Simulation of muons energy loss in lithium hydride for the neutrino factory design study

Saurabh Kumar Vij
Delhi University, India

&

ENSTA Paristech, France
Plan of the talk

- Neutrino and neutrino oscillations
- The neutrino factory
- Description of the simulations
- Results
- Conclusion
In the Standard Model, neutrinos interact through the weak force and they have no charge and no mass.
Neutrino oscillations – the dance of flavours

- Neutrinos have this weird property called neutrino oscillations.
- Neutrino with one flavour (e.g. $\nu_e$) changes to neutrino of other flavour (e.g. $\nu_\mu$).
- Experiments all around the globe have demonstrated this strange phenomena.
- Oscillation probability is given by:

$$P_{\alpha \to \beta} = \delta_{\alpha \beta} - 4 \sum_{i>j} \text{Re}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right) + 2 \sum_{i>j} \text{Im}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin\left(\frac{\Delta m_{ij}^2 L}{2E}\right)$$

- This represents the probability that a neutrino originally of flavour $\alpha$ will later be observed as having flavour $\beta$.
- This probability depends upon the square difference in the mass eigenstates of the neutrino ($\Delta m_{ij}^2 = \Delta m_{i}^2 - \Delta m_{j}^2$), the energy of the neutrino $E$, the travel length of the neutrino $L$ and coefficient of the mixing matrix $U_{\alpha i}$.
- So, if there is a non-zero probability of occurrence of neutrino oscillation then neutrinos should have mass.
The neutrino mixing matrix

\[ U_{\alpha i} \text{ is a function of the mixing angles } \theta_{12}, \theta_{23}, \theta_{13} \text{ and a CP phase violation term } \delta. \]

The matrix \( U_{\alpha i} \) links the mass eigenstates to the flavor eigenstate:

- The vector on the left hand side represents the neutrino flavour eigenstates.
- The vector on right side represents the neutrino mass eigenstates.
Over ten years of precision measurements have been done and this is what has been measured.

\[
\Delta m^2_{21} = 7.65^{+0.23}_{-0.20} \times 10^{-5} \text{ eV}^2
\]

\[
|\Delta m^2_{31}| = 2.40^{+0.12}_{-0.11} \times 10^{-3} \text{ eV}^2
\]

\[
\sin^2 \theta_{12} = 0.304^{+0.022}_{-0.016}
\]

\[
\sin^2 \theta_{23} = 0.50^{+0.07}_{-0.06}
\]

- We still do not about the mixing angle \( \theta_{13} \), the CP phase violation term \( \delta \) and the sign of \( \Delta m^2_{31} \).

Therefore we need more precise measurements. This is why we want to build a machine that can produce an intense neutrino beam to study these parameters.
The Neutrino Factory

Distance from the ring to the far detector – 7500 km

Distance from the ring to the far detector – 3000-5000 km

$10^{21}$ ν per year

(1 year = $10^7$ sec)
Muon Front-end

Front-End of the neutrino factory design

Muons phase space occupancy for the different front-end sections

Fast muons arrive early: decelerated

Slow muons arrive late: accelerated
Muon Front-End (contd.)

- The pions produced by bombarding protons on a Hg target are first captured.
- Then they enter the muon front-end where they decay into muons in a long drift region.
- An energy-time correlation is developed in the drift region.
- Bunching: creates a train of particle with small $\Delta t$ and high $\Delta p/p$.
- Rotation: reduces the momentum spread $\Delta p/p$.
- Cooling: final stage where muons loose momentum in absorbers by ionizing the material and gain longitudinal momentum in the cavity.
- Transverse emittance of the muons is reduced.
- So it is important to study the best absorber material.
Muons cooling with lithium hydride (LiH) absorbers and RF cavities

Sketch of cooling principle:
• Muons passing through the absorber material loose momentum in all directions
• The accelerating RF system placed after the absorber restores only the longitudinal momentum
• The divergence of the beam is thus reduced (and so the beam emittance)
My work

- Simulation study of muons energy loss through LiH using Geant4.
- Simulations were done for lithium with different fraction of $^6\text{Li}$ and $^7\text{Li}$ isotopes and were compared with data from the Particle Data Group.
- In order to understand the difference in the models used and estimate the difference in energy loss when the properties of the compound are changed.
- Geant4 simulation output used for the ROOT data analysis package.
Types of absorbers considered and LiH properties.

