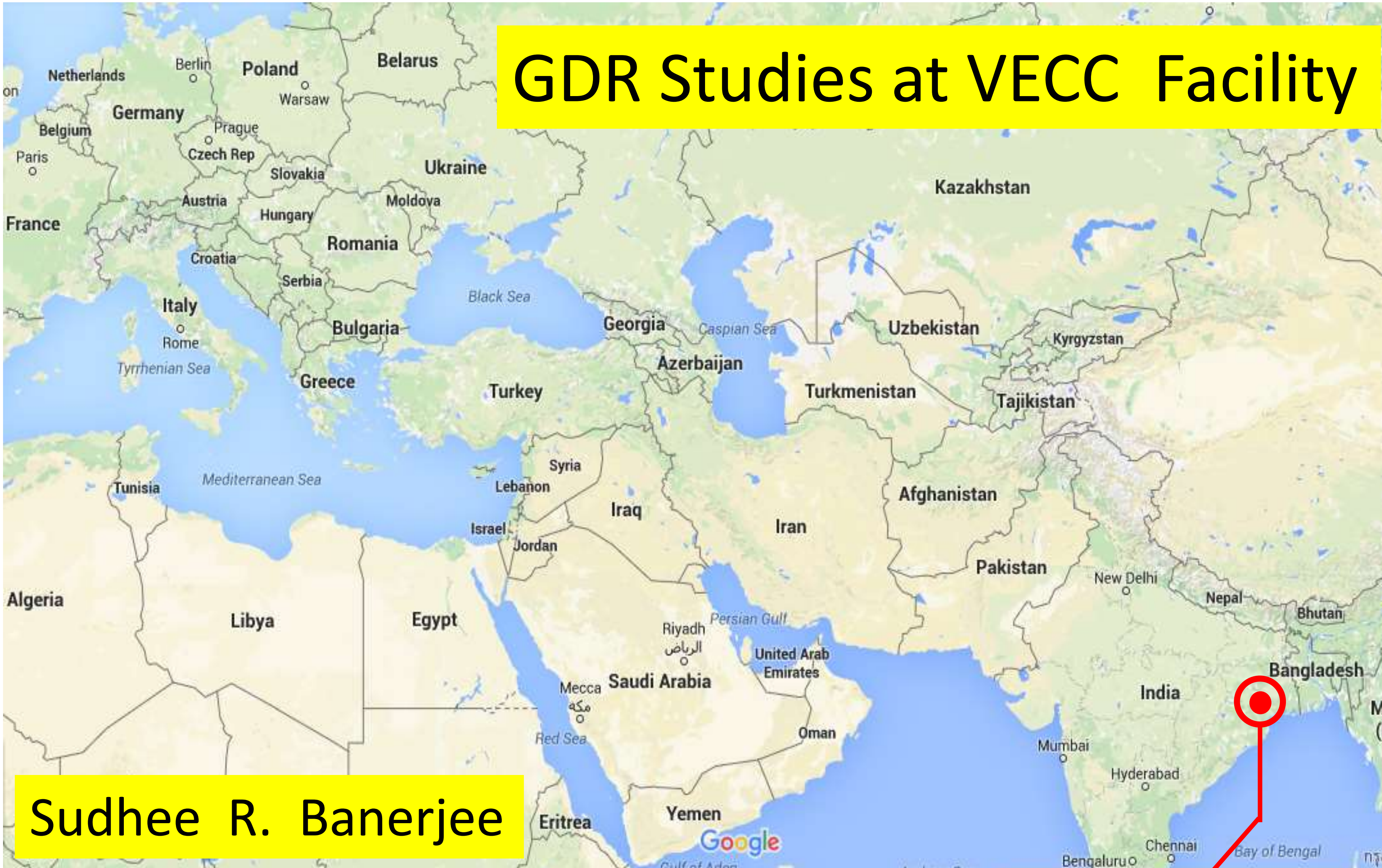
GDR Studies at VECC Facility



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Outline

Introduction

A few measurements at VECC K-130 Cyclotron

with LAMBDA photon spectrometer

- -Jacobi shape transition
- -Super-deformation in ^{32}S – orbiting or clustering?
- -Coherent bremsstrahlung in ^{252}Cf spontaneous fission
- -Evolution of GDR widths with Temperature
  - -GDR strengths in ^{252}Cf fission fragments
  - -GDR widths at very low temperatures
- -Isospin symmetry breaking/restoration in excited nuclei

