Work plan for validating nuclear level densities with CCONE

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Introduction

CCONE (Comprehensive Code for Nuclear Data Evaluation)

- Developed for evaluation of the actinides nuclear data of JENDL-4.0/Actinide File.
- Developed from scratch with C++ in object-oriented way.
- Used for the JENDL evaluations

References

- O. Iwamoto, "Development of a comprehensive code for nuclear data evaluation, CCONE, and validation using neutron-induced cross sections for uranium isotopes", J. Nucl. Sci. Technol., 44, 687 (2007)
- O. Iwamoto, "Extension of a nuclear reaction calculation code CCONE toward higher incident energies multiple preequilibrium emission, and spectrum in laboratory system", J. Nucl. Sci. Technol., 50, 409 (2013)
- O. Iwamoto, "Progress in Developing Nuclear Reaction Calculation Code CCONE for High Energy Nuclear Data Evaluation", Nuclear Data Sheets 118 (2014) 204–207
- O. Iwamoto et al., "The CCONE Code System and its Application to Nuclear Data Evaluation for Fission and Other Reactions", Nuclear Data Sheets 131 (2016) 259–288
- O. Iwamoto, "Calculation of recoil nucleus spectrum in the presence of multi-particle emission in nuclear reaction with Monte Carlo method as an extension of CCONE code", J. Nucl. Sci. Technol., 59, 1232 (2022)

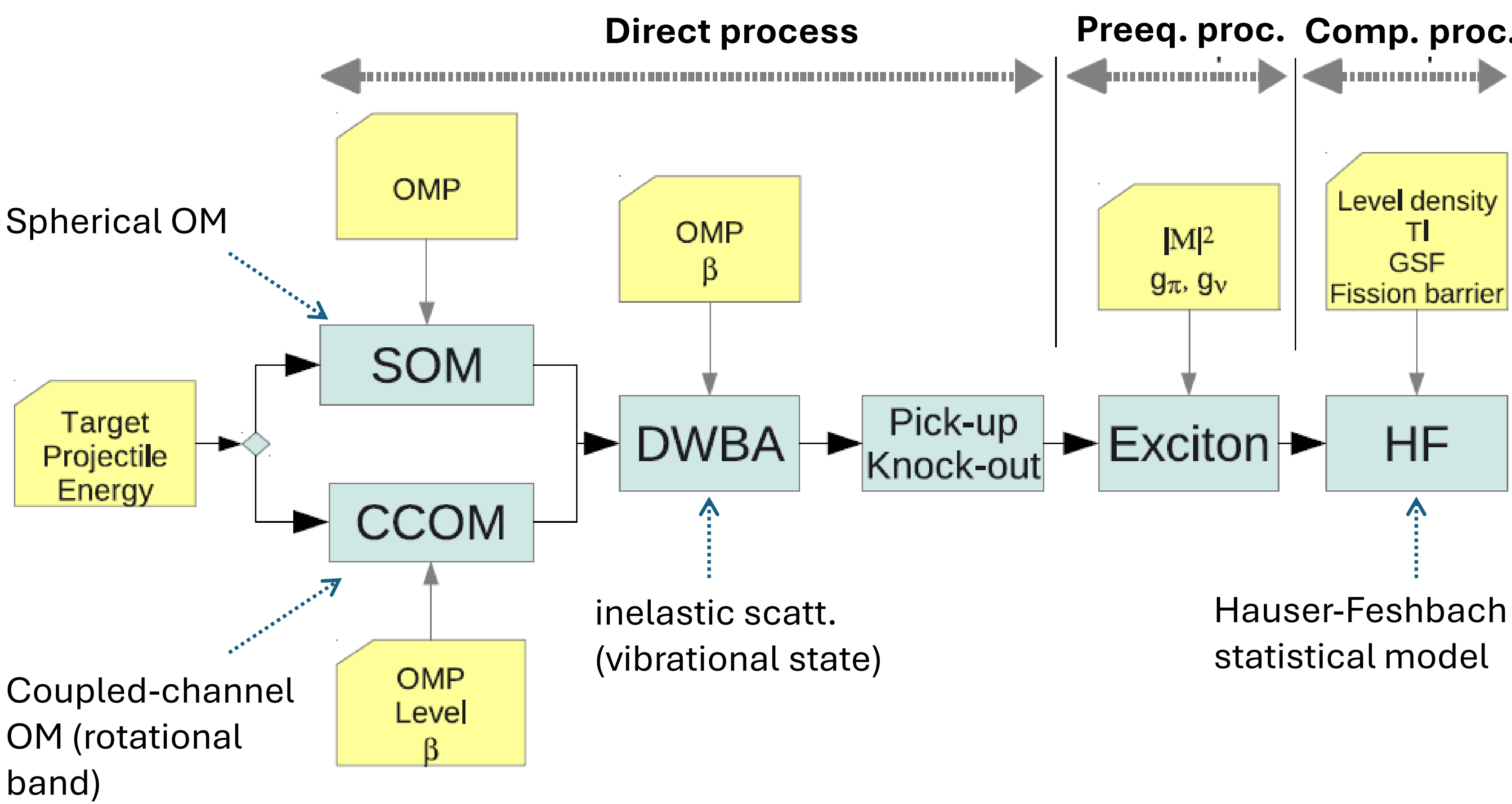
Models

- Optical model
  - spherical optical model
  - coupled channel optical model (rotational band)
  - RIPL OMP data base
- DWBA
  - vibrational state
- pre-equilibrium two component exciton model
- Hauser-Feshbach statistical model
  - channels: g, n, p, d, t, h, a, f
  - width fluctuation correction
- cluster emission
  - pickup and knockout reaction systematics by Kalbach
  - Iwamoto-Harada model
- C++ object oriented programming

