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Original Citation

Bungau, Adriana, Barlow, Roger, Alonso, J.R., Conrad, J.M., Spitz, M. and Shaevitz, M.H. (2013) Optimisation Studies of a High Intensity Electron Antineutrino Source. In: Proceedings of the 4th International Particle Accelerator Conference. IPAC 2013 . JACoW, Shanghai, China, pp. 449-451. ISBN 978-3-95450-122-9

OPTIMISATION STUDIES OF A HIGH INTENSITY ELECTRON ANTINEUTRINO SOURCE

Adriana Bungau, Roger Barlow, University of Huddersfield, United Kingdom
Michael Shaevitz, Columbia University, USA
Jose Alonso, Janet Conrad, Joshua Spitz, Massachusetts Institute of Technology, USA

Abstract

ISODAR (Isotopes-Decay-At-Rest) is a novel, high intensity source of electron antineutrinos produced by the decay of Li-8 isotopes, which aims for searches for physics beyond the standard model. The Li-8 isotopes are produced in the inelastic interactions of low energy protons or deuterons with a Beryllium target. In addition the Li-8 is produced in the surrounding materials by secondary neutrons. This paper focuses on the optimisation of the base design target, moderator and reflector.

INTRODUCTION

Li-8 is a short lived beta emitter that produces a high energy antineutrino flux which is very suitable for studies of antineutrino disappearance due to oscillations. An underground liquid scintillator detector will detect the antineutrinos via the inverse beta decay process. The ISODAR design [1] consists of an ion source, a cyclotron that initially was designed to accelerate 60 MeV/amu H_2^+ ions [2] although an alternative 80 MeV deuteron beam is considered, and a target. The current target design is based on the design presented in paper [3] and it consists of a 10 cm radius, 20 cm long Beryllium target surrounded by 5 cm thick heavy water moderator enclosed in a Li-7 sleeve. The sleeve is 150 cm long and the radius has been reduced to 50 cm. A 300 cm long graphite reflector with a radius of 150 cm is surrounding the sleeve. Beryllium was chosen as target material because it has the smallest binding energy for neutrons of any stable element and it also has a high melting point and thermal conductivity and is less reactive with air. The current target design is optimised to maximise the anti-neutrinos from isotopes that decay at rest if a deuteron beam will be used instead of protons and the simulation results with the GEANT4 code are presented in this paper.

THE GEANT4 MODEL

Although the GEANT4 code has an extensive set of theoretical, parameterised and data driven hadronic models, they cannot reproduce experimental data at low energies below 100 MeV for proton and deuteron projectiles especially for low Z targets. The standard physics models used for these type of simulations were theoretical models and initial studies of deuterons on Beryllium targets have shown these models to breakdown at these extremes. In the light of these results obtained using the theoretical models a new data driven model has been developed by Geant4 developers to simulate proton and deuteron interactions at low energies. The new charged_particle_hp package uses evaluated nuclear databases from ENDF or TENDL libraries which refer to the total cross sections, inelastic channel cross sections, double differential spectra of outgoing particles and gamma emission due to nuclear level transitions for protons, deuterons, tritium, He3, alpha and gamma projectile below 200 MeV. This new model was validated against experimental data from the SF cyclotron of the Institute for Nuclear Study at the University of Tokyo [4] where a 9 mm thick Carbon target was bombarded by an accelerated beam of 33 MeV deuterons and the neutron flux emitted at 0, 15, 45, 75 and 135 degrees with respect to the beam axis was recorded. The neutron energy spectra of Carbon at the above emission angles normalised to one incident particle are shown in Fig. 1. The neutron spectra has one component below 10 MeV which corresponds to neutrons produced isotropically by the nuclear evaporation process following the deuteron inelastic interaction, and a second component above 10 MeV corresponding to the neutrons produced in the deuteron break-up processes. The later one has a broad peak at lower angles due to the neutron forward emission, which is centered around half the incident deuteron energy, but it becomes softer at large angles where the evaporation process is prominent. The simulation results are in good agreement with the published experimental data [4].

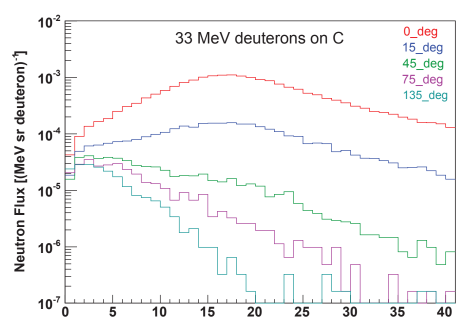

Figure 1: Neutron spectra of carbon for 33 MeV deuteron at emission angles of 0, 15, 45, 75 and 135 degrees.

