Workshop on

Nuclear Data for Science & Technology: Accelerator Driven Waste Incineration

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Nuclear Reactions at High Energies

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Design of spallation targets for ADS has raised needs for reliable numerical simulation codes

- Improvement of high energy nuclear reaction models (above 150-200 MeV)
- Validation on the bulk of newly available high energy data

Other applications:
- spallation neutron sources
- radioactive beams
- radiation damage in space
- astrophysics
Outline

1. Importance of spallation reactions for applications
   - Definition of spallation
   - Data needed for Accelerator-Driven Systems
   - Other applications

2. High energy nuclear models
   - Models and codes for high energies
   - Intra-nuclear cascade models
   - The Liège INC model

3. Comparison of models to available high energy data
   - Neutrons
   - Charged particles
   - Residues
   - Coincidence measurements

4. Conclusions
**Spallation reactions**

- **Definition:**
  interaction of a high energy (> 100 MeV) light particle with a nucleus leading to emission of light particles and leaving a heavy residue.

- **History:**
  - observation of particle cascades in cosmic rays interactions (G. Rossi, ZP82 (1933) 151)
  - first accelerators: many nucleons emitted by the target nucleus (Cunningham, PR72 (1947) 739)
  - Two step mechanism (Serber, PR72 (1947) 1114)

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Data required for the design of spallation targets

- Neutron production
  - number → power of the system / needed accelerator intensity
  - energy, spatial distribution → target optimisation, damage in window and structures
  - high energy neutrons → shielding
- Charged particle production
  - gas (H₂, He) production → embrittlement, swelling
  - energy → DPA, energy deposition

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Shape optimisation of a spallation target

$p + Pb, E = 1.2 \text{ GeV}, L = 80 \text{ cm}$

Number of low and high energy neutrons emitted through the different faces of a cylindrical lead target as a function of the target diameter.

Number of low energy neutrons emitted from the lateral face of a cylindrical lead target for fixed or an optimised geometry.

From F. Lavaud, stage DEA, CEA/SPhN (1998)
Data required for the design of spallation targets

- Residual nuclide production
  - element distribution $\rightarrow$ corrosion, change in metallurgical properties
  - isotope distribution $\rightarrow$ activity (short lived isotopes), radiotoxicity (short lived isotopes), decay heat
  - recoil energies $\rightarrow$ DPA in window and structures, energy deposition

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Activity in Pb and Pb/Bi targets after 1 year irradiation

Pb target (50x100)
Proton energy 0.8 GeV
I = 30 mA
One year irradiation

Fig. 4. Total and partial activities of lead target as a function of cooling time.

Pb-Bi target (50x100)
Proton energy 0.8 GeV
I = 30 mA
One year irradiation

Fig. 5. The same as fig. 3 for lead-bismuth target.

Analysis of the Contributions of the Proton and Neutron Spectral Components to the Accumulating Activity

From Y.N. Shublin et al., Proc. ADTRA 86, Kalmar Sweden, June 1986 p 955
Pb not 1 GeV, R=25cm, L=100cm

A residu

Z residu
p+Pb nat 1 GeV, R=25cm, L=100cm

A residu (Z=82)

A residu (Z=80)

A residu (Z=78)

A residu (Z=76)
Nuclear Reactions at High Energies

Astrophysics

- Secondary reactions of cosmic rays in interstellar medium (90% of hydrogen)
  - explanation of abundance of isotopes
  - decide among models for galactic nucleosynthesis
  - origin of cosmic rays
- Composition of meteorites

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Spallation reactions in space instruments

- Cosmic ray bombardment of the spacecraft and instruments
  - Noise due to secondary gammas, neutrons and spallation residues
  - ex: spectrometer of the INTEGRAL mission devoted to high resolution γ-ray astronomy
    - determination of the flux of secondary particles
    - background due to radioactive residues
Rare isotope production

- Direct methods
  - ISOL $p (1 \text{ GeV}) + A \Rightarrow \text{low energy RIB}$
  - fragmentation of GeV/A heavy ions $\Rightarrow \text{high energy RIB}$
- Converter methods
  - use of moderated spallation neutrons to induce fission
Spallation neutron sources

- Moderation of spallation neutrons in (heavy) water
- Reflectors to direct escaping neutrons into beam tubes
  - pulsed sources: well-defined time structure, high peak flux \( \Rightarrow \) tof experiments
  - continuous sources: high neutron flux in a large volume \( \Rightarrow \) irradiation experiments
Spallation target modelling

