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# Exploring nuclear dissipation properties at large deformations

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第十七届全国核物理大会, 武汉, 2019年10月10日

# Outline

- **Introduction**
- **Model description**
- **Current studies on dissipation properties**
- **Summary**

# Introduction

## Fission

- Observables:

→ fission probability (or complementary quantity such as evaporation residue)

→ particle emission

→ fission fragment mass and kinetic energy distributions, fragment charge-distribution widths

Lise Meitner

Otto R. Frisch

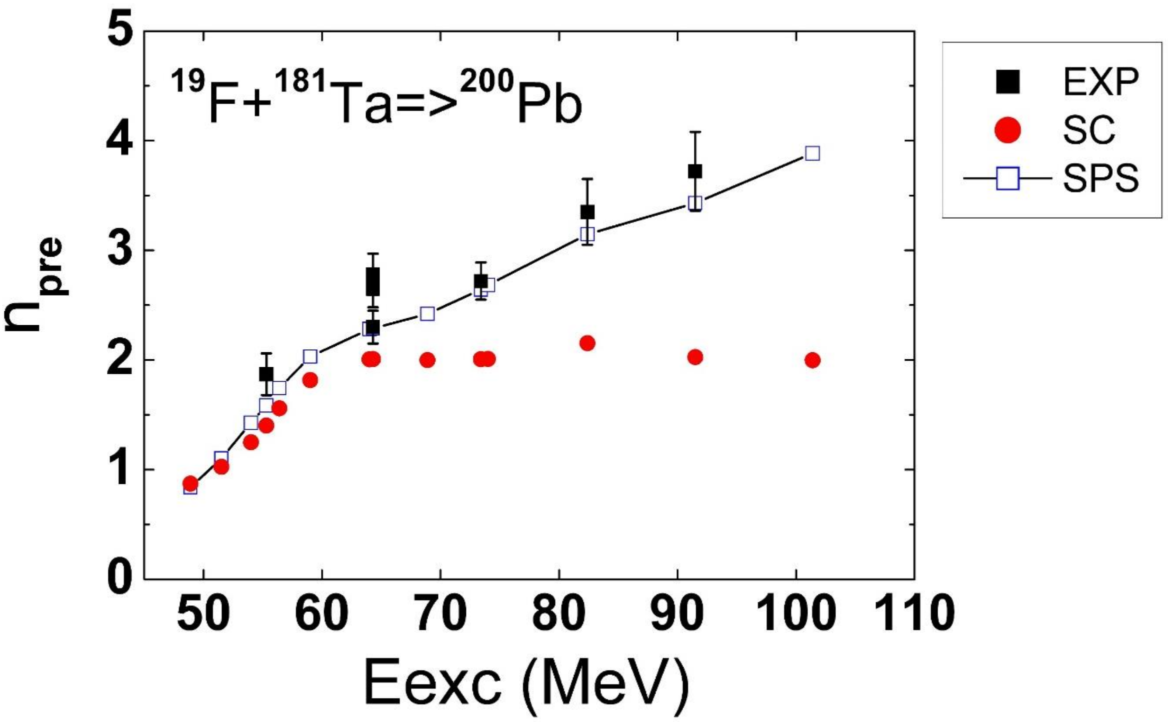
**Nature 143 (1939) 239:**
*Disintegration of Uranium by Neutrons: A New Type of Nuclear Reaction*

John A. Wheeler

Niels Bohr

**Phys Rev 56 (1939) 426:**
*The Mechanism of Nuclear Fission*

# Neutrons




An excess emission of experimental light particles in fission with respect to that predicted by standard statistical models (SM) at high energy. This discrepancy is considered to be arising from dissipation effects in fission.

