Physics process of cosmogenics $^9$Li and $^8$He production on muons interactions with carbon target in liquid scintillator

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Abstract

Simulations were performed with Geant4 to study the cosmogenics $^9$Li and $^8$He production by the interactions of the muons and their secondary shower particles in the liquid scintillator. The photonuclear reactions seem dominate their production. Their energy dependence were deduced. The results of the simulations are compared with available data.

PACS: 05.10.Ln; 24.10.Lx; 25.20.-x; 25.30.Mr

Key words: Geant4; Photonuclear; Muon; $^9$Li; $^8$He

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1 INTRODUCTION

In reactor neutrino experiments the standard detection reaction is the inverse beta decay:

\[ \bar{\nu}_e + p \rightarrow n + e^+ \]

The positron makes a prompt signal with energy \( \sim 1 \) to 8 MeV and the neutron produce a delayed signal after capture in gadolinium with energy \( \sim 8 \) MeV. The detection signal can be mimicked by a radioactive isotopes (like \( ^8\text{He} \), \( ^9\text{Li} \) and \( ^{11}\text{Li} \)) which decay by \( \beta \)-neutron cascade. This kind of isotopes is produced by the cosmic muons and their shower particles interactions with the carbon nuclei which is the main component of the liquid scintillator. Because these isotopes are produced by cosmic muons interactions they are called cosmogenics. The main problem with the cosmogenics is due to their long life time (178 ms for \( ^9\text{Li} \) and 119 ms for \( ^8\text{He} \)) which make them untagged by the veto system. Therefore the simulation to evaluate their rate for each reactor neutrino experiment becomes crucial. The knowledge of the physics processes behind cosmogenics production is of first interest in order to perform their rate simulation.
2 $^9\text{Li}$ and $^8\text{He}$ YIELD

The importance of the electromagnetic and hadronic cascades in the neutrons production in the liquid scintillator are discussed in different works [1,2]. In this paper I investigate on their importance on the cosmogenics $^9\text{Li}$ and $^8\text{He}$ production.

One physics process which can contribute to the cosmogenics production in the liquid scintillator is the real photonuclear reaction. The gammas source is the muons and their shower particles Bremsstrahlung. As shown in Fig. 1, where are plotted different gammas spectra, one from muons Bremsstrahlung and the other from delta ray and ionization electrons Bremsstrahlung, the gammas are mainly produced by muons shower particles Bremsstrahlung. The gammas will be produced on the surrounding rock and propagate inside the detector, the use of shielding will minimize their impact, also the gammas can be created inside the detector but the production of gammas in this case is not as important as the one on the rock.

To evaluate the yield of $^9\text{Li}$ and $^8\text{He}$, I performed a simulation with Geant4 Monte Carlo code (release 7.1) [3]. The geometry used is a simple cube made of $^{12}\text{C}$ in which I shot a beam of $10^7$ monochromatic energy gammas. To cover different interaction regions, the gammas energies were chosen like following: $20$ MeV, $30$ MeV, $50$ MeV, $80$ MeV, from $100$ MeV to $1000$ MeV by step of $100$ MeV and from $1$ GeV to $4$ GeV by step of $0.5$ GeV. I obtained $^9\text{Li}$
and $^8$He production only in the region corresponding to the interval of energy going from 100 MeV to 2 GeV. The Figure 2 shows the cross section obtained from the simulation as a function of the gamma energy. The variation of the energy goes from 100 MeV to 2 GeV, this energy range cover three different interaction regions: $\Delta$ region (from the pion threshold to 450 MeV), Roper resonance region (from 450 MeV to 1.2 GeV) and Reggeon-Pomeron region ($> 1.2$ GeV). Below 3 GeV, to generate the final state for gamma-nuclear inelastic scattering, the real photonuclear interaction, Geant4 uses a chiral-invariant phase space model [4]. In Geant4 the photonuclear cross sections are parametrized from several measurements performed for many nuclei and cover a large range of gamma energy [5]. Figure 3 shows the comparison between the photonuclear cross sections obtained from simulating the interactions of $10^7$ gammas on 1 meter of $^{12}C$ and one set of available data [6], we can observe the good agreement between the simulation and data, more comparisons were made in the Ref. [5].

