Fission & Giant Dipole Resonance

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Outline

- Introduction
- Giant Dipole Resonance – an experimental tool
- Using fission to learn about GDR properties
  - Fission fragment GDR excitation (low temp.)
- Bremsstrahlung radiation in spontaneous fission
- Using GDR to learn about nuclear fission
  - Dissipative fission dynamics (fission hindrance)
  - Time scale of fission
  - Temperature dependence of nuclear viscosity
  - GDR excitation in near SHE

Giant Dipole Resonance

Collective vibrational mode of nuclei (Isoscalar, isovector, electric, magnetic)

Characteristics & properties

Systematics

Measure of nuclear deformation

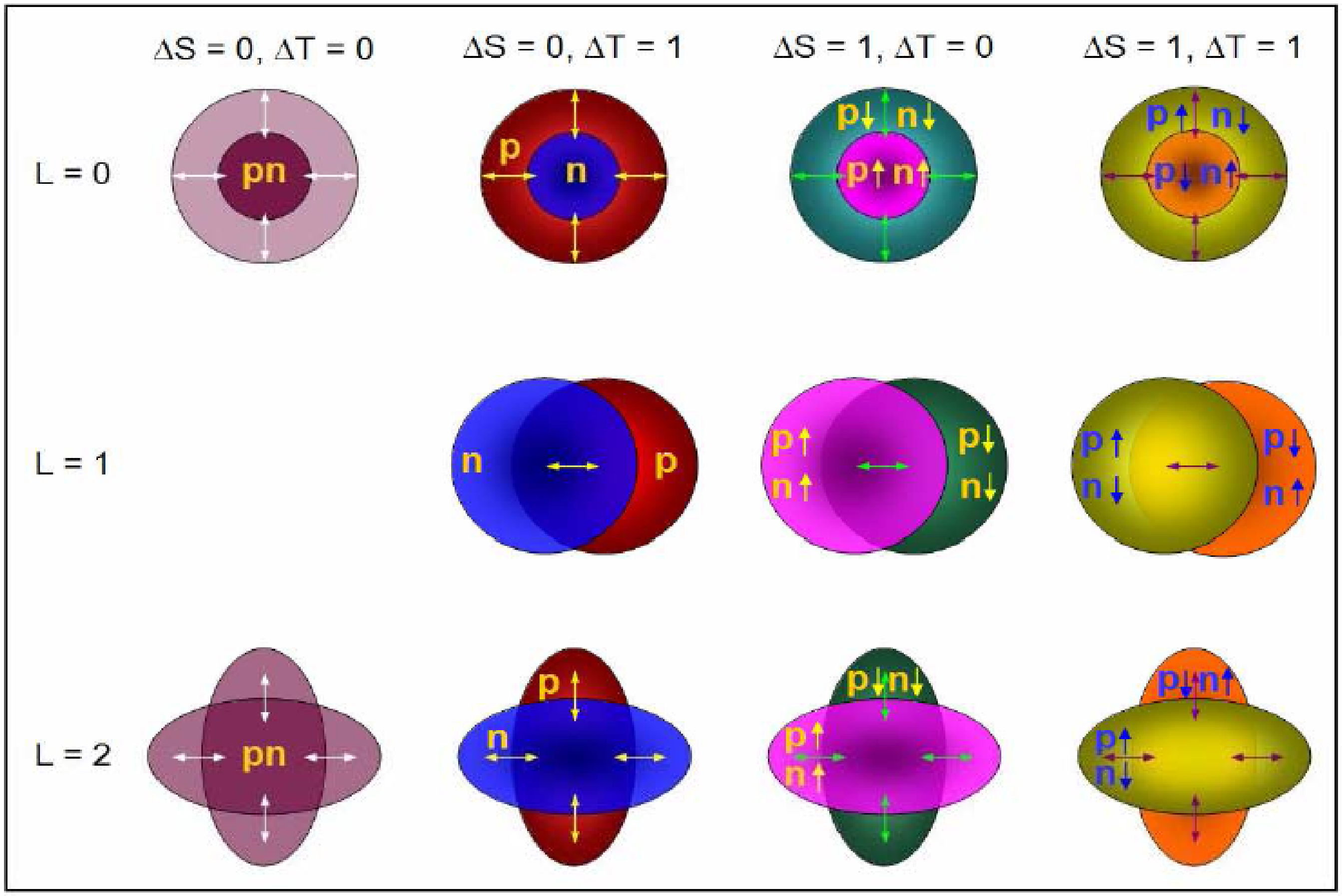
Measure of nuclear dissipation (energy damping)

GDR probes very early stages of CN decay

Detection of GDR decay photons – energy spectrum

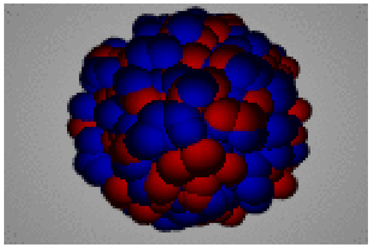
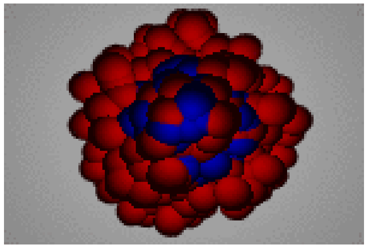
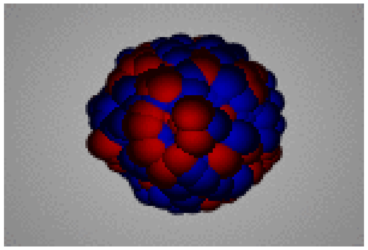
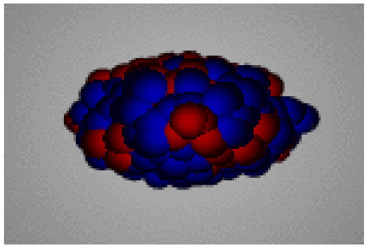
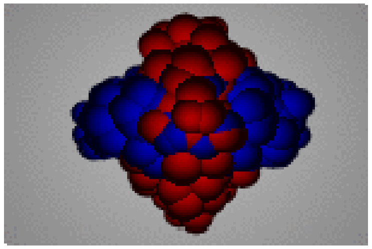
GDR can be used to probe & understand nuclear fission
Fission can be used to understand GDR properties

Giant Resonance modes

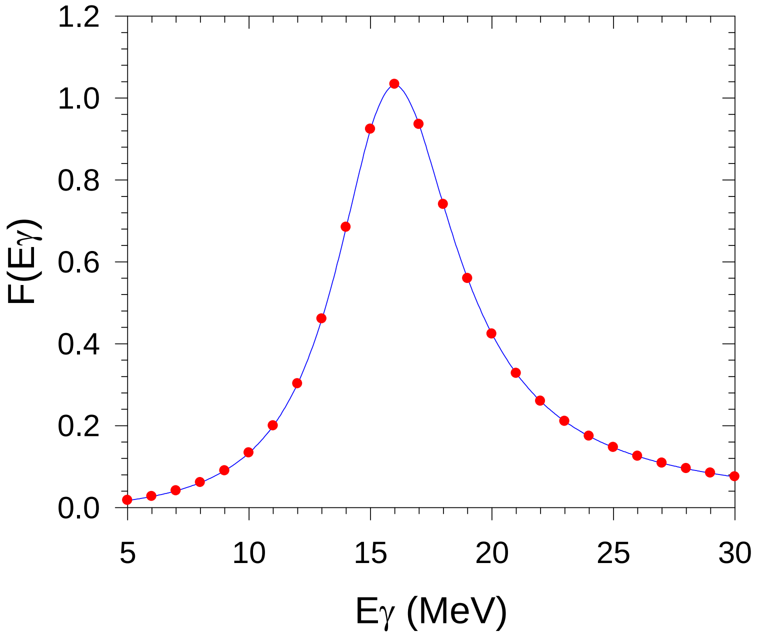


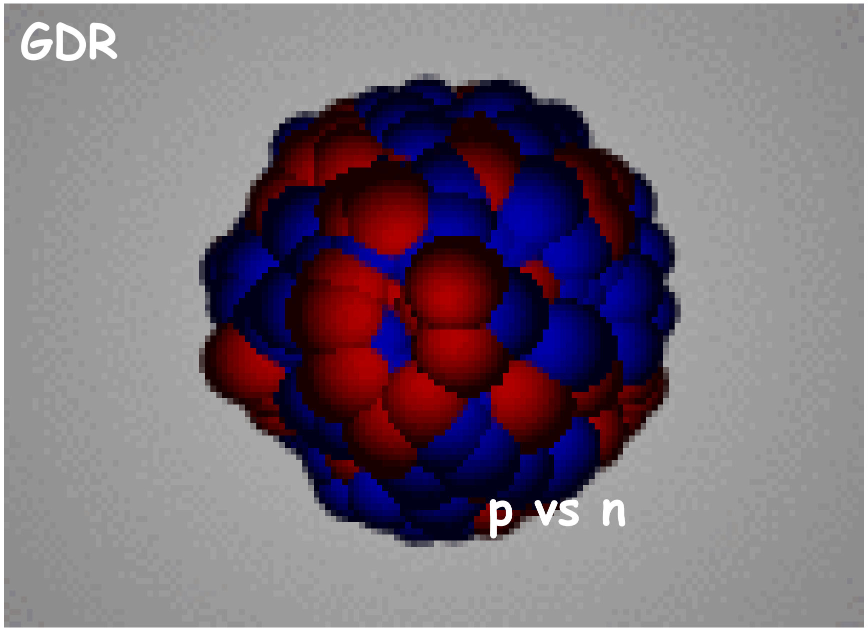
Examples of nuclear collective vibrations