## Fission cross section

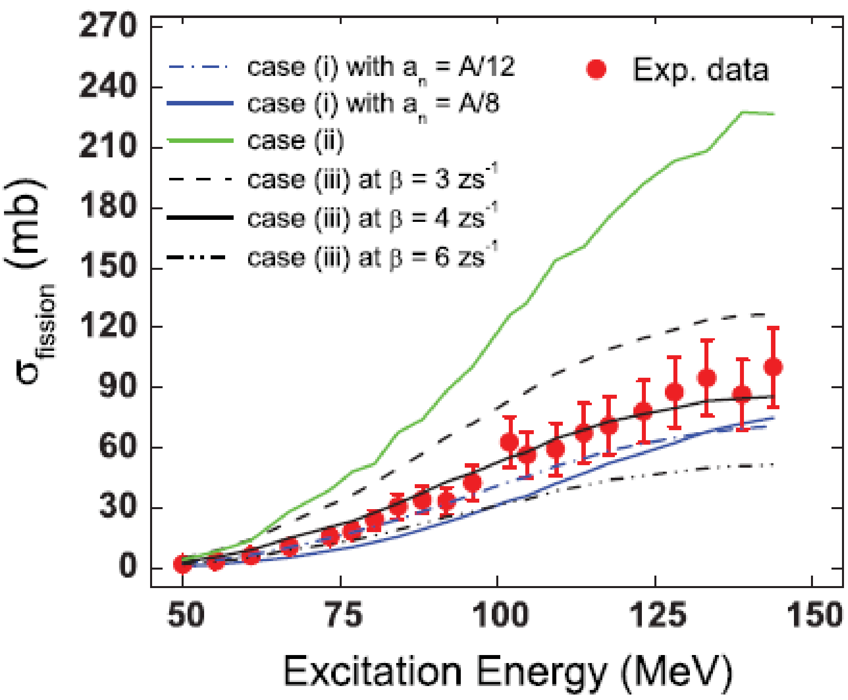



FIG. 2. (Color online) Fits to measured excitation function data of fission cross sections (denoted by red circles with error bars) in the $^{3}He + {}^{197}Au$ system [30]. Curves represent various theoretical calculations: case (i) SM without friction but with $a_f/a_n = 1$, $a_n = A/12$ (dashed dotted blue line) and $a_n = A/8$ (solid blue line); case (ii) SM without friction but with $a_f/a_n \neq 1$ (green line) and case (iii) Langevin model with $a_f/a_n \neq 1$ at friction strengths $\beta = 3$ zs$^{-1}$ (dashed black line), 4 zs$^{-1}$ (solid black line), and 6 zs$^{-1}$ (dashed-double dot black line). Note that $\beta$ represents the friction strength throughout the fission process, and it is only adjustable parameter in CDSM. The unit of $\beta$ is zs$^{-1}$; 1 zs $= 10^{-21}$s.

