Langevin Model of Low-Energy Fission

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Dedicated to the memory of J. R. Nix, 1938-2008, who led the Los Alamos fission theory efforts for 30 years and inspired the developments presented today.

Essential Contributors:

- Peter Moller for years of collaboration and for developing the potential-energy model.
- John Lestone for enlightening discussions and providing an accurate neutron-evaporation code.
- Jorgen Randrup for help with nuclear inertia calculations and discussions of dissipation.
- Morgan White for encouragement and support.

Introduction

- Fission was discovered 79 years ago.
- For the first time, a dynamical physical model of fission predicts most of the major features and some of the quantitative details of fission mass and kinetic-energy distributions.

Ingredients of a dynamical model

- Potential energy of a nucleus as a function of its shape (nuclear binding energy).
- Kinetic energy of nuclear shape motions.
- Dissipation of nuclear shape motions: damping of motion and fluctuating force (Brownian motion).
- Equation of motion.

Potential energy of a deformed nucleus

- Use the macroscopic-microscopic model.
- Parameters of the model are determined by nuclear ground-state properties.
- Fission properties are an extrapolation of the model outside where its parameters are determined.
- Excellence of predictions a tribute to its creators: Nilsson, Nix, and Moller (~1970-2015).

Kinetic energy of nuclear shape motions

- Use irrotational fluid flow to define nuclear inertia.
- Allow scaling of the inertia to crudely represent the behavior of real nuclear matter.

Dissipation in nuclear shape motions

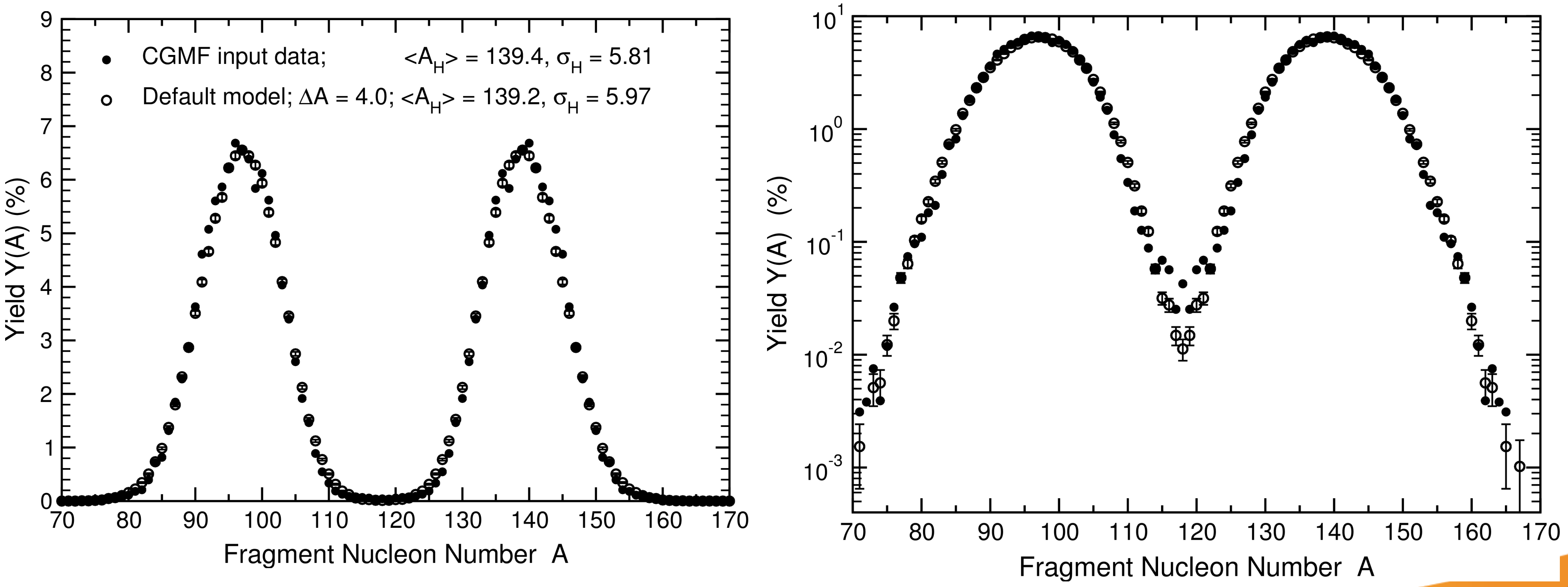
- Dissipation implies both damping of motion and a random force in the dynamics.
- Dissipation is modeled as a one-body effect with an arbitrary strength parameter.
- The random force is proportional to the square root of (nuclear temperature) x (the dissipation tensor).