Electric modes

	Isoscalar	Isovector
Monopole (GMR)		
Dipole (GDR)		
Quadrupole (GQR)		

Isovector Giant Dipole Resonance (IVGDR)





$$F\left(E_\gamma\right) = \frac{E_\gamma^2 \Gamma^2{}_{GDR}}{(E^2{}_\gamma - E^2_{GDR})^2 + E_\gamma{}^2 \Gamma^2{}_{GDR}}$$

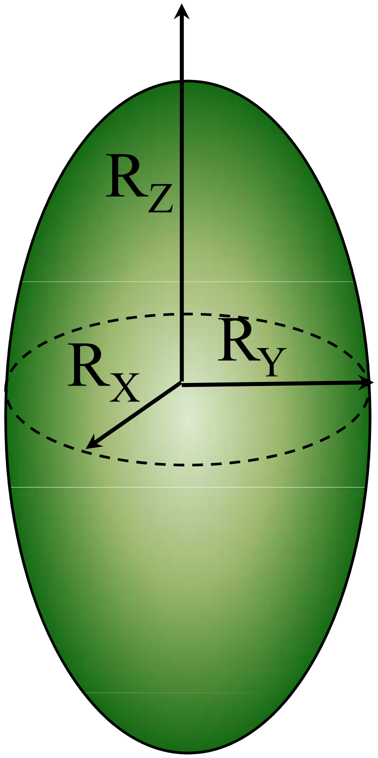
The Giant Dipole Resonance (GDR) is a small amplitude, high frequency collective mode of excitation in nuclei.

Parameters governing the GDR measurement:

E_{GDR} → Size and shape of nuclei ($E_{GDR} \propto A^{-1/3}$)

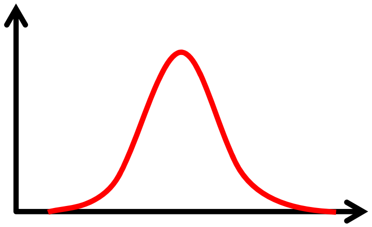
Γ_{GDR} → Damping of the collective motion (Dissipation)

GDR as a probe of Deformations



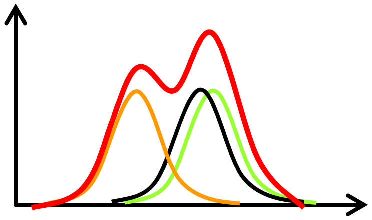
- Spherical

  $R_X = R_Y = R_Z \rightarrow \omega_X = \omega_Y = \omega_Z$



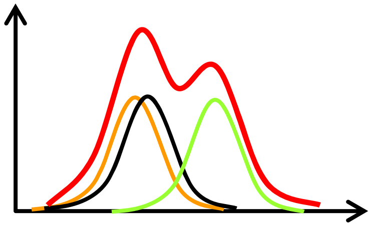
- Prolate

  $R_X = R_Y < R_Z \rightarrow \omega_X = \omega_Y > \omega_Z$



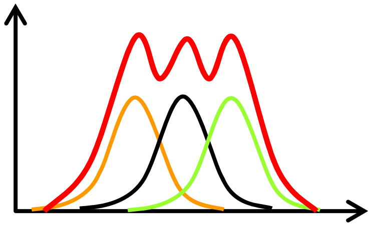
- Oblate

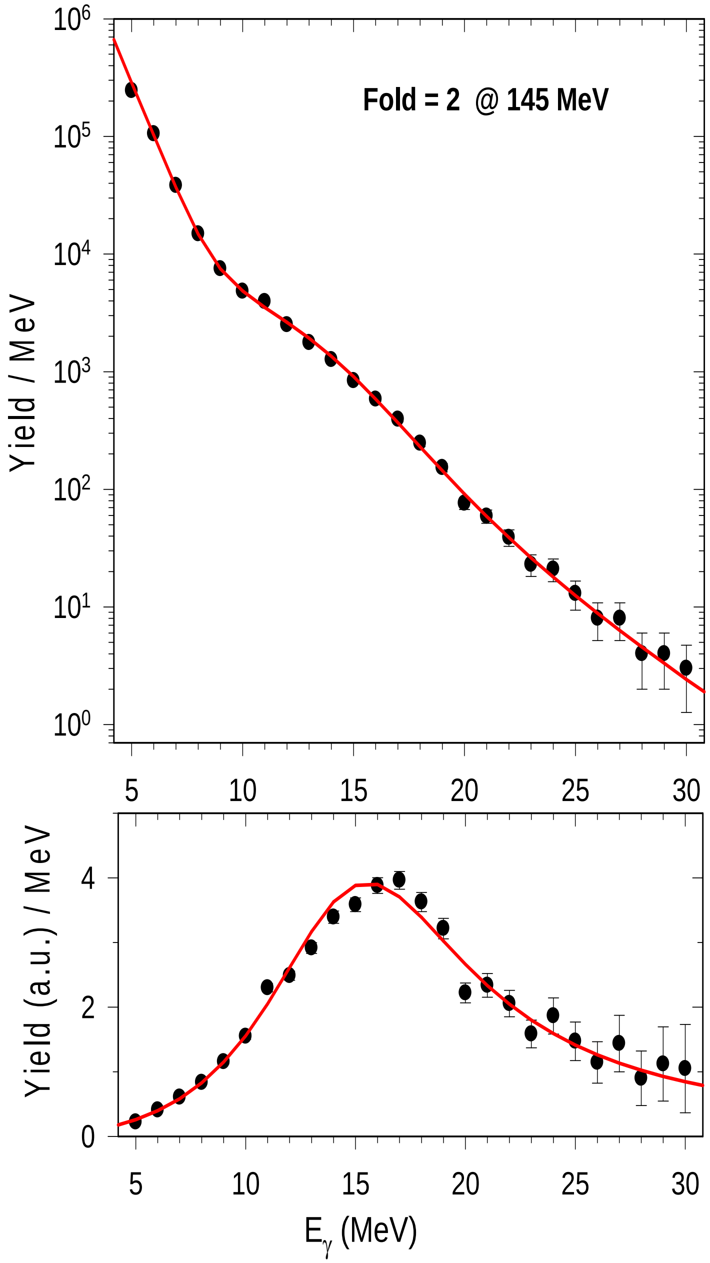
  $R_X = R_Y > R_Z \rightarrow \omega_X = \omega_Y < \omega_Z$



- General Ellipsoid

  $R_X \neq R_Y \neq R_Z \rightarrow \omega_X \neq \omega_Y \neq \omega_Z$





$^{20}Ne + ^{93}Nb \rightarrow ^{113}Sb^*$

$E_{lab} = 145$ MeV

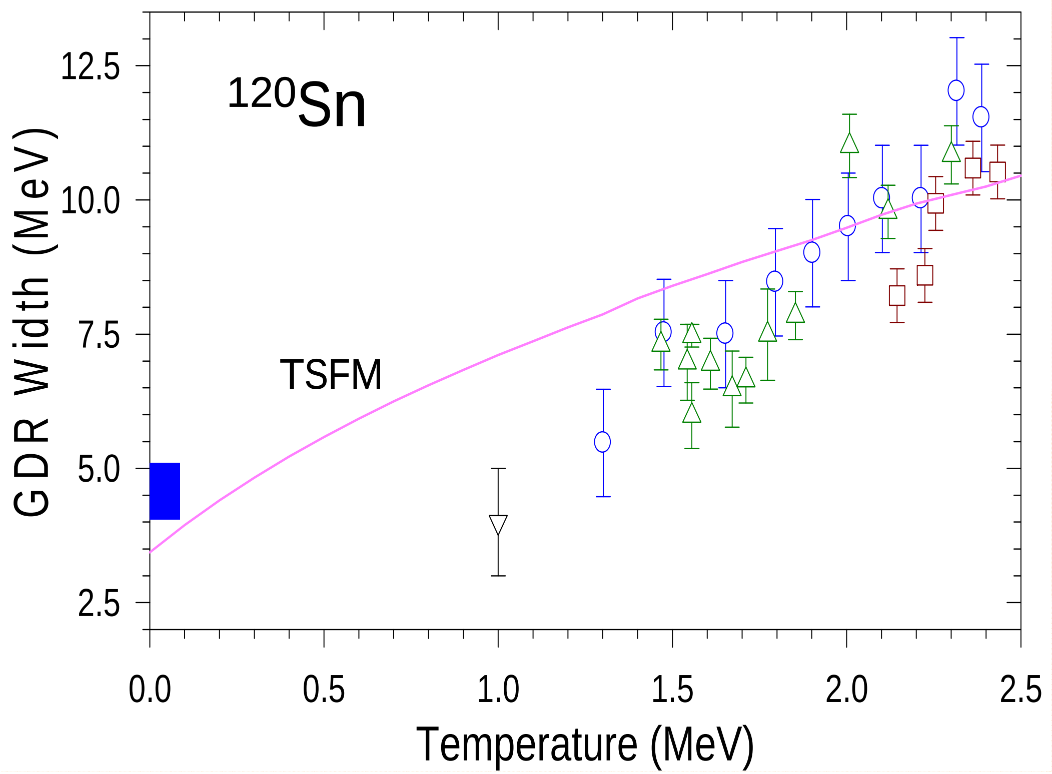
$E^* = 109$ MeV

GDR probes very early stages of Compound Nuclear decay

GDR can be used to probe & understand nuclear fission

Fission process can be used to understand GDR properties

Temperature dependence of GDR width



Width increases with temp

-increased damping

-Increased ang mom/deformation

- effect of thermal fluctuations

Description at moderate temperature is OK !!!

