GEANT4 SIMULATIONS OF THE ISIS MUON TARGET AT RUTHERFORD APPLETON LABORATORY

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Abstract

MuSR science requires the availabilty of intense beams of polarised positive muons. At the ISIS pulsed muon facility at Rutherford Appleton Laboratory the muons are generated from a low Z thin slab graphite target inserted in the proton beam. We report on the use of the Monte Carlo simulation code Geant4 in simulations of the performance of the current muon target. The results are benchmarked against the experimental performance of the target.

ISIS NEUTRON SPALLATION SOURCE

The ISIS spallation neutron source is a pulsed neutron source for condensed matter research. Negatively charged hydride ions of 70 MeV are injected from the linear accelerator into the synchtrotron where they are stripped of their electrons and accelerated to 800 MeV. The nominal beam current is 200 μA and the proton beam is double-pulsed at 50 Hz. The two pulses are directed along the proton beam channel to the intermediate muon target and then to the spallation neutron target. The muon target is inserted into the proton beam line and pions are produced as a result of the proton interaction with the target nuclei. Low-Z materials are used in order to maximise the pion production while minimising multiple scattering of the proton beam itself. The pions decay to muons and neutrinos.

THE ISIS TARGET

The intermediate target used for muon production is an edge-cooled plate of graphite with dimensions 5*5*0.7 cm oriented at 45 degrees to the proton beam giving an effective length of 1 cm along the beam. The plate is located approximately 20 m upstream from the target used for neutron production. The thickness of the intermediate target is limited by two factors: the proton transmission through the target must be kept at a reasonable level (usually 96%) to prevent the loss in neutron intensity at the neutron facility and the neutron background arising from the muon target must be low around the neutron scattering instruments. Water is used for cooling the target with the cooling system located outside the shielding of the proton beam. The muon beam is extracted at 90 degrees to the proton beam. The muon beam is separated from the main proton beam by a thin aluminium window situated at 15 cm from the target centre and having a diameter of 8 cm. Experimentally it was found that for $2.5\,10^{13}$ protons on target there are about 16000 positive surface muons counted at the entrance aperture of the beam window.

HADRONIC MODELS IN GEANT4

The Monte Carlo code GEANT4 [1] is a toolkit used to simulate particle interactions in matter and it provides a flexible framework for implementation of various types of hadronic interactions. A single hadronic model would not be able to support all user requirements, therefore GEANT4 provides an extensive set of alternative hadronic models. The intranuclear cascade model (INCL) was first proposed by Serber in 1947 [2]. This model is based on the fact that in particle-nuclear collisions, the deBroglie wavelength of the incident particle is comparable or shorter than the average intra-nucleon distance, therefore the interactions can be described in terms of particle-particle collisions. The INCL models have a wide range of applications and there was a renewed interest in them due to spallation neutron source studies. Several INCL models are implemented in GEANT4 and their performance was tested for various energy ranges, particle projectiles and target materials. Simulations of the ISIS muon target using three such models applicable in the energy range of interest are presented below.

BERTINI CASCADE MODEL

This model generates the final state for hadron inelastic scattering by simulating the intra nuclear cascade. In this model, incident hadrons collide with protons and neutrons in the target nucleus and produce secondaries which in turn collide with other nucleons, the whole cascade being stopped when all the particles which can escape the nucleus have done so. Relativistic kinematics is applied throughout the cascade and the Pauli exclusion principle and conformity with the energy conservation law is checked [3].

The Nuclear Model

The target nucleus is treated as an average nuclear medium to which excitons (particle-hole states) are added after each collision. The path lengths of nucleons in the nucleus are sampled according to the local density and free nucleon-nucleon cross sections.At the end of the cascade the excited nucleus is represented as a sum of particle-hole states which is then decayed by pre-equilibrium, fission and evaporation methods.

Model Limitations

This model has been validated by extensive simulations on proton-induced reactions in various target materials and is validated up to 10 GeV incident energy [4]. This model is performing well for incident protons, neutrons, pions, photons and nuclear isotopes.