For the process of ionization cooling many different absorbers were considered, the best absorber material seems to be liquid hydrogen (H₂) and lithium hydride (LiH).

- Lithium is found in nature as a mix of ⁶Li (7.5%) and ⁷Li (92.5%).

**LiH properties**

- Lithium hydride is a salt-like crystalline compound.
- LiH is chemically reactive and must be protected from atmospheric moisture.
- LiH properties depend on composition of Li used and purity.
1000 MeV/c momentum muons pass through a fixed LiH box: simulation study using Geant4 and ROOT

- Geant4 provides a complete set of tools for all areas of detector simulation: geometry, tracking, detector response, run, event and track management, visualization and user interface.

- Simulations were done using LiH of different compositions, either with 100% $^6$Li or 100% $^7$Li.

- ROOT is a software tool used to analyze the data.

- The output from Geant4 is used as an input for the ROOT for further analysis.

- Comparisons were made between the data provided by running different simulations and from the data provided by the PDG (Particle Data Group).
Simulation using Geant4

Green = neutral particles like gammas
Red = negatively charged secondary particles like electrons
Blue = muons
Scatter plot showing the Energy loss by 1000 muons each with momentum 1000 MeV/c passing through LiH with 100% $^6$Li

- For further comparison, we calculate the mean $<\frac{dE}{dX}>$
- Calculation method:
  - $P =$ momentum
  - $P_i =$ boundary bins (e.g. $P_i =$ 50, 100, 150 ....... 1000 MeV/c)
  - Loop over i check
    - If $P_i \leq P < P_i + 50$ MeV/c
      - sum = sum + $\frac{dE}{dX}$
    - $N = N + 1$, where $N$ is the number of data points falling in this range.
  - At the end and after the loop:
    - $<\frac{dE}{dX}> =$ sum / N

This is energy difference per cm normalized by the density
Comparison of GEANT4 simulation results with the PDG data

Saurabh Kumar Vij  Project presentation at University of Delhi, Delhi  December 10, 2010
Result and discussion

- From the comparison plot, it is quite evident that the energy loss by muons in LiH is different for different compositions of LiH.
- For the range 200-400 MeV/c, the difference in $<dE/dX>$ between LiH with 100% $^6$Li and LiH with 100% $^7$Li is shown below.
- In this range, we have points within the range (2.2 – 2.0) and (1.9 – 1.7), so taking an average, we can choose the value 2.1 for the red points and 1.8 for the blue points, so the difference would be $(2.1 - 1.8)/1.8 = 0.167 \sim 16.7\%$.
- Surprising result, as the $<dE/dX>$ values of LiH with $^6$Li are closer to the PDG data values.
- Expected result would have been that LiH with 100% of $^7$Li would give $<dE/dX>$ values closer to the PDG data values (because of the density values).
Conclusion and further studies

- Difference was found in the $\langle \mathrm{dE/dX} \rangle$ values, when LiH with different Li isotope compositions were used.
- We expected the PDG data to be closed to the $^7\text{Li}$ curve than the $^6\text{Li}$ due to the density values used.
- Further study will be done by keeping the same material density for $^6\text{Li}$ and $^7\text{Li}$ and checking whether the isotope factor plays an important role on the $\langle \mathrm{dE/dX} \rangle$ or not.
- Also studies on the LiH contamination in the material will be done.
Thank you

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Spare Slides
Solar neutrino problem
comparison of neutrino flux from experiments and theory
Solar neutrino problem

- Sun produces a lot of neutrinos by the fusion reaction between hydrogen atoms to form helium.

From the plot, we can clearly see that there is a noticeable difference between the neutrino flux predicted by the standard solar model and the flux that we got from different experiments demonstrated all around the globe.
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Where are the MISSING neutrinos? ?????