Equations of motion: Langevin Equation

$$\frac{dq_j}{dt} = \frac{\partial H}{\partial p_j} = \frac{\partial(K+V)}{\partial p_j} = \frac{\partial(\frac{1}{2}M^{-1}_{ik}p_i p_k)}{\partial p_j} = M^{-1}_{jk}p_k \tag{1}$$

$$\frac{dp_j}{dt} = -\frac{\partial V}{\partial q_j} + \frac{1}{2}\frac{\partial M_{kl}}{\partial q_j}\dot{q}_k\dot{q}_l - \eta_{jk}\dot{q}_k + \sqrt{\frac{2T}{\Delta t}}\gamma_{jk}\Theta_k(t). \tag{2}$$

Unadjusted baseline model; thermal fragment yields; U235 (n,f)



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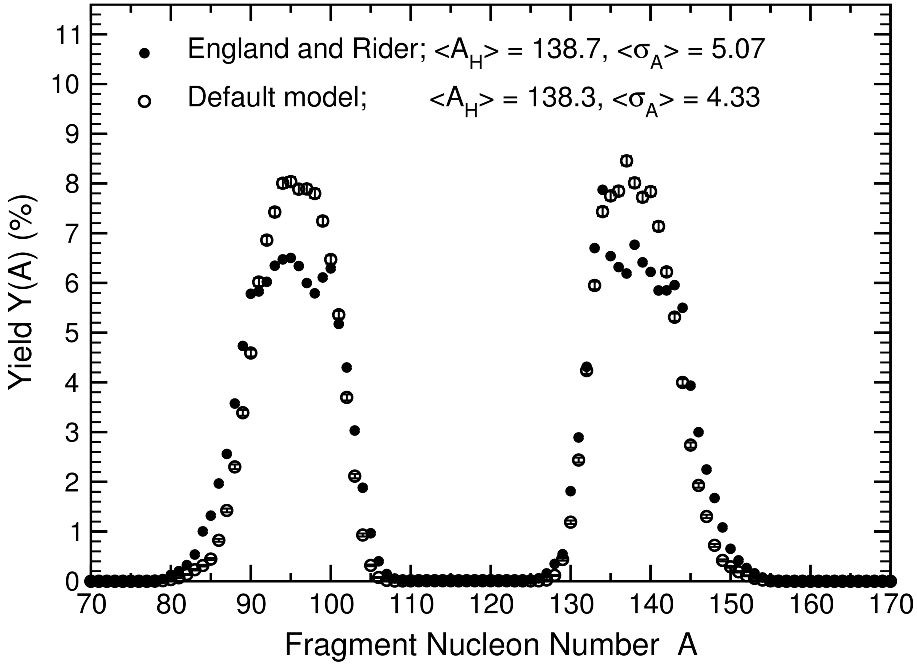
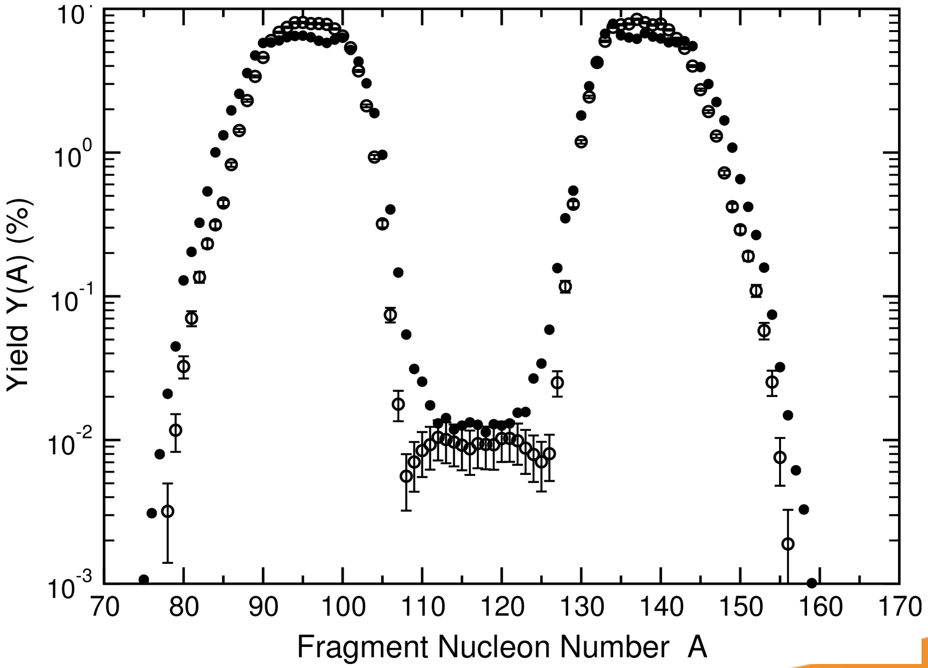
Unadjusted baseline model; thermal prompt yields U235 (n,f)