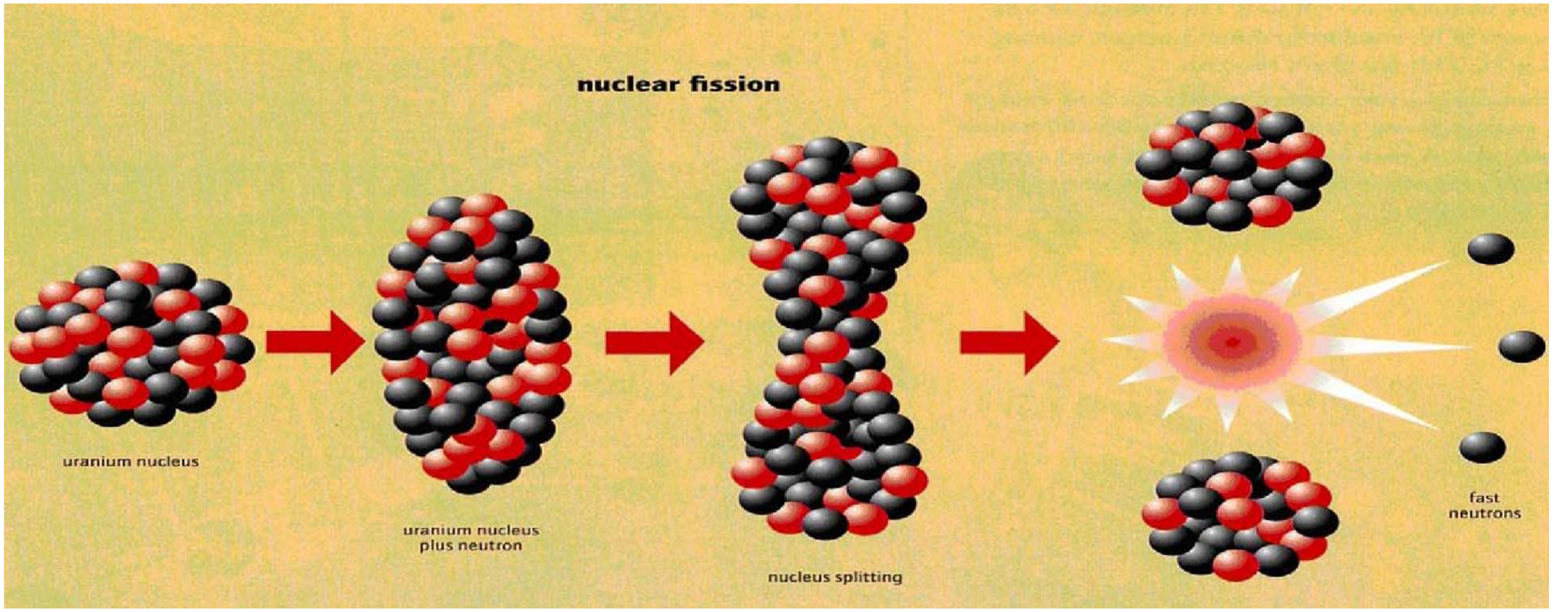
1.5 MeV < T < 2.5 MeV

Grossly over-estimated at low temperatures

-Need for more data at low T -- experimental problem

-Need for better understanding – theoretical problem

Spontaneous Fission of Cf-252



^{252}Cf undergoes spontaneous fission (3%)

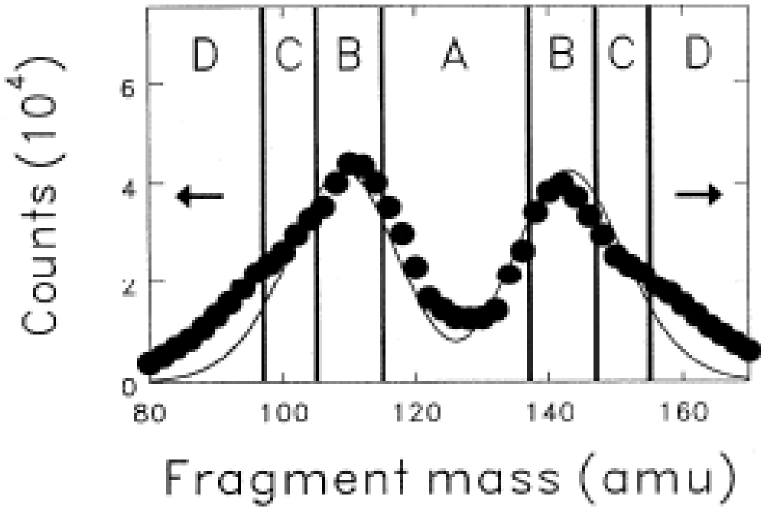
Half life – 2.65 years Alpha decay (97%)

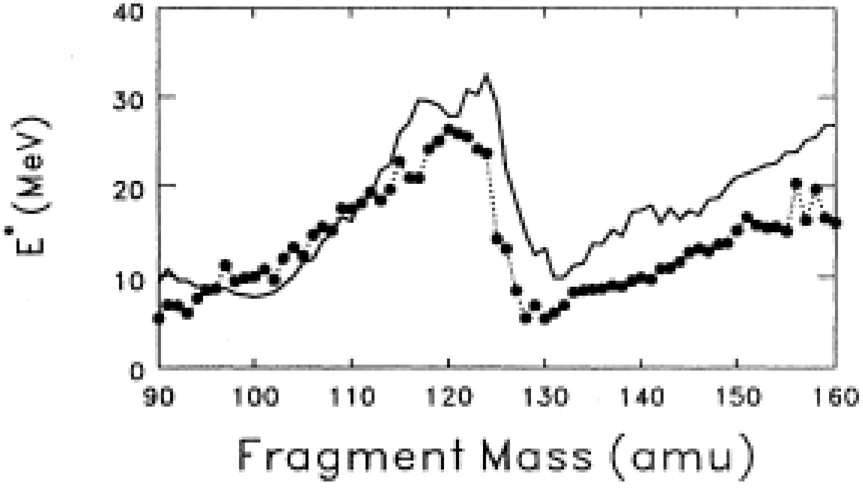
Energy released ~ 200 MeV per fission

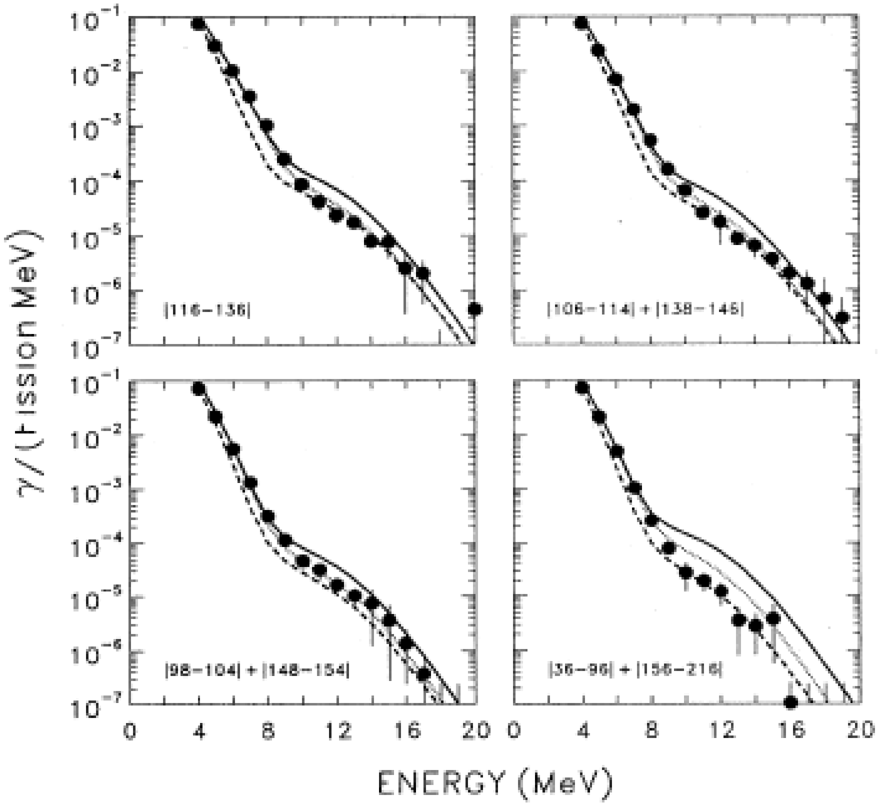
~ 70% of the energy goes to the K.E of the fission fragments.