Target Simulations Using Bertini Model

Simulations of the ISIS target were performed by sending $2.5\,10^{11}$ protons on target. The surface muons extracted at 90 degrees to the proton beam have a momentum range between 25.175 - 27.825 MeV/c as they come from pions decaying at rest and there are 12754 surface muons which fulfill this primary condition (Fig. 1).

The ISIS muon beamline viewing the target is tuned for surface positive muons and the particle acceptance must be taken into account. The particles must emerge from the target within ±0.5 cm vertically and ±3.0 cm horizontally of the centre. Particles must be parallel to the muon beamline axis within 35 mrad in the horizontal direction and 180 mrad in the vertical direction. With these two cuts, the number of surface muons is reduced to 842 for $2.5\,10^{11}$ protons on target (Fig. 2). For $2.5\,10^{13}$ protons one should find about 84200 surface muons.

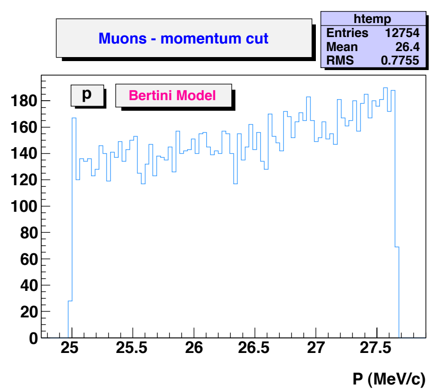

Figure 1: Surface muons with momentum cut between 25.175-27.825 MeV/c using the Bertini Cascade Model.

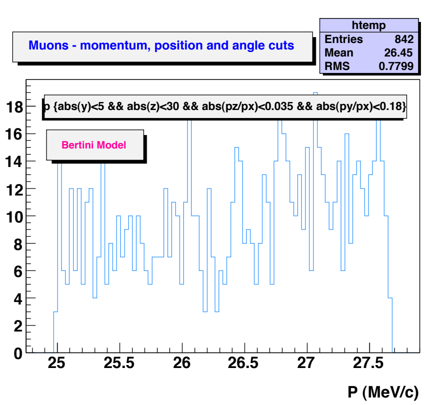

Figure 2: Surface muons obtained with Bertini model using cuts in momentum, position and angle.

BINARY CASCADE MODEL

The propagation through the nucleus of the incident hadron and the secondaries it produces is modelled by a cascade series of two-particle collision, hence the name binary cascade. Between collisions the hadrons are transported in the field of the nucleus by Runge-Kutta method.

The Nuclear Model

The nucleus is modelled as 3 dimensional and isotropic. The nucleons are placed in space according to nuclear density and the nucleon momentum is according to Fermi gas model. The primary particles interact with nucleons in binary collisions producing resonances which decay according to their lifetime producing secondary particles. The secondary particles re-scatter with nucleons creating a cascade [5].

Model Limitations

The model is valid for incident protons, neutrons and pions. It reproduces detailed proton and neutron cross section data in the region 0-10 GeV and 0-1.3 GeV for pions due to its dependance on resonances.

Target Simulations Using Binary Cascade

Similar studies were done using the Binary cascade model. For the same number of protons on target and after applying the cut in momentum, 9309 surface muons were obtained at the entrance of the beam window (Fig. 3). When all the cuts are applied, there are 627 muons for $2.5\,10^{11}$ protons on target (Fig. 4), which means that for $2.5\,10^{13}$ one should get approximately 62700 surface muons.

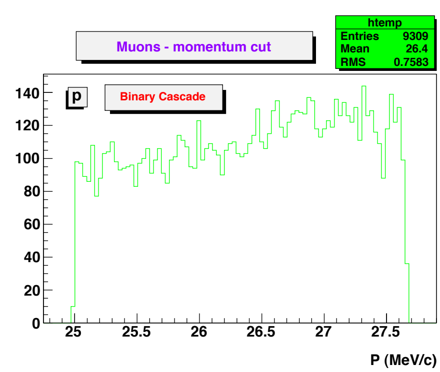

Figure 3: Surface muons obtained with Binary Cascade after applying a cut in momentum.