As we can observe from Fig. 2, $^9$Li is more likely produced than $^8$He and the cross section of the two isotopes increase with the gamma energy to reach its maximum around 2.3 $\mu$barn for a gamma energy about 300-400 MeV and decrease with increasing energy. In fact the evolution of the cosmogenics cross section follows the total photonuclear cross section behavior and the maximum of cosmogenics cross section corresponds to the maximum of total real photonuclear reaction cross section as shown in Fig. 3.
Only one experiment was dedicated to investigate the cosmogenics production in muons beam interaction with scintillator target at SPS [7]. During this experiment no distinction between $^8$He and $^9$Li was possible due to their neighboring half-lives. The measured cross section for $^9$Li and $^8$He with 190 GeV muons beam is $\sigma(^9\text{Li} + ^8\text{He}) = (2.12 \pm 0.35) \mu\text{barn}$.

3 ENERGY DEPENDENCE OF THE $^9$Li and $^8$He YIELD

At SPS experiment the energy dependence of the total cross-section was evaluated to be $\sigma_{tot}(E_\mu) \propto E_\mu^\alpha$, $\alpha$ varies from 0.50 to 0.93 with a weighed mean value $<\alpha> = 0.73 \pm 0.10$. In order to extract the value of $\alpha$, the ratio of the total cross section at 100 and 190 GeV was performed. Nevertheless, the total cross section for $^9$Li and $^8$He production was obtained only for 190 GeV muon energy, thus these two last isotopes were not taken into account to determine the $\alpha$ parameter. This energy dependence of the isotopes production is well known as described in the Ref. [8].

In the current section I describe how I obtained the $\alpha$ value, corresponding to the cosmogenics $^8$He and $^9$Li production, via appropriate simulation. I used like a target a cylindrical bloc of scintillator made from dodecane (e.g. $C_{12}H_{26}$), the cylinder has radius of 1.7 meter and high of 3.5 meters. I put the target in the center of a bloc of the rock ($SiO_2$ cube of 6 meters size) in which I shot a $10^6$ monochromatic energy muons. Since the energy dependence of
the isotopes production is valid for a wide range of muons energy [8], it can be checked with any different energies chosen within this range. Therefore, I performed two simulations one with muon energy of 100 GeV and the second of 500 GeV. All the electromagnetic and hadronic processes were allowed for the muons and their secondary shower particles. The history of each produced isotope was traced back, but all the $^9$Li and $^8$He formed inside the target scintillator were only produced from the photonuclear reactions, the other processes like direct muon-carbon interaction, electron-carbon or neutron-carbon interaction didn’t produce any $^9$Li or $^8$He. Table 1 shows the obtained yield (the number of isotopes produced in each run) for each isotope produced in the target (the bloc scintillator) and the value of the $\alpha$ parameter at 100 and 500 GeV. To obtain the value of $\alpha$ I used the ratio of the simulated yield at 100 and 500 GeV, in the same way like in SPS experiment:

$$\alpha = \frac{ln(yield(500 \text{ GeV})/yield(100 \text{ GeV}))}{ln(500 \text{ GeV}/100 \text{ GeV})}$$

The values of $\alpha$ are in good agreement, within the error bars, with experimental ones [7,8].

4 CONCLUSION

Interacting cosmic muons initiate electromagnetic and hadronic cascades which dominate neutrons production [2]. In the case of the cosmogenics $^8He$ and $^9Li$, 

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the simulations with Geant4 shows that the real photonuclear reaction seems to be the main physics process in their production. The gammas are mainly produced by Bremsstrahlung of muons shower particles on the rock. After their creation the gammas propagate inside the detection volume where they interact with the carbon target to produce radioactive isotopes and secondary particles. The simulated values for $^9$Li and $^8$He cross sections are in agreement with SPS experiment. Also, the simulated energy dependence agree with those obtained from different experiments [7,8].

Acknowledgments

I would like to thank Prof. Jacques Martino for his several helpful advices and discussions through this work.

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Fig. 1. Gamma spectra produced by Bremsstrahlung process from interactions of 50000 muons with energy of 10 GeV through 10 meters on the rock.
Fig. 2. Cross section of $^9$Li and $^8$He production from interactions of $10^7$ gammas through 1 meter on the $^{12}$C.
Fig. 3. Photonuclear total cross section normalized by the mass number A as a function of gamma energy, obtained from interaction of $10^7$ gamma on 1 meter of $^{12}C$. 
Table 1
The yield (number of isotopes produced in each run) of $^9$Li and $^8$He produced in the target (the bloc scintillator) and the $\alpha$ value obtained for the different simulated energies.

| Isotopes | yield at 100 GeV | yield at 500 GeV | $\alpha$ parameter |
|----------|------------------|------------------|--------------------|
| $^9$Li   | 7                | 38               | 1.06               |
| $^8$He   | 2                | 7                | 0.78               |