutral Z boson is exchanged (hence the name "neutral current reaction"). The net effect is just to break apart the deuterium nucleus; the liberated neutron is then thermalized in the heavy water as it scatters around.

The reaction can eventually be observed due to gamma rays which are emitted when the neutron is finally captured by another nucleus. The gamma rays will scatter electrons, which produce detectable light via the Cherenkov process, as discussed before.
Cerenkov/Heavy water approach: neutral current reaction in SNO

The neutral current reaction is equally sensitive to all three neutrino types; the detection efficiency depends on the neutron capture efficiency and the resulting gamma cascade.

Neutrons can be captured directly on deuterium, but this is not very efficient and clearly distinguishing the spectra would be challenging.

For this reason SNO has employed two separate neutral current systems to enhance the neutral current detection. The diagram below shows capture on $^{35}$Cl, which will be added to the heavy water in the form of NaCl during the second phase of detector operation.

(The Standard Solar Model predicts about 30 neutrons per day in SNO)

Third phase: helium 3 proportional counters deployed in the detector mainly to cross check results of phase 2
Cerenkov/Heavy water approach: Electron scattering reaction

iii. *Electron Scattering*

\[ e^- + \nu_x \rightarrow e^- + \nu_x \]

This reaction is not unique to heavy water and it is the primary mechanism in other light water detectors (*Kamiokande/Super-Kamiokande*). Although the reaction is sensitive to all neutrino flavours, the electron-neutrino dominates by a factor of six. The final state energy is shared between the electron and the neutrino, thus there is very little spectral information from this reaction. Good directional information is obtained.

(The Standard Solar Model predicts about 3 electron scattering events per day in SNO.)
Summary of Signatures in SNO (D$_2$O)

**Charged-Current (CC)**
\[ \nu_e + d \rightarrow e^- + p + p \]
\[ E_{\text{thresh}} = 1.4 \text{ MeV} \]
\[ \nu_e \text{ only} \]

**Neutral-Current (NC)**
\[ \nu_x + d \rightarrow \nu_x + n + p \]
\[ E_{\text{thresh}} = 2.2 \text{ MeV} \]

Equally sensitive to \( \nu_e \), \( \nu_\mu \), \( \nu_\tau \)

**Elastic Scattering (ES)** (D$_2$O & H$_2$O)
\[ \nu_x + e^- \rightarrow \nu_x + e^- \]
\( \nu_x \), but enhanced for \( \nu_e \)
Events point away from the sun.
The Sudbury Neutrino Observatory: SNO

- Acrylic vessel (AV) 12 m diameter
- 1000 tonnes D$_2$O ($300$ million)
- 1700 tonnes H$_2$O inner shielding
- 5300 tonnes H$_2$O outer shielding
- ~9500 PMT's
- Entire detector
  - Built as a Class 2000 Clean room
  - Low Radioactivity Detector materials

6800 feet (~2km) underground

Creighton mine
Sudbury, CA

The heavy water has been returned and development work is in progress on SNO+ with liquid scintillator and $^{150}$Nd additive.
PMT's sphere (external view)
An example of a cerenkov event
RADIOACTIVE BACKGROUNDs

Contributions To Cerenkov Light

• Low Energy Gammas, Betas (Mainly U, Th Chains)
  - Radioassay (Rn gas, Ra absorbers)
  - Assay by Cerenkov Light (< 5 MeV)
    - Pattern recognition discriminates U, Th
    - Rates consistent with radioassays

Large uncertainties at present. Future: Triggered sources

• External High Energy Gammas
  - Extrapolate from rates in light water
  Preliminary < few percent of CC in heavy water.

Contributions to NC Background (Neutrons)

• Photodisintegration of Deuteron (Threshold 2.2 MeV)
  - Gammas: Th Chain (2.6 MeV), U Chain (2.4 MeV)
Radioactivity in H$_2$O from Water Assays

- $^{222}$Rn [U]: Goal: $4.5 \times 10^{-13}$ g/g
- $^{224}$Ra [Th]: Goal: $3.7 \times 10^{-14}$ g/g
- $^{226}$Ra [U]: Goal: $4.5 \times 10^{-13}$ g/g


SNO Preliminary
Radioactivity in D₂O from Water Assays

- **²²²Rn [U]**
  - Goal: $4.5 \times 10^{-14}$ g/g

- **²²⁴Ra [Th]**
  - Goal: $3.7 \times 10^{-15}$ g/g

- **²²⁶Ra [U]**
  - Goal: $4.5 \times 10^{-14}$ g/g

Time (year):
- 1999.4
- 1999.6
- 1999.8
- 2000
- 2000.2
- 2000.4

SNO Preliminary
Accurate measurement of physics processes in the SNO detector requires a chain of calibrations and calculations to link the photomultiplier data to a full description of the interaction in terms of energy, direction, and particle type. Sources deployed everywhere in the detector volume.
Three Phases of SNO

**Pure D$_2$O**

- **Nov 99 – May 01**
- $n + d \rightarrow t + \gamma$
- $(E_{\gamma} = 6.25 \text{ MeV})$
- PRL 87, 071301 (2001)
- PRL 89, 011301 (2002)
- PRL 89, 011302 (2002)
- PRC 75, 045502 (2007)