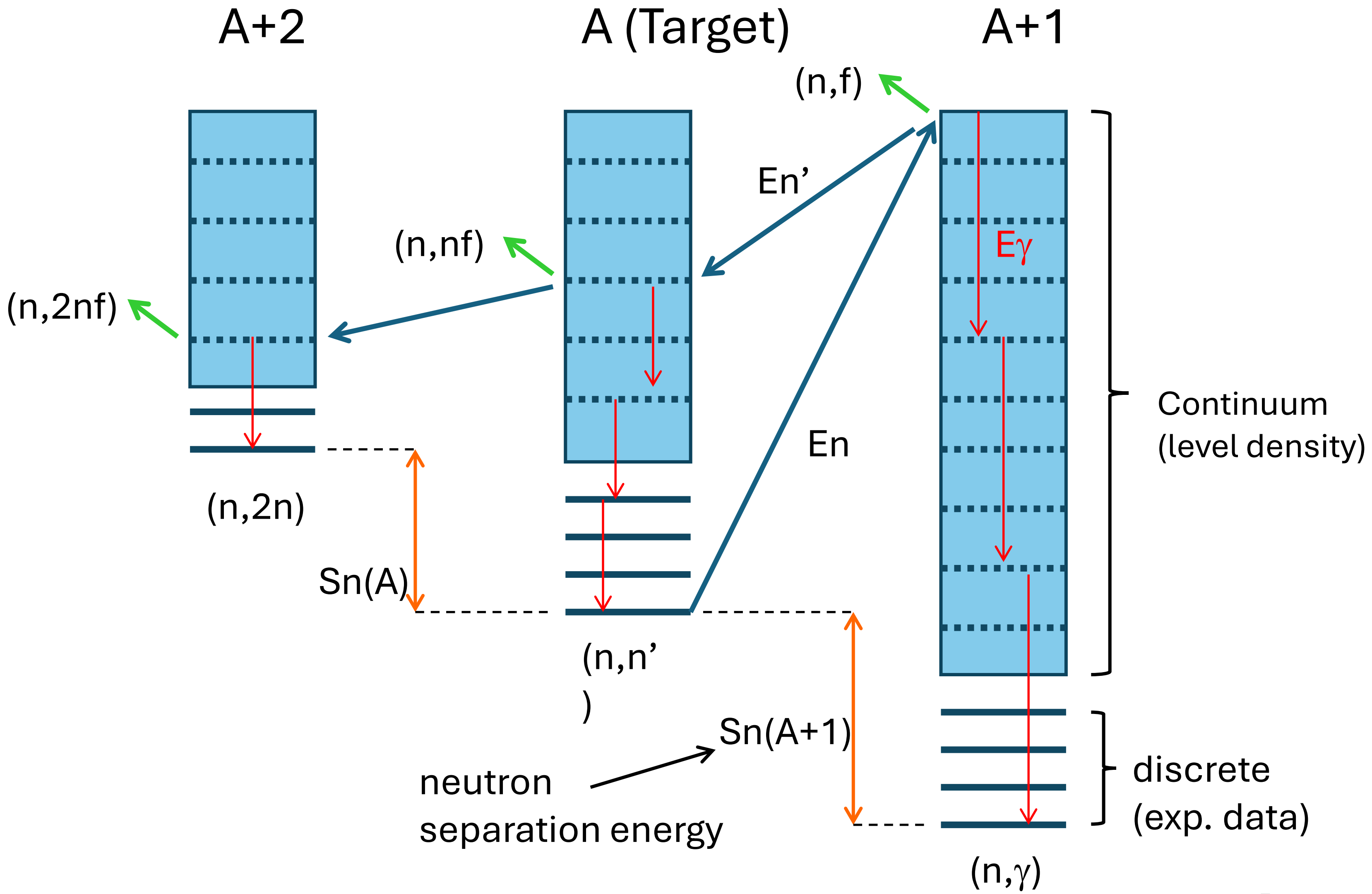
Non-resonant reactions: nuclear reaction model calculation

Comprehensive code for nuclear data evaluation (CCONE)

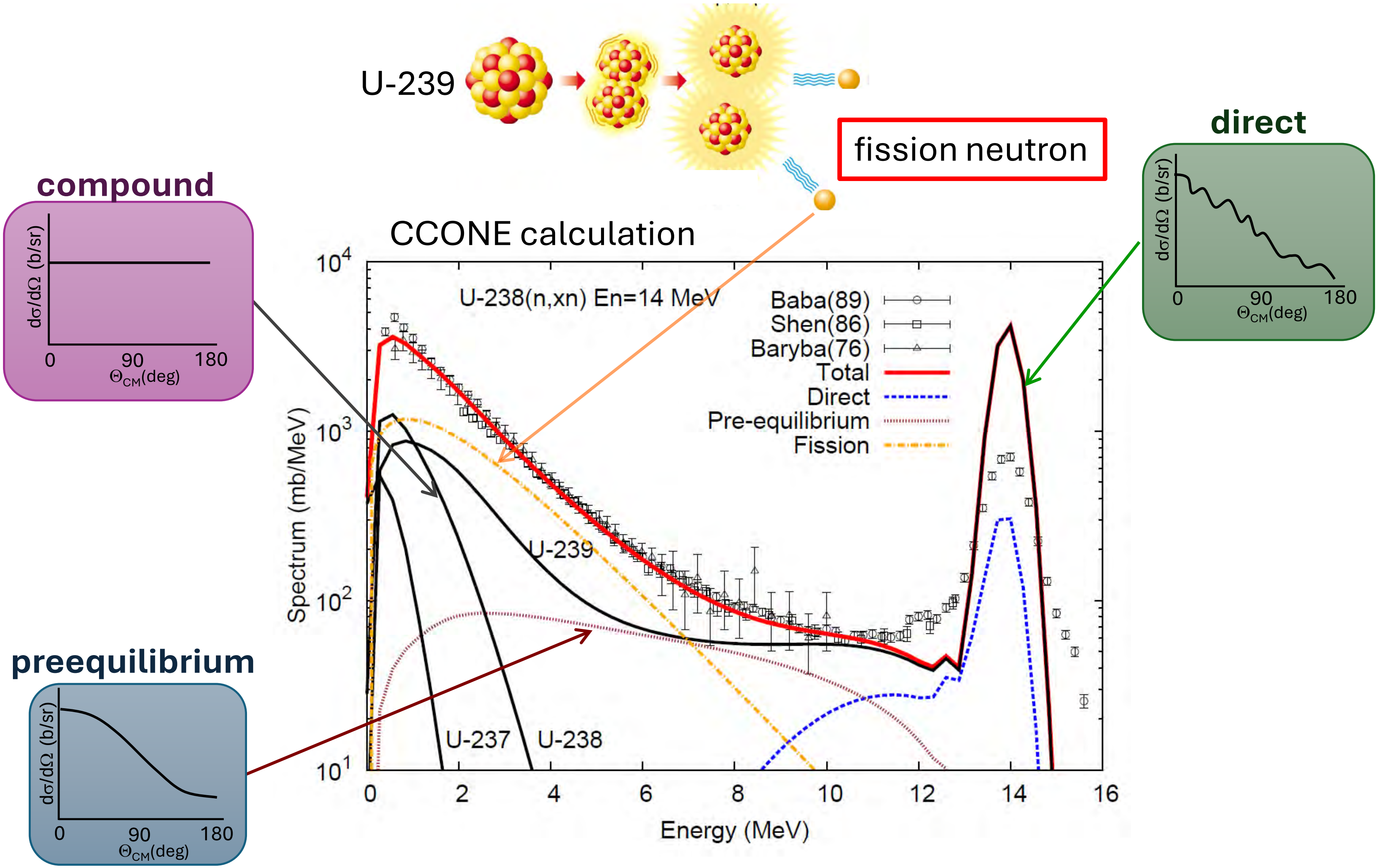
O. Iwamoto, J. Nucl. Sci. Technol. 44, 687 (2007)
O. Iwamoto, Nuclear Data Sheets, 131, 259 (2016)



