Dynamical model for fission-fragment properties

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Overview

45 years of pioneering research at LANL calculating nuclear potential energies and dynamical models of fission has matured to the point that we can now quantitatively predict fission-fragment distributions.

Method

Solve Dynamical Equations for the Fissioning Nucleus

1. The relevant degrees of freedom for fission describe the nuclear shape; we use a five-parameter parabolic spline to describe shapes.
2. Use the Macroscopic-Microscopic method to calculate the potential energy of the nucleus and its gradient as a function of shape.

3. Define inertia and dissipation tensors which relate the kinetic energy and the energy disspation rate to the time derivatives of the shape coordinates.
4. Dissipation necessarily implies that the system encounters fluctuating forces (Fluctuation-Dissipation Theorem).
5. The system is modeled using the vector Langevin equation; in this case a set of five coupled nonlinear second-order stochastic differential equations.

6. Do Monte-Carlo modeling of the trajectories of fissioning nuclei in this multidimensional space.
7. Accumulate distributions of dynamical properties of the fragments before neutron evaporation starts.

Model ingredients

Fixed in advance:

1. Potential-energy surface; microscopic model fixed in 1973, macroscopic model fixed in 2002. Parameters found from nuclear masses and a few fission-barrier heights. No information on fission fragments. Potential surface defined on a 5D lattice of 9.4×10^6 points. Use splines to define potential and its gradient everywhere.
2. Use Werner-Wheeler approximation to irrotational inertia.

3. Starting distributions found by normal-mode analysis and quasi-equilibrium at the outermost saddle point (Kramers solution; equilibrated transverse modes.)

4. The final fragment kinetic energy found by modeling the separation of the deformed fragments after scission.

5. Use a very simple level density formula to define the nuclear temperature from the local excitation energy, $a_{\mathsf{n}} = A/8.6$

6. Use a particular experiment's mass resolution to broaden predicted yields.

Model ingredients

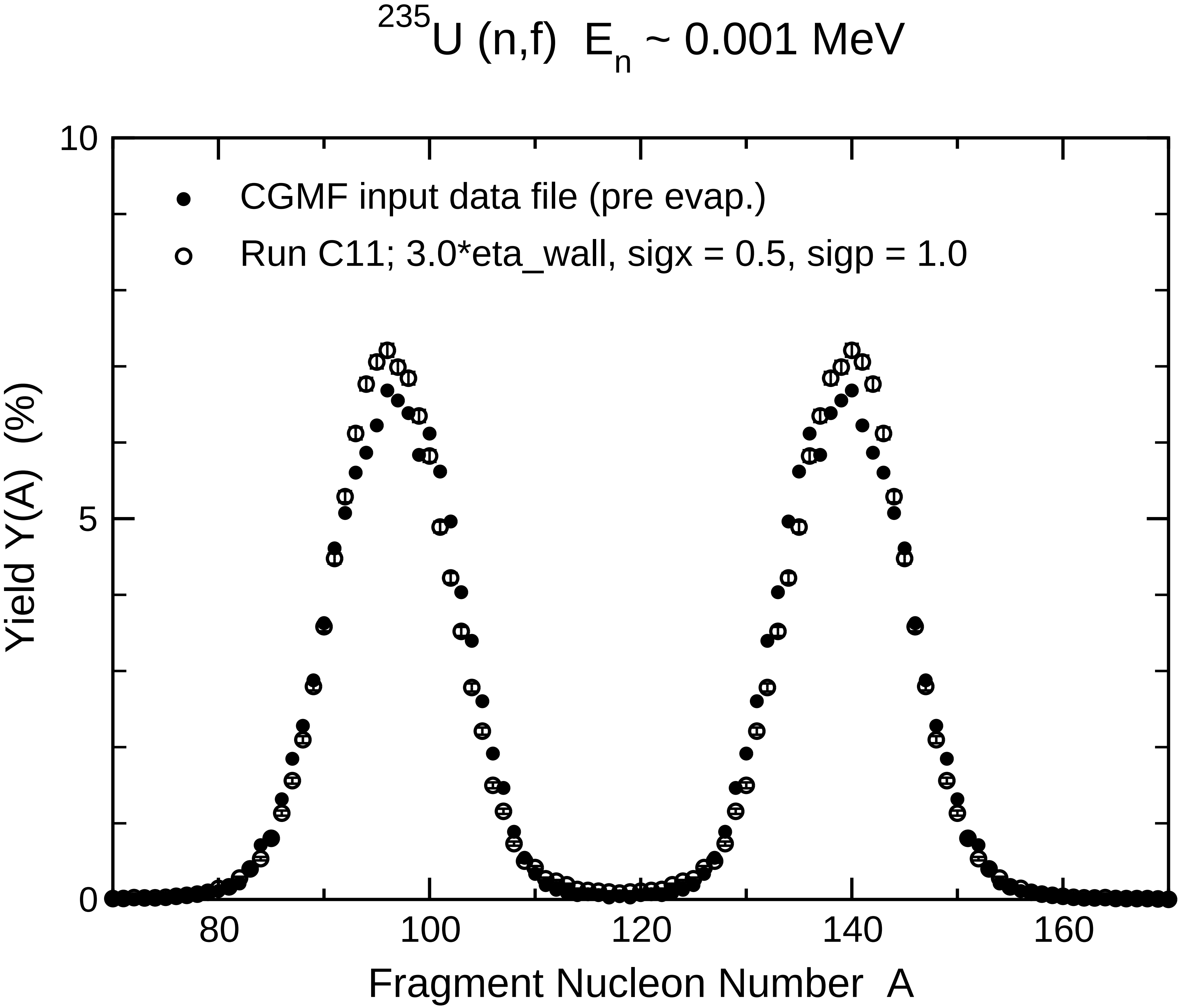
Varied to reproduce ^{236}U(n,f) yields:

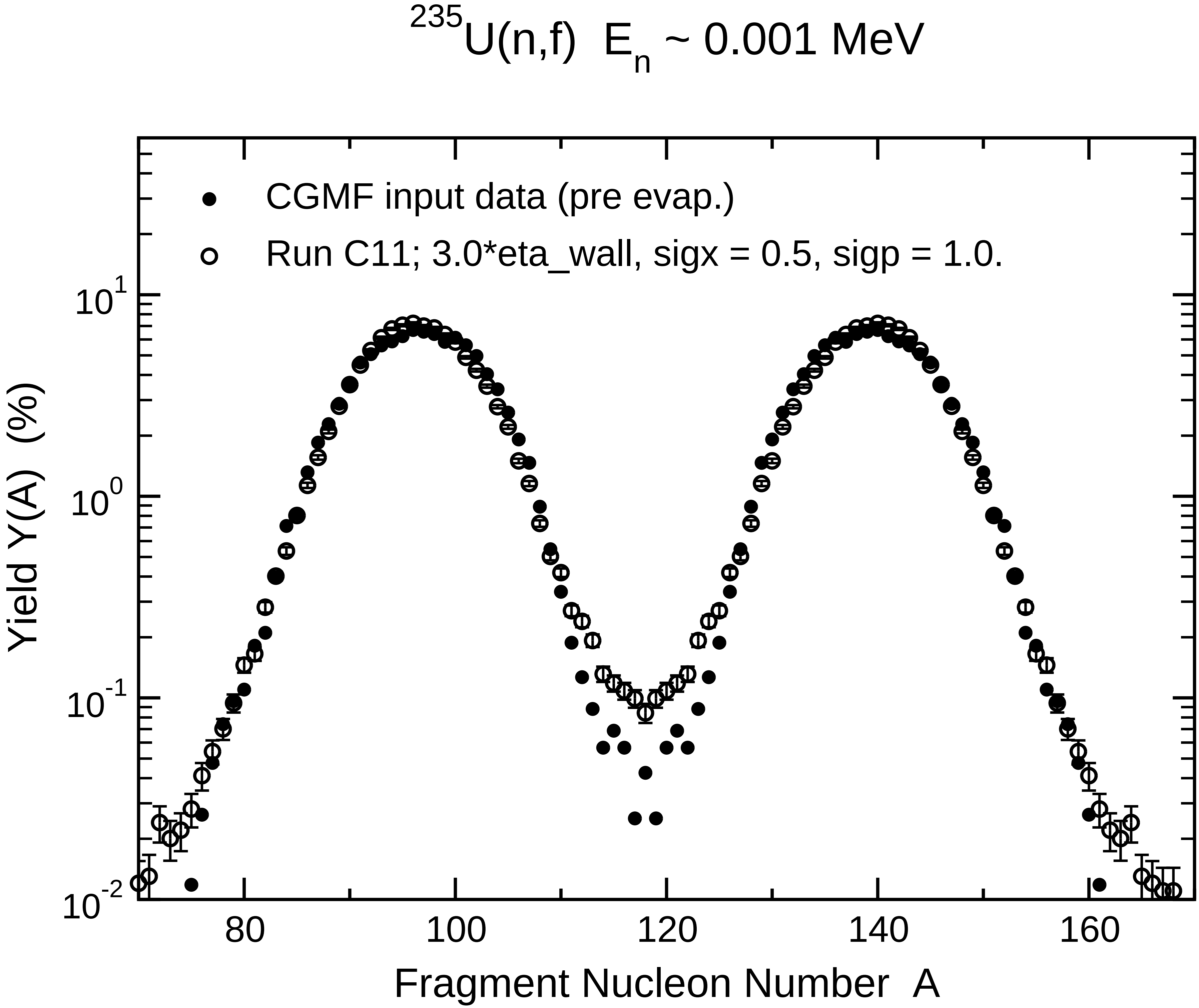
1. Scale the surface piece of the surface-plus-window dissipation model for the dissipation tensor.