- Monte-Carlo transport codes
  - propagation of all particles created in elementary interactions (HETC + MCNP type)
- Nuclear physics models (above 150-200 MeV)
  - generating cross-sections (Intra-Nuclear Cascade followed by evaporation-fission)
- Evaluated data files (below 150-200 MeV)
  - providing all reaction channels

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What is needed above 150-200 MeV for ADS and other applications

Objective: to reliably predict production rates of all produced nuclei with their energy and angular distributions

- Elementary cross-sections measurements
  ➞ to test the physics models
- Improvement of models and/or development of new ones
  ➞ validation on experimental data
- Integral measurements
  ➞ test and validation of transport codes
Models for spallation reactions

Two step mechanism (Serber 1947):

- Intra-Nuclear Cascade
  sequence of independent $N-N$ collisions

\[ \Lambda_{\text{de Broglie}} = \frac{hc}{p} \ll \lambda = \frac{1}{\rho \sigma_{NN}} \]  
mean free path

fast process ($\approx 30$ fm/c)

- Heating of the nucleus - thermalisation

- De-excitation by evaporation or fission

statistical evaporation models

slow process (hundreds of fm/c)
Intra-Nuclear Cascade

Determines the number and direction of the high energy particles
- shielding against energetic neutrons
- inter-nuclear cascade propagation
  for lead INC neutrons = 15% total nb
  but carry 80% of the energy

Determines initial conditions for evaporation-fission
- Excitation energy
- Z, A of the pre-fragment
- Angular momentum

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Intra-Nuclear Cascade models

Common features
- linear trajectory between collisions
- nuclear potentiel
- free $N-N$ cross-sections
- inelastic collisions $N+N \rightarrow N+\Delta \rightarrow N+ N+\pi$
- Pauli blocking

Main available INC models
- Bertini (Phys. Rev. 131 (1963) 1801)
- Isabel (Yariv and Frankel, Phys. Rev. C20 (1979) 2227)
Differences between the different INC models

Fig. 3: Schematic representation of the INC models of the first type (left) and of second type (right). In the latter case, nucleons promoted from the continuum are indicated by heavy dots.

<table>
<thead>
<tr>
<th></th>
<th>Bertini</th>
<th>Isabel</th>
<th>Cugnon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium</td>
<td>continuous</td>
<td>continuous</td>
<td>particles</td>
</tr>
<tr>
<td>Cascade propagation</td>
<td>collided particles</td>
<td>time steps</td>
<td>time steps</td>
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<tr>
<td>Collision criterium</td>
<td>mean free path</td>
<td>mean free path</td>
<td>minimum distance of approach</td>
</tr>
<tr>
<td>Stopping criterium</td>
<td>energy</td>
<td>energy</td>
<td>time</td>
</tr>
<tr>
<td>Surface</td>
<td>diffuse (3 density regions)</td>
<td>diffuse</td>
<td>sharp</td>
</tr>
<tr>
<td>Pauli blocking</td>
<td>strict</td>
<td>not fully strict</td>
<td>statistics</td>
</tr>
</tbody>
</table>

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The Liège INC model (INCL)


The standard INCL2 model (Cugnon et al., Nucl. Phys. A620 (1997) 457)

- succession of binary collisions well separated in space and time
- generation of initial positions of target nucleons at random inside a sharp surface sphere
- stochastical generation of initial momenta of target nucleons inside a Fermi sphere
- straight line trajectories until minimum distance of approach or hitting of the wall of the potential
- statistical Pauli blocking
- inelastic collisions, pion production and absorption: $N+N \leftrightarrow N+\Delta$, $\Delta \leftrightarrow N+\pi$
- isospin degree of freedom
- improved parameterisation of NN cross-sections
- self-consistent determination of the stopping time

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$np$ angular distributions
rise at backward angle (charged pion exchange)
mainly affect $0^\circ$ in $(p,xn)\,$

E$_{\text{lab}}$=650 MeV

- H.W. Bertini, PRC 131 (63) 1801
- J. Cugnon et al, NPA 352 (81) 505
- New parametrisation
  - M. L. Evans et al, PRC 26 (82) 2525
  - Y. Terrien et al, PRL 59 (1987) 1534
Parametrisation of the $\Delta$ production cross-section

**Parametrisation of Delta production**

- Data n-p scattering at 0 deg.
- Bertini angular distribution
- Cugnon angular distribution

**p(1600 MeV)+Pb**

[0–5] degree

- Cugnon
- X. Ledoux et al.
- Bertini

$\frac{d^2\sigma}{dE \, d\Omega}$ (MeV/MeV sr)

$E_\pi$ (MeV)

The new INCL4 version
(Boudard et al., to be published)