TARGET SIMULATIONS

The goal is to design a neutrino target to produce 2.6×10^{22} electron antineutrinos per year with a mean energy of 6.4 MeV. Design considerations refers firstly to a high antineutrino flux and a low background but the target should

ISBN 978-3-95450-122-9

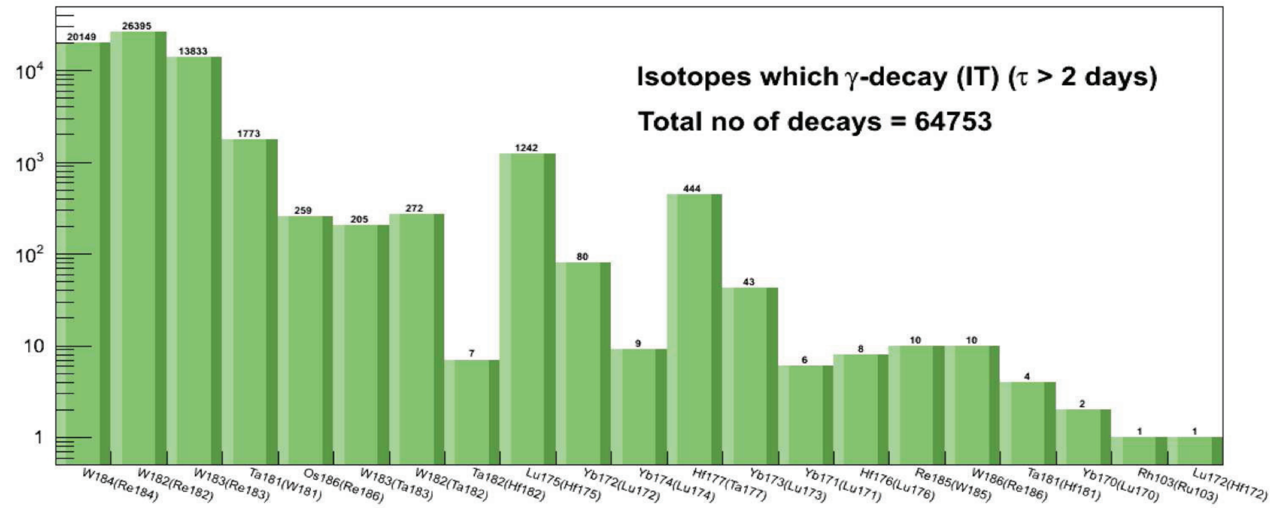

Figure 2: Tungsten target activation after two days. The radioactive isotopes are shown together with the parent nucleus from which they are produced. Results are for 10^7 protons on target.

also pose a low technical risk and be designed for underground operations. Previous studies using a proton beam have shown that high Z materials like Tungsten give a higher Li-8 yield (Table 1). These results are for 10^7 protons on target. However, simulation studies have shown that a Tungsten target would produce a large number of radioactive isotopes (Fig. 2) and the induced radioactivity would make the target handling extremely difficult in a confine space in an underground tunnel. Therefore low Z materials were preferred instead of Tungsten.

Table 1: Li-8 yield in alternative target materials for several incident proton energies. Results are for 10^7 protons on target.

Ep (MeV)	Be	W	Cu
30	30204	34051	23151
40	49539	75416	46028
50	86333	132151	75777
60	142689	200918	112004

The next step was to look at the deuteron beam alternative and to adapt the target and the surrounding components to accommodate the more forward-peaked distribution of higher-energy neutrons. Using deuterons instead of protons would require a smaller cyclotron that would fit inside the Kamland tunnel where the experiment is proposed to take place. For 60 MeV proton beam impacting on a Be target the figure of merit is 0.0145 Li8 isotopes per proton in both target and sleeve. For deuterons the trend is higher energy more neutrons are produced and implicitly more Li8 isotopes, so the deuteron energy needed should be what would at least match the isotope yield from 60 MeV protons. Simulations have shown that a 80 MeV deuteron beam produces almost three times more Li8 isotopes (0.0392 Li8 per projectile) while a 120 MeV deuteron beam produces 0.07169 Li8 isotopes per deuteron. The difference is due to the fact that the 120 MeV deuteron has a lower (dE/dx) than the 60 MeV proton, and the penetration depth in Be is twice than that for the proton. In addition we have to consider the neutrons coming directly from the break up deuterons which in turn can produce further neutrons via:

$$n + ^9Be \rightarrow n + n + ^8Be \rightarrow n + n + \alpha + \alpha \qquad (1)$$

The net efficiency for 80 MeV deuterons is 2.7 times higher than for 60 MeV protons indicating that we can use this energy and proceed further with target optimisation.

Using this energy and reducing the Lithium sleeve radius to 50 cm, the Li8 isotope production did not decrease substantially. For 5×10^8 deuterons on target, the Li8 yield has been reduced from 1.87×10^7 to 1.58×10^7 isotopes in both target and sleeve. Carbon was considered an alternative target material as it has a lower specific heat capacity and thermal conductivity than Beryllium and it is much easier to handle. However it was found that for a 5 cm long Carbon target the Li8 yield is 35% of the initial yield in 20 cm Beryllium as the neutron production is much lower (2.8×10^7 neutrons in Carbon compared with 8×10^7 neutrons in Beryllium).

