Bungau, Adriana, Cywinski, R., Bungau, Cristian, King, Philip and Lord, James

GEANT4 Validation Studies at the ISIS Muon Facility

**Original Citation**

Bungau, Adriana, Cywinski, R., Bungau, Cristian, King, Philip and Lord, James (2010) GEANT4 Validation Studies at the ISIS Muon Facility. In: IPAC'10 - Proceedings of the 1st International Particle Accelerator Conference. IPAC 10 OC/ACFA, Kyoto, Japan, pp. 247-249. ISBN 9789290833529

# GEANT4 VALIDATION STUDIES AT THE ISIS MUON FACILITY

Adriana Bungau, Robert Cywinski, University of Huddersfield, Huddersfield, UK
Cristian Bungau, Manchester University, Manchester, UK
Philip King, James Lord, STFC/RAL, Chilton, Didcot, Oxon, UK

*Abstract*

GEANT4 provides an extensive set of alternative hadronic models. Simulations of the ISIS muon production using three such models applicable in the energy range of interest are presented in this paper and compared with the experimental data.

## INTRODUCTION

The Monte Carlo particle transport code Geant4 [1] represents a powerful tool for simulating the passage of particles through matter. The simulation package includes a large set of physics processes, geometry models, particles and materials over a wide energy range of incident particles starting in some cases from 250 eV and extending in others to the TeV energy range. The physics processes offered cover also a wide range, from electromagnetic and optical processes to hadronic processes. As far as hadronic processes are concerned, a single hadronic model would not be able to support all user requirements, therefore Geant4 provides an extensive set of alternative hadronic models. This paper addresses the validation of three hadronic models (Bertini, Binary Cascade and INCL-ABLA) applicable in the energy range of interest for the ISIS pulsed neutron and muon facility at the Rutherford Appleton Laboratory, UK. The ISIS facility uses an 800 MeV, 200 $\mu$A proton beam to produce neutrons and muons for studies of atomic-level properties of materials. All simulations were performed with version 4.9.3 p01 of the Geant4 toolkit. A description of the hadronic models, as well as an overview of the experimental setup together with the models predictions for the ISIS muon production are presented in this paper.

## HADRONIC MODELS

Given the vast number of possible modelling approaches, three hadronic models applicable in the ISIS interest energy range were chosen. The Bertini model is performing well for incident protons, neutrons, pions, photons and nuclear isotops and is validated up to 10 GeV incident energy [2]. The Binary Cascade model is valid for incident protons, neutrons and pions and 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. The INCL-ABLA code was recently validated agains spallation data and it reproduces cross-section data for protons, neutrons, pions, deuterium, tritium, helium and alpha particles in the energy range 200 MeV - 3 GeV. In the Bertini cascade 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 [1]. In the Binary cascade 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 [3]. To respond to the increasing user requirements from the nuclear physics community, the Geant4 collaboration 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 [4].

## EXPERIMENTAL DATA

Pion production cross-sections on a liquid hydrogen target and various solid targets over a wide range of production angles and pion energies were measured at the cyclotron at Lawrence Radiation Laboratory [5]. The experiment used the proton beam of the cyclotron, a liquid hydrogen target and various solid targets and a pion spectrometer consisting of a bending magnet and an array of 12 counter telescopes. The beam passed through a pre-magnet collimator, a steering magnet and a quadrupole doublet and then through a pipe in the shield, into the physics cave. The initial setup inside the physics cave was for forward angles. A quadrupole doublet was used to focuse the beam to the primary target. The target was followed by a second doublet quadrupole used for stopping the beam in a steel block, 10 m downstream. When the aparatus was set up for backward angles, the second quadrupole doublet was used to focuse the beam to a secondary target. The solid targets were either 7.5 cm or 10 cm in diameter. After taking the backward-angle data, the setup was changed to forward angles with the pre-magnet collimator opened for these cross-section measurements. Several secondary beam channels over a wide range of angles were viewed by the magnetic spectrometer [5]. The measured differential cross-sections for pion production by 730 MeV protons on eleven different targets (H, D, Be, C, Al, Ti, Cu, Ag, Ta, Pb, Th) provided a reliable guide for the design of pion beams at various meson facilities.

