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Nuclear Reaction Theory and Data
Challenge and Future Activities

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Reaction Data and Modeling Highlights

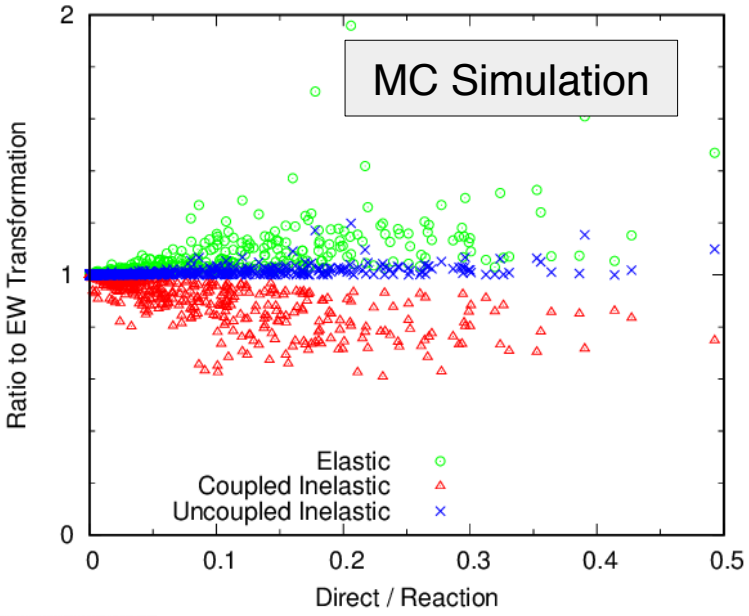
- **GND Format for Nuclear Data Libraries**
  - LLNL and BNL leading to define the new XML-base format in collaboration with international nuclear data communities, under OECD/NEA
- **New Standards**
  - NIST leading the international collaboration, and the standards are significant contributions to 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 CoH_3 teams [PRC **94**, 014612 (2016)]
- **Incorporating Nuclear Structure Models into Reaction Calculations** [Eur. Phys. J. A **51**, 164 (2015)]
  - 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**

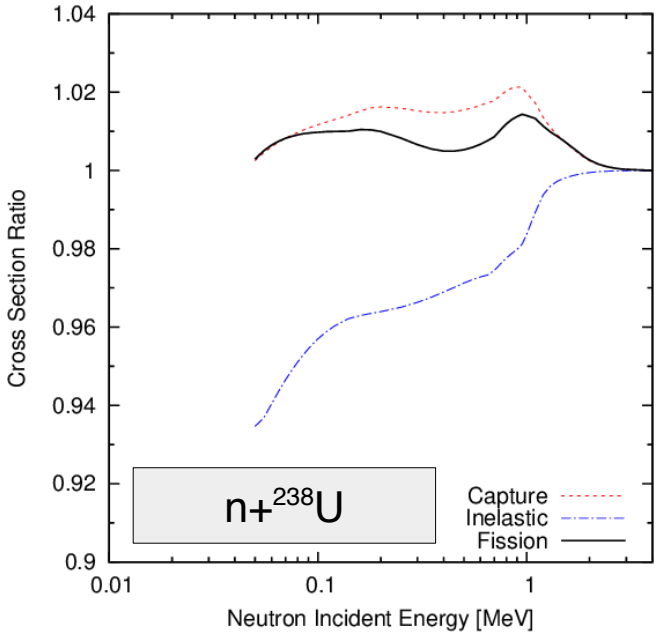
Brown: will be covered by each Laboratory report