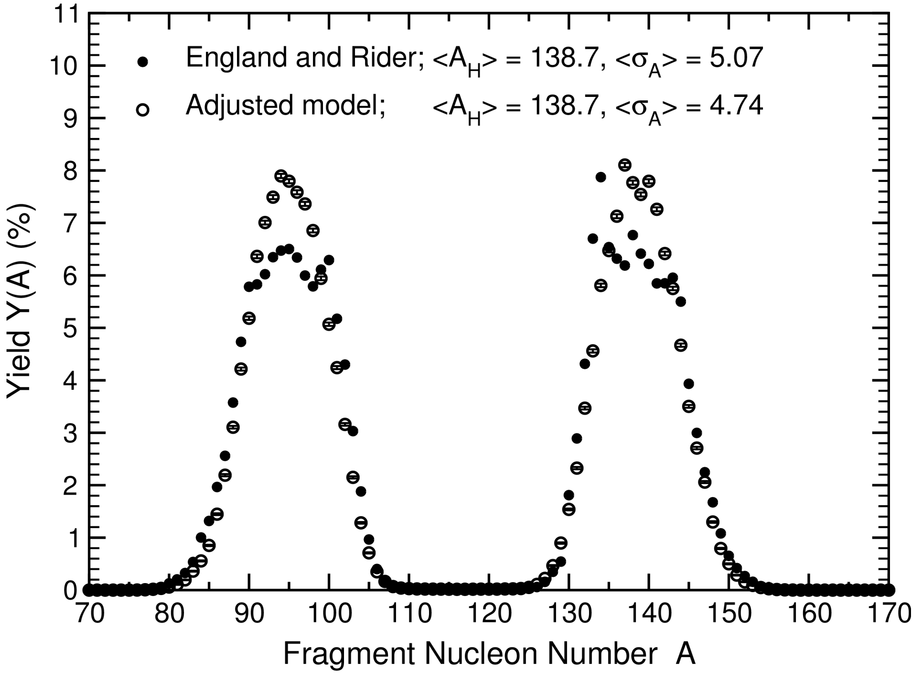
Default model predictions

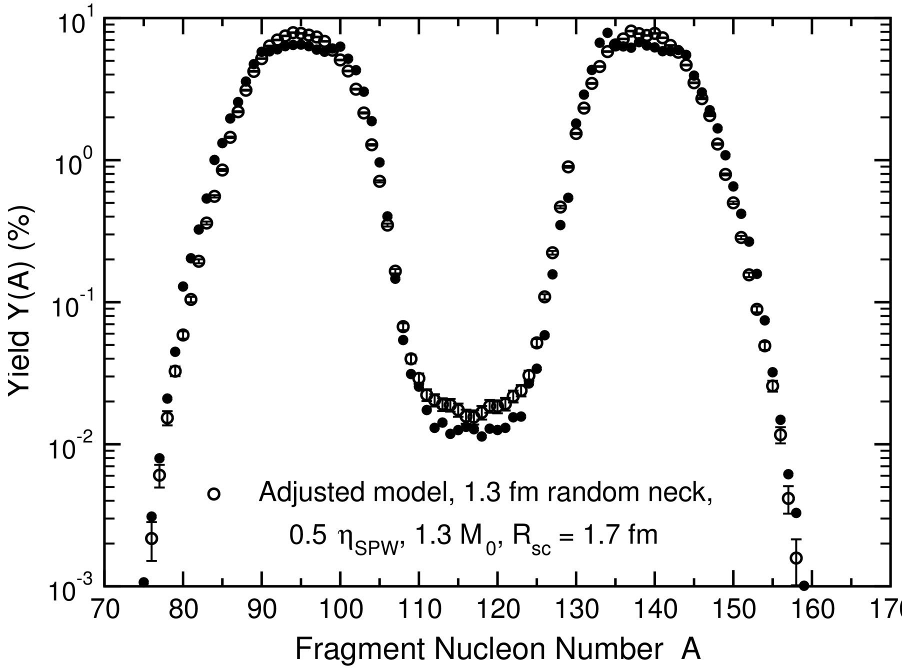
- Prompt yields poorly predicted.
- Primary yields consistent with measurements.
- Model <TKE> = 173.7 MeV; Expt. = 170.9 MeV.

Physical parameters in 'adjusted' model

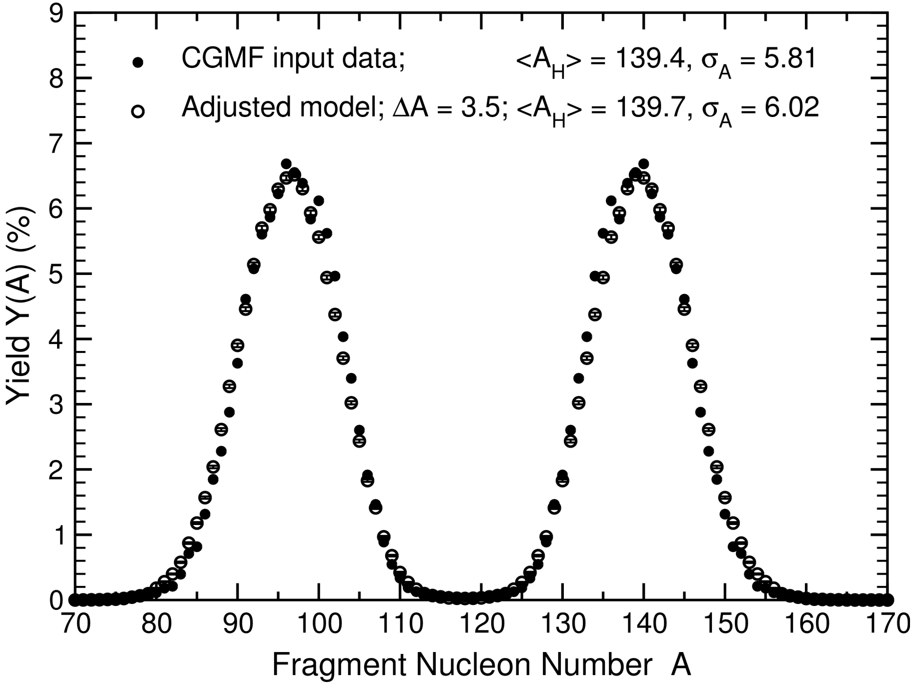
- Scaling of hydrodynamical inertia; value 1.3.
- Dissipation strength; scale = 0.5 of default.
- Neck radius at scission; 1.7 fm vs. 1.0 fm.
- Random neck rupture;
  gaussian with standard deviation of 1.3 fm.
- Probability of starting in symmetric valley; 0.0.