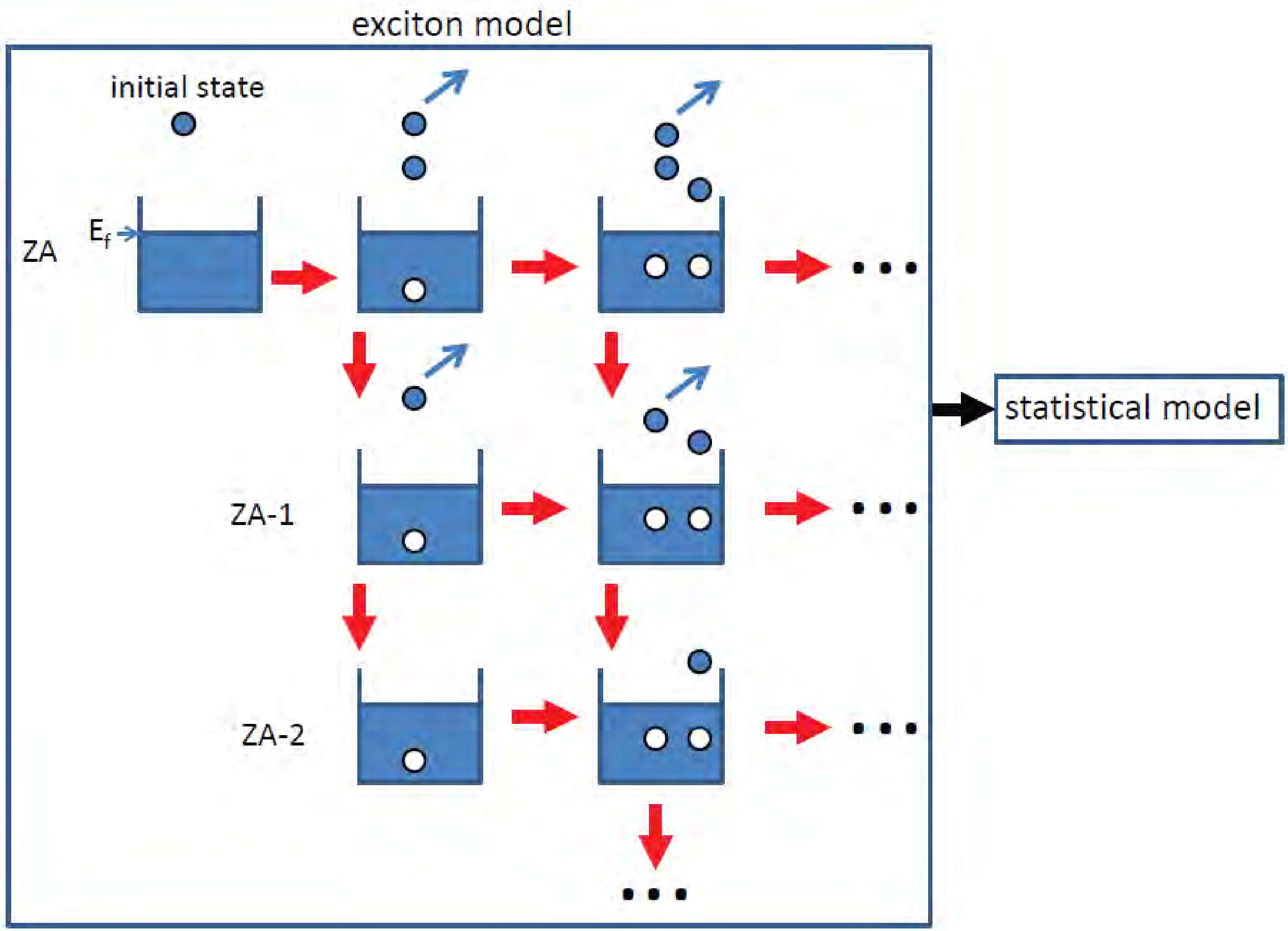
Decay chain on statistical model



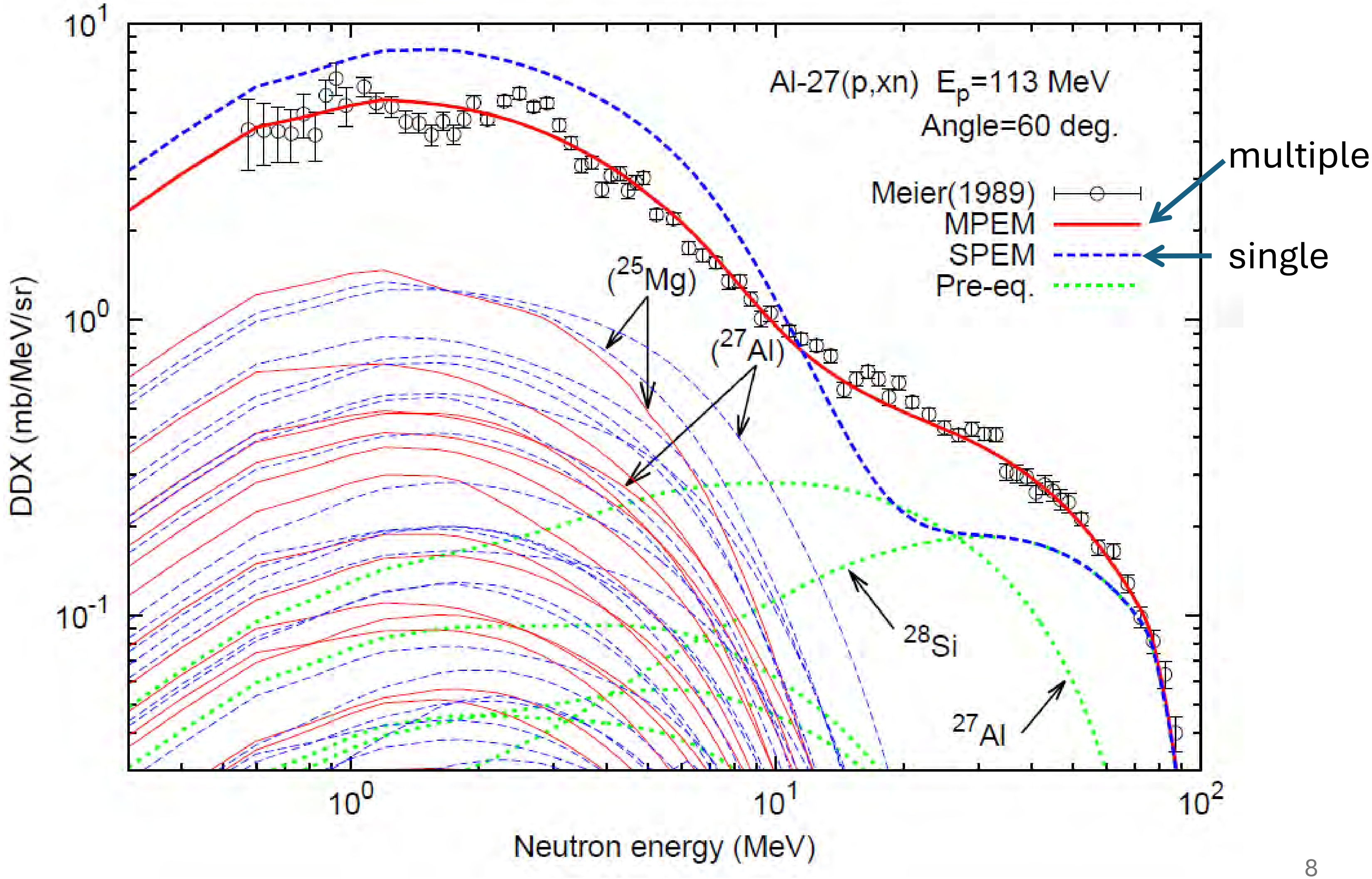
Energy spectrum



Multi-particle emission (exciton model)