2. Scale the widths of the equilibrium coordinate and momentum widths of the transverse normal modes.

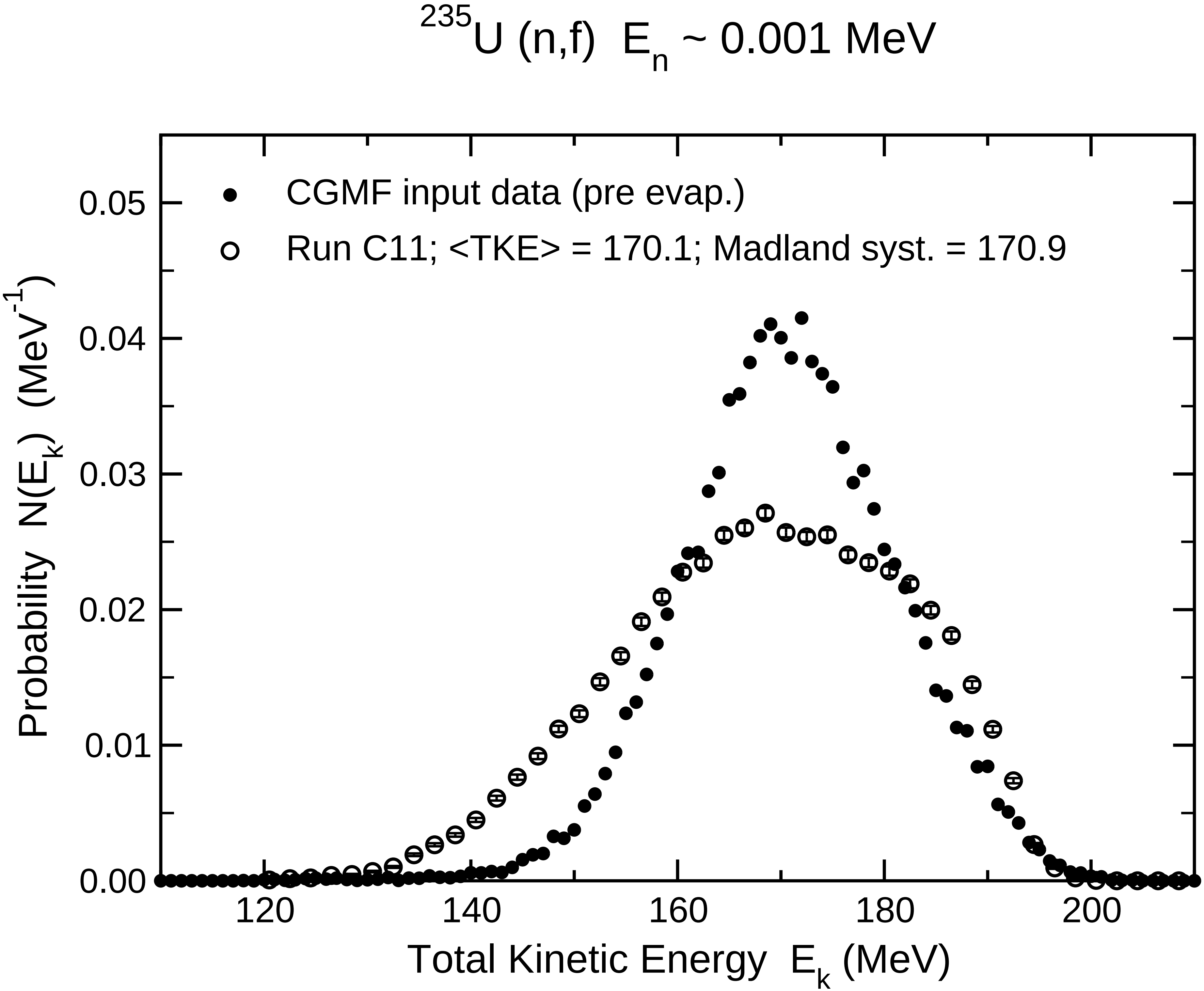
3. Introduce a random neck rupture into the location of the plane of scission.