Green: will be shown later

Statistical Model for Coupled-Channels + Hauser-Feshbach

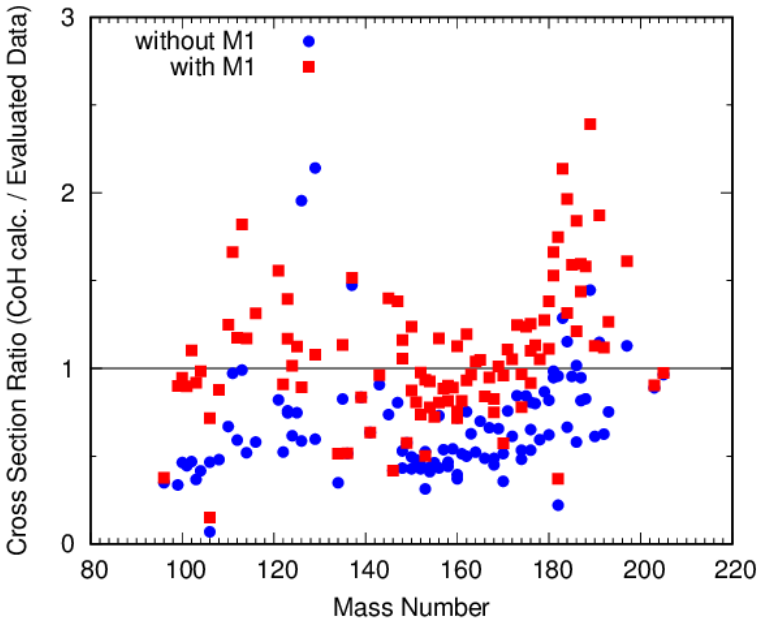
- Inclusion of strongly coupled-channels in Hauser-Feshbach
  - Monte Carlo technique applied to study deficiencies in the current HF codes when direct reactions exist
  - Extension of Moldauer's approach based on the random matrix theory
  - Diagonalization of *P*-matrix (Engelbrecht-Weidenmeller transformation) still required, but practical implementation of GOE-equivalent model
  - Implemented in CoH_3 and TALYS (in-house version), EMPIRE ongoing

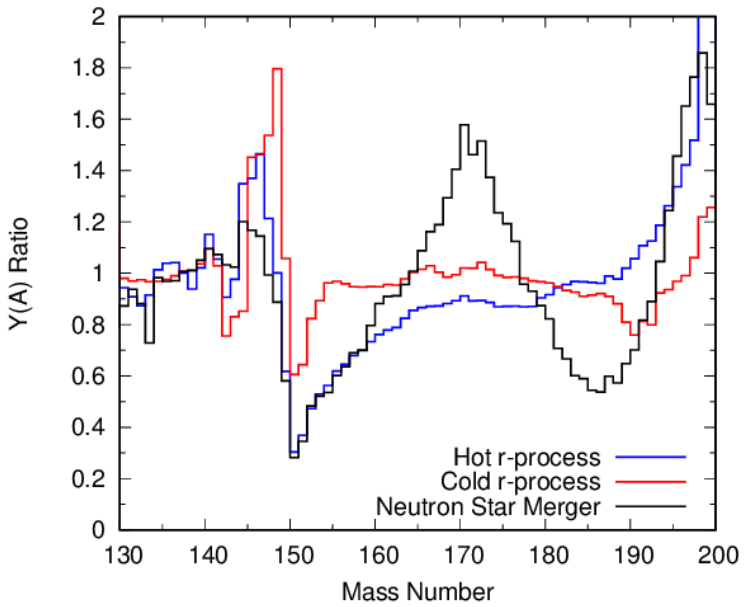




Global HF Calculations for Astrophysics Feasible

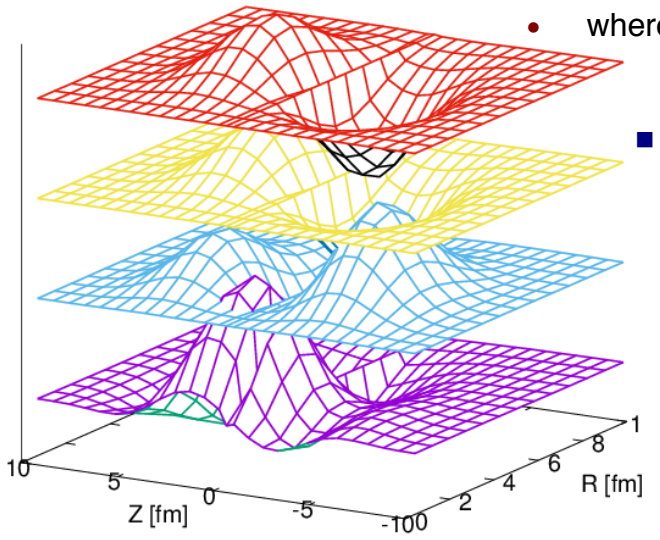
- Statistical model calculations for r-process nucleosynthesis
  - M1 scissors mode strength estimated from the evaluated capture cross sections, by correlating with nuclear deformation
  - Neutron capture rates with M1 scissors mode produced and tested in the r-process network calculations (M.R. Mumpower)