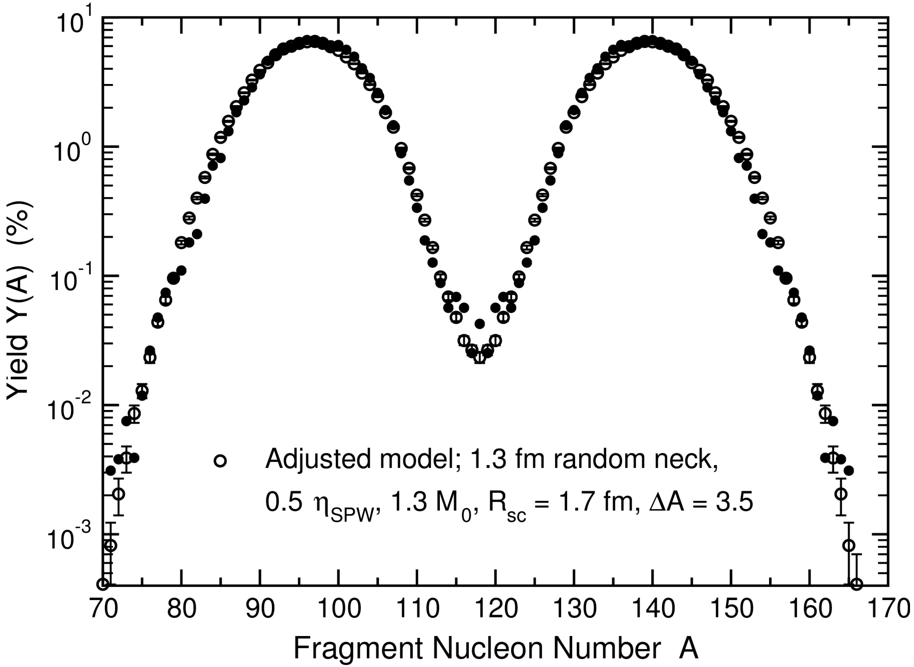
'Adjusted' model; thermal prompt yields; 235U(n,f)



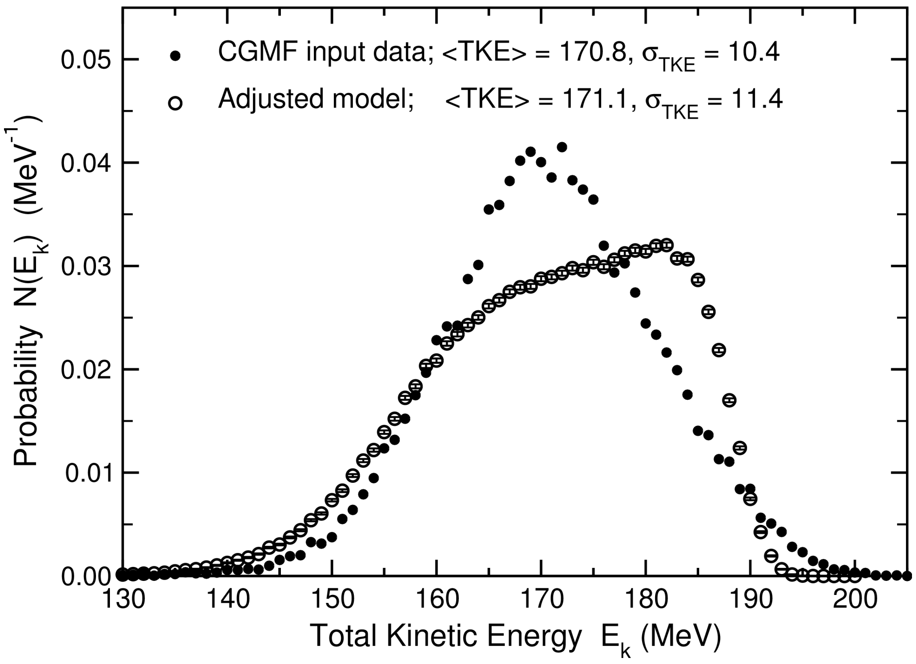


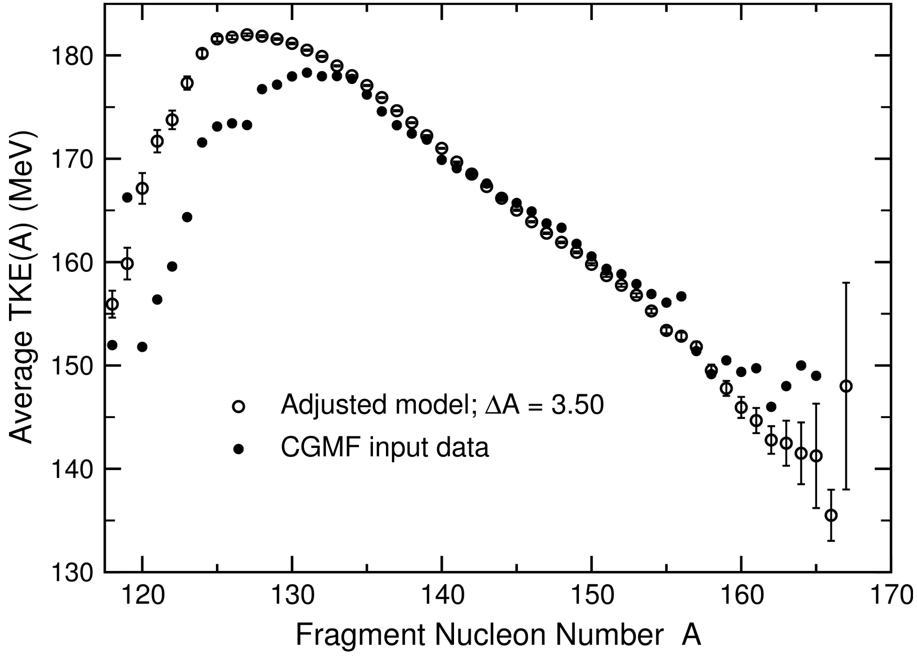
'Adjusted' model; thermal fragment yields; U235 (n,f)