Effect of multi-particle emission in neutron emission spectrum



options of level density

- Gilbert-Cameron (constant temparature + Fermi gas)
- generalized super-fluid model (not used)
- tabulated level density (RIPL-3 format)
- hybrid level density (N. Furutachi et al., JNST 56, 412 (2019))

GC Level density

$$\rho(U, J^\pi) = \rho(U)\rho(J^\pi),$$
$$U = E - \Delta.$$

$$a(U) = a^*\left(1 + E_{sh}\frac{1 - e^{-\gamma U}}{U}\right)$$

$$\rho(U) = \begin{cases} K_r \dfrac{e^{2\sqrt{aU}}}{12\sqrt{2}\sigma U (aU)^{1/4}}, & (U > U_m) \\ \dfrac{1}{T}\exp\dfrac{U + \Delta - E_0}{T}, & (U \le U_m) \end{cases}$$

Rotational enhancement (AS):

$$K_r = I_\perp t,$$
$$t = \sqrt{U/a},$$

$$\rho(J^\pi) = \frac{1}{2}\frac{(2J+1)}{2\sigma^2}\exp\left\{-\frac{\left(J+\frac{1}{2}\right)^2}{2\sigma^2}\right\},$$

$$I_\perp = \frac{2}{5}\frac{mAR^2}{\hbar^2}\left(1 + \sqrt{\frac{5}{16\pi}}\beta\right),$$
$$R = 1.2A^{1/3} \quad \text{(fm)},$$

Spin cutoff parameters

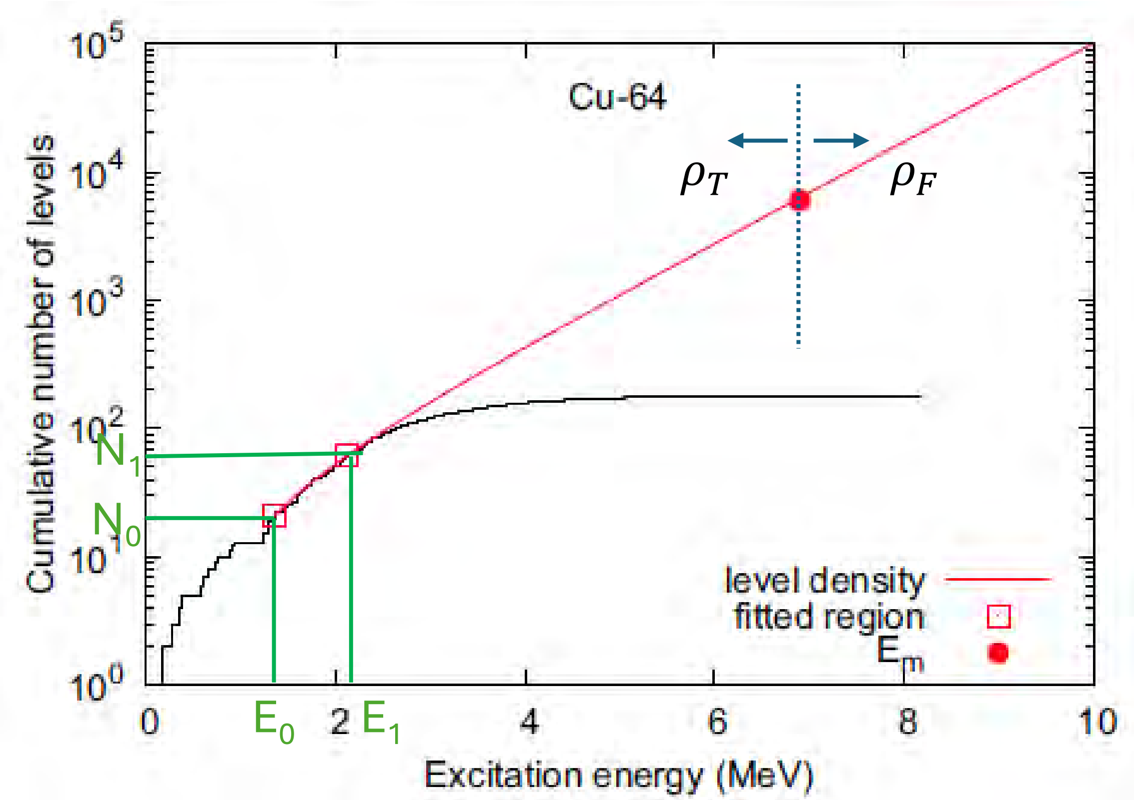
FG: $\sigma = \sigma_F(U) = \sqrt{I_\perp t} \quad (U \ge U_m).$

CT: $\sigma = \sigma_T(U) = \sigma_F(U_0) + \{\sigma_F(U_m) - \sigma_F(U_0)\}\dfrac{U + \Delta}{U_m + \Delta},$ (U_0=0.5 MeV)

matching energy of CT & FG LDs

determine Em with conditions:

