Event-by-Event Simulation of Induced Fission

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We are developing a novel code that treats induced fission by statistical (or Monte Carlo) simulation of individual decay chains. After its initial excitation, the fissionable compound nucleus may either deexcite by evaporation or undergo binary fission into a large number of fission channels each with different energetics involving both energy dissipation and deformed scission prefragments. After separation and Coulomb acceleration, each fission fragment undergoes a succession of individual (neutron) evaporations, leading to two bound but still excited fission products (that may further decay electromagnetically and, ultimately, weakly), as well as typically several neutrons. (The inclusion of other possible ejectiles is planned.)

This next-generation approach makes it possible to study more complex observables than could be addressed with previous treatments which have tended to focus on average quantities. In particular, any type of correlation observable can readily be extracted from a generated set of events. With a view towards making the code practically useful in a variety of applications, emphasis is being put on making it numerically efficient so that large event samples can be generated quickly.

The development of this qualitatively new tool is still at an early stage and quantitative reproduction of known data should not be expected until a number of refinements have been implemented.

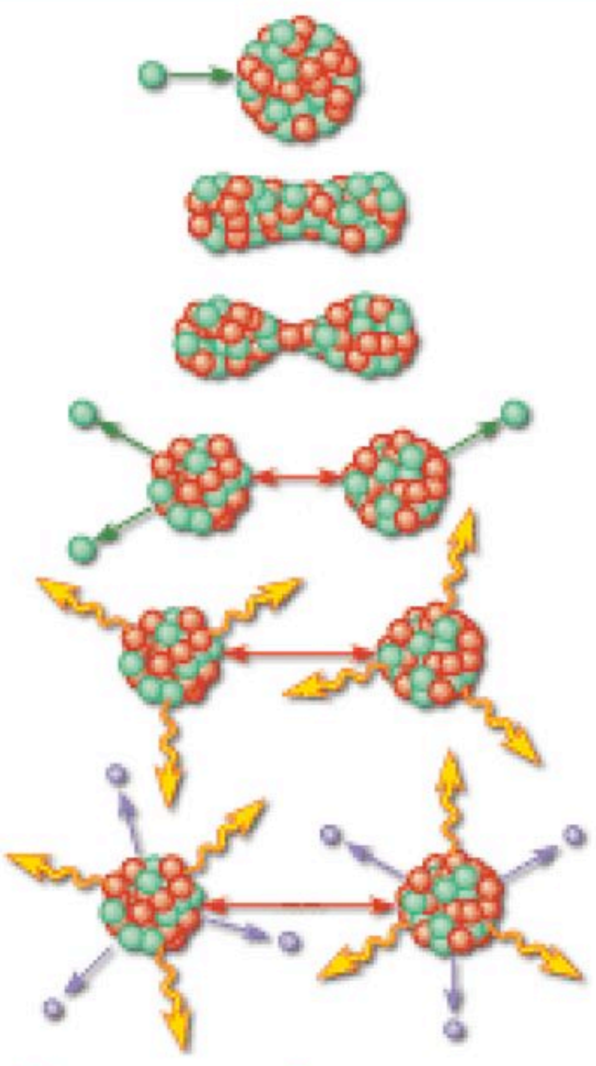
We Are Developing a Detailed Model of Fission Correlations:

- Binary fission
- Excited, moving fragments
- Prompt neutron emission simulated by neutron evaporation
- Gamma and charged particle emission to be added later

Our Monte Carlo Method Allows Rich Account of Fission in Codes:

- Accounts for microphysics leading to neutron production
- Can provide energy, neutron multiplicity and angle correlations event-by-event
- Follows neutrons from individual fragments

Schematic Fission Process: Compound Nucleus to Fission Products



The neutron strikes the nucleus and is absorbed.

The absorbed neutron causes the nucleus to undergo deformation. In about 10^{-14} second, one of the deformations is so drastic that the nucleus cannot recover.

The nucleus fissions, releasing two or more neutrons.

In about 10^{-12} second, the fission fragments lose their kinetic energy and come to rest, emitting a number of gamma rays. Now the fragments are called fission products.

The fission products lose their excess energy by radioactive decay, emitting beta particles and gamma rays over a lengthy time period (seconds to years).