Spontaneous Fission of Cf-252

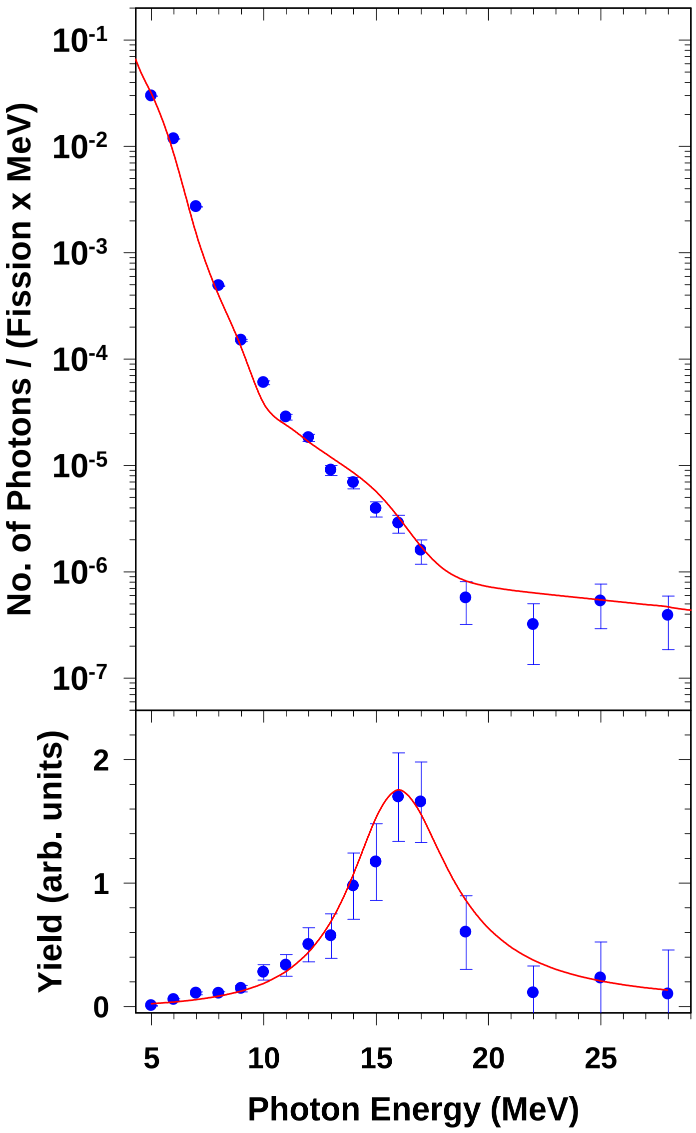
Earlier attempt - 1995

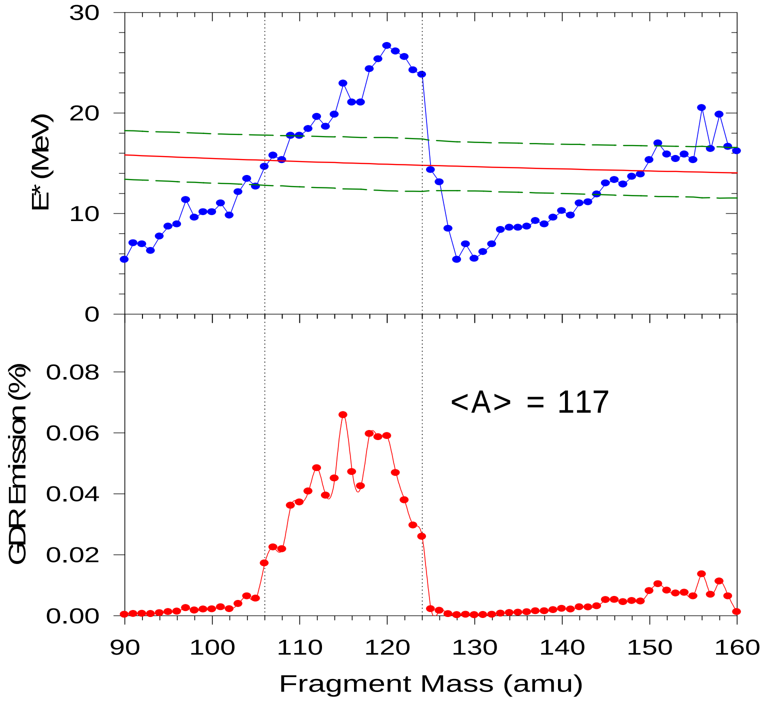


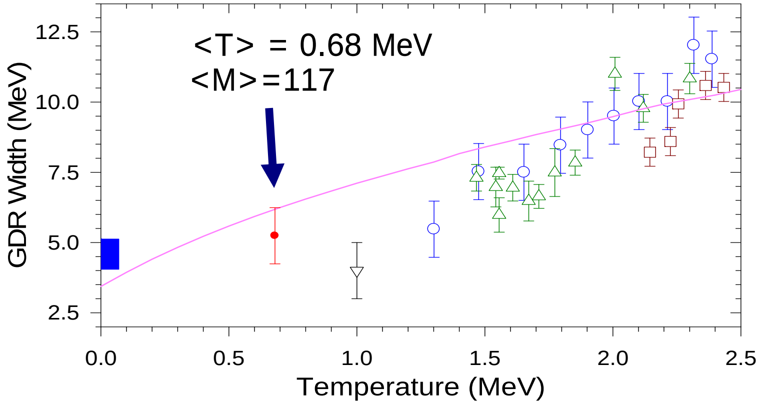




GDR width from excited fragments of ^{252}Cf







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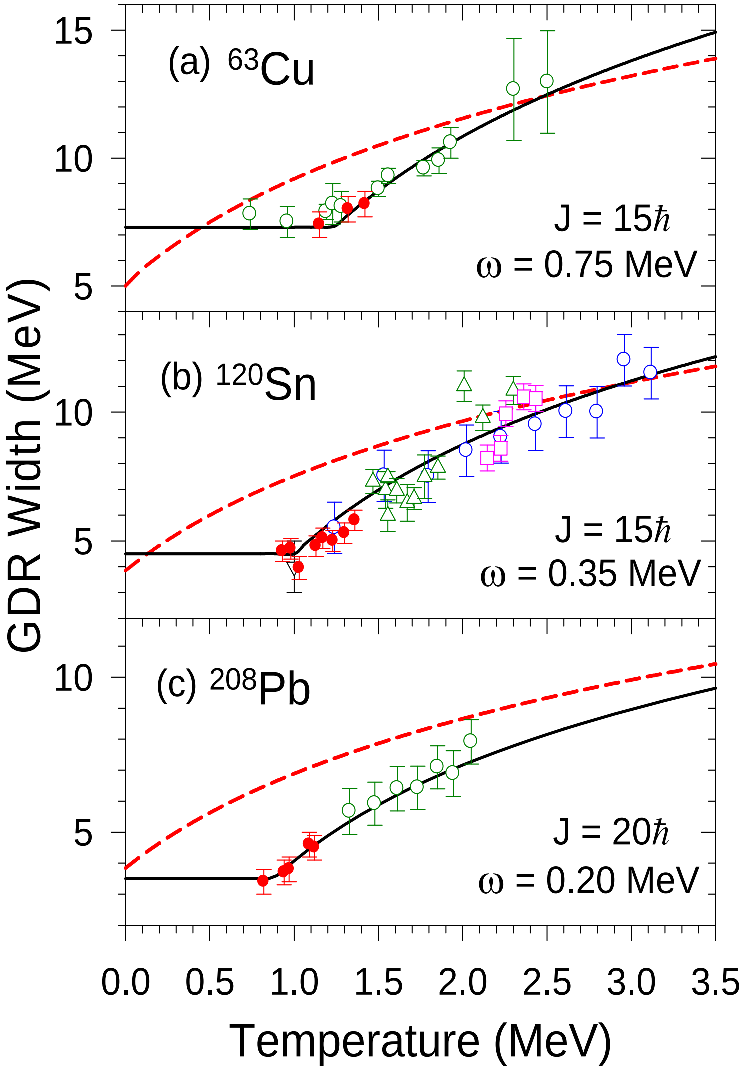
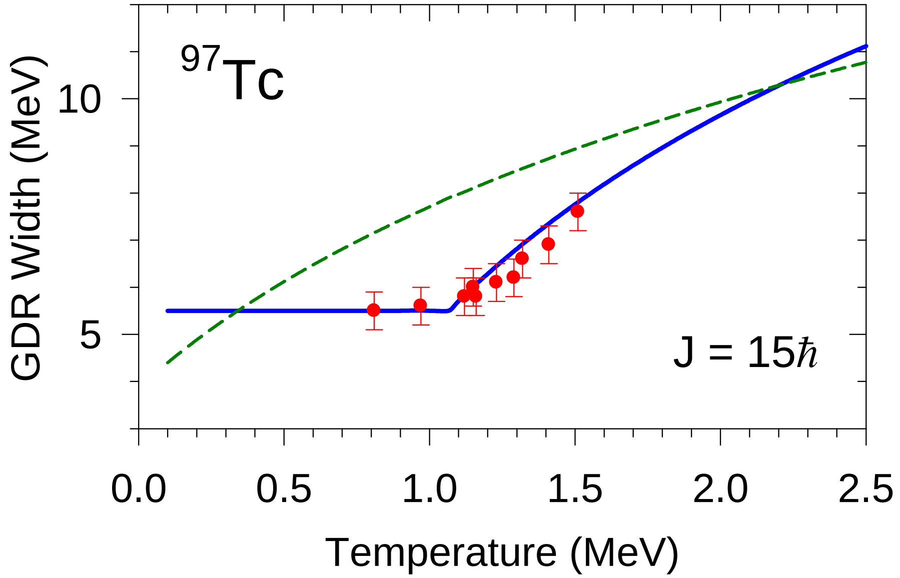
GDR width at low temperature