Plans for the VECC Super-conducting cyclotron

- -GDR in the entrance channel of the reaction
- -GDR in near Super-Heavy nuclei

Conclusion

224cm Variable Energy Cyclotron; Operating Since 1977

Available Projectile Beams from VECC

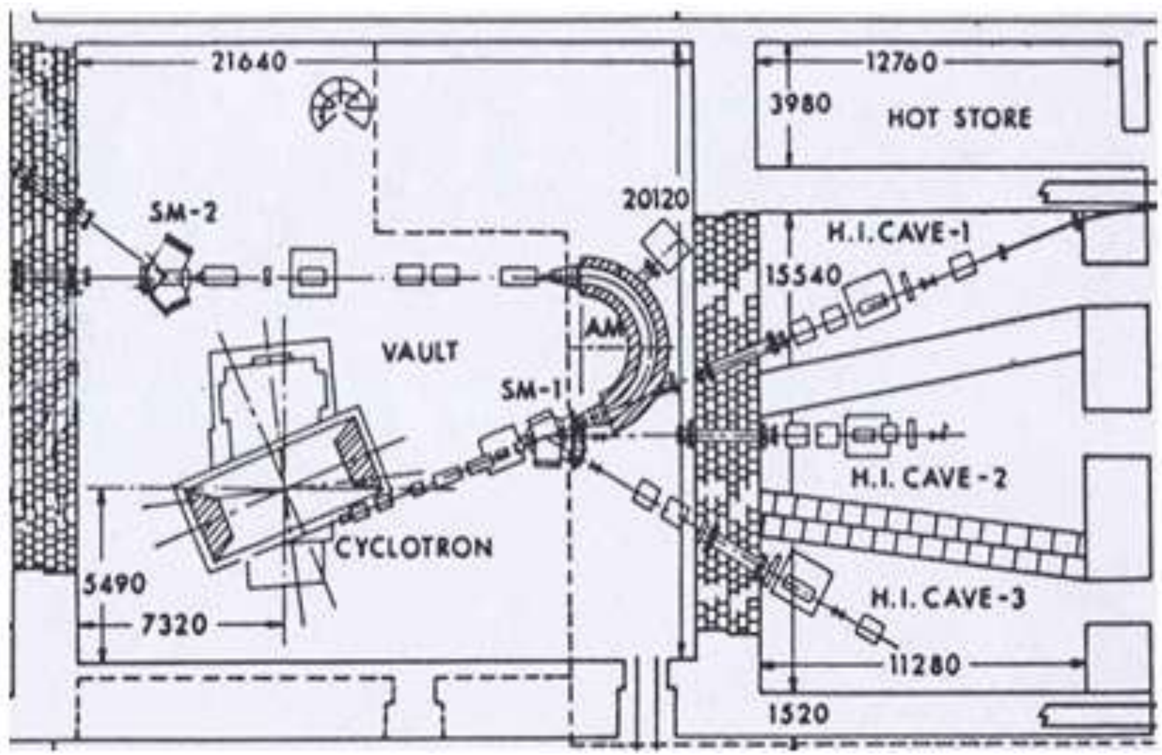
Alpha (He^{2+}) : 28 – 60 MeV

5.5 – 7.5 MeV

(He^{+}): 3.33 MeV

Proton : 7 – 20 MeV

Deuteron : 25 MeV



We plan to provide:

Nitrogen (14) → 5+, 6+

Oxygen (16) → 5+, 6+, 7+

Neon (20) → 6+, 7+

Argon (40) → 11+, 12+, 13+

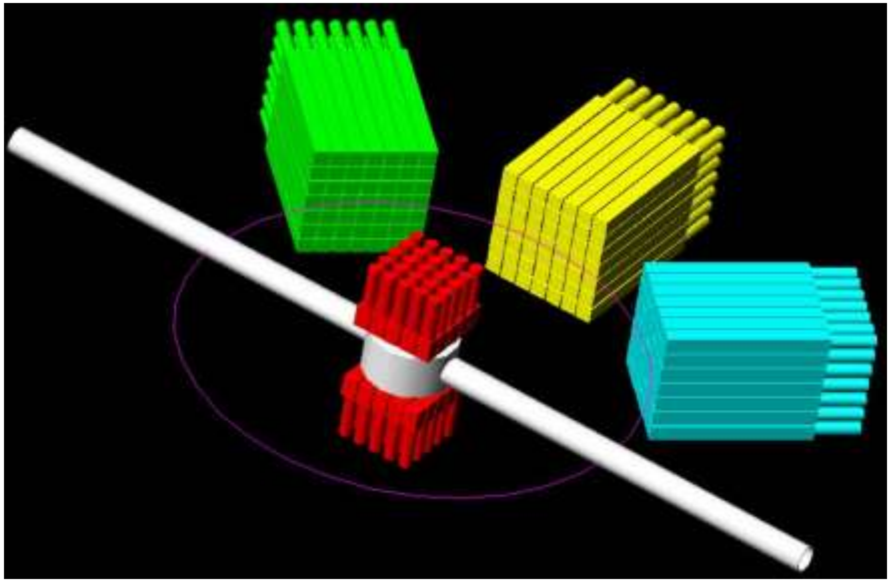
Ni (58) → 16+ and above

Cu (63) → 17+ and above

Zn (65) → 17+ and above

High Energy Gamma Spectrometer

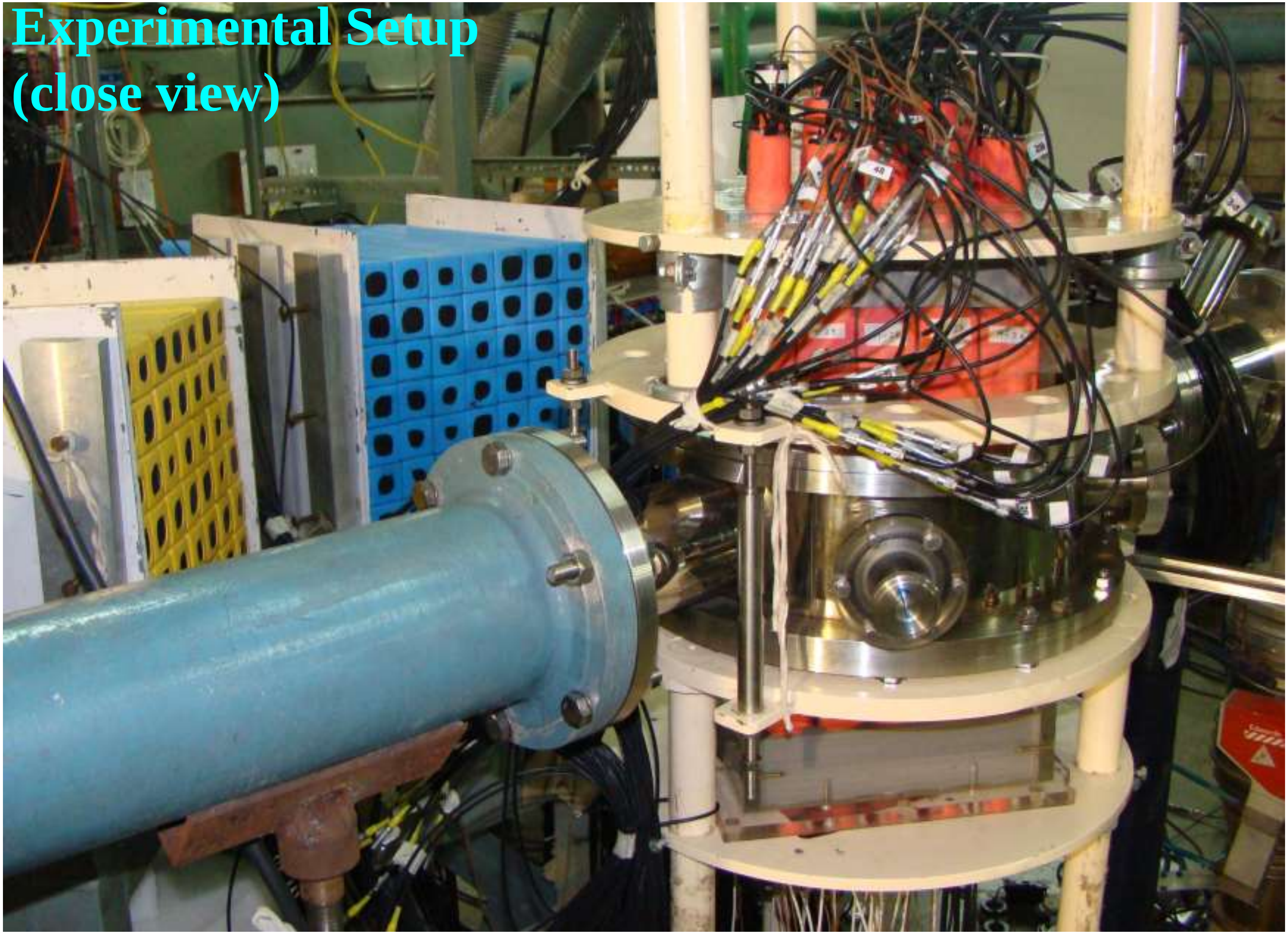
(LAMBDA) Large Area Modular BaF_2 Detector Array