4. Scission neck radius (unchanged from initial value of 1.0 fm.)

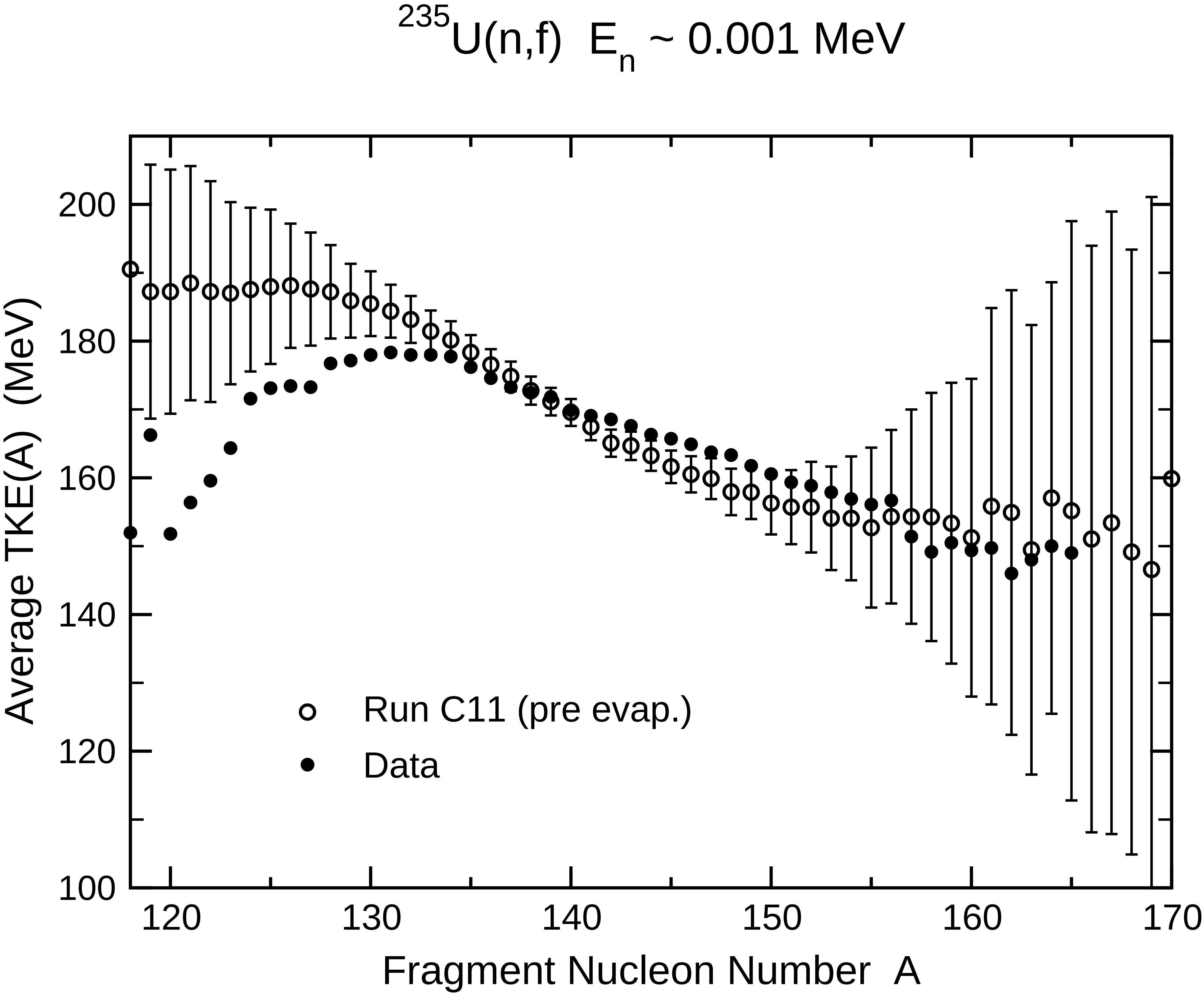

^{235}U (n,f) E_n ~ 0.001 MeV
CGMF input data file (pre evap.)
Run C11; 3.0*eta_wall, sigx = 0.5, sigp = 1.0
Yield Y(A) (%)
Fragment Nucleon Number A