Alpha induced fusion reactions used to populate low temperatures





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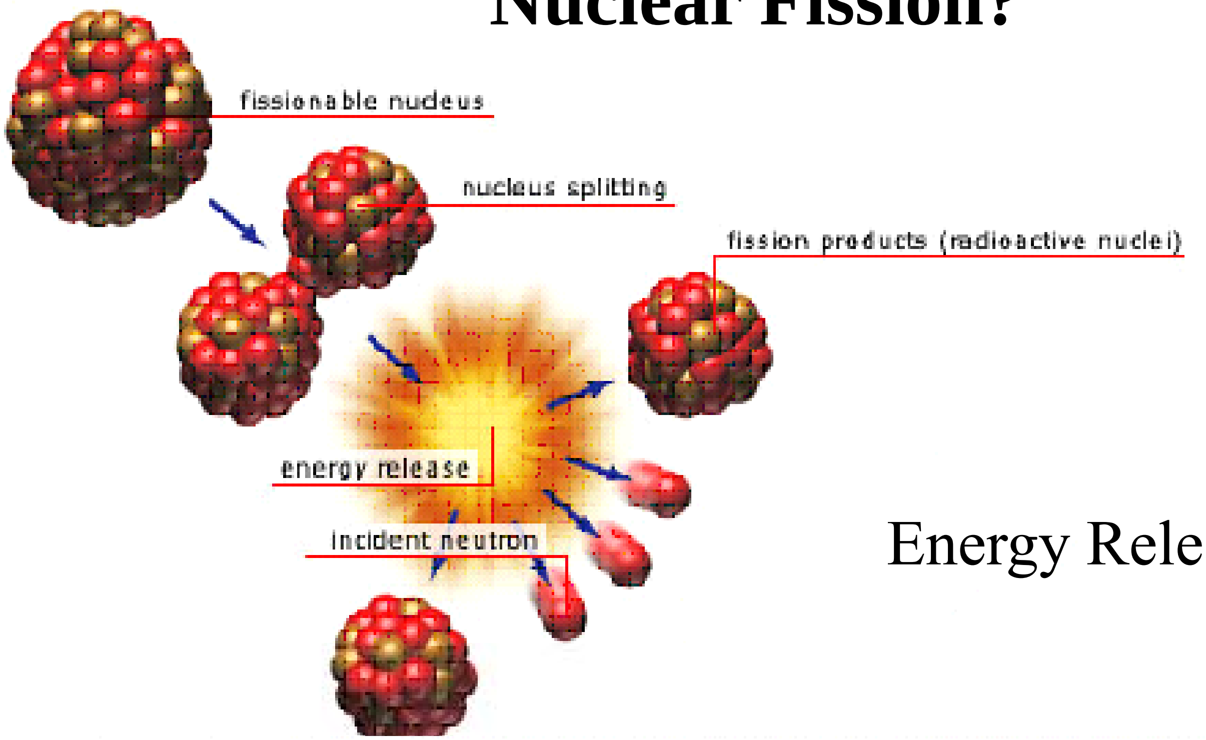
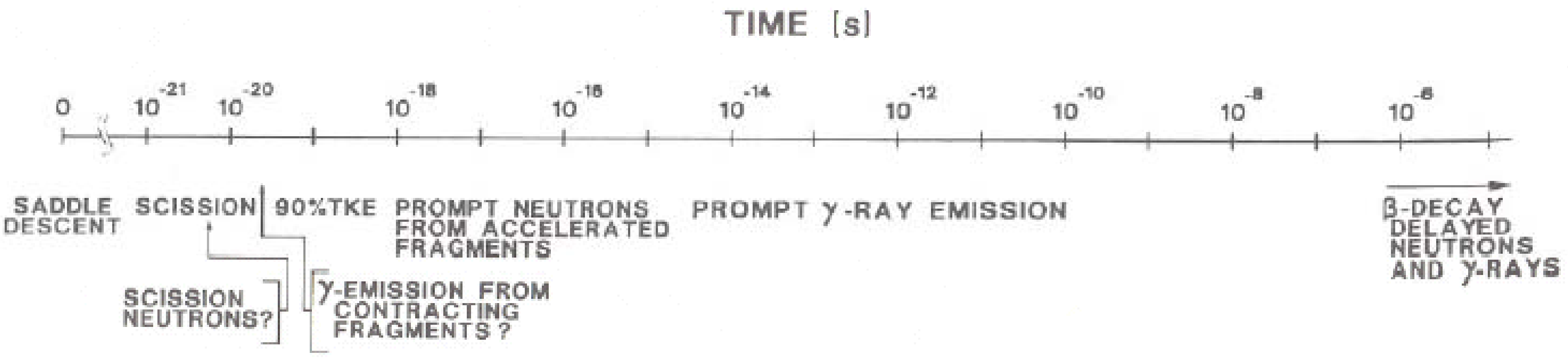
Can bremsstrahlung radiation be observed in Nuclear Fission?



Energy Released = 200 MeV



Emission of bremsstrahlung photons from Cf-252 Spontaneous Fission

Is it possible ? ---- Rapid acceleration in mutual Coulomb field

What energy scales are involved ?

Experimental determination

Theoretical interpretation
- Classical – Quantum mechanical

Coulomb Acceleration Model: This model assumes coulomb acceleration of the two fission fragment from a scission like configuration to infinity .

J. D. Jackson

$$\frac{d^2 I}{d\omega\, d\Omega} = 2 \mid \mathbf{A}_1(\omega) + \mathbf{A}_2(\omega) \mid^2$$

$$\mathbf{A}_i(\omega) = \left(\frac{1}{\sqrt{2\pi}}\right)\left(\frac{c}{4\pi}\right)^{\frac{1}{2}}\left(\frac{1}{c}\right)\int_{-\infty}^{\infty} dt \quad \left[\frac{\hat{\mathbf{n}} \times [(\hat{\mathbf{n}} - \boldsymbol{\beta}_i) \times \dot{\boldsymbol{\beta}}_i]}{(1 - \boldsymbol{\beta}_i \cdot \hat{\mathbf{n}})^2}\right] q_i e^{-i\omega[t - \hat{\mathbf{n}}\cdot\mathbf{r}_i(t)/c]}$$

In the non-relativistic limit, $\beta << 1$

$$\frac{d^2 I}{d\omega\, d\Omega} = \frac{1}{4\pi^2 c}\left|\int_{-\infty}^{\infty} dt \quad \sum_{i=1}^{2} [\hat{\mathbf{n}} \times (\hat{\mathbf{n}} \times \dot{\boldsymbol{\beta}}_i)]\, q_i e^{-i\omega[t - \hat{\mathbf{n}}\cdot\mathbf{r}_i(t)/c]}\right|^2$$

$$\dot{\boldsymbol{\beta}}_1 = \ddot{\mathbf{x}}\mu/cm_1 \qquad \dot{\boldsymbol{\beta}}_2 = -\ddot{\mathbf{x}}\mu/cm_2$$

Motion of the two fission fragment is confined to one dimensional motion along the fission axis. Thus the relative acceleration is $\ddot{\mathbf{x}} = \ddot{\mathbf{x}}_1 - \ddot{\mathbf{x}}_2$

Energy spectrum, in the non-relativistic limit, of bremsstrahlung produced from the acceleration of the fission fragments.

$$\frac{d^2N}{dE_\gamma d\Omega_\gamma} = \frac{\mu^2}{4\pi^2(\hbar c)c^2}\frac{e^2}{E_\gamma}\left|\int_{-\infty}^{\infty} dt \quad [\hat{\mathbf{n}} \times \ddot{\mathbf{x}}]e^{-i\omega t}\left(\frac{z_1}{m_1}e^{i(\omega/c)(\mu/m_1)\hat{\mathbf{n}}\cdot\mathbf{x}} - \frac{z_2}{m_2}e^{-i(\omega/c)(\mu/m_2)\hat{\mathbf{n}}\cdot\mathbf{x}}\right)\right|^2$$