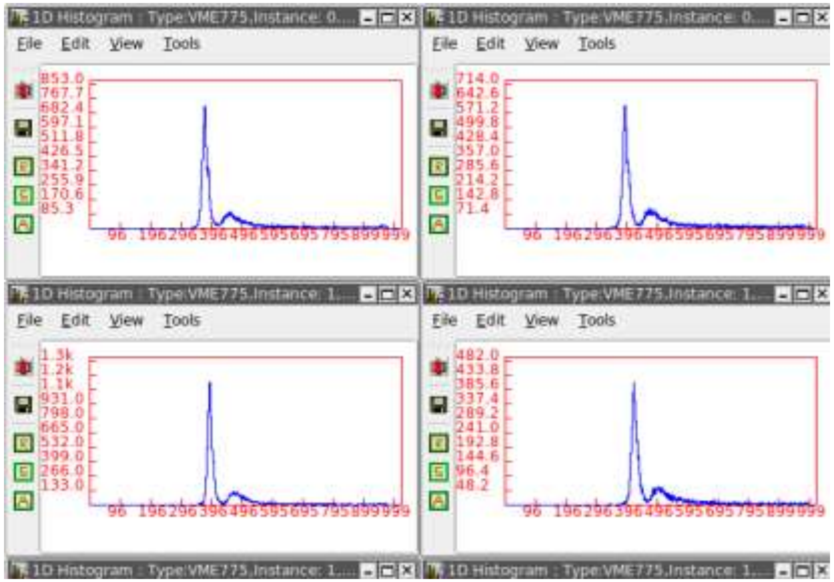
S. Mukhopadhyay et al, NIM A 582 (2007) 603

- 162 large BaF_2 Detector elements
- Detector dimensions: 3.5 x 3.5 x 35 cm^3
- Fast, quartz window PMT (29mm, Phillips XP2978)
- Highly Granular & Modular in nature
- Dedicated CAMAC front end electronics
- Dedicated Linux based VME DAQ
- Solid angle coverage ~ 6% of 4π

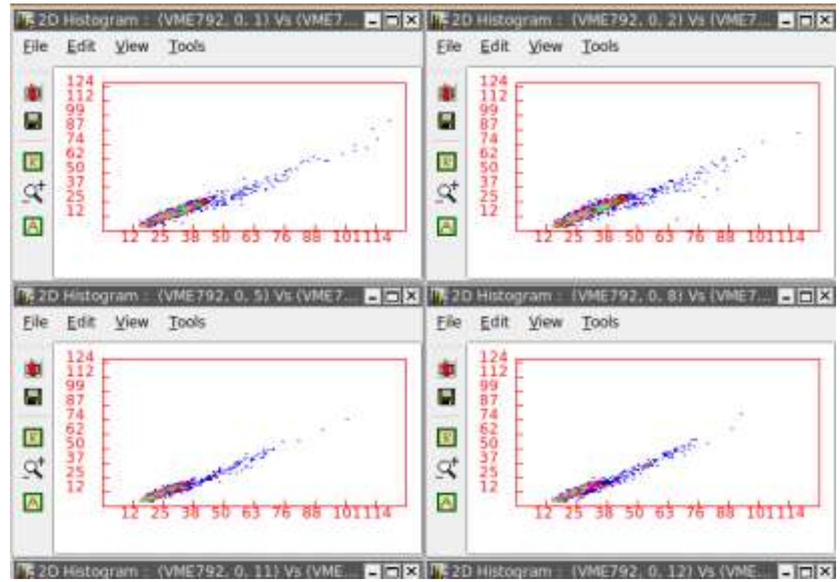
Experimental Setup (close view)



Individual TOF



Individual PSD



Dynamic cluster summing

0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	2.3	0.0
0.0	0.0	0.0	0.0	9.1	0.6	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0

0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	12.3	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0

0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	9.8	10.2	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.5	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0

0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	19.5	0.0	0.0	0.0	0.0
0.0	1.0	8.3	0.7	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0