INCL-ABLA

To respond to the increasing user requirements from the nuclear physics community, the Geant4 collaboration

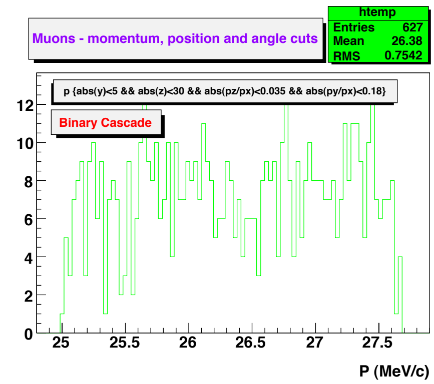

Figure 4: Surface muons obtained with cuts in momentum, position and angle.

set a goal to complement the theory-driven models in this regime (the Bertini cascade and Binary cascade being the most widely used) with the inclusion of the INCL code also known as Liege cascade, often used with the evaporation/fission code ABLA [6].

Model Limitations

The code was validated recently against spallation data. It supports projectiles like protons, neutrons, pions, deuterium, tritium, helium and alpha particles in the energy range 200 MeV - 3 GeV. The target material can be from Carbon to Uranium.

Target Simulations Using INCL-ABLA

An analysis of the number of muons coming from pions decaying at rest was done with the new INCL-ABLA model. The same restrictions were applied as in the previous models. When the cut in momentum was applied, the number of surface muons obtained was 6061 for $2.5\,10^{11}$ protons on target (Fig. 5) , and with the cuts in position and angle this number was reduced to 275 (Fig. 6). That means for $2.5\,10^{13}$ protons, we should expect 27500 muons.

CONCLUSION

A study of the surface muon production for the ISIS target has been done using the Monte Carlo code GEANT4 with three hadronic models applicable in the interest range of energy. Preliminary results show that all three models overestimate the number of muons passing through the beam window. For this particular application it was found that the new released model INCL-ABLA seems to be the most realistic of all three models. The GEANT4 collaboration announced improvements with respect to pion production models in the latest released GEANT4 version 4.9.2.p01 patch [7]. There is ongoing work ragarding muon production with hadronic models with the latest patch and preliminary results show a reduced number of surface muons than initially obtained.

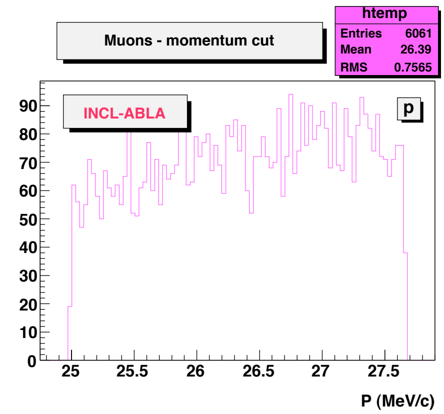

Figure 5: Surface muons obtained with INCL-ABLA model and having a momentum range 25.175-27.825 MeV/c.

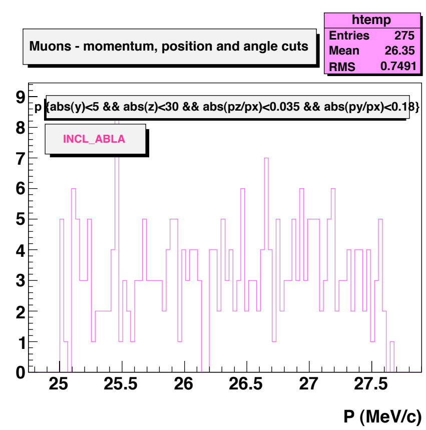

Figure 6: Surface muons using INCL-ABLA model with cuts applied in momentum, position and angle.

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