Motion of the fragments can be determined by solving the equation for the two particles under the influence of a repulsive coulomb potential

$$\frac{1}{2}\mu\dot{r}^2 + \frac{k}{r} = E$$

$$\ddot{x} = \frac{k}{\mu r^2}$$

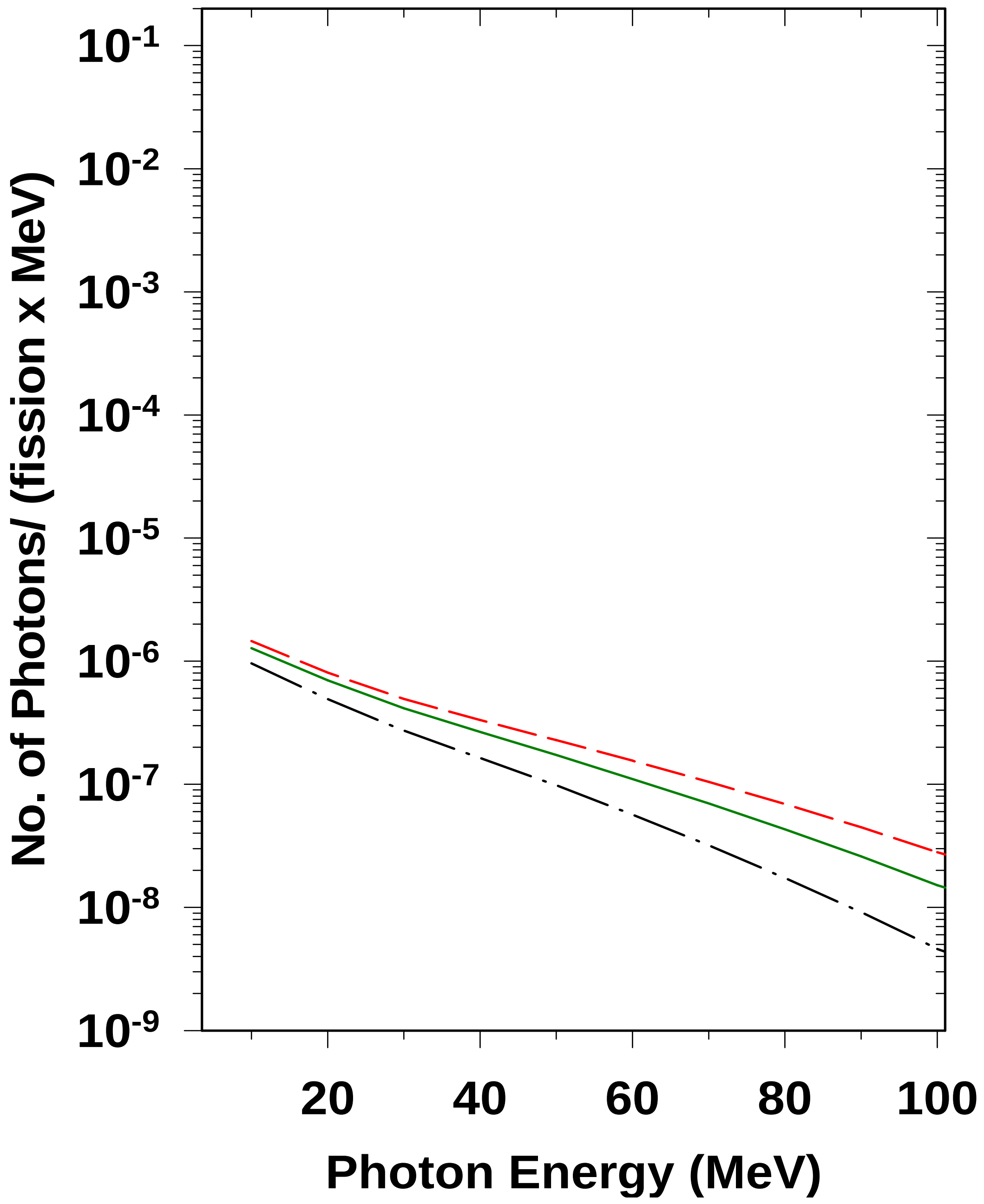
μ is the reduced mass

$k = z_1 z_2 e^2$

$\dot{r}$ is the relative velocity

E is the energy of the system

$$t(r) = \left\{\sqrt{\frac{\mu}{2E}}\left[\sqrt{r^2 - \frac{kr}{E}} + \frac{k}{2E}\ln\left(\left(r - \frac{k}{2E}\right) + \sqrt{r^2 - \frac{kr}{E}}\right)\right]\right\}_{r_{\min}}^{r}$$



$R_{min} = Z_1 Z_2 e^2/E$

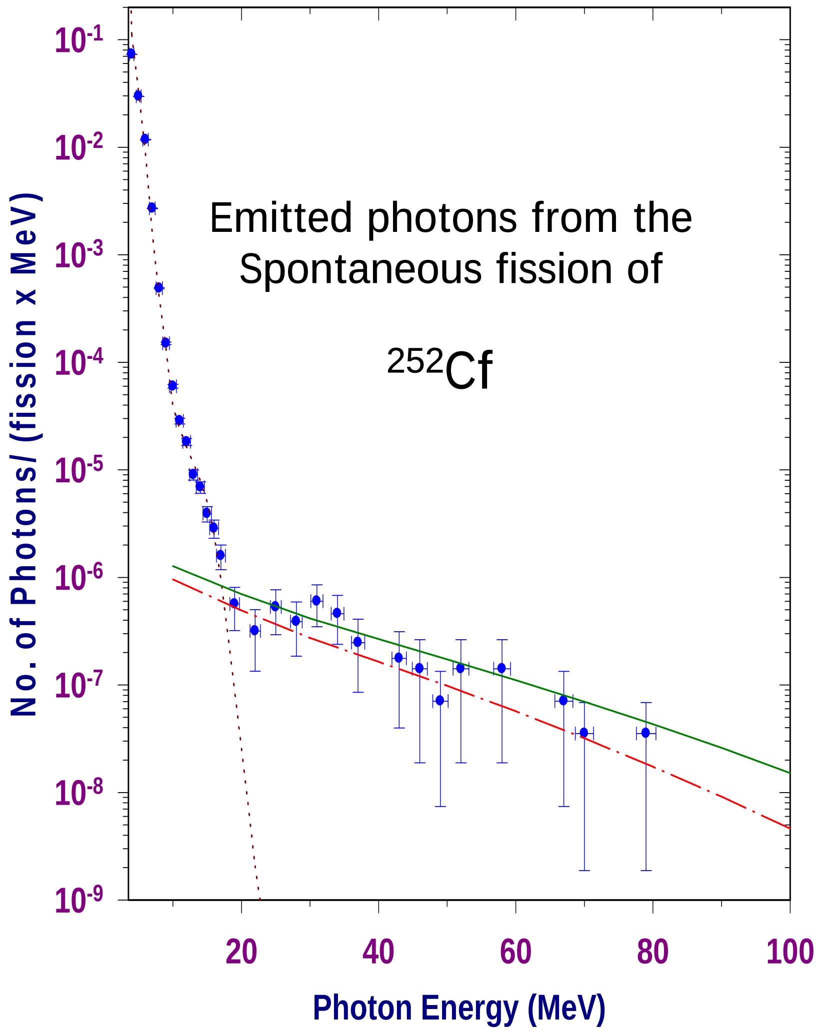
Pre-scission kinetic energy = 25-30 MeV

Conservation of Energy

$(1 - \hbar\omega/E)$

Emission probablity of the bremsstrahlung photons very small.

High Energy Photons from ^{252}Cf



Coherent Bremsstrahlung emission observed for the first time up to 80 MeV

-- from the Coulomb accelerated fission fragments from spontaneous fission of ^{252}Cf

The spectrometer LAMBDA is capable of measuring photons up to ~ 200 MeV with very good efficiency for full energy

Classical bremsstrahlung considering the pre-scission kinetic energies of the fission fragments

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Also verified by another group later by detecting neutrons in coincidence.

Next Day

Part-II

Fission & Giant Dipole Resonance

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Dissipative Fission Dynamics

Fundamental nuclear property - viscosity of nuclear matter & its dependence on T

Transport properties of viscous nuclear matter - mass flow in fission process

Fission process -- Tunnelling through barrier
-- Crossing over the barrier

Time scale of fission -- 1. Flux build-up inside barrier $\sim 20 \times 10^{-21}$ s
2. Flow across the barrier
3. Saddle to scission motion $\sim 3 \times 10^{-21}$ s

for non-viscous fission process

Any dissipation inside or outside saddle -- lengthens these times -- slower fission

Clocks for measuring fission time scale -- pre-scission neutron multiplicity
-- pre-scission GDR gamma-decay

GDR as clock

High energy gamma-rays are emitted from the decay of Giant Dipole Resonance

$$F(E_\gamma) = 2.09 \times 10^{-5} \frac{NZ}{A} \cdot S \cdot \frac{\Gamma_{\mathrm{GDR}} E_\gamma^4}{(E_\gamma^2 - E_{\mathrm{GDR}}^2)^2 + \Gamma_{\mathrm{GDR}}^2 E_\gamma^2}.$$

GDR decay photons are emitted at the very early stages of CN decay

GDR clock has several advantages --

1. Simplicity of GDR strength function and absence of truly free parameter
2. GDR vibration is much faster than fission time scales
3. Sensitivity to deformation (GDR strength fn. & gamma-fission ang corr.)