'Adjusted' model; TKE yields; U235 (n,f)





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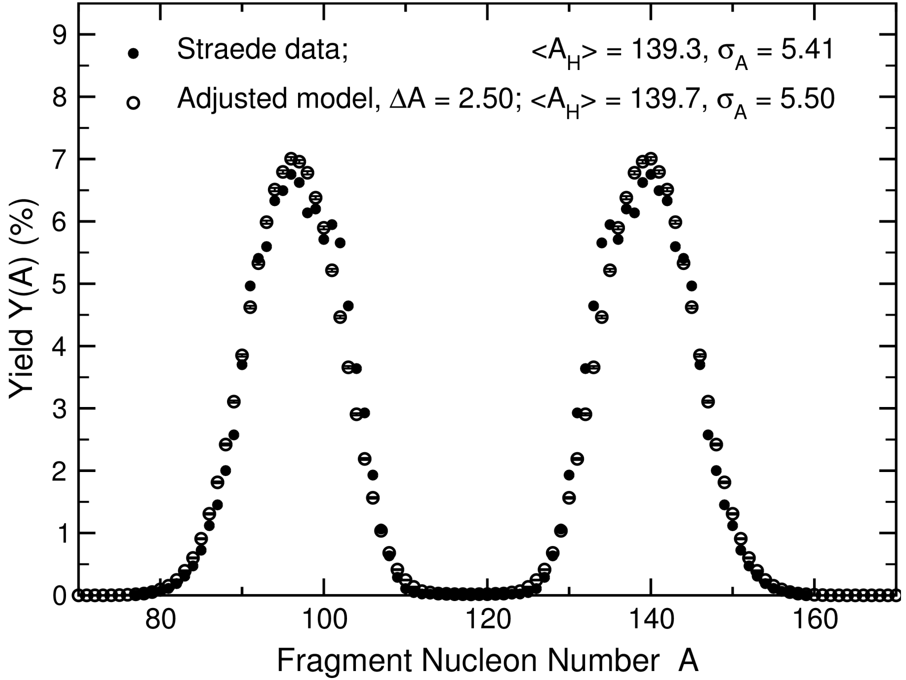
