"The role of secondary pions in spallation sources for neutrons and photons production"

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Outline

1. **Introduction**
2. **Spallation Reaction**
   - The Liège Intra-nuclear Cascade model (INCL)
3. **Pions in Thin Target**
   - INCL Results
   - INCL vs HARP Experiment
4. **Pions in Thick Target**
   - GEANT4 Results (different Physics Lists)
   - GEANT4 Results (INCL++ vs INCL4.6)
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Introduction

In recent publications [1], the GEANT4 toolkit for particle transport [2] was used to characterize the neutron and photon fluxes directed towards the n_TOF [3] experimental areas. Monte Carlo calculations of neutron and photon fluences performed with different GEANT4 physics lists (PL) exhibited large relative differences.

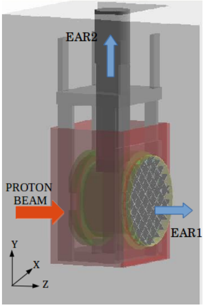

Figure 1 : View of the n_TOF spallation target by GEANT4.

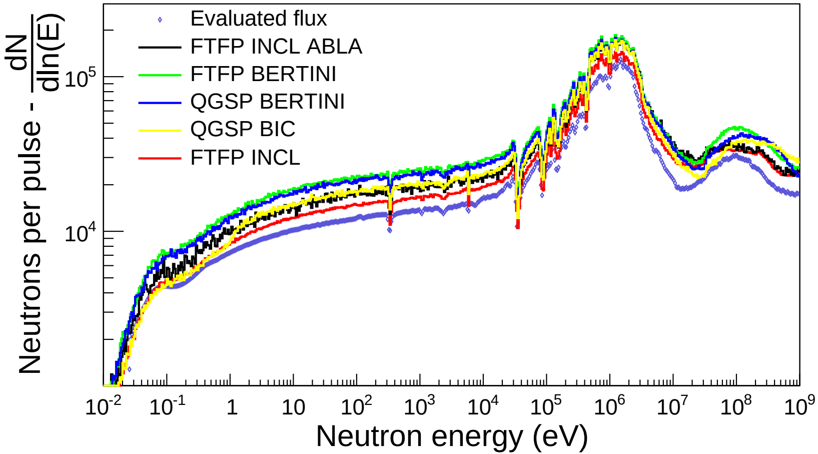

Figure 2 : Total number of neutrons per proton pulse reaching EAR1, simulated with GEANT4 for different PLs.

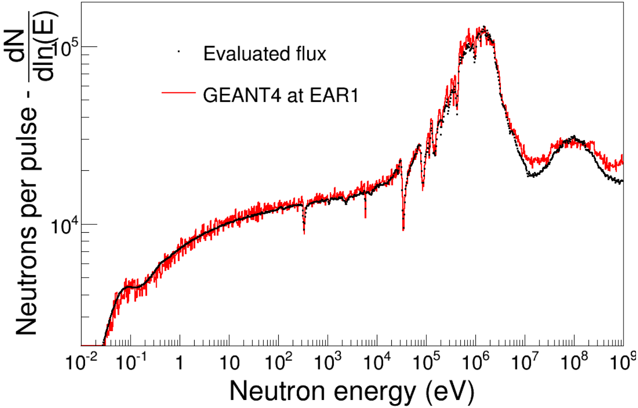

Figure 3 : GEANT4 simulations of the total number of neutrons per pulse reaching EAR1 at n_TOF by using FTFP_INCLXX_HP Physics List. The simulations have been normalized to the experimental data in the neutron energy region from 10 eV to 10 keV, with a normalization factor of 0.79.

Introduction

The authors observed anti-correlation between neutron and photon production.

Big Question: What is causing the difference between Intra-Nuclear Models? Whatever it is, could that also explain the difference between the models and measured flux?

Possible answer: The authors suggested at the time that this difference could be related to different treatments of pion production and pion-induced reactions.