- diffuseness of the nuclear surface:
  Wood-Saxon distribution with parameters in accordance with experimental values
    → good total reaction cross-sections
    → better prediction of peripheral collisions

- consistent dynamical Pauli blocking:
  phase space occupation probability evaluated
  collisions leading to energy $\sum \epsilon_i > E_{GS}(A_R)$ forbidden
    → no more negative excitation energies

- collisions between spectators forbidden
  → no spurious nucleon evaporation
  → dynamical evolution of the phase space preserved

- angular momentum of the remnant calculated
  → important for input in evaporation-fission

- possibility of composite incident particles
  with realistic momentum distribution
1GeV p+Pb, INCL4 (INCL3) + KHS_V3p, V=45MeV

Cross Section (mb)

Mass Number

Cross Section (mb)

Mass Number

Hg

Tl

Pb
p + Pb 1.2 GeV

ID: 114
Entries: 100000
Mean: 147.6
RMS: 117.7

Entries
Mean
RMS

115
2033991
187.7
15.78

Ex

Mass

INCL4

INCL4-Pauli strict
Angular momentum distribution

2001/09/07 15.13

ID | Entries | Mean | RMS
---|---------|------|------
1  | 141365  | 17.34| 8.930|

ID | Entries | Mean | RMS
---|---------|------|------
2  | 141365  | 2.760| 2.760|
1GeV Pb+p, INCL4 + KHSV3p (J mean de Jong)
1600 MeV d+Pb, INCL4 + KHSV3p

$\frac{d^3\sigma}{dE_\gamma dE_{n}}$ (mb/ster.MeV), normed=1 for $0^\circ$

neutron energy ($eV$) vs neutron energy ($MeV$)
The Liège INC model (INCL)

- The new INCL4 version

  - no really free parameters:
    stopping time fixed by consideration on the variation rate of several observables
    - results insensitive to a variation of ± 5fm/c
  
  Potential = 45 MeV (E_F+S)
  - could be slightly varied

  - Further possible improvements
    - realistic momentum density
    - medium effect on N-N cross-sections
    - emission of composite particles (d, t, $\alpha$, IMF)
    - special treatment of the first collision (quasi-elastic reactions)
    - energy dependence of the potential
    - improvement of pion dynamics

  - Implementation in LAHET3 in progress

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$p+Pb \ (T_p=1.0 \text{ GeV}), \ b=4 \text{ fm}$

**Excitation energy ($E^*$)**

- Time (fm/c): 0 to 150
- Energy: 100 to 2000

**Average kinetic energy of ejectiles**

- Time (fm/c): 0 to 150
- Energy: 10 to 1000

**$dE^*/dt$**

- Time (fm/c): 0 to 150
- Energy: 1 to 1000

**Momentum asymmetry of participants**

- Time (fm/c): 0 to 150
- Momentum: 0 to 25
$1000 \text{ MeV } p+Pb, \text{ INCL4 + KHSV3p, } t=63, 70, 77 \text{ fm/c}$

$n$ energy vs. $\text{remnant mass}$

$\text{Exini}$ vs. $\text{residual mass}$
Models for the de-excitation

Evaporation: statistical models

Emission probability of one particle governed by

- inverse capture cross-section (detailed balance principle)
- Coulomb barriers
- density of available states

+ Most widely used model: Dresner (ORNL-TM-196 (1962))

- Weisskopf-Ewing formalism
- all types of LCP evaporation
- GCC-Ignatyuk level density parameter ($\rightarrow A/8$)
- Coulomb barriers lowering with $E^*$


- Weisskopf-Ewing formalism
- only n,p,$\alpha$ evaporation
- Level density parameter $\rightarrow \sim A/12$
- realistic Coulomb barriers

Fermi-Break-up

- For $A < 22$
- break-up probabilities from available phase space
Nuclear Reactions at High Energies

Models for the de-excitation

**Fission:**

- Models used in high-energy transport codes
  - Bohr-Wheeler formalism
  - phenomenological parameterisation of barriers
  - phenomenological parameterisation of Z and A distribution of fission fragments
  - only n/fission competition
  - ORNL, Z>91 (Alsmiller, ORNL-7528 (1981))
  - RAL, Z>70 (Atchison, KFA Julich conf-34 (1981))

- GSI model
  - friction introduced through a delay time
  - full particle/fission competition
  - Z and A distribution of fission fragments based on potential energy surface at saddle
  - GGE-Ignatyuk level density parameter (→ A/9)
  - Coulomb barriers lowering with E

- GEMINI model (Moretto et al., NP A247 (1975) 211)
  - Transition state method
  - particle, IMF and fission treated on an equal footing

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