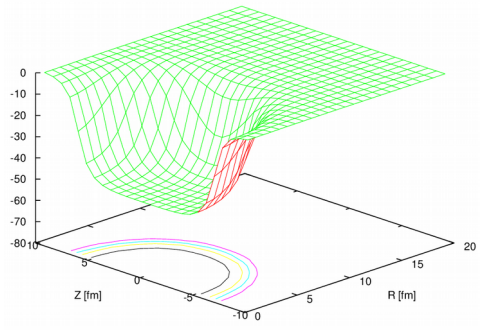


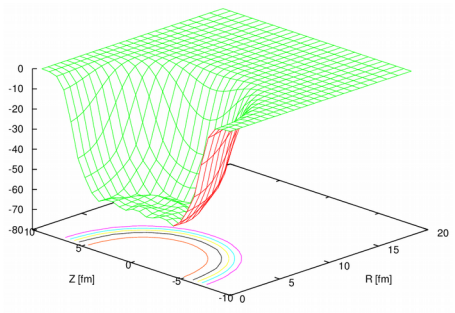
Mean-Field Model as Reaction Calculation Inputs

- 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 CoH_3





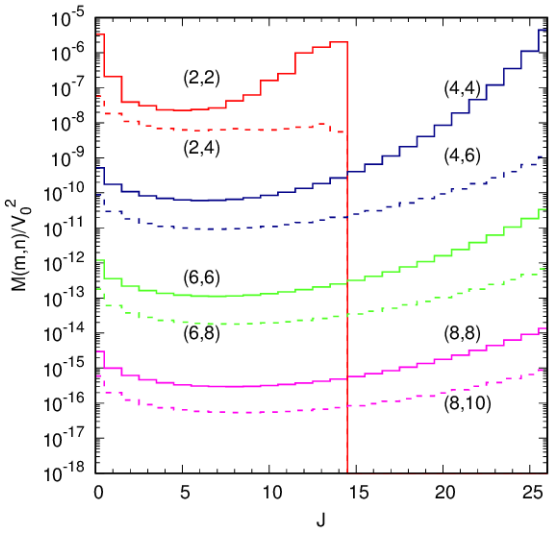
Microscopic Level Density Calculation inside HF Code

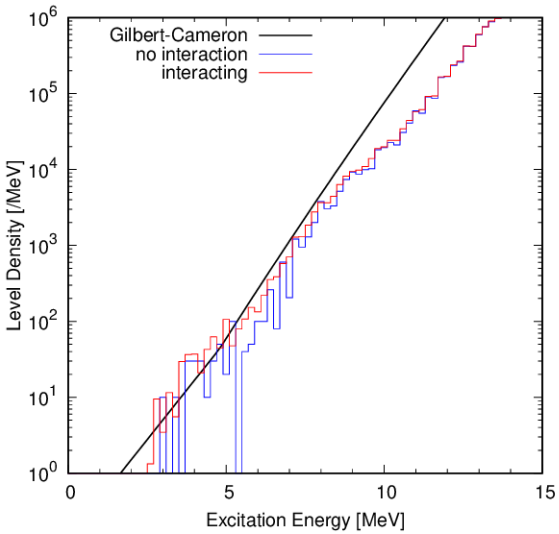
- Random matrix approach to microscopic level density

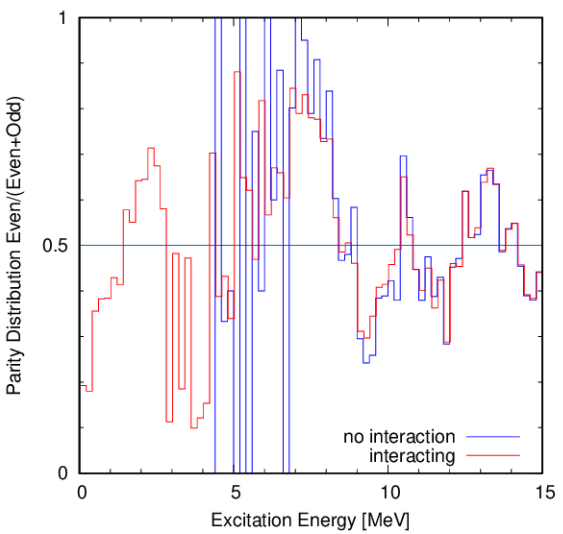
  Z.Pluhar, H.A. Heidenmueller PRC 36, 1046 (1988), TK, Yoshida, PRC 63, 0246003 (2001)