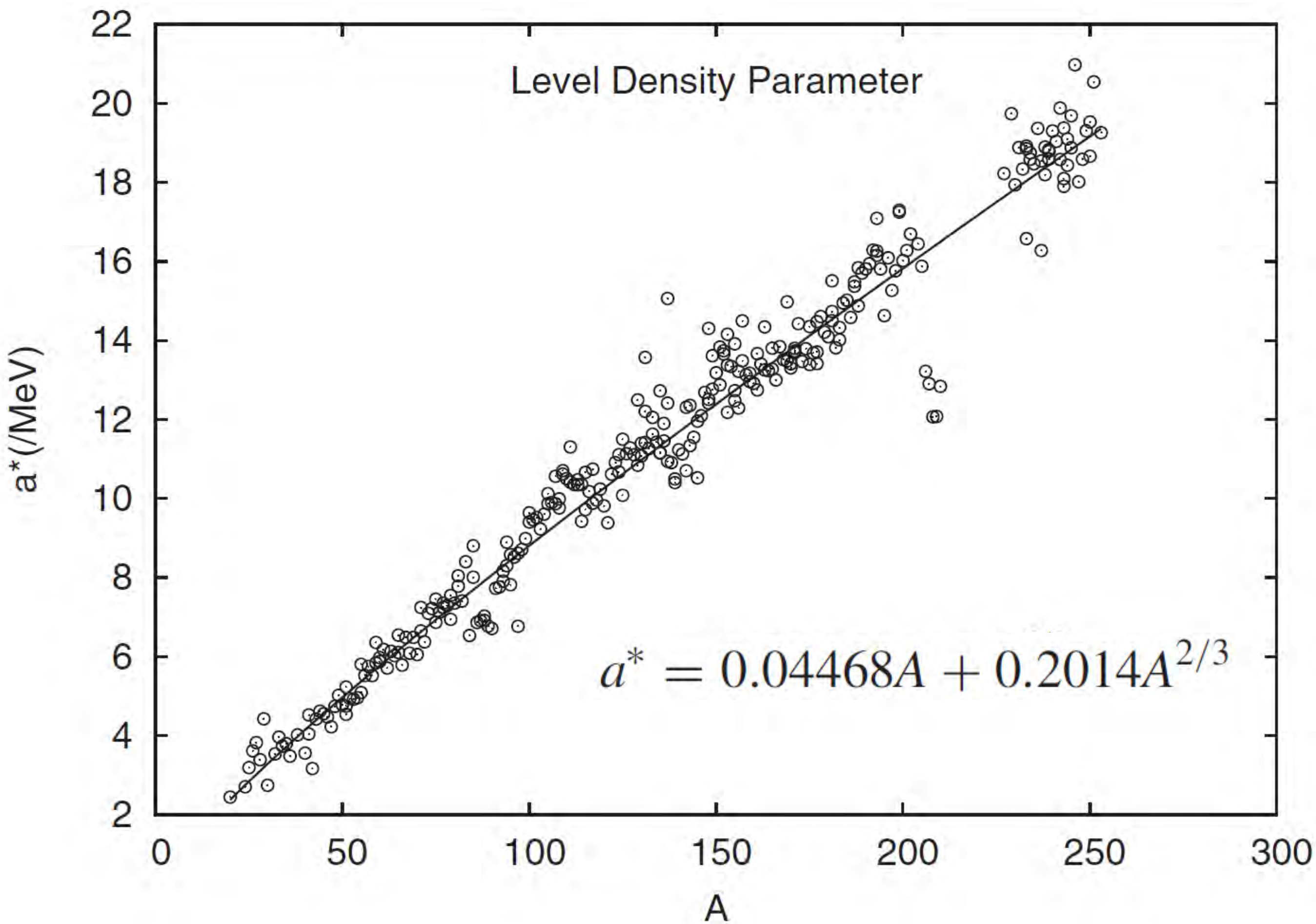
$$\rho_F(U_m) = \rho_T(U_m),$$
$$\left.\frac{d\rho_F(U)}{dU}\right|_{U=U_m} = \left.\frac{d\rho_T(U)}{dU}\right|_{U=U_m}$$



$$N_1 - N_0 = \int_{E_0}^{E_1} \rho(E)dE$$

LD parameter systematics

a* was deduced from D0



Hybrid LD

N. Furutachi et al., JNST 56, 412 (2019)

$$\rho_{\mathrm{h}}(U,J) = \begin{cases} (1 - f_{\mathrm{dam}}(E_x))\rho_{\mathrm{sph}}(U - E_{\mathrm{def}}, J) + f_{\mathrm{dam}}(E_x)\rho_{\mathrm{def}}(U,J) \\ \rho_{\mathrm{sph}}(U,J) \end{cases}$$

spherical $$\rho_{\mathrm{sph}}(U,J) = R_{\mathrm{s}}(U,J)\frac{\omega_{\mathrm{s}}(U)}{\sqrt{2\pi}\sigma_{\mathrm{s}}},$$

deformed $$\rho_{\mathrm{def}}(U,J) = K_{\mathrm{rot}}R_{\mathrm{d}}(U,J)\frac{\omega_{\mathrm{d}}(U)}{\sqrt{2\pi}\sigma_{\mathrm{d}}},$$

dump of deformation

$$f_{\mathrm{dam}}(E_x) = \frac{1}{1 + e^{(E_x - E_{\mathrm{ts}})/d_{\mathrm{e}}}}, \quad d_e = CE_{\mathrm{ts}}$$

