EMPIRE-3.2

Nuclear reaction code system

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EMPIRE scope

- Incident energies up to ~150 MeV
- Projectiles: n, p, d, t, 3He, 4He, γ, and Heavy Ions (HI)
- Outgoing channels: projectiles (except HI), multi-particle emission, discrete levels (including isomers), γ lines, fission
- Reaction mechanisms: direct, pre-equilibrium and statistical model
- Provides: reaction cross sections, residue production cross sections, angular distributions, spectra (incl. PFNS), angle-energy distributions of reaction products
- Targets A > 20 (light nuclei excluded)
- Low energy range for neutron reactions covered by interface to Atlas of Neutron Resonances (to be updated)
EMPIRE’s convenience

- Operation via Graphic User Interface (GUI)
- Easy input (extensive use of defaults, built-in internal logic)
- Choice of reaction models (Fus. 7, Dir. 2, PE 3, LD 3, G-str. 6, Fiss. 5)
- Manipulation and verification of ENDF-6 files
- Interactive plots of experimental and calculated results
- Automated calculation of sensitivity matrices for Kalman fitting and covariances
EMPIRE-3.2 (Malta)
Nuclear Reaction Model Code

Neutron Resonances  Coupled Channels  DWBA
Optical Model

Multistep Direct  Multistep Compound
Exciton Model  Hybrid MC Simulation

HRTW  Hauser-Feshbach
Optical Model for Fission

ENDF Formatting  Verification  Kalman Filter  Covariances
EMPIRE-3.2 (Malta)

Nuclear Reaction Model Code

Atlas of n resonances

Neutron Resonances

Coupled Channels

DWBA

Optical Model

Multistep Direct

Multistep Compound

Exciton Model

Hybrid MC Simulation

HRTW

Hauser-Feshbach

Optical Model for Fission

Direct reactions, absorption, T_{ij}

Pre-equilibrium

Compound nucleus

ENDF

ENDF Formatting

Verification

Kalman Filter

Covariances

Fitting & Covariances

ENDF

Fitting & Covariances
Reaction models

- **Fusion**
  - Spherical optical model (ECIS-2006),
  - Coupled-channels (ECIS-2006, OPTMAN)
  - Distorted Wave Born Approximation DWBA
  - Simplified coupled-channels for HI (CCFUS)
  - Distributed barrier model for HI
  - Deuteron absorption
  - Photo-absorption for incident gammas
  - ‘read in’

- **Direct inelastic**
  - Coupled-channels (ECIS-2006, OPTMAN)
  - Distorted Wave Born Approximation DWBA (ECIS-2006)
    can be used in addition to CC & for levels in the continuum
Reaction models (cont.)

• Pre-equilibrium
  - TUL Multistep Direct (ORION + TRISTAN)
  - NVWY Multistep Compound with γ-emission
  - Exciton model (PCROSS)
  - Iwamoto-Harada model for complex particle emission (PCROSS)
  - Hybrid Monte Carlo Simulation (DDHMS) with multiple PE emission

• Compound nucleus
  - HRTW or Moldauer for widths’ fluctuation
  - Multi-emission Hauser-Feshbach model with full γ-cascade
  - Engelbrecht-Weidenmueller transformation for direct-compound interference

• Level densities
  - EMPIRE Superfluid Model with dynamical deformation effects
  - Gilbert-Cameron
  - HFB microscopic tables (RIPL-3)

• γ-strength functions

![Graph showing γ-strength functions](image-url)
Reaction models (cont.)

- Fission
  - Symmetric, single barrier fission for HI
  - More advanced fission for incident n, p and γ
    - multi-hump barriers
    - microscopic barriers
    - optical model for fission
    - multimodal fission
- Prompt fission neutron spectra (PFNS)
  - Los Alamos model
  - Kornilov model
Needed to improve predictive power

- Level densities
  - Collective lev. den. enhancements’ dumping at higher energies
  - $D_0$ out of stability line
- Spin distributions
- Multiple preequilibrium > ~30 MeV
- Reliable theoretical models for going out of the stability line or…
- Experimental data to calibrate phenomenological input parameters

\[
1.3^5 = 3.7 = 370\% \quad 5 \text{ emissions assuming } 30\%, \text{ fully correlated error for strong channels} \\
2.0^5 = 32 = 3200\% \quad 5 \text{ emissions assuming } 100\%, \text{ fully correlated error for weak channels}
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