Cosmic rejection

0.0	0.0	0.0	0.0	0.0	0.0	21.9
0.0	0.0	0.0	0.0	1.7	0.0	3.2
0.0	0.0	0.0	15.2	19.3	0.0	0.0
0.0	0.0	22.3	17.8	0.0	0.0	0.0
4.4	0.0	0.0	0.0	0.0	0.0	0.0
16.5	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0

0.0	0.0	0.0	0.0	0.0	0.0	0.0
19.6	30.8	0.0	0.0	0.0	0.0	0.0
0.0	2.3	0.0	21.4	0.0	0.0	0.0
0.0	0.0	0.0	15.2	30.1	1.1	0.0
0.0	0.0	0.0	0.0	0.0	21.1	28.5
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0

0.0	0.0	26.4	0.0	0.0	0.0	0.0
0.0	0.0	20.5	0.0	0.0	0.0	0.0
0.0	0.0	27.5	0.0	0.0	0.0	0.0
0.0	0.0	21.1	0.0	0.0	0.0	0.0
0.0	0.0	21.5	0.0	0.0	0.0	0.0
0.0	0.0	18.5	0.0	0.0	0.0	0.0
0.0	0.0	12.0	0.0	0.0	0.0	0.0

0.0	0.0	0.0	0.0	27.4	0.0	0.0
0.0	0.0	0.0	0.0	21.4	0.0	0.0
0.0	0.0	0.0	3.4	10.6	0.0	0.0
0.0	0.0	0.0	32.4	0.0	0.0	0.0
0.0	0.0	0.0	20.3	0.0	0.0	0.0
0.0	0.0	0.0	16.2	0.0	0.0	0.0
0.0	0.0	32.4	0.0	0.0	0.0	0.0

A few measurements at VECC K-130 Cyclotron

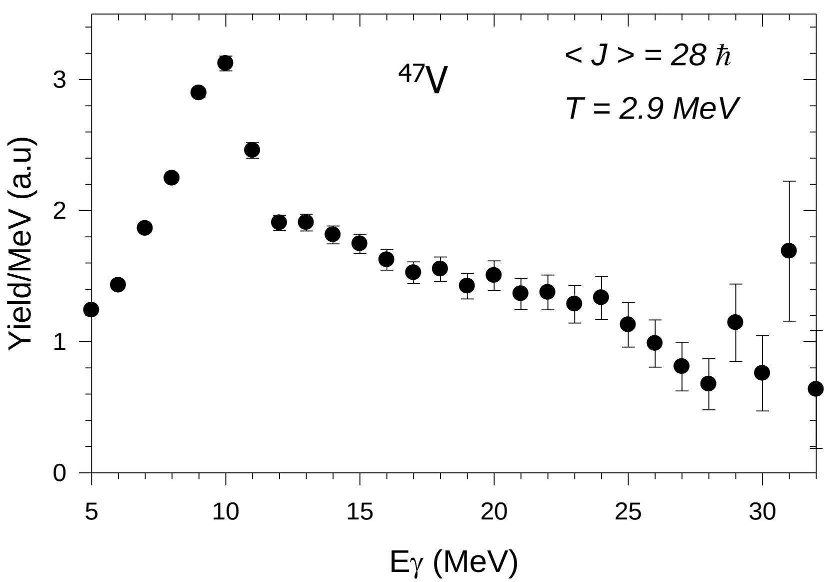
Jacobi shape transition & Super-deformation / orbiting

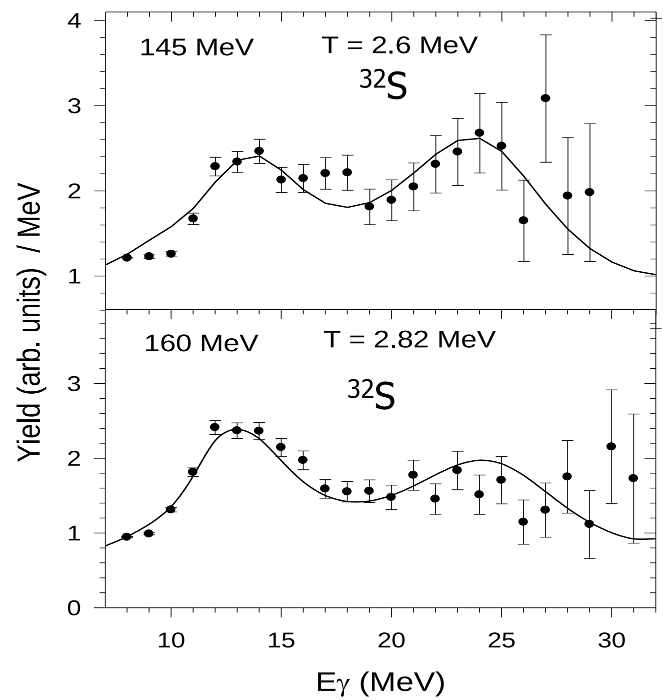
Experiments done at VEC with 145 & 160 MeV ^{20}Ne beams populating ^{47}V, ^{32}S at high excitations and angular momenta