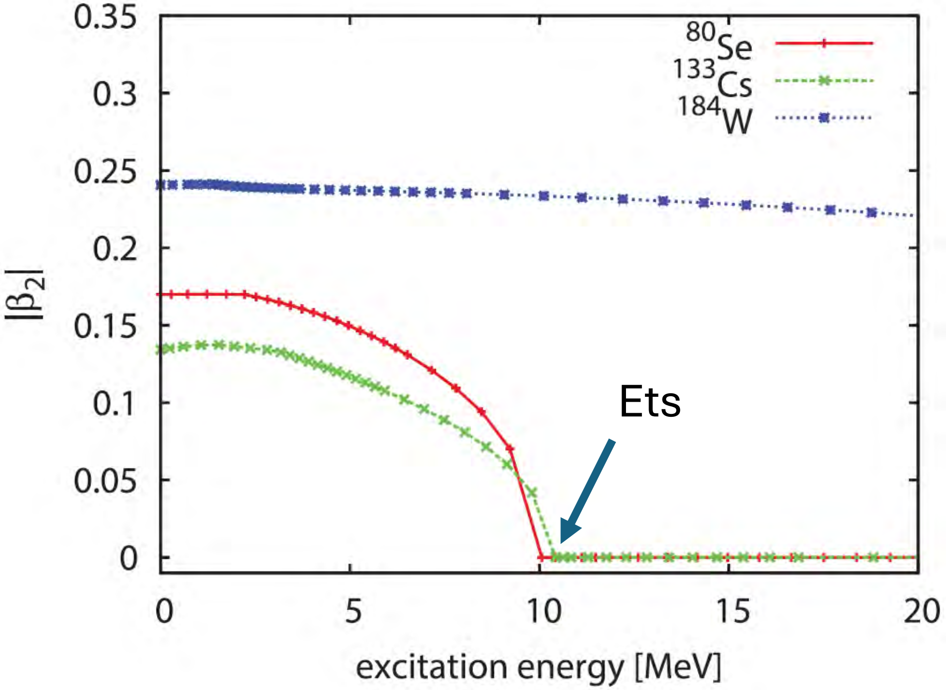
deformation energy

$$E_{\mathrm{def}} = E_{\mathrm{const.}}^{\beta_2=0}(T=0) - E(T=0)$$ FTHFB

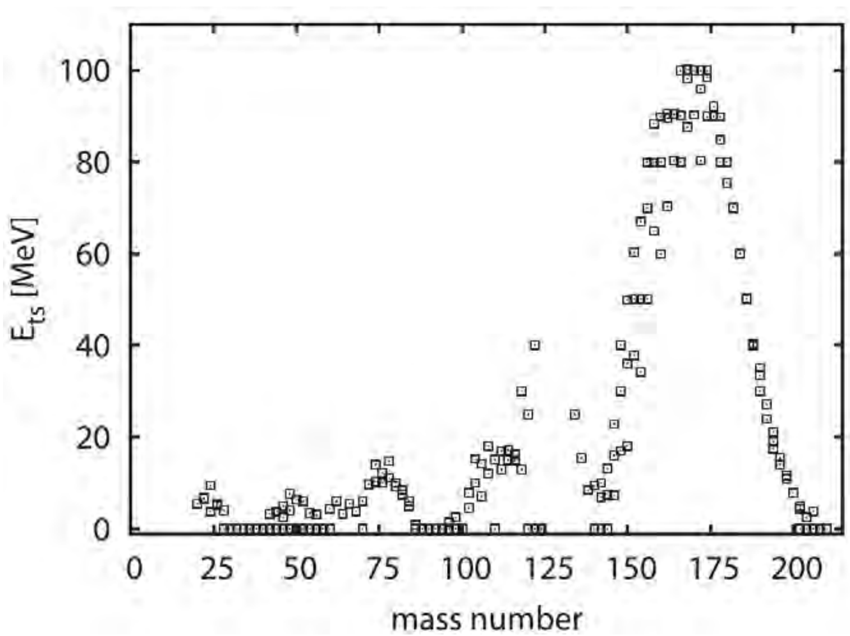
Estimation of transition energy

$$f_{\mathrm{dam}}(E_x) = \frac{1}{1 + e^{(E_x - E_{\mathrm{ts}})/d_{\mathrm{e}}}}$$