0
5
10
80
100
120
140
160



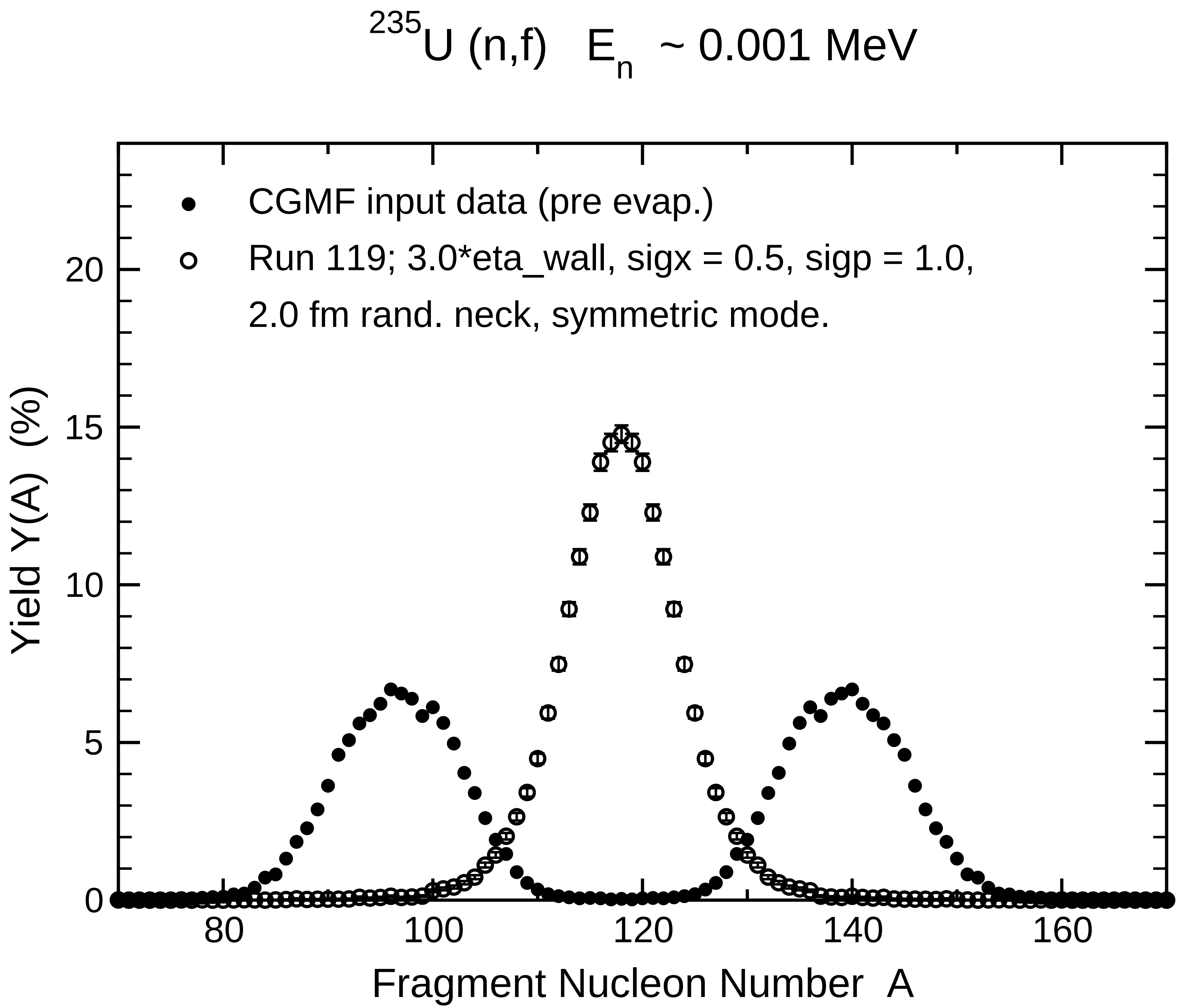
235U(n,f) En ~ 0.001 MeV
CGMF input data (pre evap.)
Run C11; 3.0*eta_wall, sigx = 0.5, sigp = 1.0.
Yield Y(A) (%)
10-2
10-1
100
101
80
100
120
140
160
Fragment Nucleon Number A