  - 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

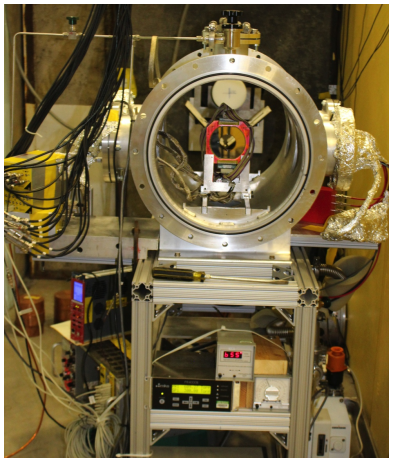


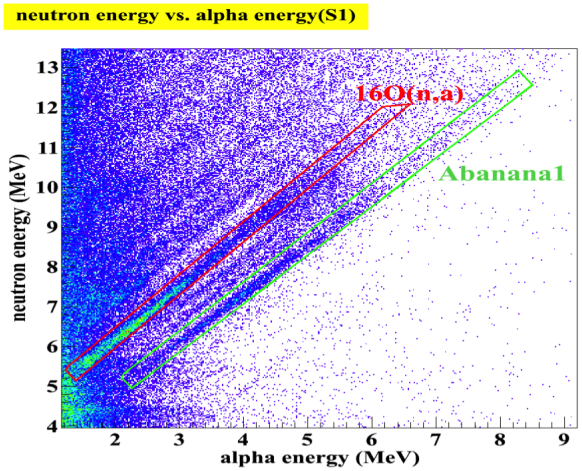


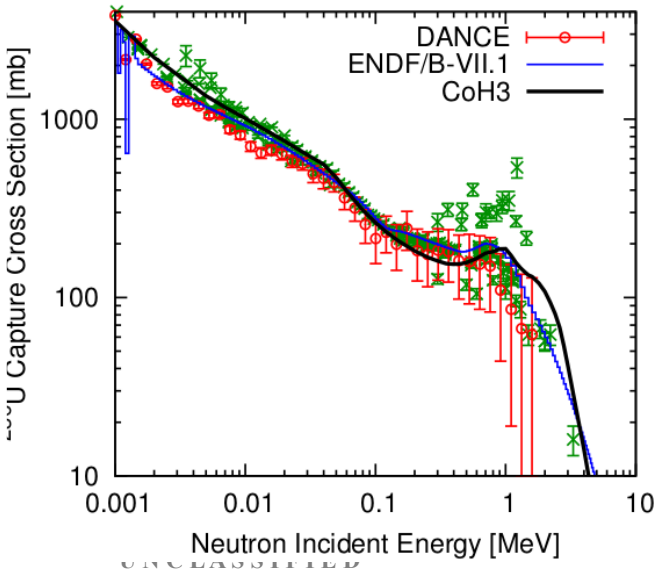


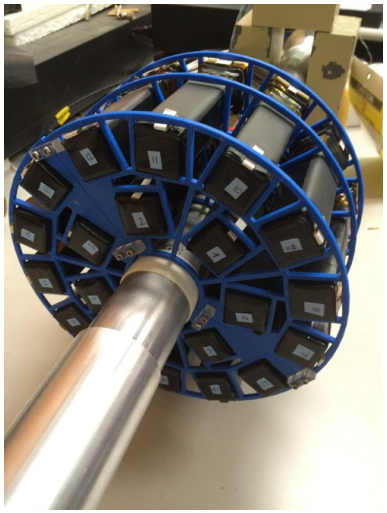
Experimental Programs Under LANL Nuclear Data Program