In this work, we study the role of pion production and its influence on the spallation yields and we shall demonstrate that the production of high-energy prompt photons is essentially dominated by π^0 decay, while the production of neutrons is affected by both secondary $\pi^{\pm}$-nucleus reactions and π^0 production.

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Spallation Reaction (SR)

In spallation reactions, a high-energy (> 150 MeV) light projectile collides with a nucleus and on average leads to the emission of a large number of particles, mostly neutrons. Standard theoretical tool for the description of spallation reactions is a hybrid nuclear-reaction model where an intranuclear-cascade (INC) stage is followed by a statistical de-excitation stage [4].

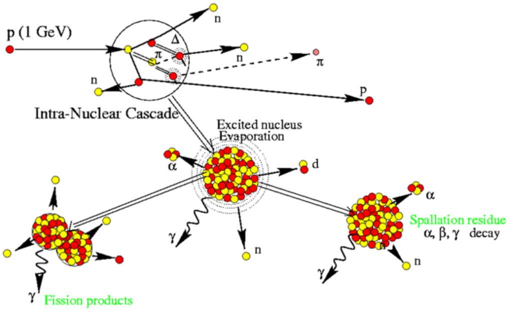

Figure 4 : Spallation Reaction.

SR: The Liège Intra-nuclear Cascade model

The Liège Intranuclear Cascade model (INCL) [5, 6] is a tool for description of spallation reactions.

The model is currently maintained and developed jointly by the University of Liège (Belgium) and CEA (Saclay, France). The model assumes that the first stage of the reaction can be described as an avalanche of independent binary collisions.

In the latest version of the INCL model (INCL++), the production and decay of individual mesonic and baryonic resonances, not present in INCL4.6, (except for $\Delta(1232)$) is bypassed and replaced by:

Multipion Collisions

$$N + N \rightarrow N + N + x\pi \quad (1a)$$

$$\pi + N \rightarrow N + x\pi \quad (1b)$$

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Pions in Thin Target: INCL Calculations

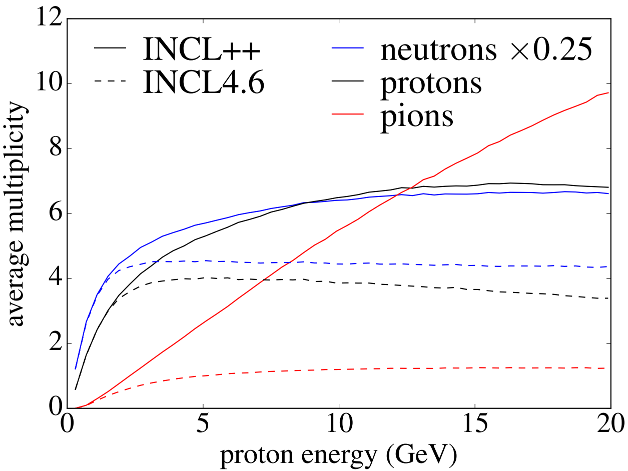

Figure 5 : Average neutron, proton and pion multiplicities in the final state of p+^{208}Pb reactions.

Pions in Thin Target: INCL vs HARP Experiment

In order to assess the validity of the INCL++ and other models, it is very useful to compare the obtained results with data collected by the HARP experiment at CERN [10, 11].

HARP have measured the double differential cross sections for charged pion production in proton and pion induced reactions.

Figure 6 shows inclusive pion production cross sections (Xs) integrated over the acceptance of the HARP experiment.

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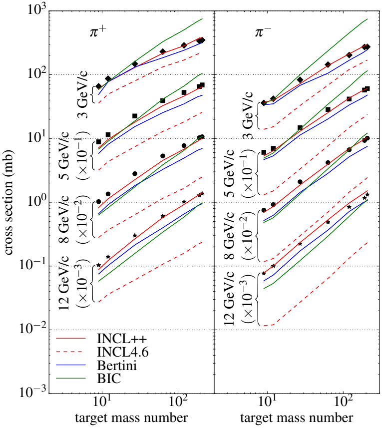

Figure 6 : Xs for the production of π^+ (left) and π^- (right) from proton-nucleus reactions vs HARP data.

