IsoDAR Neutrino Experiment Simulation with Proton and Deuteron Beams *

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Abstract:
In this paper we consider high-intensity source of electron antineutrinos from the production and subsequent decay of $^8$Li. It opens a wide range of possible searches for beyond standard model physics via studies of the inverse beta decay interaction. In IsoDAR experiments Lithium 8 is a short lived beta emitter producing a high intensity anti-neutrinos, which is very suitable for making several important neutrino experiments. In this paper we used the GEANT4 program. to simulate neutrino production using proton and deuteron beams. We find that the neutrino production rate is about 3 times from deuteron beam than from proton beam in low energy region.

Key words: IsoDAR, neutrino, Geant4 simulation, ADS

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1 Introduction

As the next step, neutrino physics requires high intensity experiments for precision measurements. We propose the neutrino experiment on proton or deuteron beam hits target. The Isotope Decay At Rest (IsoDAR) technique provides a high-intensity, low energy source of antineutrinos with sensitivity to antineutrino oscillations. The experiment can perform compelling tests of models for new physics that explain high $\Delta m^2$ oscillations through the introduction of one or more sterile neutrinos.

IsoDAR can emit anti-electron neutrino at a rather high-flux by beta decay of short lived isotope. Lithium 8 is a nice candidate of this isotope and it can be produced by injection of proton or deuteron on a beryllium 9 target. To meet the required neutrino flux of oscillation experiment, the intensity of proton beam should be at least 10 mA with energy of $60 \sim 1000$ MeV. This requirement is the main limitation to IsoDAR source for the last decades. But now, by taking advantage of high intensity proton beam technique, this becomes very promising and worth a detailed simulation. IsoDAR sources provide an opportunity for the precision measurements required for the future of neutrino physics.

2 IsoDAR Design

Fig. 1. Initial design for IsoDAR target.

Fig. 1 shows initial design for IsoDAR target (Ref. [4]). It's like a neutrino converter: absorb proton (or deuteron) and then emit neutrino.

When proton inject on the Beryllium target, several interactions happen subsequently:

$$p + ^9 Be \rightarrow ^8 Li + 2p$$  (1)
\[ p + ^9 Be \rightarrow n + p + ^4 He \]  
(2)

\[ n + ^7 Li \rightarrow ^8 Li \]  
(3)

\[ ^8 Li \rightarrow \nu_e + e + ^8 Be \]  
(4)

With proton beam incidences, the Beryllium 9 target can produce Lithium 8 and neutron, to which we pay more attention, as Eq. 1 and Eq. 2 describes. Also, we can see from Eq. 3 that the production of neutrino is directly related to that of Lithium 8. So in our primary design, there is a FLiBe sleeve outside and inside of the Be target respectively to absorb neutrons and produce Lithium 8, which process is described by Eq. 3. FLiBe is molten salt made from a mixture of lithium fluoride (LiF) and beryllium fluoride (BeF₂) with abundance of Li up to 99.99%. It has a high melting point and a better mechanical property compare to elemental Lithium. The heave water between Be target and inner FLiBe sleeve is moderator for neutron to improve its absorptivity by Li, besides, the heavy water sleeve can be design as cooling system to carry out heat from beam injection. The graphite layer outside the outer FLiBe sleeve is set as a reflector to improve the utilization for neutron. To prevent neutron radiation, a thick concrete sleeve is set outside covering the whole equipment as a shielding layer.

While using Geant4 to simulate interactions of neutrino production, we need to specify relevant model for every process and every particle, i.e., the PhysicsList package in Geant4. In our primary simulation, we choose QGSP_BIC_HP, a reference physics list from Geant4, to describe relevant reaction channels and cross section. This package implies quark gluon string model to high energy interaction (5-25 GeV), the excited nucleus created is then passed to the pre-computed model modelling the nuclear de-excitation. As for interactions below 10 GeV, it uses binary cascade model (BIC) to describe the propagation of incident hadron and secondary through nucleus, which is regard as a series of two-particle collision. For energy from 20 MeV down to thermal particle, this model takes data driven high precision neutron package (NeutronHP) to transport neutrons below 20 MeV down to thermal energy. Compare to other physics list package, QGSP_BIC_HP is able to rebuild the production of secondary particles from p-A or n-A interactions well and is more precise in low energy region. It can gives us a more accurate isotope production rate and neutrino distribution in IsoDAR.