- 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









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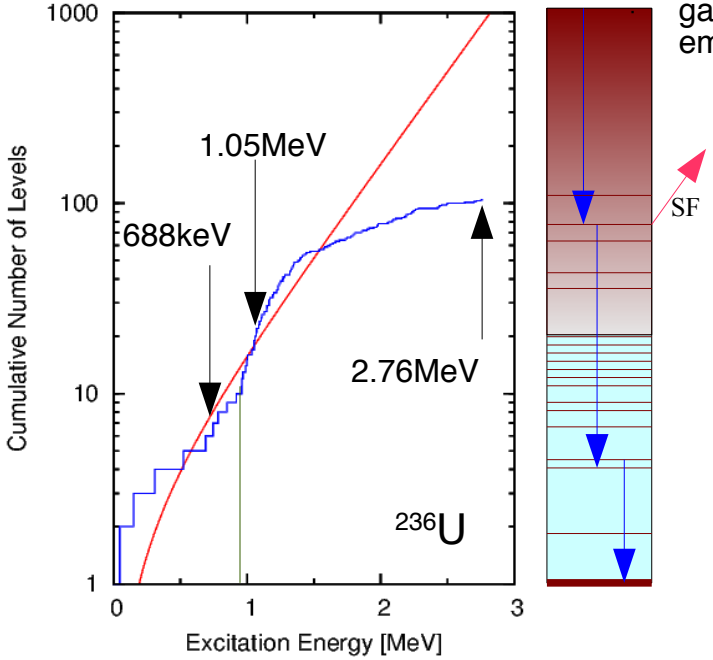
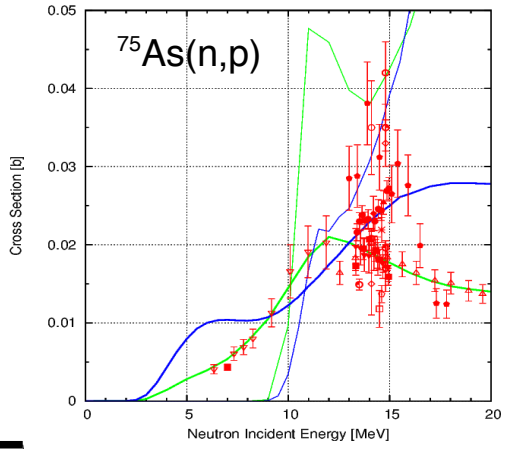
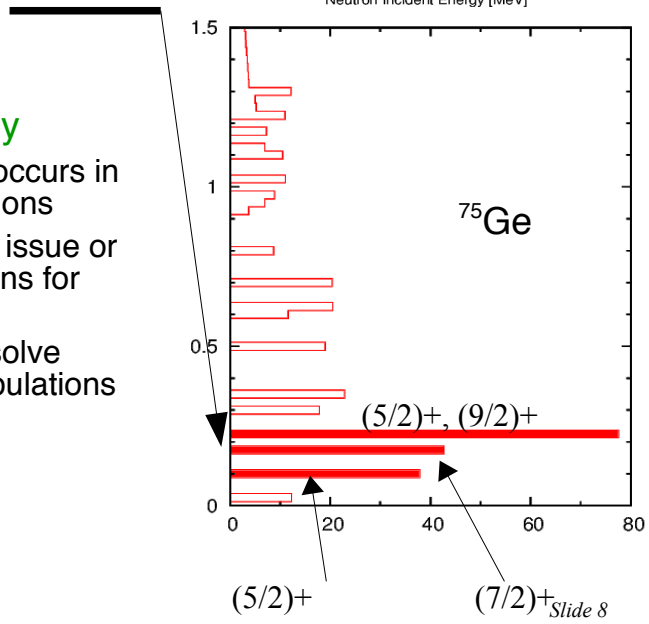
Significance of Nuclear Structure Inputs in HF Calculations