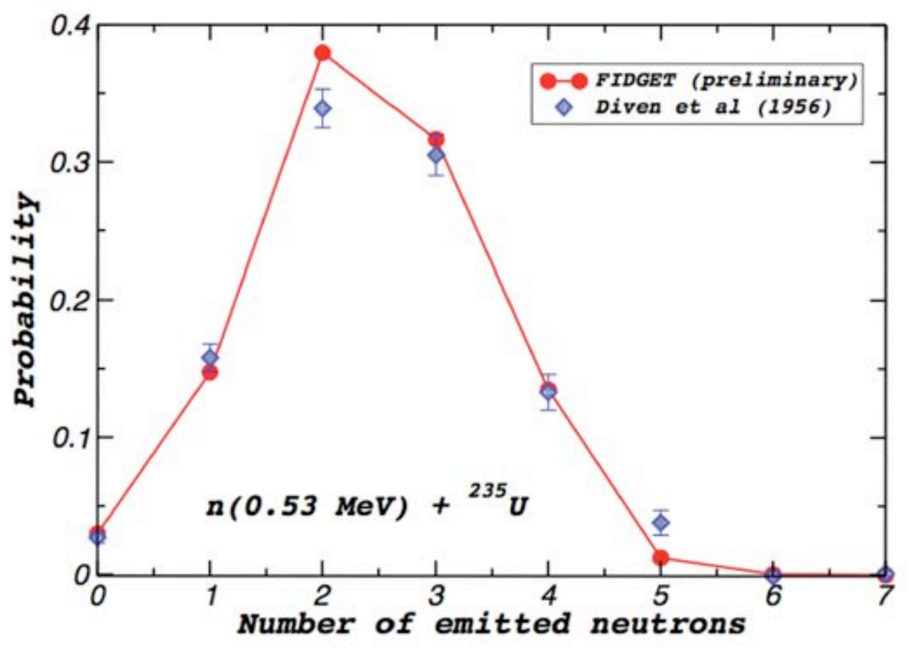
neutrons · protons · beta particles · gamma rays

Why Monte Carlo?

Monte Carlo event-by-event simulations provide full information and can thus give access to any correlation observable of interest:

- The treatment is based on available data supplemented by models.
- The code can make predictions of new observables and can help identify future measurements of particular importance.
- Monte Carlo can provide energy and momentum of all emitted particles: fission products, neutrons, gammas and charged particles (p, d, t, ^{3}He, ^{4}He).
- Fast: The code generates 1,000,000 events in 12 s on a MacBook.

Neutron Multiplicity Distribution

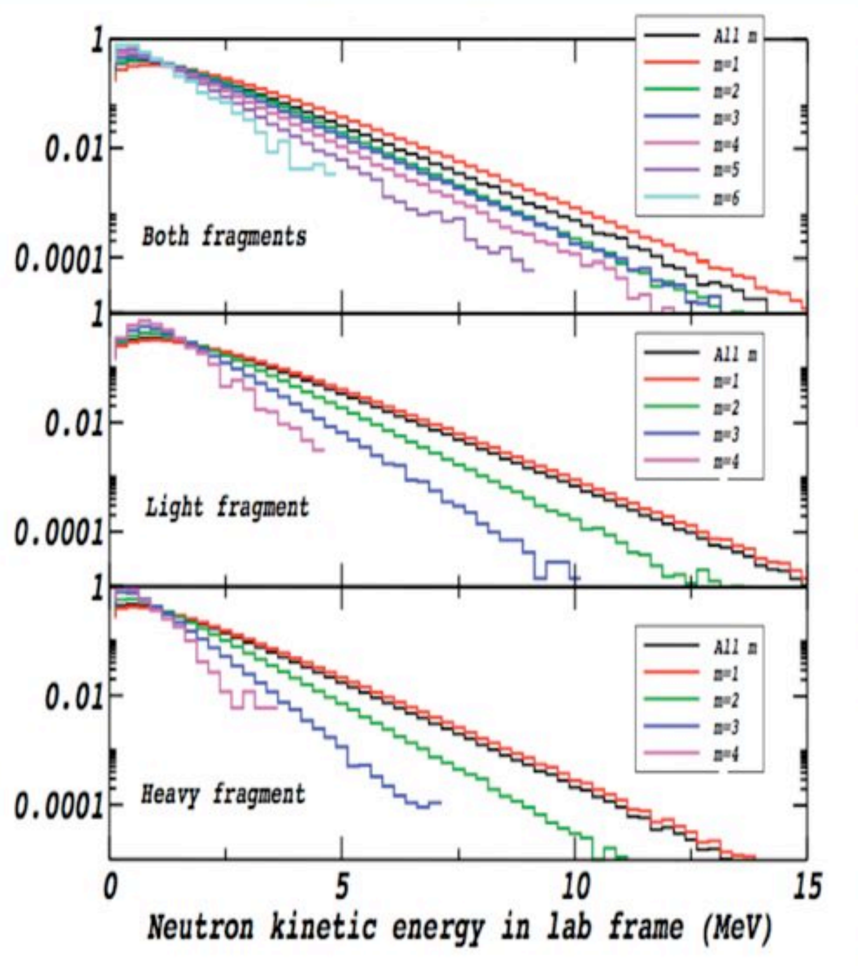


Basic Method:

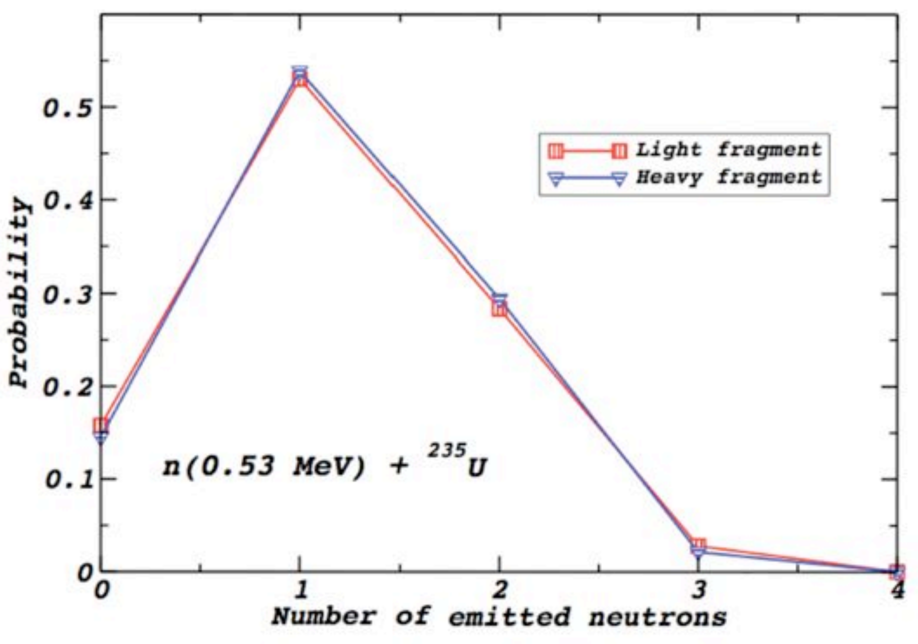
For a given incident neutron energy, E_n, and target nucleus A with charge Z:

- Select mass and charge of light, L, and heavy, H, fragments from fission fragment distributions;
- Pick velocities and excitation energies of the fission fragments;
- Evaporate neutrons from the moving and excited fragments until their excitation energy is too low for further neutron emission;
- Preliminary results shown here for 0.53 MeV neutrons on ^{235}U.

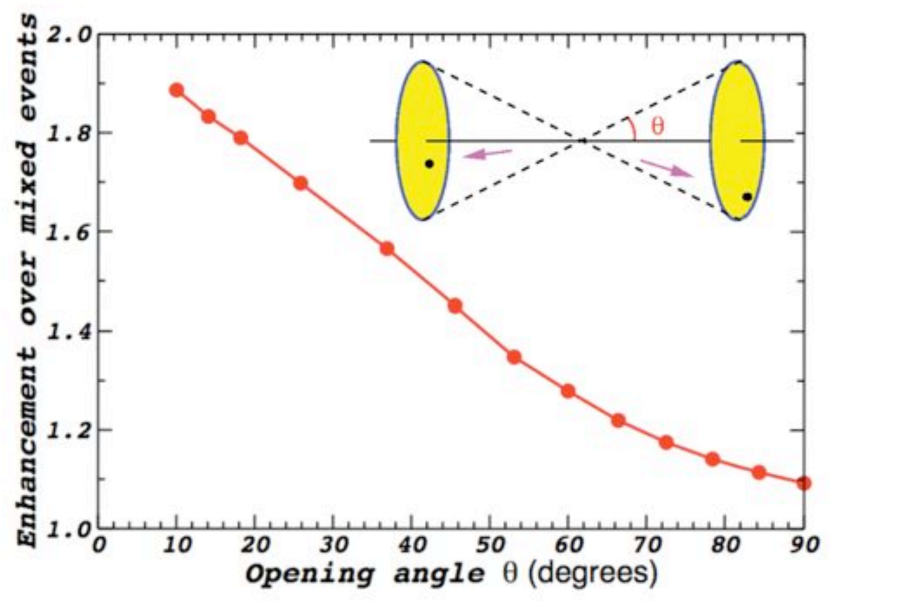
Neutron Kinetic Energy Spectra n(0.53 MeV) + ^{235}U