**pre-saddle friction (small deformation)**

$$\beta_{\text{in}} = 4\ zs^{-1}$$

**W. Ye, PRC 87, 014610 (2013)**

# Neutrons

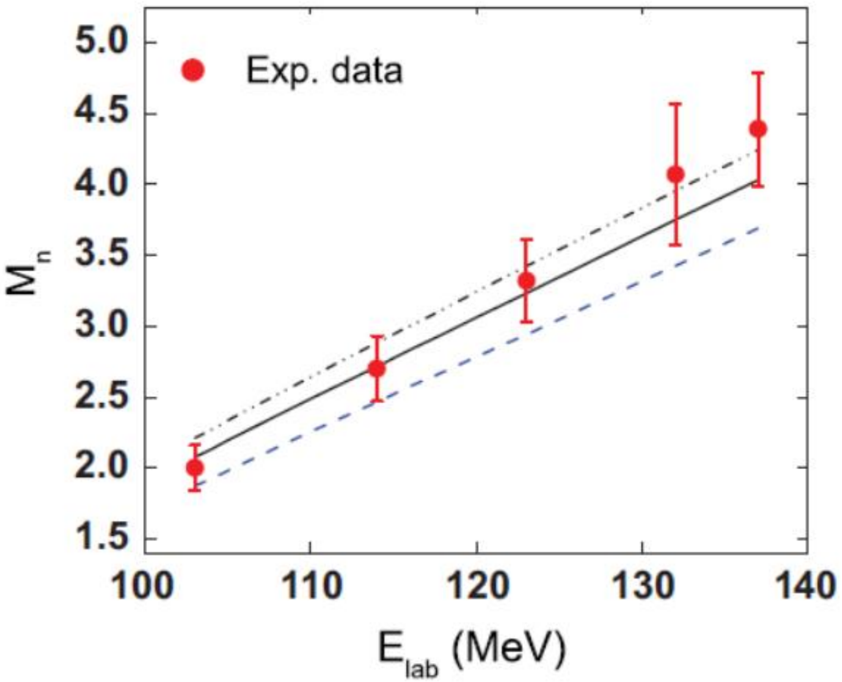


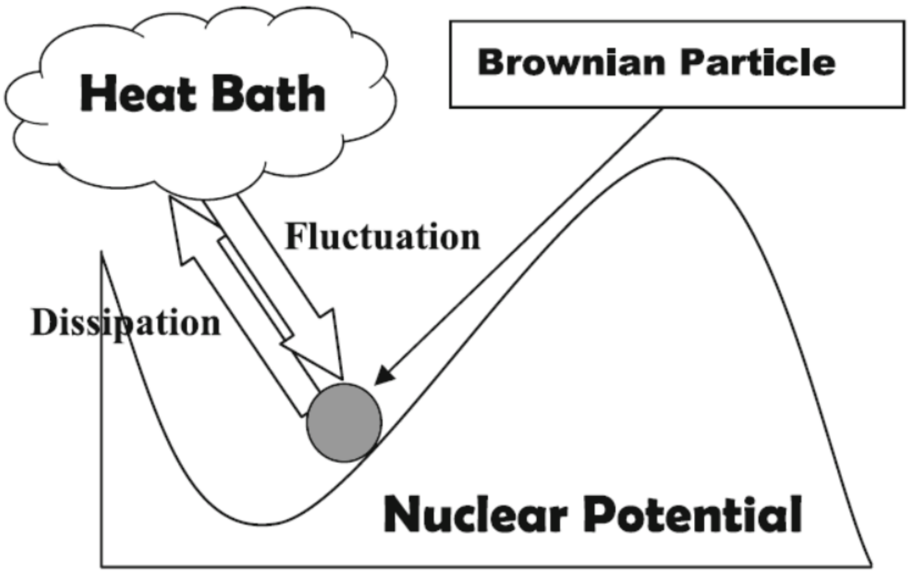

FIG. 3. (Color online) Prescission neutron multiplicities calculated for the system $^{19}F + ^{232}Th \longrightarrow ^{251}Es$ versus laboratory energy. Dashed blue line is the calculations at $\beta = 13\ zs^{-1}$ but without deformation effects, predicting a lower $M_n$ compared to data points at high incident energies. Solid black line and dash-double-dot line represent the calculations at $\beta = 13\ zs^{-1}$ and $15\ zs^{-1}$ but with deformation effects, respectively. Experimental data (●) are taken from Ref. [36].

**post-saddle friction (large deformation)**

$$\beta_{out} = 13\ zs^{-1}$$

**N. Wang and W. Ye, PRC 87, 051601(R) (2013)**

# Model description: Langevin model




Frobrich, Pal, and many others

$$\frac{dq}{dt} = \frac{p}{M(q)}$$

$$\frac{\mathrm{dp}}{\mathrm{dt}} = \frac{1}{2}\left(\frac{\mathrm{p}}{\mathrm{M(q)}}\right)^2 \frac{\partial \mathrm{M(q)}}{\partial \mathrm{q}} - \frac{\partial F}{\partial \mathrm{q}} - \beta(\mathrm{q})\mathrm{p} + \sqrt{\beta(\mathrm{q}) \cdot \mathrm{M(q)} \cdot \mathrm{T}}\,\Gamma_{\mathrm{L}}(\mathrm{t})$$

