High-energy nuclear data for ADS

Sylvie LERAY

CEA/Saclay, IRFU/SPhN
Spallation neutron production

In a heavy metal target (Pb, W, Ta, Pb-Bi) around 20 neutrons per incident proton and GeV

Applications:
- ADS
- Spallation neutron sources
- Rare isotope beams (RIB)
Interactions in a thin target

- ~2 neutrons with E>20 MeV (intra-nuclear cascade)
- ~15 neutrons with E<20MeV (evaporation)
- But energy carried out by cascade neutrons = 85% (95% for protons)

- a lot of light charged particles produced (including helium and tritium)
- Hundreds of different residues produced
Interactions in a thick target

- Protons interact before slowing down
- Large number of secondary neutron interactions
- 3.6 residues per incident protons (not taking into account E<20 MeV)
- Highest mass residue coming mostly from low-energy interactions
- Light evaporation residues, fission fragments from high-energy reactions
Activity in a thick target

Comparison of activity from spallation and activation

S. Lemaire et al., ND2007, Nice
Results obtained during the last years

- Large amount of high quality data collected
  - Neutron and light charged particle production, isotopic residue distributions, excitation functions

- Improvement of nuclear models
  - INCL4/ABLA tested against all the available data with the same set of parameters (A. Boudard et al., PR C66 (2002) 044615)
  - but also FLUKA and CEM

- Implementation of INCL4/ABLA and CEM into MCNPX, INCL4/ABLA now in GEANT4

≈ HINDAS FP5 and EUROTRANS/NUDATRA FP6 projects
Neutron production

- Total production, energy and angular distribution: general trends well understood

Differential spectra from a thick Pb target (SATURNE data)

From T. Aoust et al., ND2004, Santa Fe
Residue production: heavy systems

- Models behave differently especially for fission fragments, light evaporation residues and isotopic distribution shape.

- Generally intermediate mass fragments badly predicted.

Data from Enqvist et al.

Data from Michel et al.
Residues close to the target

Data from R. Michel

Calculation with INCL4/ABLA
(S. Lemaire et al., ND2007, Nice)

Same results with other models

Activity in the MEGAPIE target
Volatile isotope production

Results from ISOLDE
p + Pb-Bi 1400 MeV (L. Zanini et al., ND2004 Santa Fe)

Activity due to noble gas in MEGAPIE

Data from Michel et al.
Residue production: light systems

Fe + p INCL4

FRS experiment (inclusive)
Fe + p:

impossibility to conclude on the mechanism producing IMFs and on the best model

Data: C. Villagrasa et al., PRC 75 (2007) 044603; Napolitani et al. PRC 70 (2004) 054607

— INCL4 + ABLA
— INCL4 + GEMINI (which includes an asymmetrical fission mode for light nuclei) (Charity et al., NPA 483 (1988) 371)
— INCL4 + SMM (multifragmentation model) (A. Botvina et al., NPA 507, 649 (1990))
Events with 2 fragments ($Z \geq 3$) for different bins of particle multiplicity:

Difference between the charges of the two heaviest fragments

SPALADIN experiment Fe + p:

differences between the models (and mechanisms) when looking at the evolution of the de-excitation channels with excitation energy estimated from particle multiplicities

(E. Le Gentil et al., PRL 100 (2008) 022701)
Gas production in Fe

- **Helium**
  - p + Fe
  - Incident energy (MeV)
  - Helium production cross-section (mb)
  - From Rapp et al., SATIF-8, Pohang (2006)

- **Tritium**
  - E_proton (MeV)

- **INCL4/ABLA does not produce tritium**
- **No good model for gas prediction in MCNPX**
Tritium activity in the MEGAPIE target

Total activity in the Pb-Bi

From S. Lemaire et al., ND2007
Gas production in Fe

- INCL4.4-ABLA07 now produces tritium
- situation improved compared to models presently in MCNPX

From Rapp et al., SATIF-8, Pohang (2006)
Light charged particle production

$p + Ta \ 1.2 \text{ GeV}$

$\sigma_{PE}/(\sigma_{EL}+\sigma_{PE})$ (%)


Important non-evaporative contribution in d, t, $^3$He spectra
Cluster emission

$p + Ta \ 1.2 \text{GeV, INCL4.43-GEM}$

$p + Au \ 2.5 \text{GeV, INCL4.43-GEM}$

Intermediate mass fragment emission in INCL4

2.5 GeV p+Au  PISA@COSY

Benchmark of Spallation Models

Objectives

➢ To assess the prediction capabilities of the spallation models used or that could be used in the future in high-energy transport codes

➢ To understand the reason for the success or deficiency of the models in the different mass and energy regions or for the different exit channels

➢ To reach a consensus, if possible, on some of the physics ingredients that should be used in the models.
New FP7 project : ANDES (Accurate Nuclear Data for nuclear Energy Sustainability)

WP4 - High-energy model validation in the 150-600 MeV domain

General objectives:

- To identify remaining deficiencies and not understood features of the nuclear models used in high-energy transport codes between 150 and 600 MeV (ADS demo)
- to use/do a few specific experiments to solve the identified problems
- to further improve the models
- to do a few specific integral validation experiments
- to assess the uncertainty with which quantities related to high-energy reactions can be predicted
WP4 - High-energy model validation in the 150-600 MeV domain

Task 4.1: State-of-the-art of high-energy model predicting capability in the 150-600 MeV domain (CEA-Saclay, Univ. Liège, GSI Darmstadt, Univ. Santiago de Compostella)

Task 4.2: SPALADIN p+Pb at 500 MeV: measurement of the two fission fragments and light evaporation residues in coincidence with neutron and light charged particles (CEA-Saclay, GSI Darmstadt, Univ. Santiago de Compostella)

Task 4.3: Improving of the predicting capabilities of the simulation tools in the 150-600 MeV in order to reduce the uncertainties on key parameters of the demonstration facility spallation target (Univ. Liège, CEA-Saclay, GSI Darmstadt, CEA-Bruyères/NRG)

Task 4.4: Validation on the results from the post irradiation analysis of MEGAPIE samples (PSI Zürich, CEA-Saclay)

Task 4.5: Measurement of (n,n), (n,xn) and (n, lcp) at 175 MeV on Fe and Bi (Uppsala Univ., LPC Caen)
Conclusion

- Specific features of spallation reactions: high energy particles, huge number of produced residues, high gas production
- Necessity of good physics models validated on good experimental data to be implemented in simulation codes
- The benchmark of spallation models should allow:
  - to assess the predicting capabilities of the different available models
  - to identify the best parameters/ingredients to be used in the models
- Work still needed (model improvement and more constraining experiments) ⇒ ANDES FP7 project