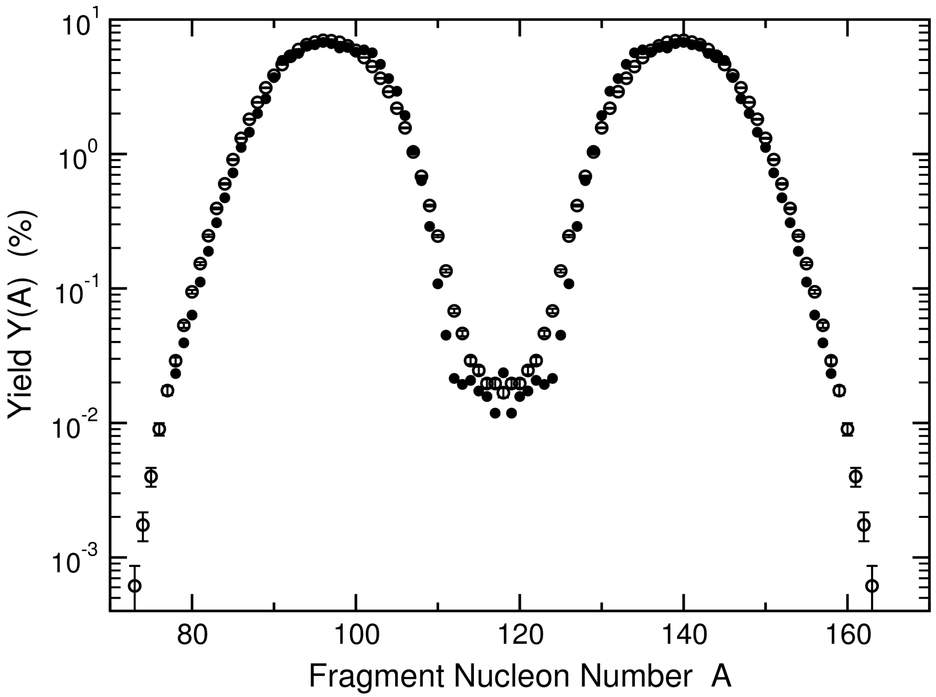
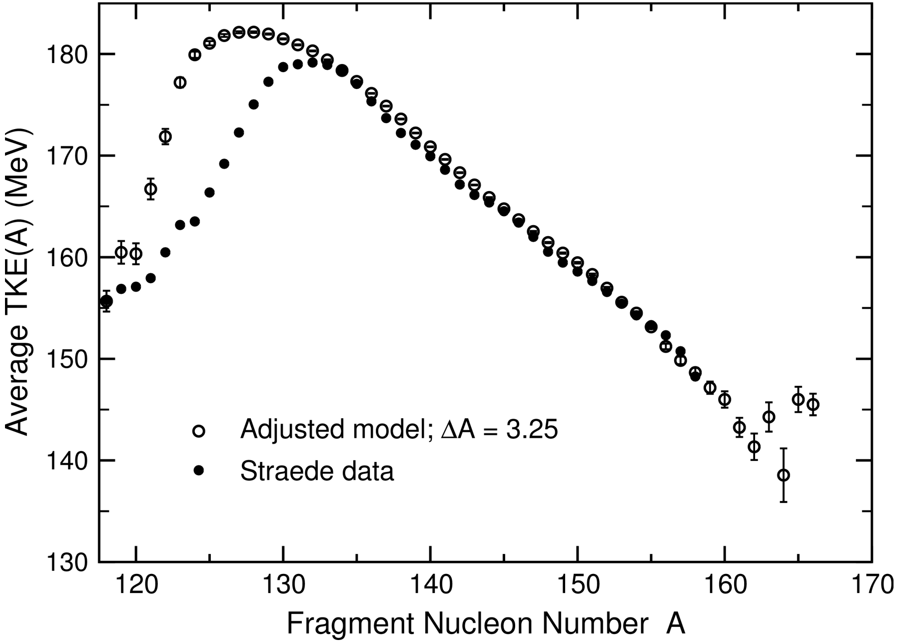
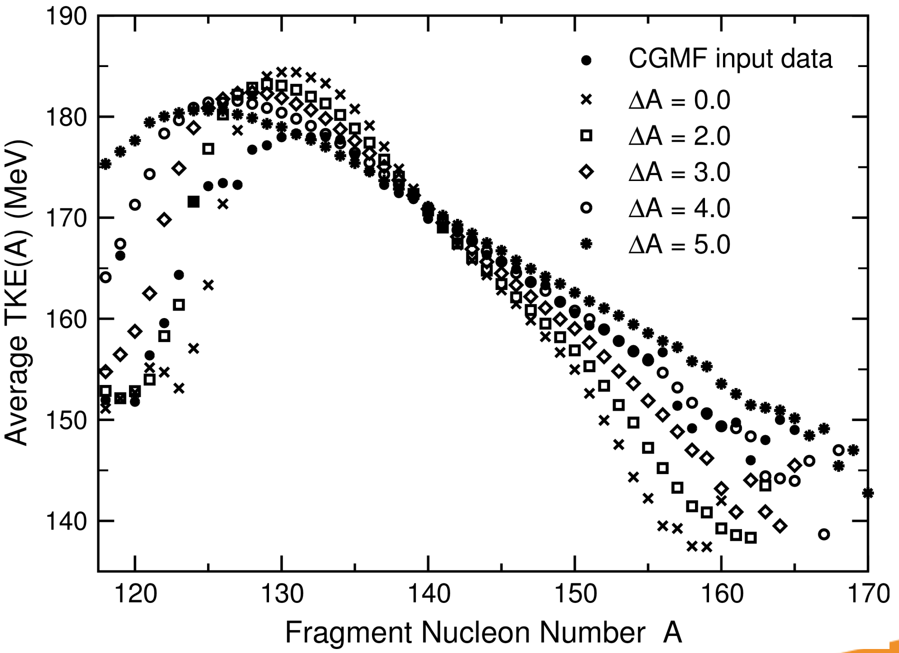
'Adjusted' model; thermal fragment yields; U235 (n,f)