Neutron Multiplicity: Light and Heavy Fragments



Back-to-Back Neutron Correlations

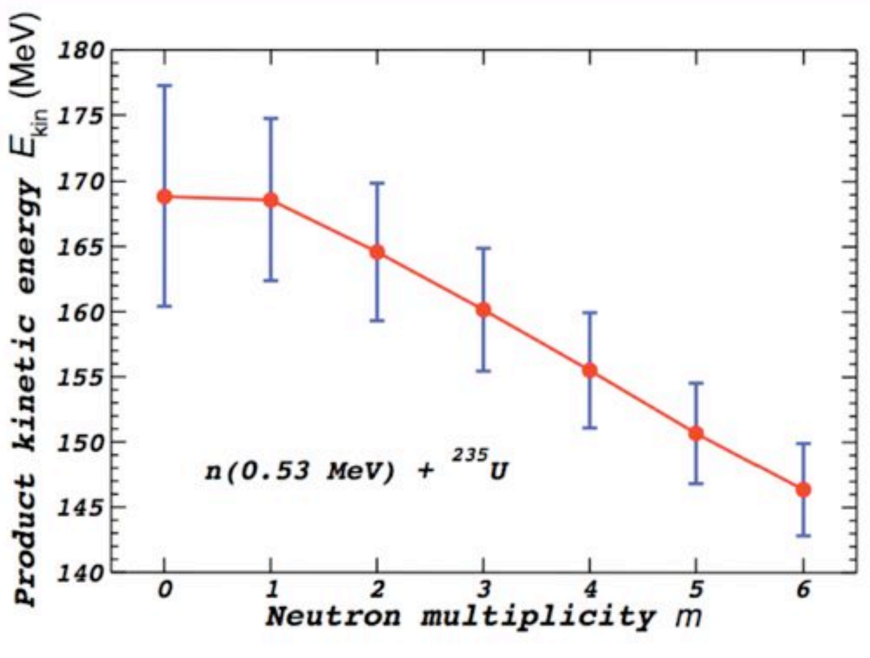


The emitted neutrons are expected to exhibit an enhanced angular anti-correlation because they arise from two oppositely-moving excited fragments. The figure shows the enhancement of coincident emission into two opposite angular cones as a function of their opening angle θ.

Average number of emitted neutrons		
Fragment	$\langle m\rangle$	σ_m
Both	2.37	0.75
Light	1.18	0.67
Heavy	1.19	0.42

The average number of neutrons emitted from each fragment and the associated variances.

Product Kinetic Energy and Neutron Multiplicity



The average combined kinetic energy of the two fission products as a function of the total neutron multiplicity. The bars indicate the associated dispersion in the kinetic energy.

Average neutron lab kinetic energy, dispersion		
m	$\langle E\rangle$ (MeV)	σ_E (MeV)
Both Fragments		
all	1.80	1.41
1	2.10	1.56
2	1.68	1.28
3	1.54	1.25
4	1.35	1.11
5	1.18	0.95
6	1.01	0.74
7	0.99	0.53
Heavy Fragment		
all	1.56	1.25
1	1.70	1.32
2	1.25	1.01
3	0.95	0.72
4	0.75	0.53
Light Fragment		
all	2.02	1.73
1	2.17	1.57
2	1.73	1.23
3	1.43	0.75
4	1.21	0.71

The average neutron kinetic energies in the lab frame and the associated dispersions for different neutron multiplicities *m*. Results are shown for both fragments combined and for each fragment separately.

Summary:

While earlier numerical treatments of the decay processes associated with fission have tended to focus on average quantities, which are often sufficient, the next generation of treatments involves direct Monte Carlo simulations of individual event chains. Such treatments give access to essentially any conceivable correlation observable and thus have vastly expanded potential utility. This undertaking presents challenges with regard to both the physics inputs and programming techniques.

On the physics side, the available information is far from sufficiently detailed to uniquely determine the treatment and a considerable degree of extrapolation to unknown territory must be made, based as far as possible on plausible physical ideas. The development work naturally identifies various kinds of new data that would be particularly helpful. The code may become especially useful in connection with the planned TPC fission detector. To facilitate the incorporation of known data, which is expected to remain an ongoing process, the code has a modular structure.

An important technical challenge is designing the code to be sufficiently fast for practical application in transport studies where many different event samples must be generated. The code is very competitive in this regard.

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