Fission Time Scale & Dissipation

Approach: Fokker-Plank eqn – describes evolution of collective coordinates through phase space with dissipation coeff. $\eta = \beta m$ (β – red. diff. coeff. In units of 10^{21} s^{-1})

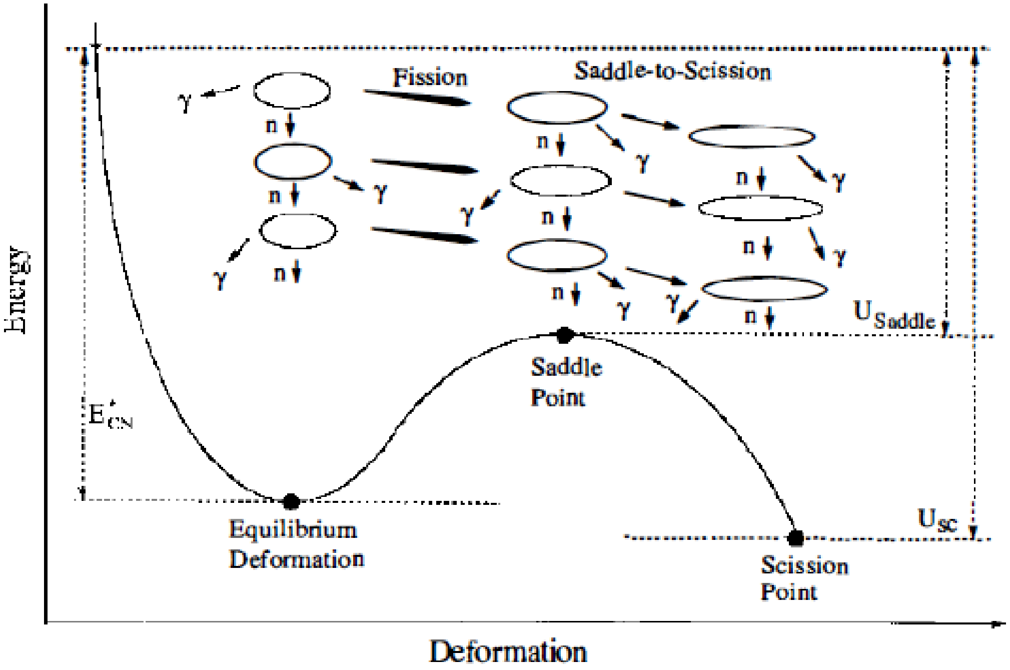
Also, we can define η from Einstein's eqn. for Diffusion const. $D = \eta T$

We also define, $\gamma = \beta/2\omega$ as nuclear friction coeff. (dimensionless, natural scale)

where, ω describes oscillation damping in inverted oscillator

$\gamma =$ 1 – Critical damping
< 1 – Under-damped
> 1 – Over-damped

Presence of dissipation influences the fission process and also the particle and gamma emission



Effects of dissipation

Enhanced emission of particles & gamma-rays -- in three regions

1. Inside the saddle Fission width is given by $\Gamma_f(t) = \Gamma_f{}^0[1-\exp(-t/\tau_D)]$

τ_D is the fission delay time – allows for enhanced emission
For over-damped situation $\tau_D = \gamma_i/\omega_1 \ln(10E_{bf}/T)$

2. At the saddle $\Gamma_f{}^{Kramers} = \Gamma_f{}^{BW}(\sqrt{(1+\gamma^2)} - \gamma)$ $\gamma = \beta/2\omega_2$

Typically, $\omega_1 = \omega_2$ Γ_f^0 → is replaced by $\Gamma_f^{Kramers}$
Further reduction in fission width - enhances particle & gamma-rays from the interior

3. Saddle to Scission $\tau_{ssc} = \tau^0{}_{ssc}(\sqrt{1+\gamma_0{}^2} + \gamma_0)$

γ_0 is the friction outside barrier, $\tau^0_{ssc} = 3 \times 10^{-21}$ s, is the undamped time constant

Introduction of dissipation reduces the fission widths – fission process slows down

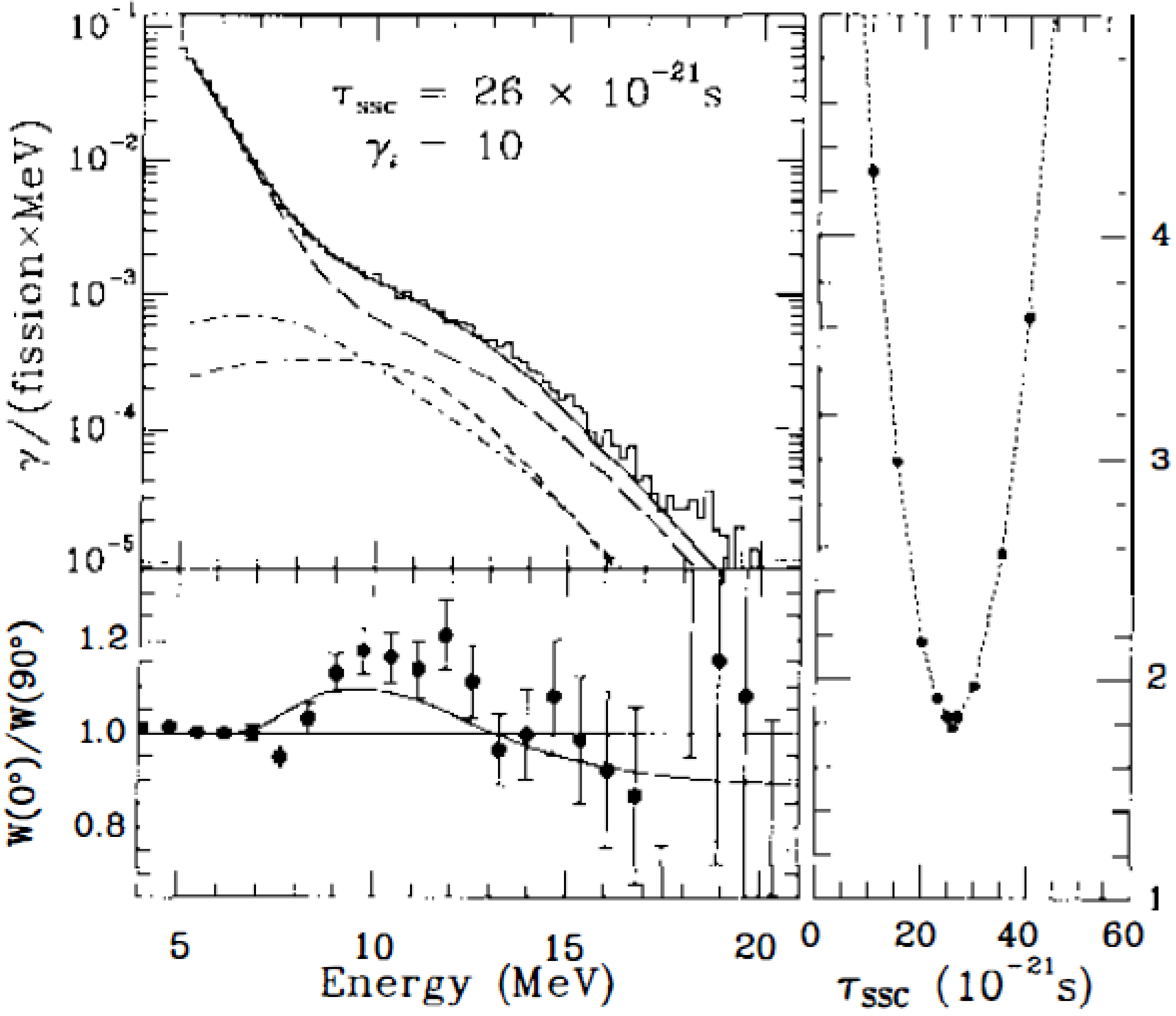
GDR decay photons & particles get more time to escape – enhanced emission

Consistent with experimental data

Experimental method

Measure GDR decay photons, fission fragments and/or ang. mom.