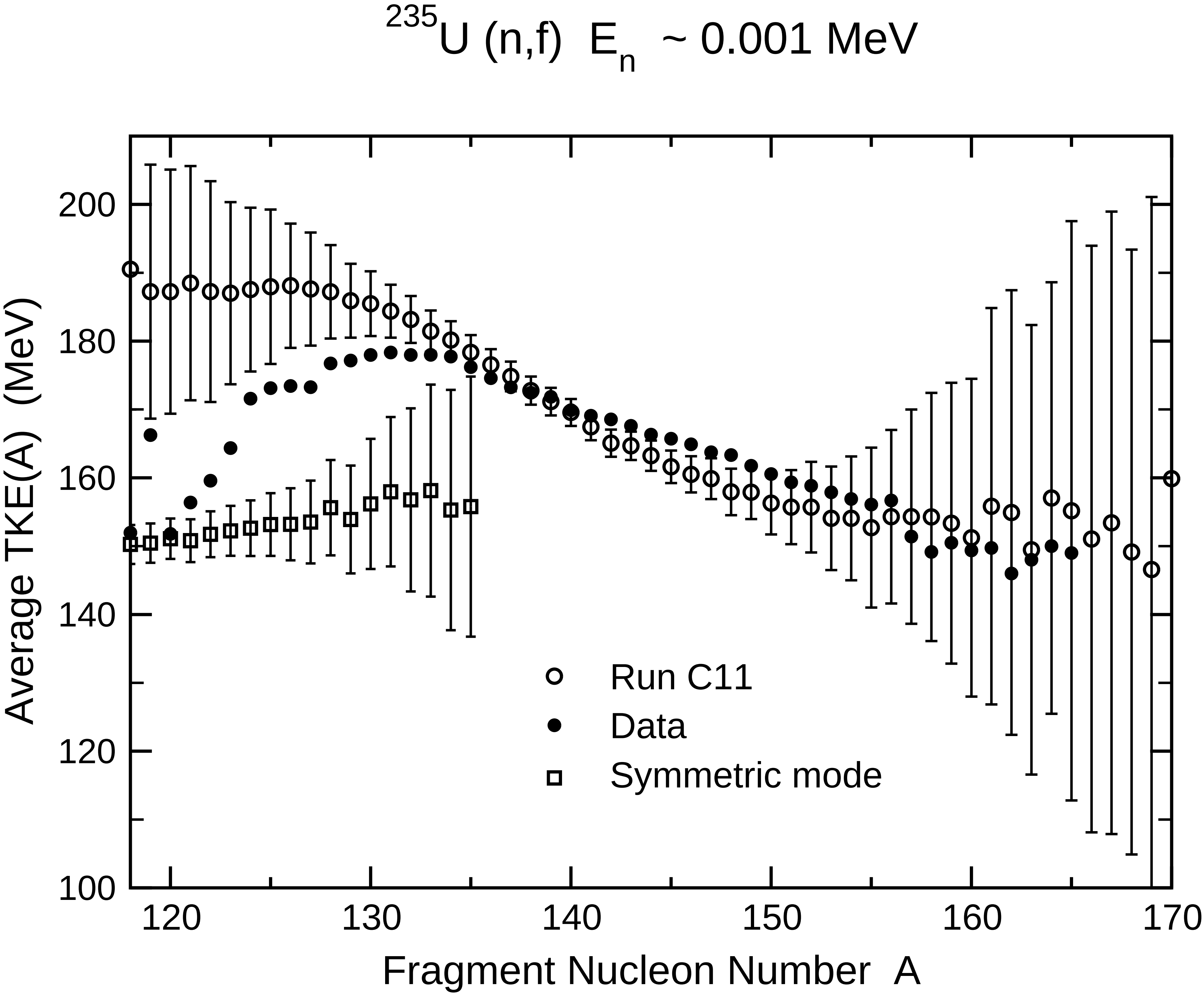
^{235}U (n,f) E_n ~ 0.001 MeV
CGMF input data (pre evap.)
Run C11; <TKE> = 170.1; Madland syst. = 170.9
Probability $N(E_k)$ (MeV^{-1})
0.05
0.04
0.03
0.02
0.01
0.00
120
140
160
180
200
Total Kinetic Energy E_k (MeV)