**Salt**

- **Jul 01 – Sep 03**
- $n + ^{35}\text{Cl} \rightarrow ^{36}\text{Cl} + \Sigma\gamma$
- $(E_{\Sigma\gamma} = 8.6 \text{ MeV})$

SNO+ enhanced NC rate and separation
- PRL 89, 011301 (2002)
- PRL 89, 011302 (2002)
- PRD 72, 055502 (2005)

Archival papers with complete details
Results of the 3 Phases

NC Flux (corrected to Winter $^8$B spectrum)

- Salt - 391 days
- NCD - 385 days
- D$_2$O - 306 days

CC Flux

- Salt - 391 days
- NCD - 385 days
- D$_2$O Constrained - 306 days

ES Flux

- SuperK-I - 1496 days
- D$_2$O Constrained - 306 days
- Salt - 391 days
- NCD - 385 days

\[ \frac{\phi_{SNO}^{CC}}{\phi_{SNO}^{NC}} = 0.301 \pm 0.033 \text{ (total)}. \]

p-value for consistency of NC/CC/ES in the salt & NCD phases + D2O NC(unconstr) is 32.8%

Art MacDonald@Neutel 2009

Rome - 3 July, 2009

Gioacchino Ranucci - I.N.F.N. Sez. di Milano
The two outputs (measured neutrino flux) of the SNO experiment compared to the model prediction.
For general information
The NC and CC measurements from SNO together with the other solar (and KamLAND) experiments proved to be pivotal to determine the values of the oscillation parameters.
Detection via $\nu e$ scattering as third detection method in SNO

Other example of Cerenkov detector
Example of Cerenkov ring
How to exploit the Cerenkov light directionality

Solar Peak above 5 MeV

SK-I 1496 day 5.0-20MeV 22.5kt (Preliminary)

Background level
Super-Kamiokande History

inner detector mass: 32kton    fiducial mass: 22.5kton

<table>
<thead>
<tr>
<th>Year</th>
<th>Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>SK-I</td>
</tr>
<tr>
<td>1997</td>
<td>SK-II</td>
</tr>
<tr>
<td>1998</td>
<td>SK-III</td>
</tr>
<tr>
<td>1999</td>
<td>SK-IV</td>
</tr>
<tr>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>2001</td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td></td>
</tr>
<tr>
<td>2003</td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td></td>
</tr>
</tbody>
</table>

**1996**

- **SK-I**
  - 11146 ID PMTs (40% coverage)
  - Acrylic (front) + FRP (back)
  - Energy Threshold: 5.0 MeV

**1997**

- **SK-II**
  - 5182 ID PMTs (19% coverage)
  - Energy Threshold: 7.0 MeV

**1998**

- **SK-III**
  - 11129 ID PMTs (40% coverage)
  - Energy Threshold: 4.5 MeV

**1999**

- **SK-IV**
  - Electronics Upgrade
  - Work in progress
  - Energy Threshold: < 4.0 MeV (target)
Background issues

5.0-5.5MeV

5.5-6.0MeV

6.0-6.5MeV

- Fiducial volume is central 13.3kt
- SK has lower background level in these central 13.3kt throughout the years of operation
SK-III: Less Radioactive Background

clean central
13.3kton
The two outputs (measured neutrino flux) of Kamiokande/Superkamiokande compared to the model prediction.
Scintillation technique

The scintillation technique is suited to build massive experiments devoted to the detection of low energy rare events.

In particular in the neutrino field this kind of technique has been exploited fruitfully for the

a) reactor neutrino experiments
   Gosgen
   Bugey
   Chooz
   Palo Verde
   Kamland

b) accelerator based experiments
   LSND
   Kameň

c) supernova neutrino experiment
   LVD

d) and for low energy solar neutrino detection
   Borexino
   LENS and SNO+ (planned)
Scintillation

Detection of ionising radiation through the scintillation light induced in special organic or inorganic materials.

Fundamental properties for a good scintillating material:
1. High scintillation efficiency
2. Linear dependence between energy deposit and produced light
3. Limited self absorption
4. Short decay time of the scintillation light (fast pulses generation)
5. Suited to be easily shaped in various forms and dimensions
6. Refractive index similar to the glass (phototube matching)
Light emission process

1. **Fluorescence**: prompt emission of visible radiation after original the material excitation

2. **Phosphorecence**: emission of visible radiation of longer wavelength than fluorescence, with longer decay time

3. **Delayed fluorescence**: production of emission light of wavelength equal to that of fluorescence emission, but with emission time substantially longer
Scintillating materials of common use

1. Plastics, liquids and some crystals realized with aromatic polycyclic hydrocarbons with one or more benzene rings (organics)

2. Alkali Halide Cristals (inorganic materials)

Organic scintillators: fast response but less emitted light

Suited for beta spectroscopy and fast neutron detection

Inorganic scintillators: better light yield and linearity, but longer time response. Particularly good for gamma spectroscopy (high Z and density)
Scintillation mechanism in organic materials

The fluorescence process takes place in transition between the energetic levels of the single molecule, independently from its physical state.