friction force    random force

dissipative force

# Known and new elements introduced to describe fission of a hot nucleus

- Shape parameters: {c,h,α} parametrization
- V(q) : finite-range liquid-drop model
- M(q): Werner-Wheeler approximation for incompressible irrotational flow
- $\Gamma(t)$ : stochastic part of the interaction between fission degree of freedom and heat bath

$$\langle\Gamma(t)\rangle = 0,\ \langle\Gamma(t)\Gamma(t')\rangle = 2\delta(t-t')$$

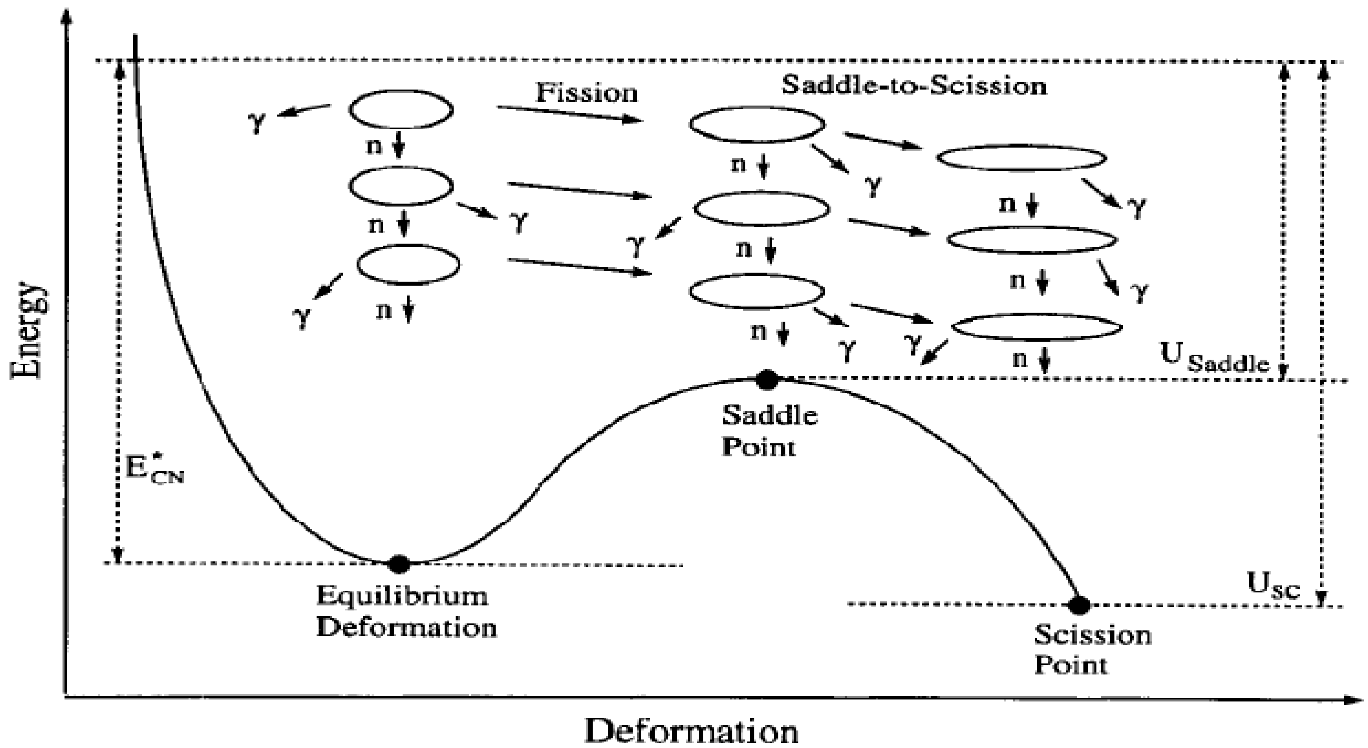
- F = [V(q) –a(q)$T^2$] and not bare potential V(q) as driving force of a thermonuclear system

a(q): *q* dependence of level density parameter plays a crucial role on fission

$\beta$ : most uncertain part in the description

its strength and possible dependence on *q*, etc. is the focus of current studies