- 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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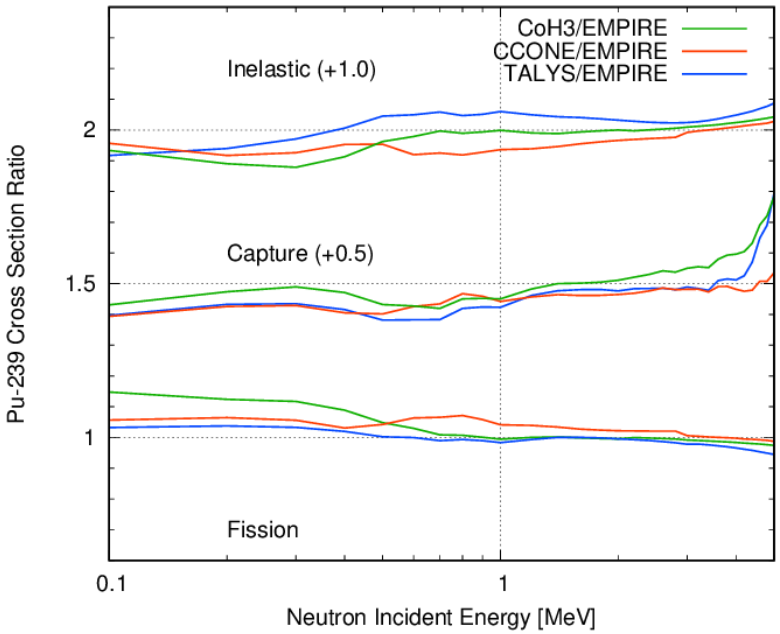
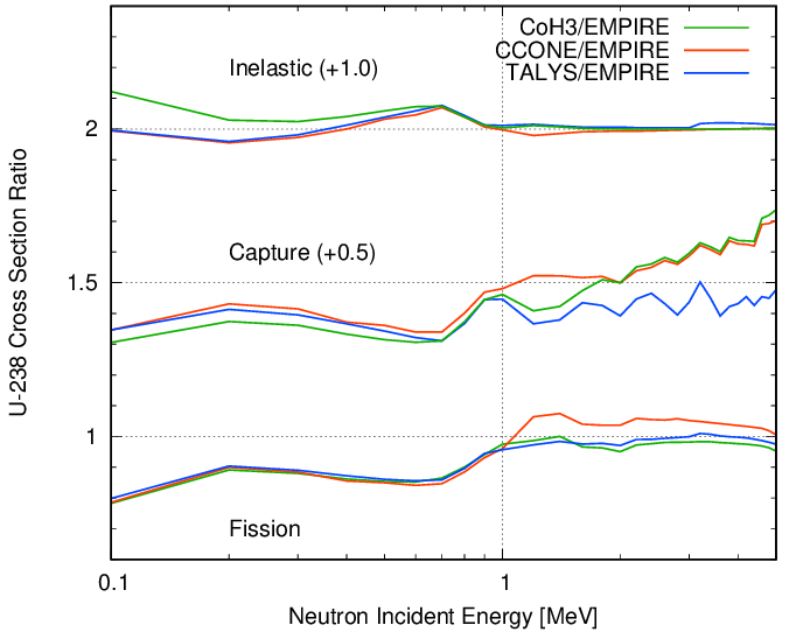
Hauser-Feshbach Code Comparison