Pions in Thin Target: INCL vs HARP Experiment

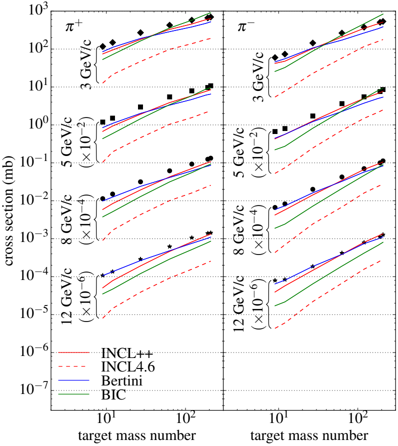

Figure 7 : Same as Fig. 6, but for π^+-nucleus reactions.

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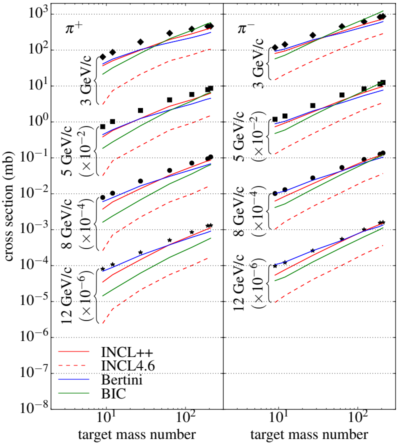


Figure 8 : Same as Fig. 6, but for π^--nucleus reactions.

Pions in Thick Target: GEANT4 Results (different PLs)

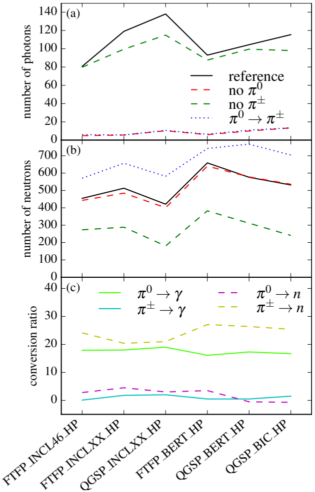
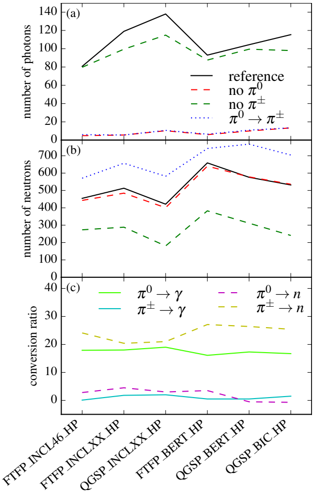


Figure 9 : Pions in Thick Target: GEANT4 Results (different PLs)

Several considerations can be made on the basis of the results in Fig. 9.

- At least 90% of the prompt photons descend in some way from π^0 decay.
- The influence of π^0 decay on neutron production is sensibly smaller and of the order of a few percent only.
- Large π^0 production rates correlate well with small neutron yields.



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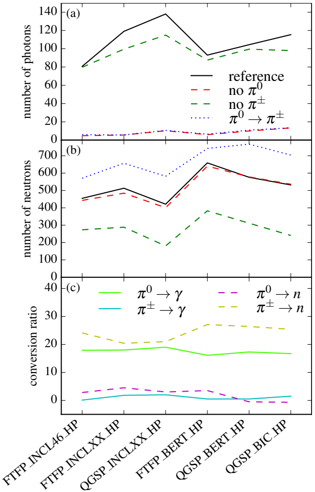

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- In particular, for a larger number of pions produced, 40% of which are π^0, a larger fraction of energy will be diverted from the hadronic cascade to the electromagnetic one, and become unavailable for neutron production.
- Suppression of one charged pion entails a reduction of 20–25 neutrons per incident proton.
- There is also an effect on the photon yields, which also decrease by 5–20% when charged pions are suppressed.
- When π^0 production is randomly replaced with the production of a π^+ or a π^-, the effect on photon yields is essentially the same as in the calculation without π^0 decay.