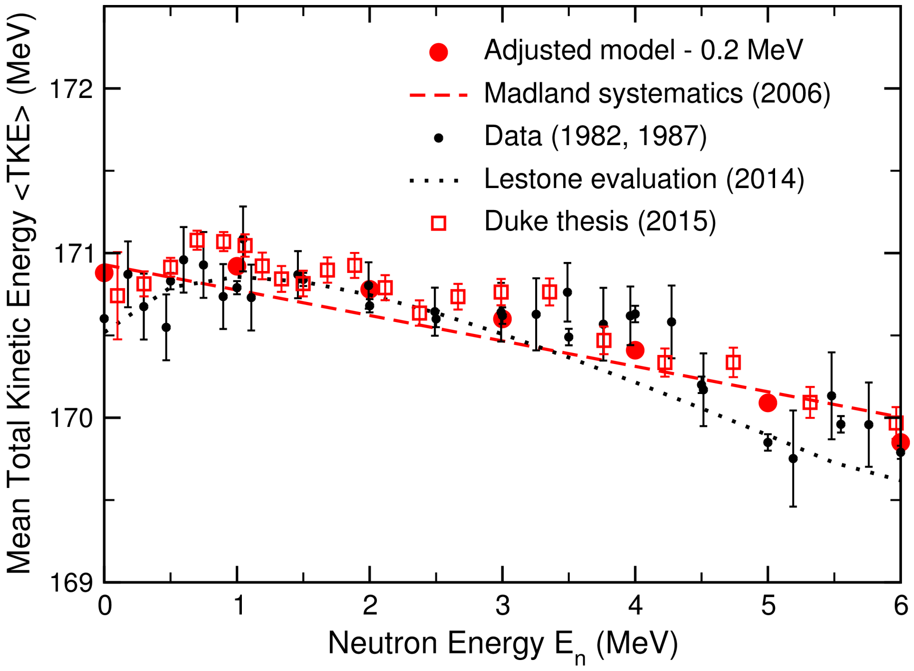


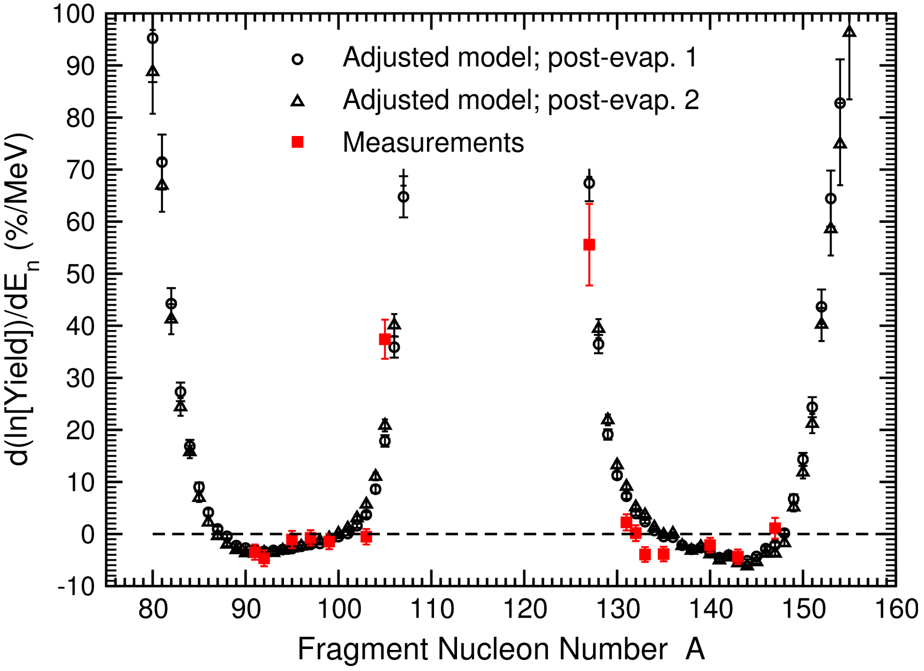
'Adjusted' model; TKE yields; U235 (n,f)



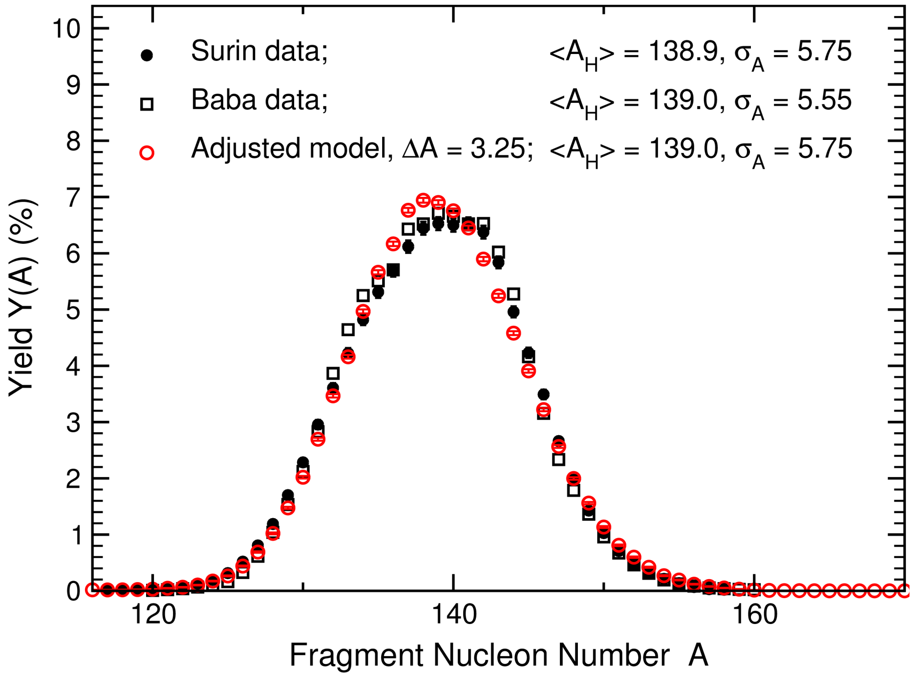


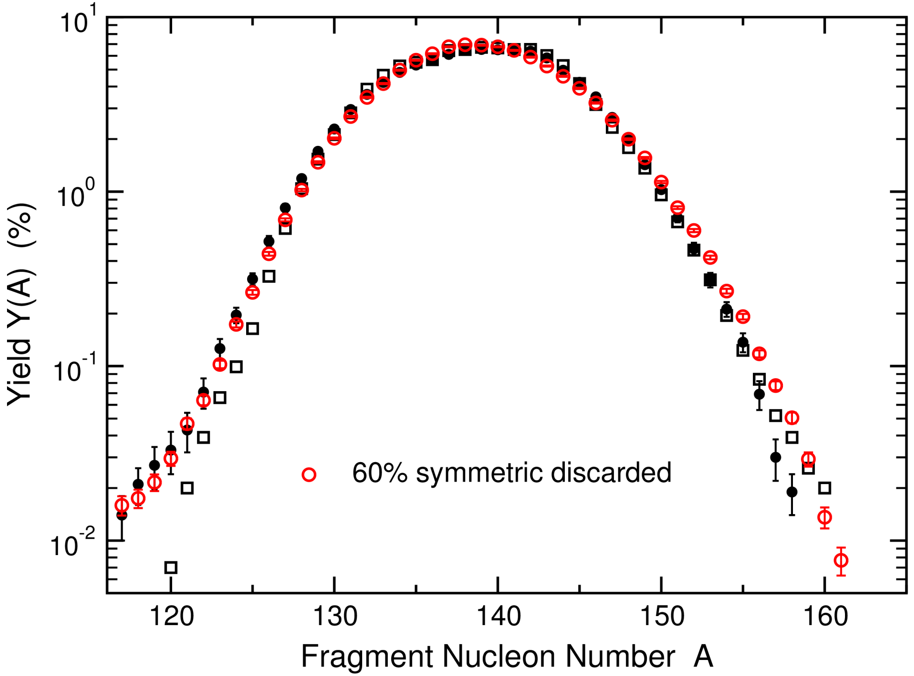
'Adjusted' model; neutron energy dependence