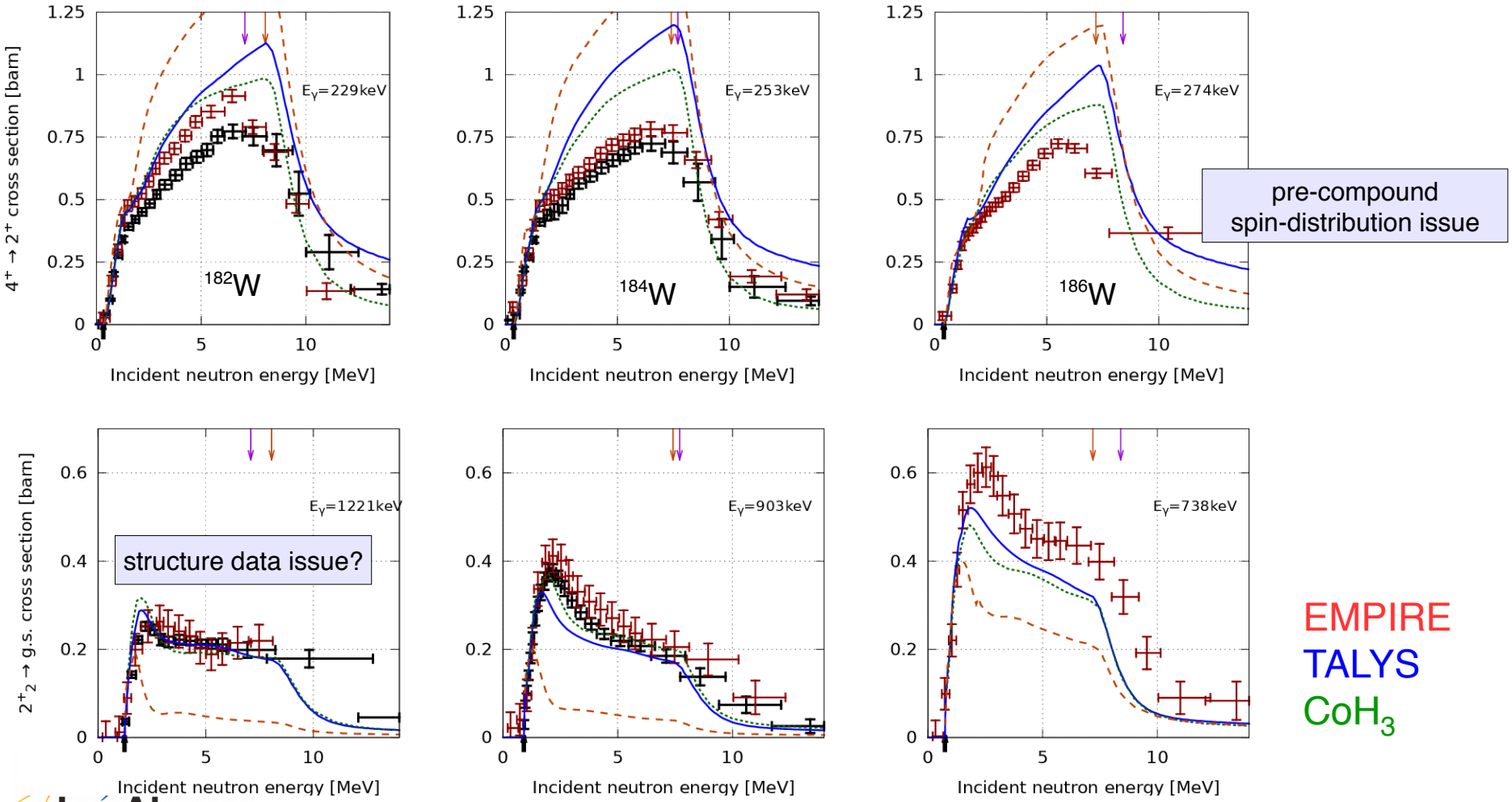


	Lang.	Lines	Maintained by
EMPIRE	F77/90	113K	BNL/IAEA
TALYS	F77/90	118K	IAEA/CEA/ULB
CCONE	C++	35K	JAEA
CoH_3	C++	46K	LANL

- 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}U, and fission case, ^{239}Pu, with carefully defined consistent model parameters (INDC(NDS)-0654)
- Discrepancy less than 10% confirmed

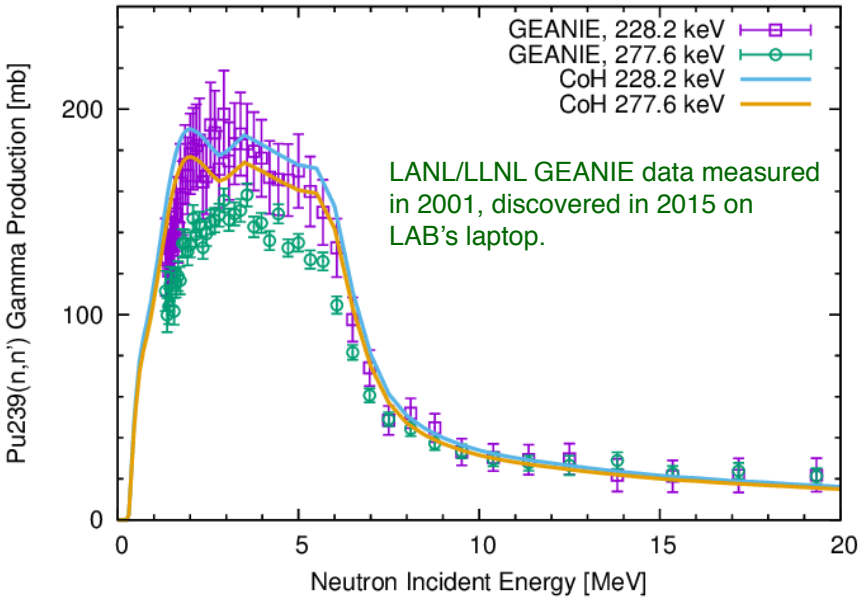


HF Code Comparion for Photon Production Data of W



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