## MODELS VALIDATION

A thin (1 cm) carbon target was simulated with the Geant4 code and four pion detectors were placed at 15, 45, 90 and 135 degrees with respect to the proton beam. The solid angle from the target interaction point to each detector is 5 mrad. A beam of $10^9$ protons having an energy of 730 MeV was sent to the carbon target. Bertini model, Binary cascade and the INCL-ABLA model were used to model the proton interactions inside the target. The predictions of each model were then compared with the experimental data from [5]. Figures 1, 2, 3 and 4 show the positive pion production double differential cross-sections for 15, 45, 90 and 135 degrees.

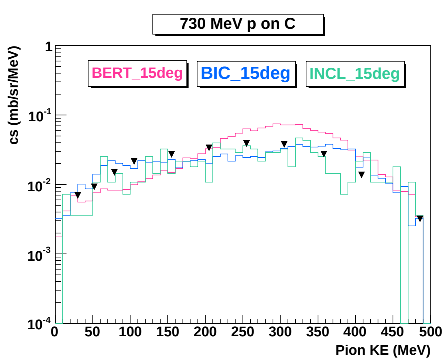


Figure 1: Double differential cross section for positive pion production at 15 degrees with respect to the proton beam.

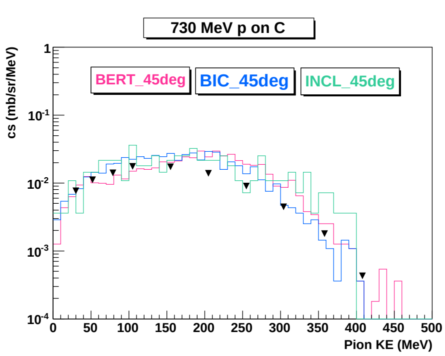


Figure 2: Double differential cross section for positive pion production at 45 degrees with respect to the proton beam.

One can see that the predictions of the Geant4 models and the experimental data are in good agreement. Bertini model predictions are more accurate at large angles, while Binary model predictions are more accurate at small angles. However, all three models (Bertini, Binary and INCL-ABLA) are in reasonably good agreement with data.

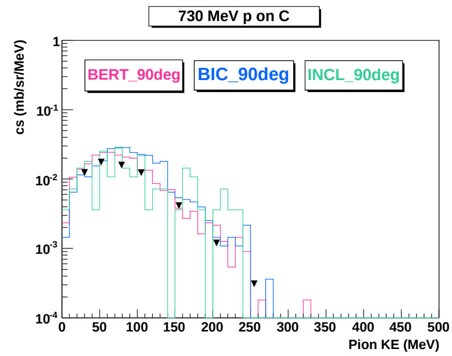


Figure 3: Double differential cross section for positive pion production at 90 degrees with respect to the proton beam.

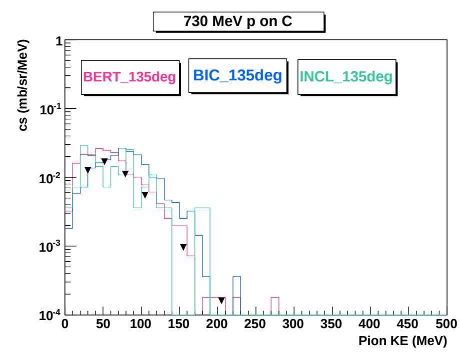


Figure 4: Double differential cross section for positive pion production at 135 degrees with respect to the proton beam.

## ISIS PREDICTIONS

Simulations of the muon production for the ISIS muon target were performed using all three Geant4 models. The ISIS target is an edge-cooled plate of graphite with dimensions (5x5x0.7) cm oriented at 45 degrees to the proton beam giving an effective length of 1 cm along the 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. The surface muons have a momentum range between 25.175 - 27.825 MeV/c as they come from pions decaying at rest. 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 $\pm 0.5$ cm vertically and $\pm 3.0$ 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.

Simulations of the surface muon production after applying the cuts in momentum, position and angle and using the three Geant4 models are shown in figures 5, 6, and 7. Validation results after scaling for 2.5x$10^{13}$ protons give 46275$\pm$1075 muons with the Bertini model, 43312$\pm$1645 muons with the Binary cascade and 43750$\pm$5229 muons with the INCL-ABLA model. All three predictions seem to converge to similar numbers of positive muons.