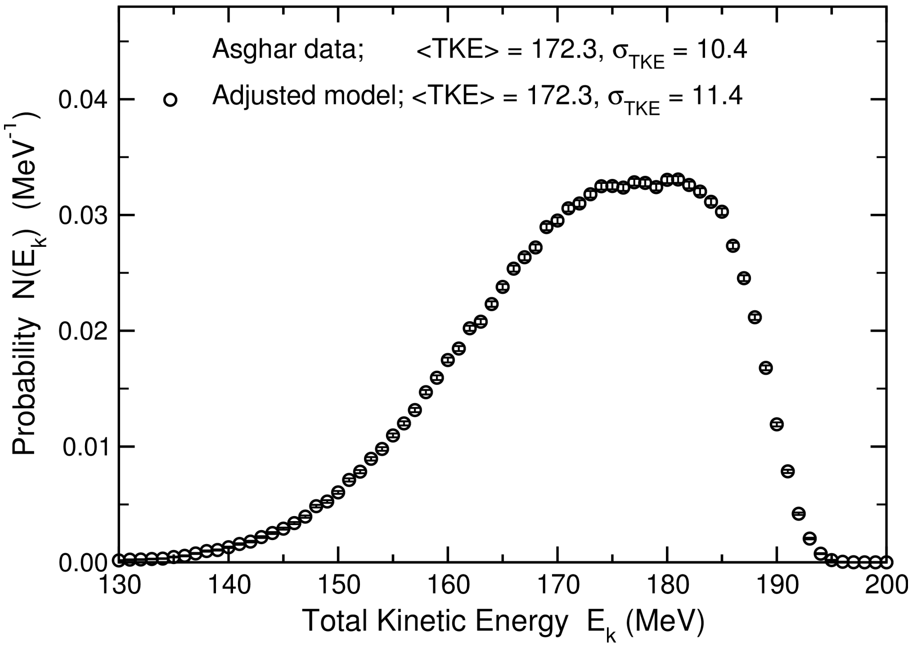


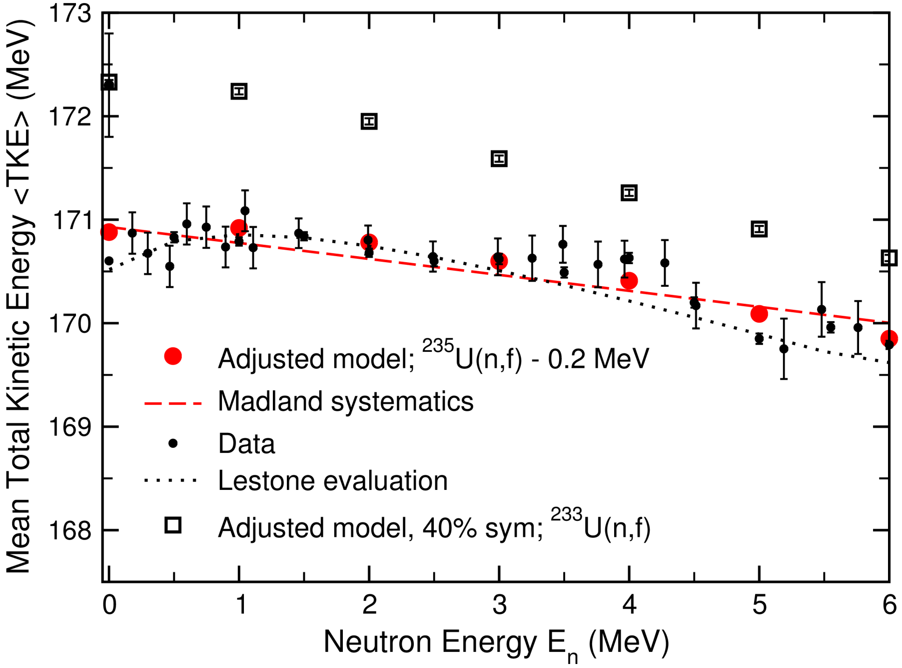
'Adjusted' model; thermal fragment yields; U233 (n,f)





'Adjusted' model; TKE observables; U233 (n,f)





Summary

- For the first time, a dynamical physical model of fission predicts most of the major features and some of the quantitative details of fission mass and kinetic-energy distributions.
- The neutron-energy-dependence of average TKE and yields are predicted.

- This model is already useful for constraining yield and TKE correlations.
- The TKE distributions can be improved by straightforward improvements in the post-scission dynamical model.
- It may be possible to improve detailed yields by relaxing the fixed-isospin assumption.

Reference:

- Physical Review C 96, 034603 (2017)