# Large deformation (post-saddle): particle emission at high energy

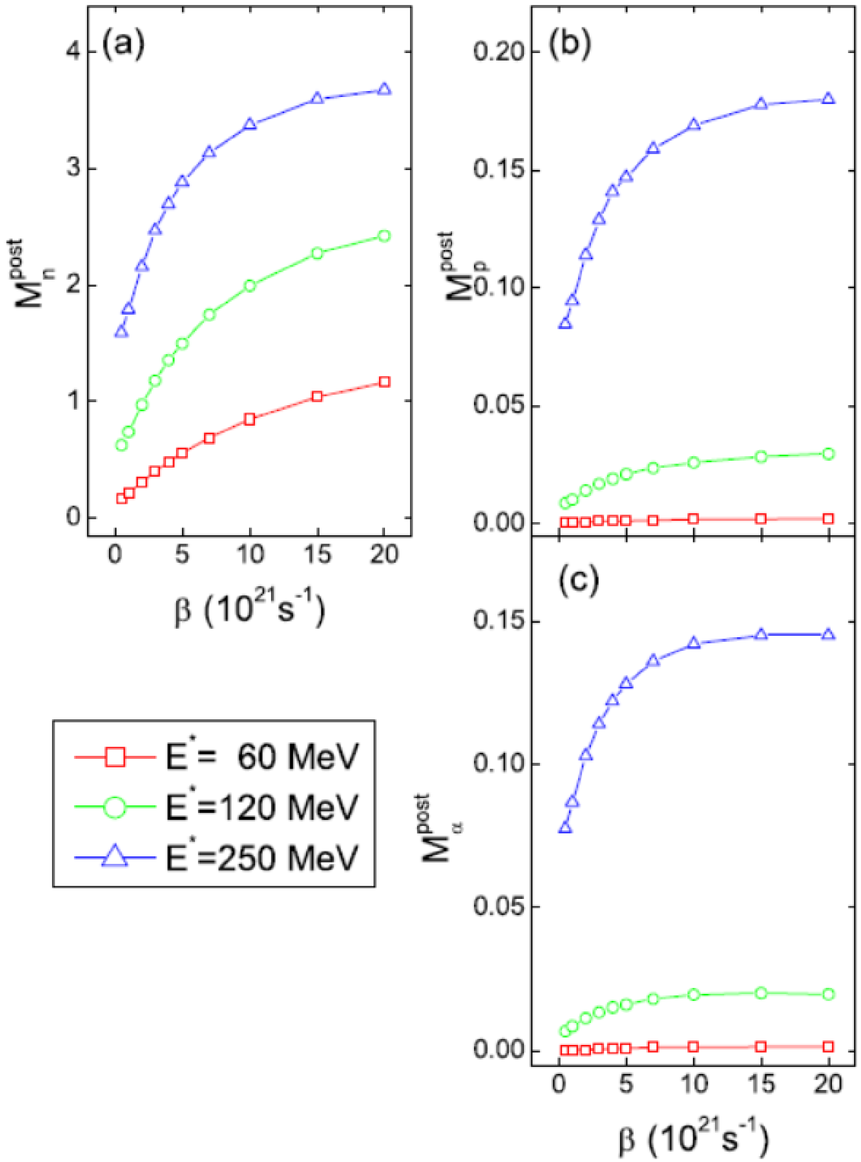



Two requirements: generate heavy and hot fissioning systems

| fusion reactions | versus | intermediate-energy heavy-ion collisions |
| --- | --- | --- |
| • (low E*, large L) | | • near-central case (very high E*, small L)<br>• peripheral case (high E*, large L) |