An alternative target design was considered to be a 5 cm Carbon followed by 20 cm Beryllium and the isotope yield is shown in Fig. 3. However, the total Li8 production is reduced to 44% of the yield when the 20 cm Be target is used. This suggested that Beryllium produces more secondary neutrons than Carbon. The Li8 distribution along z have shown that more neutrons were produced backwards, the yield increasing towards the sleeve margin. The target was moved more central towards the opposite sleeve edge so that more neutrons can be produced. However the

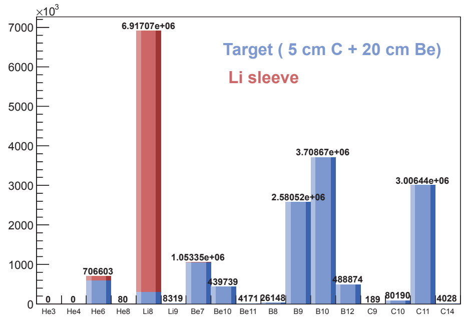

Figure 3: Isotopes production for a target consisting of 5 cm C followed by 20 cm Be. Results are for 5×10^8 deuterons.

Li8 production varied slightly, only the isotope distribution along z for target positions between (35 cm, -35 cm) in 5 cm step changed. The Li8 yield increased towards the opposite sleeve edge as the target was moved closer to it suggesting that is due to the low energy neutrons reflected back in the sleeve by the graphite.

Another target design that was considered was a 2 cm Beryllium followed by 3 cm of Carbon and 20 cm Beryllium. The Carbon layer is inserted at the Bragg peak location to dissipate the heat deposition. The isotope yield with this geometry is presented in Fig. 4. The total Li8 production is reduced to 88% of the yield when the 20 cm Be target is used. The target was positioned at the centre of the geometry set-up. A transverse x versus y Li8 yield distribution is shown in Fig. 5. It can be seen that the isotope production can be increased even further by using a better moderator. Currently, the 5 cm heavy water can not moderate the high energy neutrons and a fraction of them pass through the Li sleeve producing Li8 in the graphite reflector via this process:

$$n +^{12} C \rightarrow p + \alpha +^{8} Li \tag{2}$$

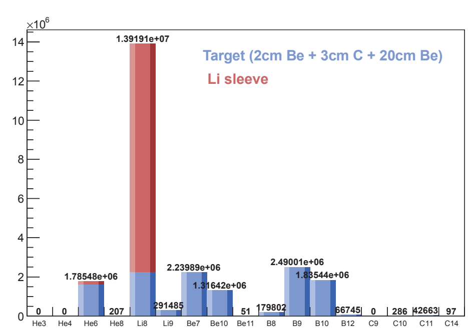

Figure 4: Isotopes production for a target consisting of 2 cm Be followed by 3 cm C and 20 cm of Be. Results are for 5×10^8 deuterons.

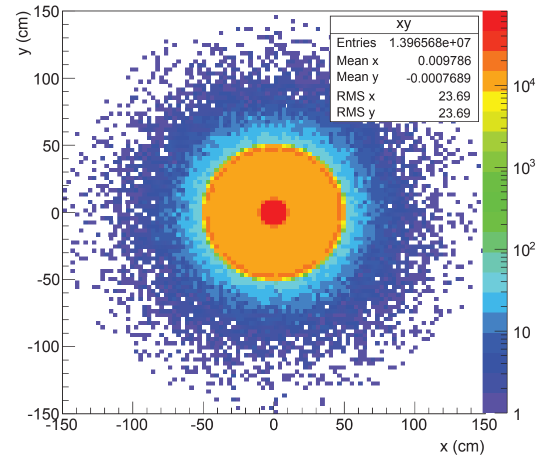

Figure 5: Isotopes X-Y transverse distribution for a target consisting of 2 cm Be followed by 3 cm C and 20 cm of Be. Results are for 5×10^8 deuterons.

CONCLUSIONS

A successful low energy data driven model for proton and deuterons projectiles has been developed and tested. This new model can be used in Geant4 for the first time in order to simulate the low energy deuteron interactions applicable for this study. Both for proton and deuteron projectiles, the Li8 isotopes production is due mainly to secondary neutrons inelastic interactions. However for deuteron projectiles, the neutrons are produced not only in nuclear evaporation, but also as a result of the deuteron break-up processes. These processes produce high-energy neutrons preferentially in the forward direction. Especially if a Be target is used, these neutrons will also produce additional secondary neutrons which, if thermalized, will be captured inside the surrounding Li sleeve, resulting in Li8 production. In order to dissipate more easily the heat deposition inside the target, a 3 cm Carbon layer has been proposed to be added around the Bragg peak location, having 2 cm of Be in front and 20 cm of Be behind it. This new design results in a total Li8 yield being equal to approximately 88% of the yield when only a 20 cm Be target was used.

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