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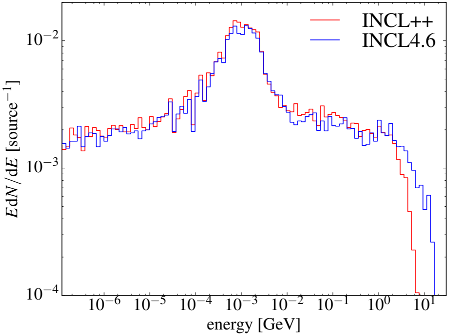

Figure 10 : Neutron spectrum per unit lethargy emitted from the n_TOF spallation source in a 2° cone directed towards EAR1, as calculated by our GEANT4 simulation.

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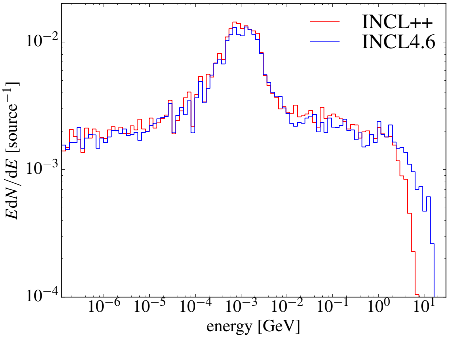

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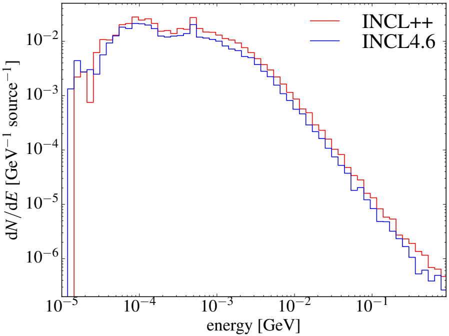

Figure 11 : Photon spectrum emitted from the spallation source within 100 ns of the beam pulse, in a 2° cone directed towards EAR1.

Conclusions

- Pion Multiplicity in N + N collisions affect thin target particle yields, but not thick target production, such as spallation neutron sources (consequence of energy and momentum conservation, holds for geometrical dimensions larger than the reaction mean free path).
- Higher pion production in models lead to a lower neutron flux consequence of π^0 effect, which transfers energy from the hadronic cascade to the electromagnetic one.
- All models currently used in GEANT4 simulations underestimate pion production.
- **More data on pion production in proton-induced reactions are needed.**
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Bibliography

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[2] S. Agostinelli *et al.*, Nucl. Instr. and Meth. A **506** (2003) 250.

[3] `https://ntof-exp.web.cern.ch/ntof-exp/`

[4] D. Filges and F. Goldenbaum, *Handbook of spallation research. Theory, experiments and applications* (Wiley- VCH, Berlin, 2009).

[5] A. Boudard *et al.*, Phys. Rev. C **51** (2002) 044615.

[6] D. Mancusi *et al.*, Phys. Rev. C **90** (2014) 054602.

[7] J. M. Quesada *et al.*, Prog. Nucl. Sci. Technol. **2** (2011) 936.

[8] J.-J. Gaimard *et al.*, Nucl. Phys. A **531** (1991) 709.

[9] A. Junghans *et al.*, Nucl. Phys. A **629** (1998) 635.

[10] M. G. Catanesi *et al.*, (HARP Collaboration), Phys. Rev. C **77**(2008) 055207.

[11] M. Apollonio *et al.*, (HARP Collaboration), Phys. Rev. C **80** (2009) 065207.

[12] M. Barbagallo *et al.* (The n_TOF Collaboration), European Physical Journal A **49** (2013) 156.

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`http://arxiv.org/abs/1603.05453v1`

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