^{32}S + ^{208}Pb at 230 MeV



We have already seen

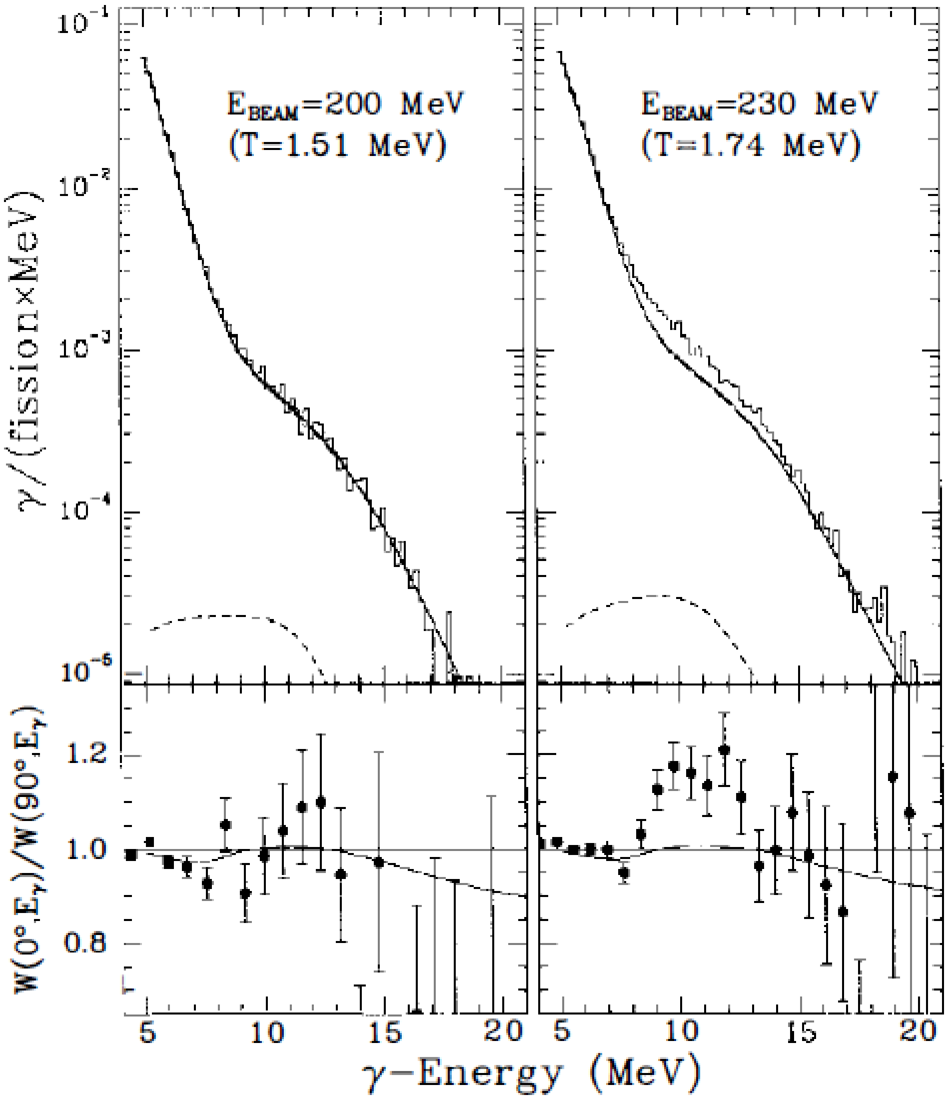
$\tau_f = (\gamma/\omega_1)\ \ln(10.E_{bf}/T)$

γ = 10 corresponds to a Fission delay time of 6.4×10^{-19} sec Averaged over all decay steps.

Important to note: Fission is hindered, but total fission probability is conserved.

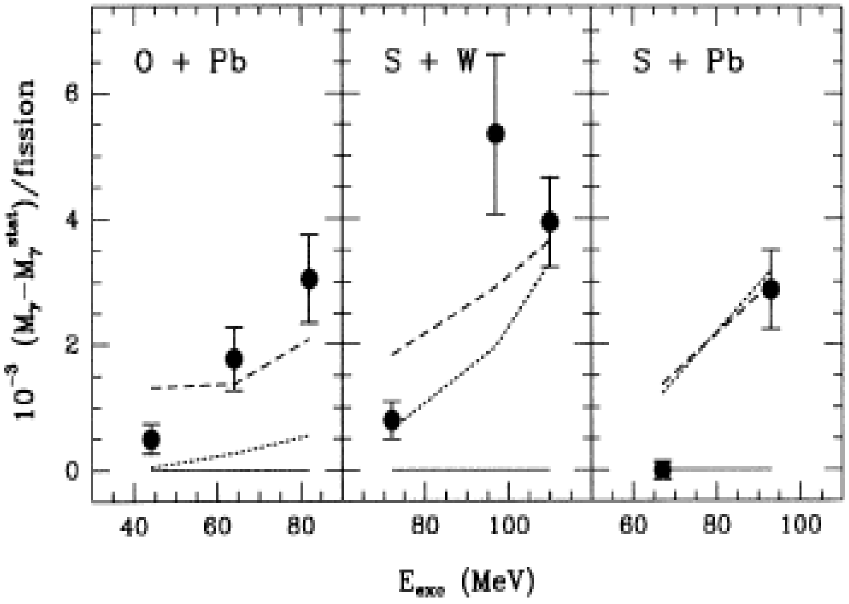
Energy dependence of dissipation

$^{32}S + ^{208}Pb \rightarrow ^{240}Cf$

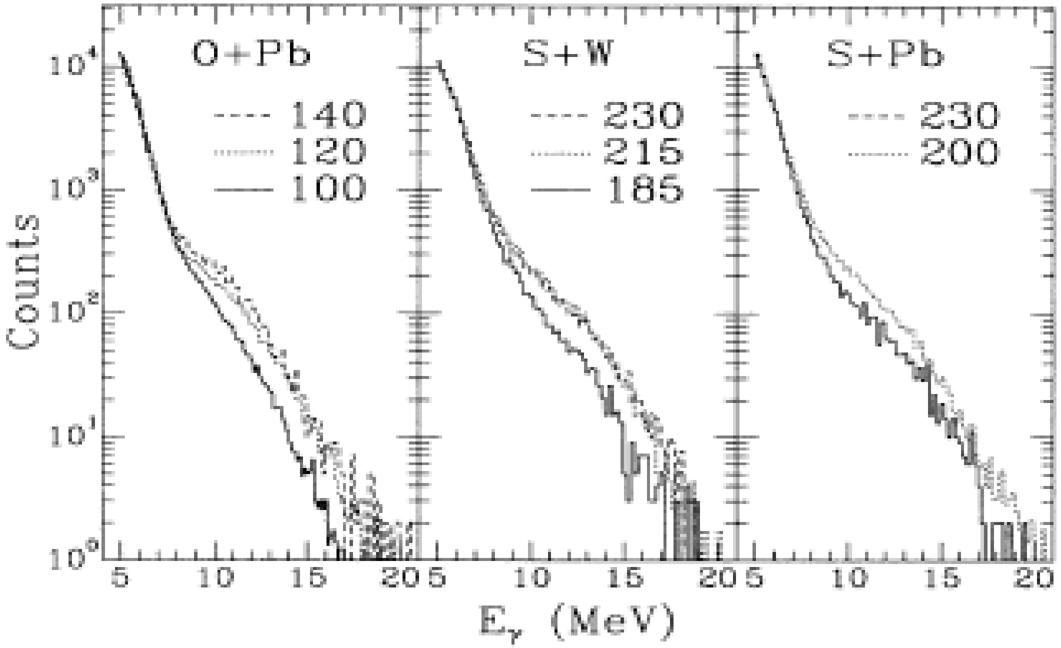


Enhanced GDR emission

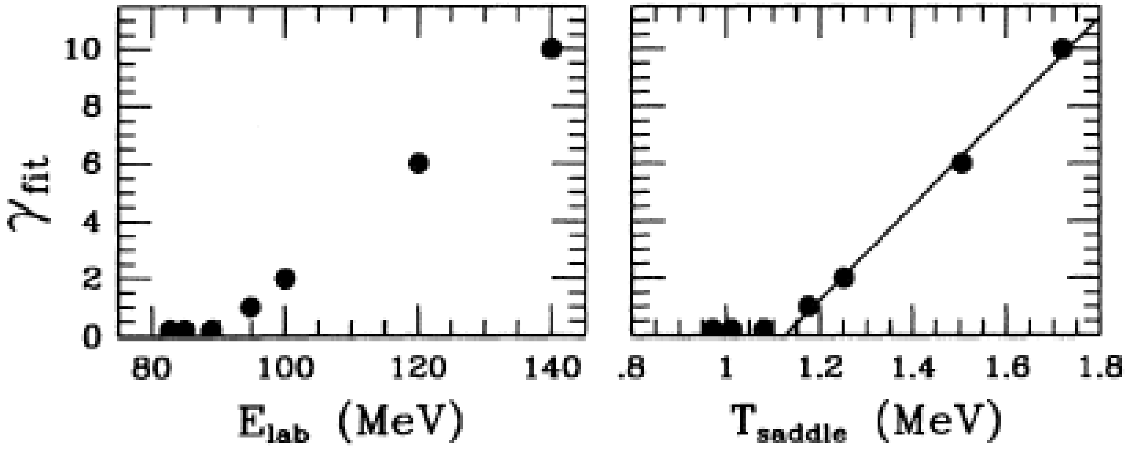
Statistical model fit with
non-dissipative fission



Energy dependence of dissipation



^{16}O + ^{208}Pb



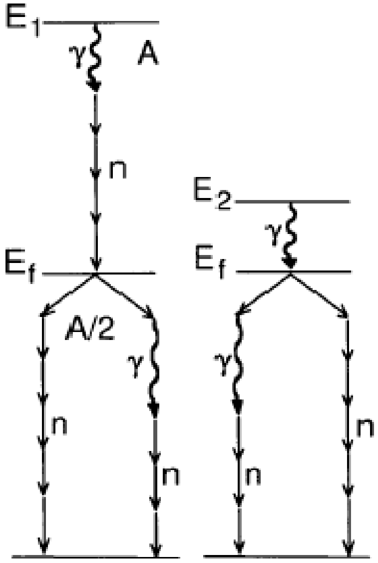
What next

As excitation energy increases – Dissipation increases – still slower fission
Can be used to populate & study (GDR decay) near SHE at high excitation

Very heavy nuclei [Z > 105, A > 250] may be populated at high excitation
and their GDR characteristics studied (T ~ 2.5 – 3 MeV)

These are highly fissile systems

At still higher excitation fission further hindered, so that,
--- Prefission GDR γ emission competes with fission,
--- possible to see GDR decay photons cleanly (using difference method)



$^{232}Th + ^{40}Ar \rightarrow ^{272}_{108}Hs$ at 10.5 & 15 MeV/A