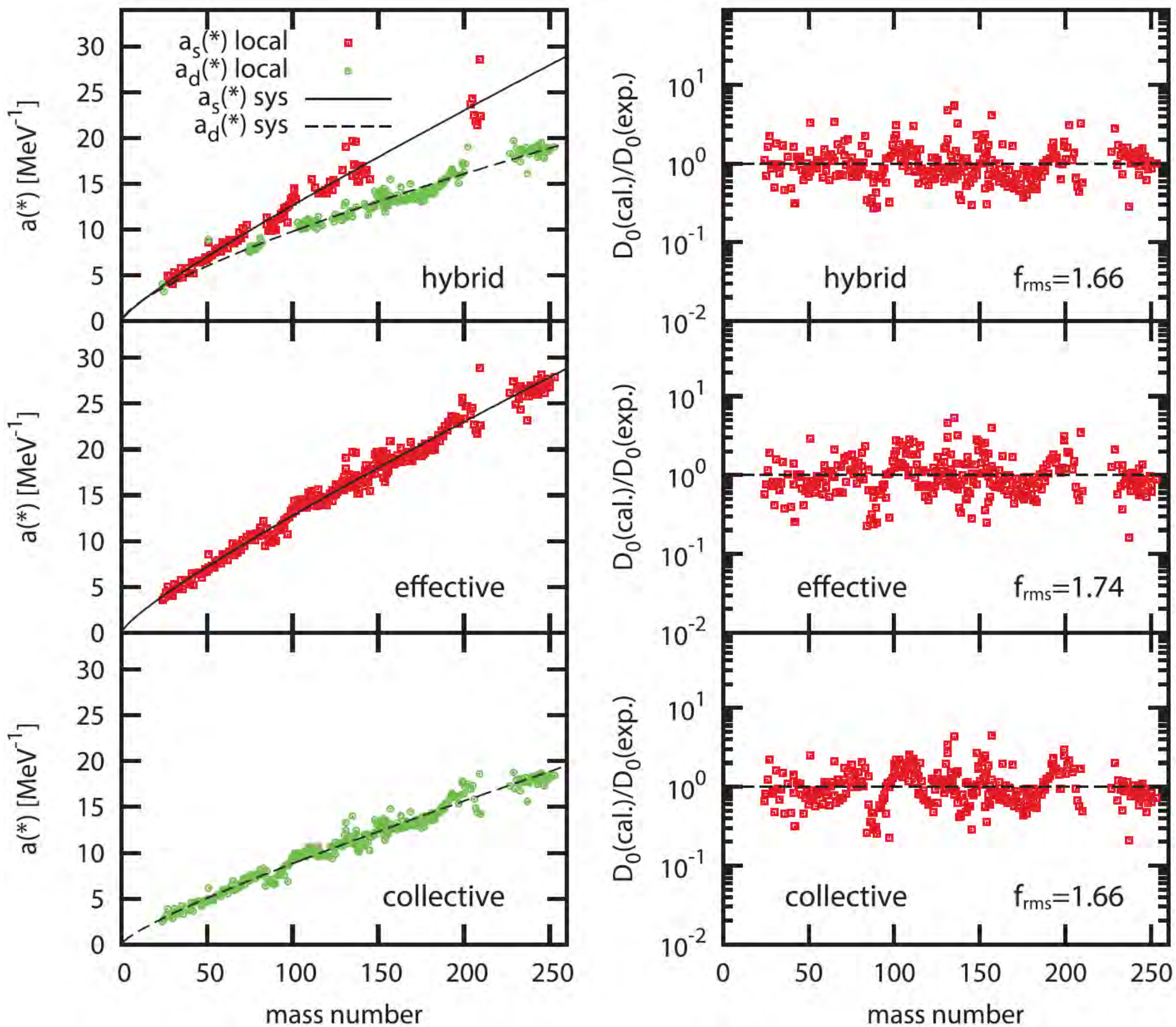
Most probable deformation β2 by FTHFB



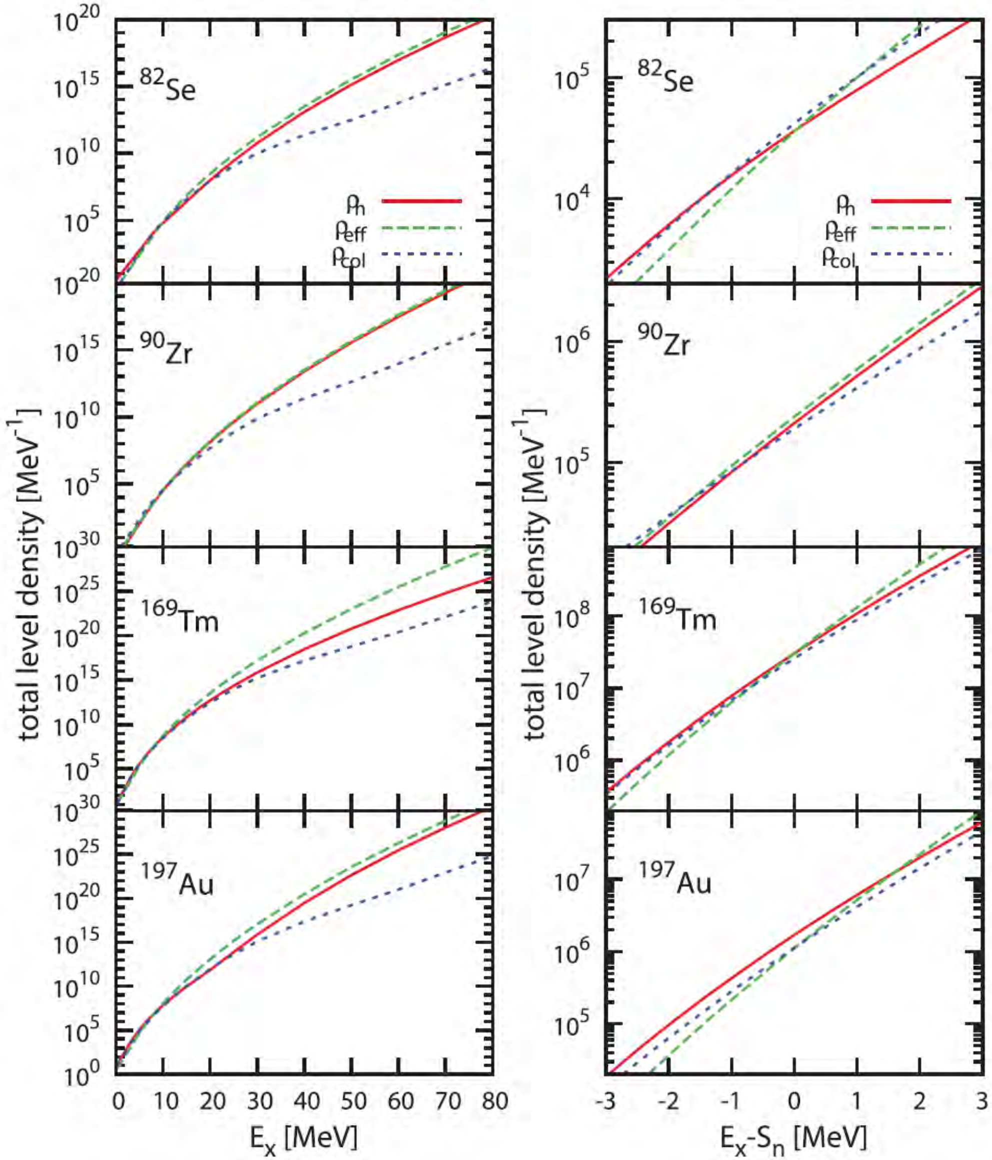
Parameter Ets derived from FTHFB



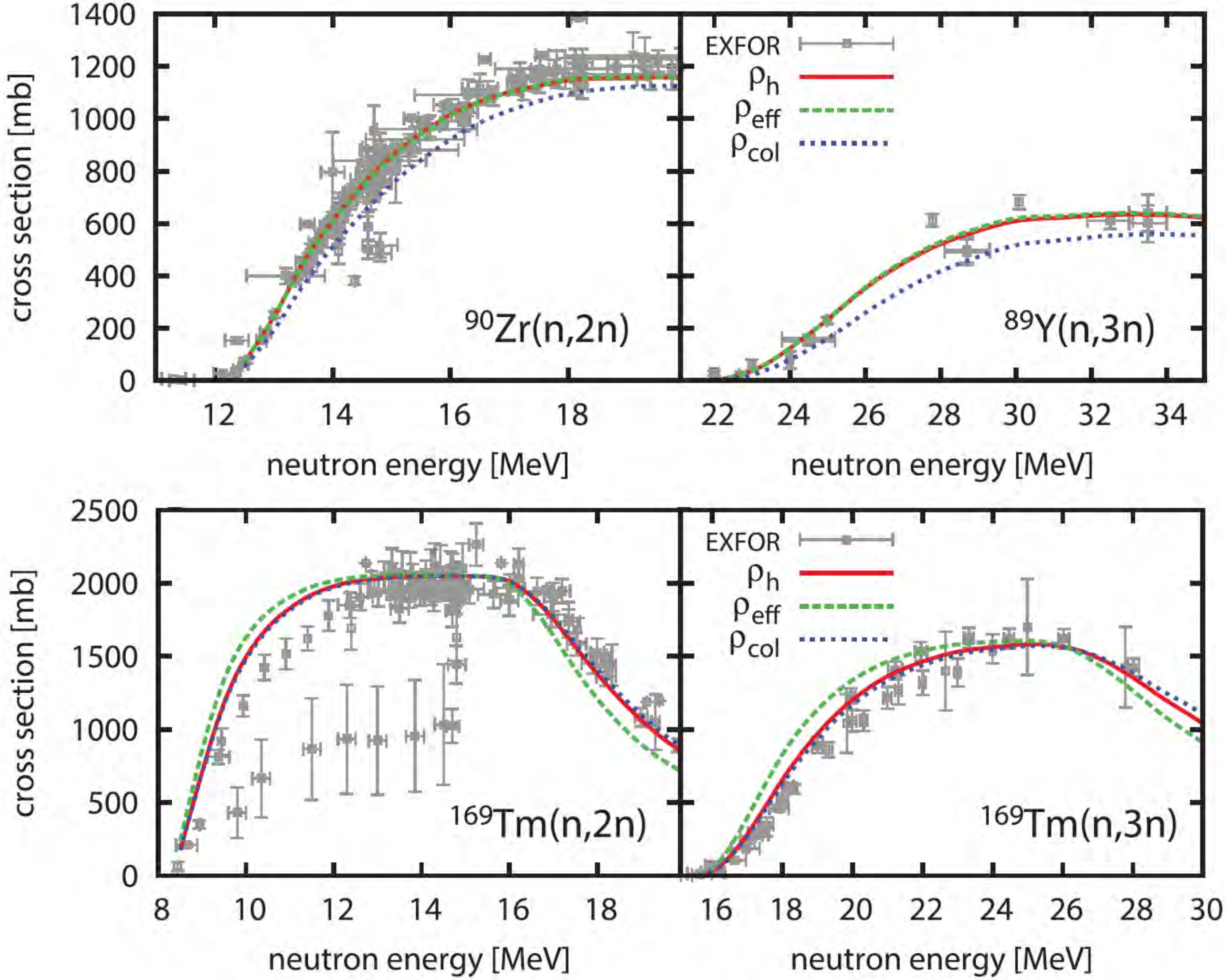
LD parameter systematics



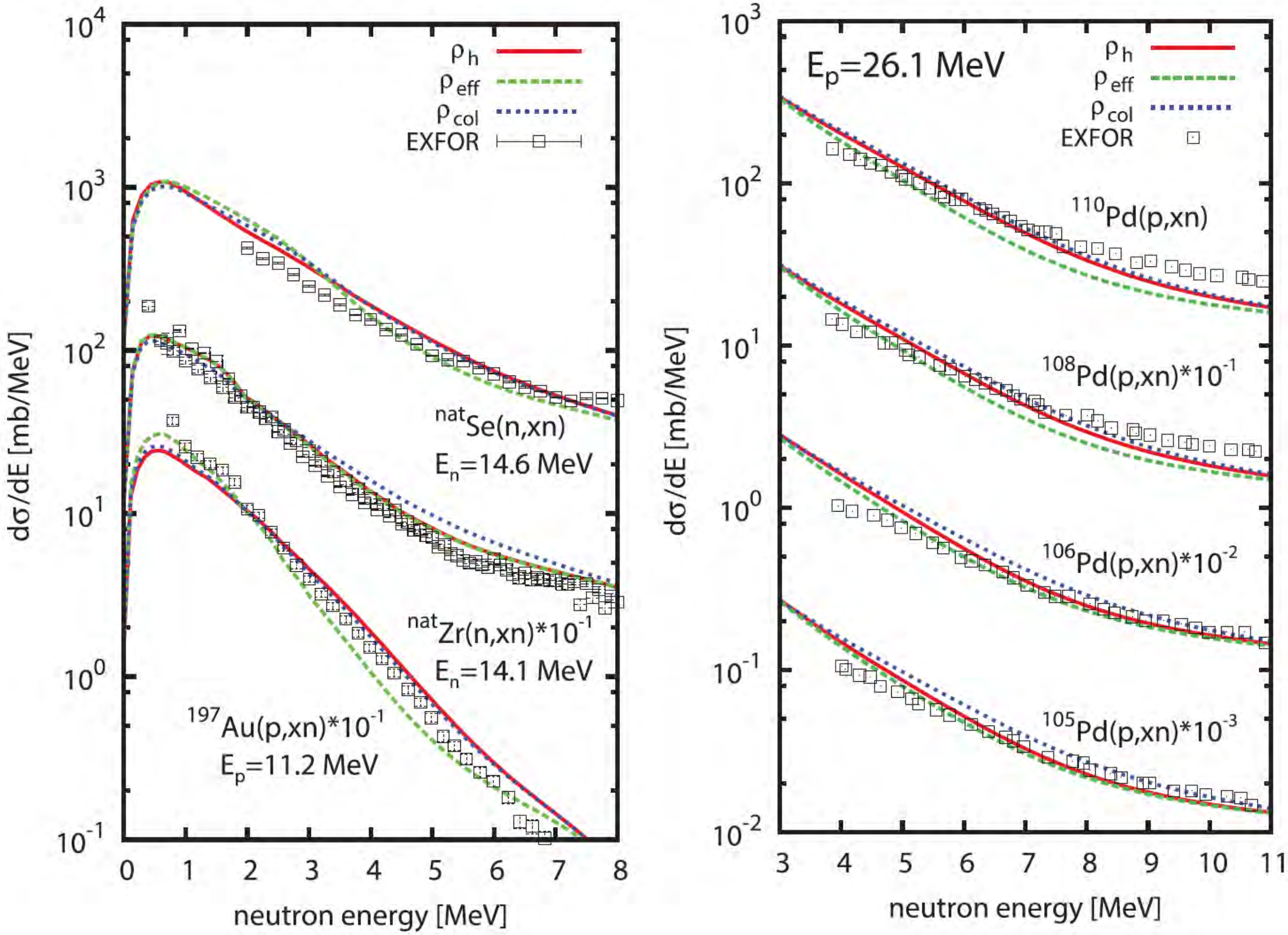
Ex dependence of level density



LD dependence of calculated



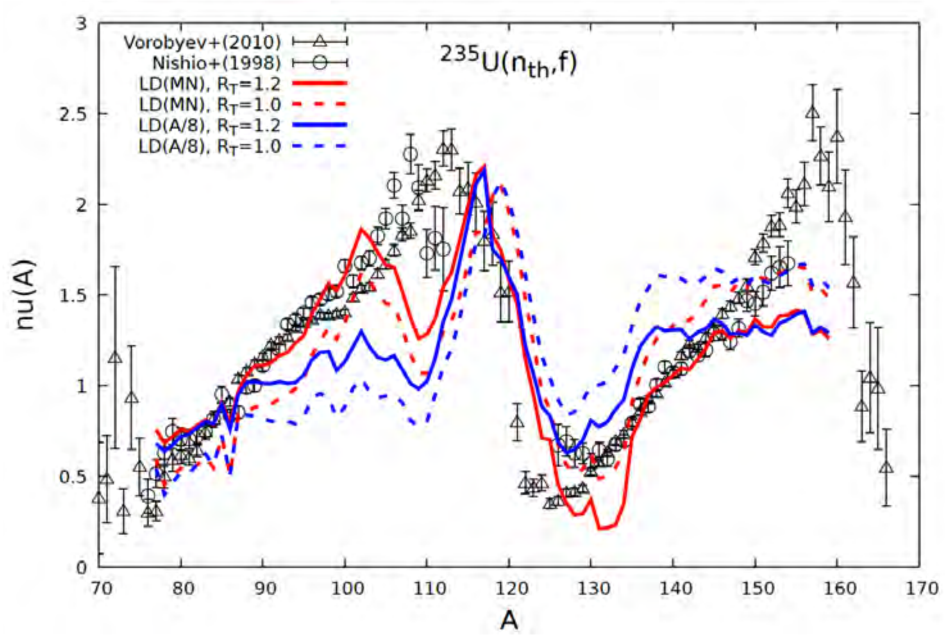
LD dependence of spectrum



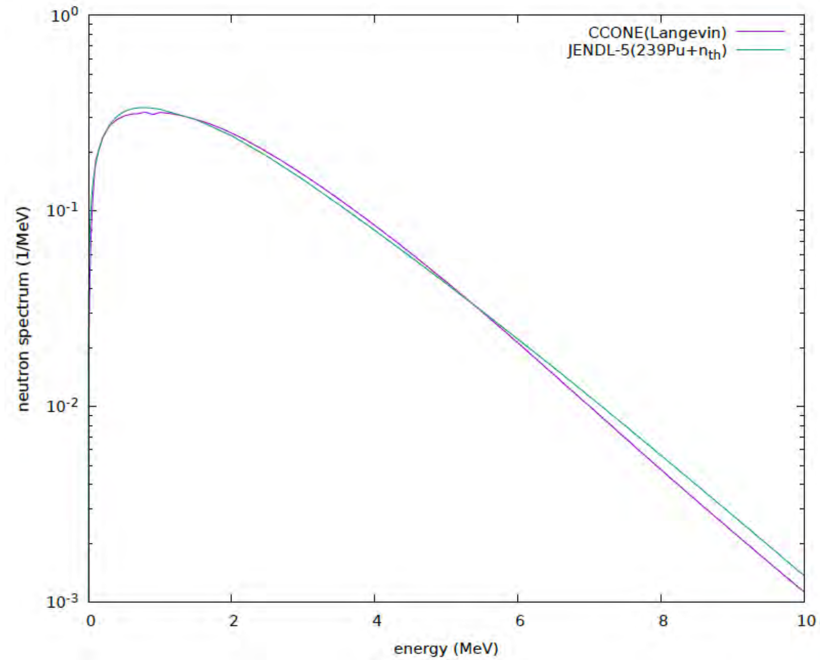
Fission neutrons with CCONE

Fission neutron and gamma-ray emission were estimated with statistical decay model for ~400 fission fragments that were created according to A. E. Lovell et al., PRC 103, 014615 (2021) and K. Fujio et al., JNST 61, 84 (2024).

number of fission neutron (^{235}U+n)



fission neutron spectrum (^{239}Pu+n)



work plan

- Validate the nuclear densities with CCONE
- Calculate cross sections and emission spectra with NLD implemented in CCONE and compare with experimental data
- Derive reasonable LD model and parameter set in terms of reaction model calculation with adjusting NLD parameters.
- Implement other NLDs discussed in the CRP and calculate cross sections.
- Finalize validation and contribute to the final CRP report.