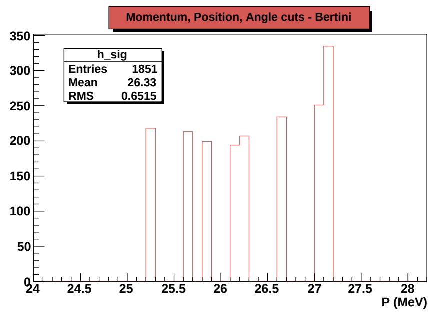


Figure 5: Surface muon production for the ISIS muon target using Bertini model after applying cuts in momentum, position and angle. The simulation used $10^{12}$ protons on target.

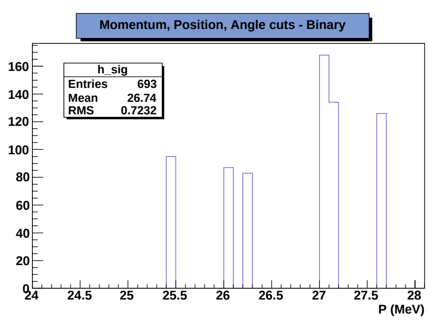


Figure 6: Surface muon production for the ISIS muon target using Binary cascade model after applying cuts in momentum, position and angle. The simulation used $4\text{x}10^{11}$ protons on target.

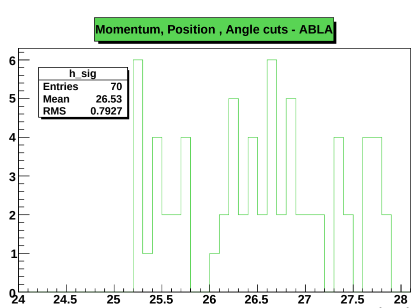


Figure 7: Surface muon production for the ISIS muon target using INCL-ABLA model after applying cuts in momentum, position and angle. The simulation used $4\text{x}10^{10}$ protons on target.

## ANGULAR DISTRIBUTION

The predictions of the models for the ISIS muon production are similar, therefore is difficult to chose one model over another based on the rate at ISIS alone because the uncertainty in the solid angle being collected is larger than the rate differences. A comparison of the pion momentum spectra in various directions relative to the proton beam has been done by having in the simulation model eight detectors around the muon target and by comparing the results in the detectors that sit diagonally opposed. Figure 8 shows the momentum spectra for pions forward scattered at 45 degrees and back scattered at 135 degrees relative to the proton beam and one can see that there are no significant differences between the models. Similar results have been seen for the other detectors.

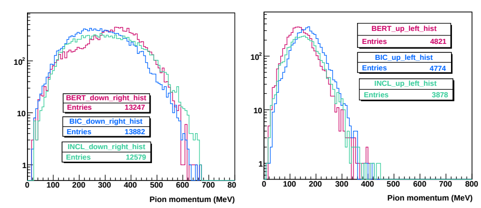


Figure 8: Pion momentum spectra predicted by three hadronic models, Bertini, Binary and INCL-ABLA.

## CONCLUSION

A validation of three physics models applicable in the energy range of interest for ISIS was done in this paper. Simulation and experimental data for pion production cross section for 730 MeV protons on Carbon target are in good agreement for several production angles. All three models give similar predictions for ISIS muon production. A comparison of the pion momentum spectra in various directions relative to the proton beam shows that there are no significant differences between the models.

## REFERENCES

[1] Geant4 - a toolkit for simulation of the passage of particles through matter, version 4.9.3.p01, `http://geant4.cern.ch`.

[2] A. Heikkinen "Implementing the Bertini Intra-Nuclear-Cascade in the Geant4 Hadronic Framework", The Monte Carlo Method: Versatility Unbounded in a Dynamic Computing World, Chattanooga, Tennessee, 2005.

[3] G.Folger, J.P.Wellisch, "The Binary Cascade", CERN, Geneva, Switzerland.

[4] A.Heikkinen, P. Kaitaniemi, A.Boudard, "Implementation of INCL cascade and ABLA evaporation codes in GEANT4", Journal of Physics: Conference series 119 (2008) 032024.

[5] D.R.F. Cochran *et al.*, "Production of Charged Pions by 730-MeV Protons from Hydrogen and Selected Nuclei", Phys.Rev.D, Vol.6, 1972.