3 Simulation Results

In the present work, the GEANT4 simulation code [3] has been used to simulate the low-energy protons induced isotopes production in Be targets.

After a simulation of a number of proton incidence, we can get the neutron spectra crossing different barrier components as Fig. 2 shows:

![Neutron spectra](image)

From the above figure we can see the following points:

1. A mass of neutrons are produced after protons incidence. And the neutrons coming from Be target to heavy water sleeve has the highest average energy.

2. We can see the moderator effect of heavy water.

3. Many neutrons escape out from the target sleeve, so it’s necessary to add a thick FLiBe sleeve surrounding target to have a good usage of neutrons.

Besides, we can get the isotope production in different parts from proton incidence and deuteron incidence.
Fig. 3. Isotope production in different parts. Top: 60 MeV proton incidence; Bottom: 80 MeV deuteron incidence.

We can see from Fig. 3 that Li8 is mainly produced in the outer FLiBe sleeve, which is reasonable as more neutrons enter into this sleeve. Also, we can see that Deuteron’s Li8 production rate is higher than Proton’s. This result is meaningful and worthy of further research as it will tell us which incident beam is better in IsoDAR experiment. So we have a comprehensive comparison between proton and deuteron incidence with different energies.

Fig. 4 shows the production rate of Neutron and Li8 respectively with different incident energy for proton and deuteron beams. We can see approximately a linear relation between production rates and incident energies. We fit the two plots and get the following formulas. For the neutron production rate,

\[ N_{Pn} = 2.7 \times 10^{-3} \times E^{1.2}, \]  
\[ N_{Dn} = 1.1 \times 10^{-2} \times E^{1.1}. \]  

and for Li8,

\[ N_{PLi8} = 1.4 \times 10^{-4} E^{1.2}, \]  
\[ N_{DLi8} = 9.1 \times 10^{-4} E^{-0.94}. \]  

Here, \( N_{Pn} \) and \( N_{Dn} \) corresponds to the neutron production rate for proton incidence and deuteron incidence respectively, while \( N_{PLi8} \) and \( N_{DLi8} \) means the Li8 production rate. \( R^2 \)s in the above plots are close to 1, which means this linear fitting is pretty accurate. Compare proton’s production rate at 100 MeV and deuteron’s production rate at 200 MeV, we can see that the later is not simply twice as many as the former. This indicates that our simulation includes the nucleus effect, which is more realistic.

To have an intuitive comparison between proton and deuteron beams, we have this picture below.

Fig. 5. Li8 production ratio (Blue) and neutron production ratio (Red) of Deuteron injection over Proton injection. This two sets of data have been fitted with a power function: \( \text{ratio} = p_0 \times E^{p_1} \)

In Fig. 5 we compare the neutron and Li8 production rate for proton and deuteron incidence with different energy, and then fitted them with power function respectively. We can see that in the low energy region around
100 MeV, the Li8 production rate for deuteron is about three times of that for proton. But as beam energy increases, the ratio approaches to about 1.5. So we can expect that several hundred MeV deuteron beam has much advantages than proton beam with half energy to generate neutrino.

![Graph showing energy spectrum of Li8 isotope](image)

Fig. 6. The Li isotope DAR anti-electron-neutrino flux spectrum distribution.

We simulate one hundred thousand Li8 decay at rest. The neutrino spectrum produced from IsoDAR Li8 is shown in Fig. 6 we can see that the spectrum is in agreement with experimental result [7].

4 Discussions and Conclusions

IsoDAR represents both a novel concept of application to neutrino physics measurements. Neutrino experiment on the China Accelerator Driven Sub-critical System (ADS) is being proposed [8]. The first phase of ADS is named China Initial ADS (CIADS). The CIADS facility will offer the highest intensity protons or deuteron beams over the world with energy between dozens of MeV and 1 GeV.

IsoDAR is a novel design, extensive and precise simulations targeting the most challenging aspects of experiments are highly required. In this preliminary simulation, we can see that by taking advantage of ADS technique, IsoDAR is a feasible neutrino source for experiment searching for sterile neutrino. And we recommend deuteron beam to hit the target as it has advantages over proton below 1 GeV. As we see, the deuteron beam has much advantage over proton beam around several hundred MeV. It will offer an opportunities for high precision neutrino measurements, such as sterile Neutrino Searches, precision electroweak tests of the standard model, and coherent neutrino scattering, etc.

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