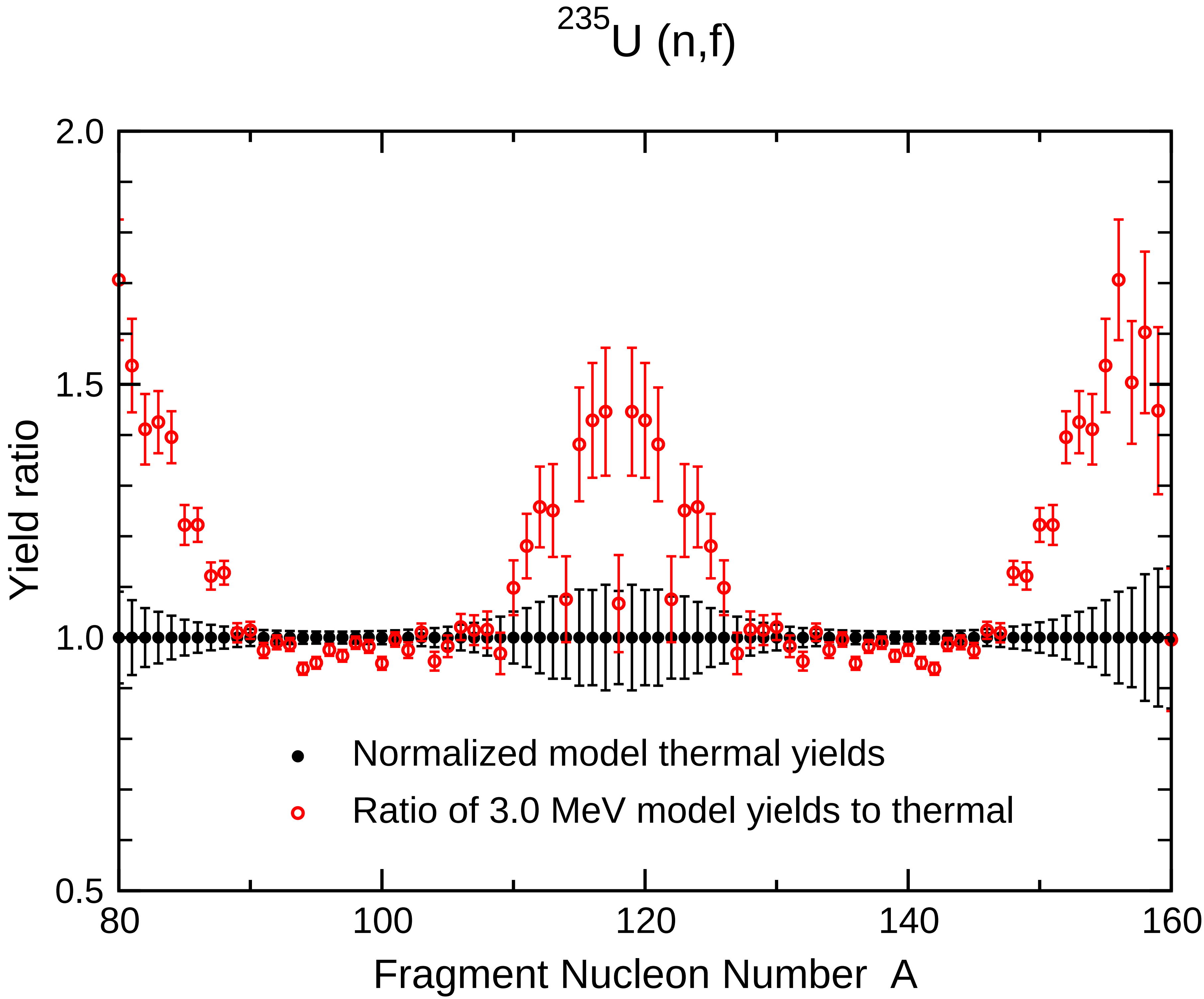


$^{235}U(n,f)$ E_n ~ 0.001 MeV
Average TKE(A) (MeV)
Fragment Nucleon Number A
Run C11 (pre evap.)
Data
100
120
140
160
180
200
120
130
140
150
160
170



^{235}U (n,f) E_n ~ 0.001 MeV
CGMF input data (pre evap.)
Run 119; 3.0*eta_wall, sigx = 0.5, sigp = 1.0,
2.0 fm rand. neck, symmetric mode.
Yield Y(A) (%)
Fragment Nucleon Number A
0
5
10
15
20
80
100
120
140
160


235U (n,f) En ~ 0.001 MeV
Average TKE(A) (MeV)
100
120
140
160
180
200
120
130
140
150
160
170
Fragment Nucleon Number A
Run C11
Data
Symmetric mode



^{235}U (n,f)
2.0
1.5
1.0
0.5
Yield ratio
80
100
120
140
160
Fragment Nucleon Number A
Normalized model thermal yields
Ratio of 3.0 MeV model yields to thermal

Model Predictions

^{235}U(n$_{\text{th}}$,f)

	Model	Eval.
• $\langle \text{TKE} \rangle (E_\text{n} = 0)$:	170.2	170.9
• $d\langle \text{TKE} \rangle / dE_\text{n}$:	-0.19	-0.15
• $\langle \text{TKE} \rangle$(Symm.):	151	152

- $\langle \text{TKE} \rangle (A)$
- $dY(A)/dE_\text{n}$
- $\langle E^*_\text{L} \rangle > \langle E^*_\text{H} \rangle$

Conclusions

1. A multidimensional Langevin model quantitatively explains and correlates many of the features of low-energy actinide fission.
2. Inertial effects are necessary to correlate fragment energies with fragment mass yields.
3. Complicated microscopic inertias are not required.
4. A dissipation is necessary to model fragment energies.
5. The width of the mass distribution is due to the random forces arising

from the dissipation; a dissipation needed for fragment energetics.

6. No exotic shell structure is required to quantitatively explain the mass yield.
7. The dynamical time for fission (saddle to scission time) is about 1×10^{-20} s; longer times are not consistent with fragment energies.
8. As was long ago inferred, low-energy symmetric fission in actinides proceeds through a separate mode (path in configuration space) from asymmetric fission.

9. Earlier studies have demonstrated that at least 5 degress of freedom are needed to capture the essence of fission statics and dynamics.