Nuclear Reaction Theory and Data
Challenge and Future Activities

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Reaction Data and Modeling Highlights

- **GND Format for Nuclear Data Libraries**
  - LLNL and BNL leading to define the new XML-base format in collaboration with international nuclear data communities, under OECD/NEA

- **New Standards**
  - NIST leading the international collaboration, and the standards are significant contributions to ENDF/B-VIII, e.g., fission cross sections of major actinides

- **ENDF Hackathon by BNL, LANL, LLNL**
  - One-week sprint event in Sep. 2015 and Oct. 2016 for a large number of ENDF fixes

- **Neutron Capture Rates Including M1 Scissors Enhancement** [JPS Conf. Proc.]

- **ENDF-6 File Manipulation Code, DeCE, Open Source at GitHub**

- **Monte Carlo Approach to Gaussian Orthogonal Ensemble** [PRC 92, 044617 (2015)]
  - Direct Reactions in the Hauser-Feshbach Theory
    - Collaboration of EMPIRE, TALYS, and CoH3 teams [PRC 94, 014612 (2016)]

  - Mean-field theories combined with the Hauser-Feshbach code at LANL
  - Microscopic level density calculation based on the random matrix theory

- **Inter-comparison of Hauser-Feshbach Codes**

Brown: will be covered by each Laboratory report

Green: will be shown later
Statistical Model for Coupled-Channels + Hauser-Feshbach

- Inclusion of strongly coupled-channels in Hauser-Feshbach
  - Monte Carlo technique applied to study deficiencies in the current HF codes when direct reactions exist
  - Extension of Moldauer’s approach based on the random matrix theory
  - Diagonalization of $P$-matrix (Engelbrecht-Weidenmeller transformation) still required, but practical implementation of GOE-equivalent model
  - Implemented in CoH$_3$ and TALYS (in-house version), EMPIRE ongoing

![MC Simulation](image)

![n+${}^{238}\text{U}$](image)
Global HF Calculations for Astrophysics Feasible

- Statistical model calculations for r-process nucleosynthesis
  - M1 scissors mode strength estimated from the evaluated capture cross sections, by correlating with nuclear deformation
  - Neutron capture rates with M1 scissors mode produced and tested in the r-process network calculations (M.R. Mumpower)
Mean-Field Model as Reaction Calculation Inputs

- By solving Schroedinger equation for one-body potential, we have
  - Single-particle energy spectrum
    - level density calculations, …
  - Single-particle wave-functions and occupation probabilities for
    - direct reactions to the bound states, DWBA, quantum-mechanical pre-equilibrium process, direct/semidirect capture model, …
  - where the residual interaction plays an important role

- Incorporate (reasonably fast) mean-field theories into the Hauser-Feshbach calculations for better prediction of experimentally unknown reaction cross sections
  - Microscopic-macroscopic approach of FRDM and
  - Hartree-Fock BCS added to CoH₃
Microscopic Level Density Calculation inside HF Code

- Random matrix approach to microscopic level density
  
  - Hamiltonian $H = H_0$ (single-particle) + $V$ (Gaussian Orthogonal Ensemble)

- Second moments of the matrix elements of residual interaction are calculated, and averaged by the statistical technique
Experimental Programs Under LANL Nuclear Data Program

- **LENZ, Low Energy NZ experiments upgrade**
  - HyeYoung Lee, R.C. Haight (retired)
  - Resolve discrepancies in $^{16}$O$(n,\alpha)$ cross section
  - Charged particle production cross sections for astrophysics, material damages, and medical isotope production studies

- **DANCE, time-dependent signals in fission and capture**
  - M. Jandel’s early career award
  - NEUANCE (NEUtron Array at daNCE) for correlated data between neutron and gamma
Significance of Nuclear Structure Inputs in HF Calculations

- CGM(F), Monte Carlo Hauser-Feshbach approach
  - Actively used to interpret LANSCE experiments
  - Isomer we are looking at is higher than all known levels
  - Levels completed by statistical assumptions in the HF code
  - Overlapping ENSDF and continuum level density

Gamma-ray emission from discrete levels embedded in the continuum

- (n,p) Threshold Anomaly
  - Strange bump occurs in the HF calculations
  - Final state spin issue or strength functions for proton
  - LENZ could resolve partial level populations

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75 Ge

(5/2)+, (9/2)+

76 As

(n,p) Threshold Anomaly

Strange bump occurs in the HF calculations

Final state spin issue or strength functions for proton

LENZ could resolve partial level populations
Hauser-Feshbach Code Comparison

- Conducted by LANL/IAEA with contributions by CEA, JAEA, and U. Bucharest to compare EMPIRE, TALYS, CoH$_3$, and CCONE
  - (Almost) no-fission case, $^{238}\text{U}$, and fission case, $^{239}\text{Pu}$, with carefully defined consistent model parameters (INDC(NDS)-0654)
- Discrepancy less than 10% confirmed
HF Code Comparison for Photon Production Data of W

- Pre-compound spin-distribution issue
- Structure data issue?

EMPIRE
TALYS
CoH$_3$

courtesy G. Henning (IPHC/CNRS)
Conclusions

- Nuclear reaction model, code development, data production in progress
  - Compilation of evaluated reaction data (ENDF) always in coordination with CSEWG

- Toward unification of nuclear reaction and nuclear mean-field models
  - An example shown for the microscopic level density calculation
  - Inclusion of realistic fission penetration will be our long-term goal

- High quality nuclear structure data (ENSDF or RIPL) should be maintained
  - Increasing important applications, such as isomer production, gamma-ray production, etc
  - If not provided, reaction codes may make up something with a random number generator
  - Each time, the code gives different cross sections!

- Detailed Hauser-Feshbach code comparison performed for the first time