# E* effects

postsaddle particle multiplicity




| | Neutrons | LCPs |
|---|---|---|
| E* ↑ Multiplicity: | ↑ | ↑ |
| β sensitivity: | ↑ | ↑ significantly |

Fusion: strong interference from quasi-fission competition

Intermediate-energy heavy-ion collisions can deposit high E* into the fissioning systems.

fission events stemming from different collision centrality can be identified and selected with folding angle techniques

FIG. 1. Postsaddle multiplicities of neutrons (a), protons (b), and $\alpha$ particles (c) of fissioning nuclei $^{240}$Am as a function postsaddle dissipation strength ($\beta$) at angular momentum $\ell = 40\hbar$ and at three excitation energies $E^* = 60$ MeV (squares connected by red lines), 120 MeV (circles connected by green lines), and 250 MeV (triangles connected by blue lines).

# L effects

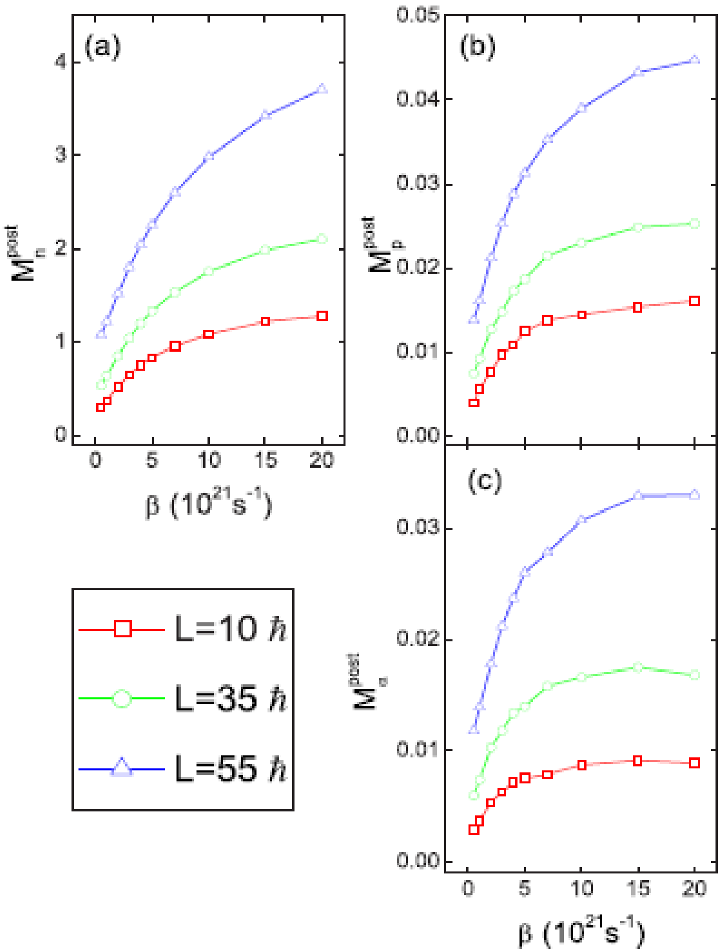
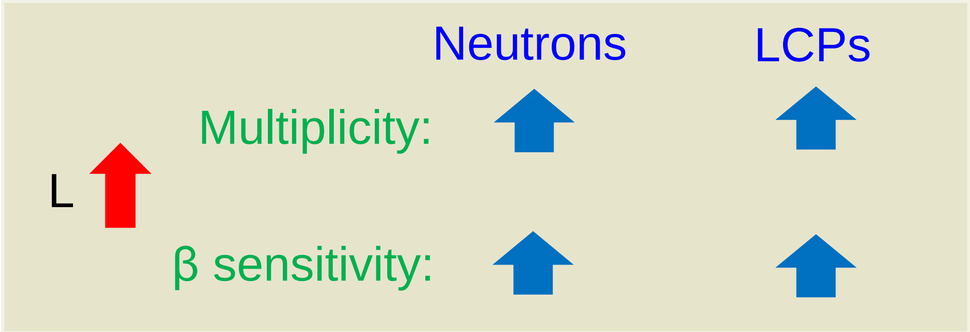