In the so-called polycyclic aromatic hydrocarbons the molecular level involved in the process are the so-called electronic level $p$ which stem from the trigonal hybridisation ($sp^2$) of the four valence electrons of the carbon atoms at the vertex of the hexagonal planar molecule $C_6H_6$ (benzene ring).
Electron configuration of the carbon atom in the ground state

$$1s^22s^22p^2$$

Configuration of the carbon atom ready for the chemical binding

$$1s^22s^22p^3$$

Possible hybridisation of the 4 valence electron orbitals

1. Tetraedric or sp$^3$: 4 equivalent orbital spatially directed according to the vertex of a tetraedric, angle 109 28'. (diamond, methane). Non luminescent materials.
2. **Trigonal or sp²**: an unaltered p orbital (π) and three equivalent orbital (σ), coplanar and at 120 degree. This is the typical hybridisation of the aromatic polycyclic hydrocarbons (planar and luminescent molecules). The π orbital is symmetric with respect to the plane of the σ bounds (molecular plane).

3. **Digonal or sp**: two unaltered p orbitals and two equivalent orbitals at 180 degree. Linear molecules as acetilene.
Benzene

In Benzene the $\sigma$ orbitals interact as shown in the figure giving rise to localized $\sigma$ binds C-C and C-H.

The six atomic orbital $\pi$ interact originating molecular orbitals $\pi$ completely delocalised whose excited states cause the molecular luminescence.
Delocalized molecular orbital
Energetic levels of the molecular orbitals $\pi$

S0, S1, S2 .... spin 0 levels (singlet level)

T0, T1, T2.... Spin 1 levels (triplet levels)

The dashed sublevels (spacing around 0.15 eV) are vibrational molecular levels

S0 - S1 gap $\sim 3 - 4$ eV

The highest excited states de-excite to S1 through non-radiative internal conversion in time interval of ps. Also thee vibrational levels S11, S12..... go rapidly to S10.
Fluorescence

Transition between $S_{10}$ and one of the levels $S_0$:

fluorescence (main component of the scintillation light)

Fluorescence Decay time of the $S_{10}$ level: $\tau$

Time profile of the fluorescence light intensity: $I = I_0 e^{-t/\tau}$

$\tau \sim$ few nanoseconds in the majority of the organic scintillators
Phosphorescence

Populating $T_1$

1. Non radiative transition $S_1 - T_1$ (intersystem crossing)

2. Direct ion recombination to $T_1$

Phosphorescence light originated in the (highly inhibited) transition $T_1 - S_1$. Wavelength longer than in the fluorescence case since $T_1$ is below $S_1$

$T_1$ lifetime: $10^{-3} - 10^{-4}$ s
Delayed fluorescence

Inverse transition $T_1 - S_1$ followed by a normal fluorescence decay. The transition takes place according to the so called triplet annihilation reaction

\[ T_1 + T_1 \rightarrow S_1 + S_0 + \text{phonons} \]
Emission and absorption spectra

The transparency of an organic scintillator to its own light is measured by the relative displacements of the two spectra (Stokes shift).

Since the excitation transitions require photons of energy higher that those resulting from the de-excitation the emission spectrum is shifted towards the right with respect to the absorption one.

The overlapping region corresponds to the de-excitation $S_{10} - S_{00}$
Scintillation efficiency

Fraction of the energy of the incoming particle converted into visible light.

Competing non radiative de-excitation modes limit the energy available for light production (quenching, heat production).

The oxygen dissolved in the liquid scintillator is an important additional quenching factor, which has to be removed.

By exploiting the energy migration process typical of the hydrocarbon solvent through the addition of a small quantity of an high efficiency solute the overall efficiency is highly enhanced:

Binary plastic or liquid scintillators
Pulse shape discrimination

The fast fluorescence component is followed by the slow component due to the phosphorescence and delayed fluorescence whose origin is connected to the presence of the so called triplet state $T_1$ (typical time of hundreds of nanoseconds).

The light fraction which is comprised in the slow component depends upon the particle type

**Discrimination of particle types**

The density of the triplet states increases as function of the specific loss ($dE/dx$) of the incident particle

**Tail more pronounced for heavily ionising particles**
Pc+pmp (6.6 g/l)

Contesti

Canale (1024–500 ns)

$\alpha$

$\beta$
Time evolution of the fluorescence light

Unitary scintillator: monoexponential decay

Taking into account the population process of the optical levels:

\[ I = I_0 (e^{-t/\tau_1} - e^{-t/\tau}) \]

\( \tau_1 \): time constant for the population of the optical levels

\( \tau \): time decay constant of the optical levels

For a fast scintillator \( \tau \sim 3 - 4 \tau_1 \)

Binary or ternary scintillators: one or two more exponential terms
Some examples of scintillator based detectors

Borexino (low energy solar neutrino detector) described in the following at length as paradigmatic example of a scintillator detector

Chooz (reactor neutrino detector)

KamLAND (reactor neutrino detector)

Planned: SNO+ and LENS