FIG. 2: (Color online) Postsaddle multiplicities of neutrons (a), protons (b), and $\alpha$ particles (c) of fissioning nuclei $^{240}$Am as a function of $\beta$ at excitation energy $E^* = 120$ MeV and at three angular momenta $\ell = 10\hbar$ (squares connected by red lines), $35\hbar$ (circles connected by green lines), and $55\hbar$ (triangles connected by blue lines).



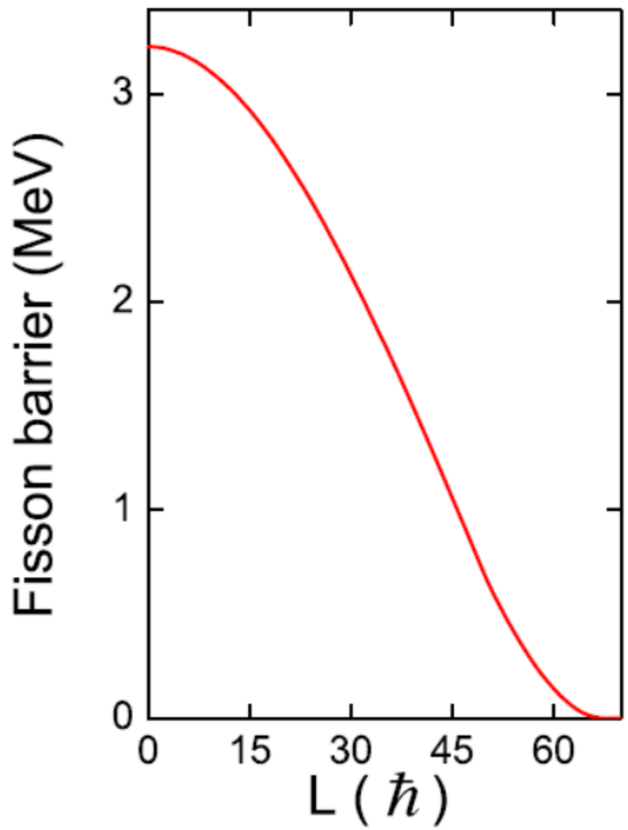
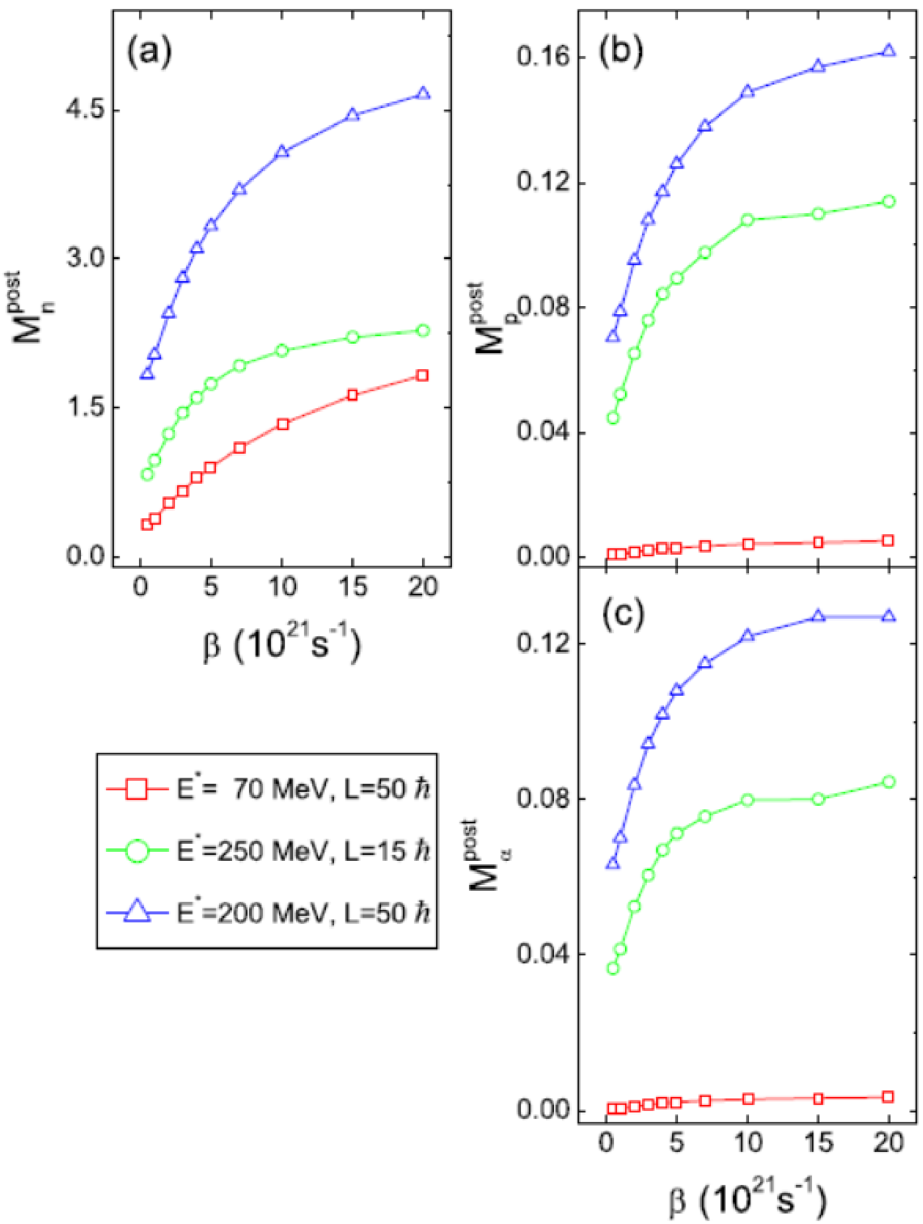




FIG. 3. Fission barriers of the $^{240}$Am system as a function of angular momentum calculated with the method in Refs. [58,60,62].

# Fusion vs. Intermediate-energy collisions




post-saddle dissipation effects probed with neutrons or light charged particles provide in typical conditions of fusion and intermediate-energy collisions

- intermediate-energy peripheral heavy-ion collisions provide a preferable condition than fusion reactions

FIG. 4. Comparison of postsaddle multiplicities of neutrons (a), protons (b), and $\alpha$ particles (c) of fissioning nuclei $^{240}$Am vs postsaddle dissipation strength $\beta$ between case (i) $E^* = 250$ MeV and $\ell = 15\hbar$ (circles connected by green lines) and case (ii) $E^* = 70$ MeV and $\ell = 50\hbar$ (squares connected by red lines). Results calculated at $E^* = 200$ MeV and $\ell = 50\hbar$ are shown by triangles connected by blue lines.

**N. Wang and W. Ye, PRC 98, 034614 (2018)**

# Summary

- The sensitivity of light particles to postsaddle dissipation strength (β) is enhanced significantly at high energy and high spin.
- Light charged particles are more sensitive to β under the conditions of high E* and low L than under the conditions of low E* and high L.
- On the experimental side, to accurately determine β through the measurement of light particle multiplicity, intermediate-energy heavy-ion collisions may be an avenue to yield highly excited heavy fissioning nuclei.

Thank you!

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