(using "LAMBDA" photon spectrometer at VECC)

$^{20}Ne + ^{27}Al \rightarrow ^{47}V$

$^{20}Ne + ^{12}C \rightarrow ^{32}S$





Highly fragmented GDR line-shape

How to explain such lineshapes

Now when the nucleus is subjected to rotation --- deformation sets in

Our aim is to calculate the equilibrium deformation at a given J & T

Total free Energy

$$F(\beta, \gamma, J, T) = E_{DLD} + (E - E_{av})_{shell} - T.S - \tfrac{1}{2} I_{zz} \omega^2$$

Where,

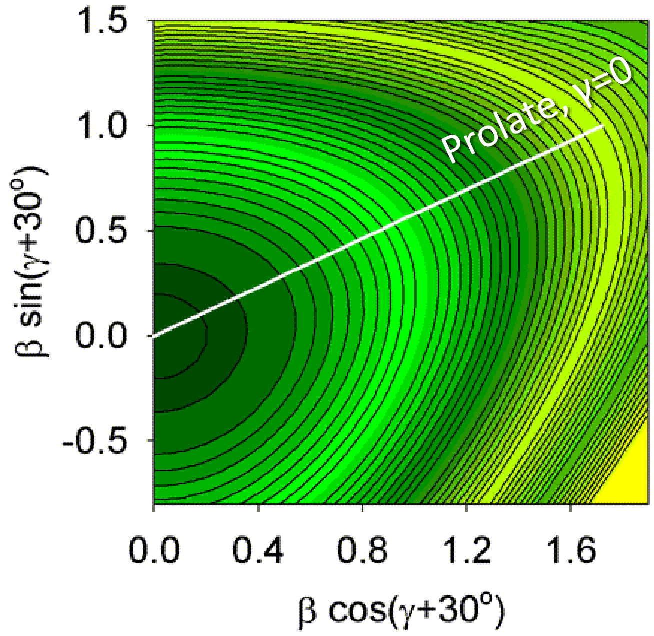
$$E = \sum n. f_i . e_i$$

$$f_i = \left[1 + \exp\{(e_i - \mu)/T\}\right]^{-1}$$

$$S = \sum - f_i . \ln(f_i) - \sum (1 - f_i) . \ln(1 - f_i)$$

- e_i are the single particle energies
- E_{av} is the Strutinsky averaged energy
- S is Entropy of the system
- f_i are the Fermi occupation nos.
- μ is the chemical potential

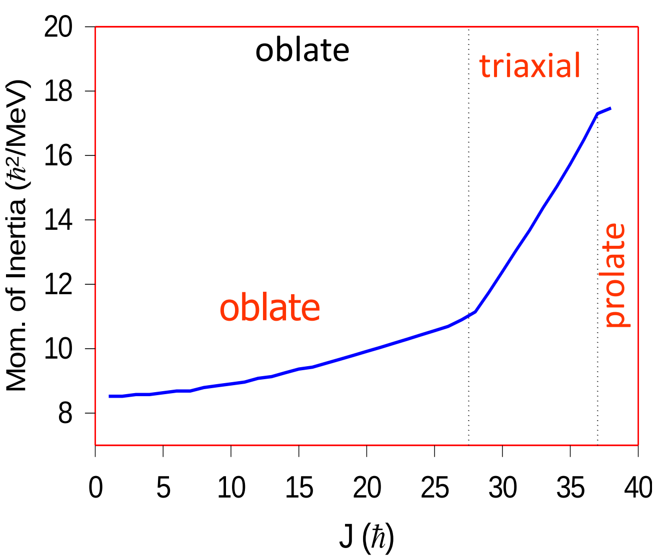
At high temperatures (T > 2 MeV), the shell correction is negligible and may be ignored

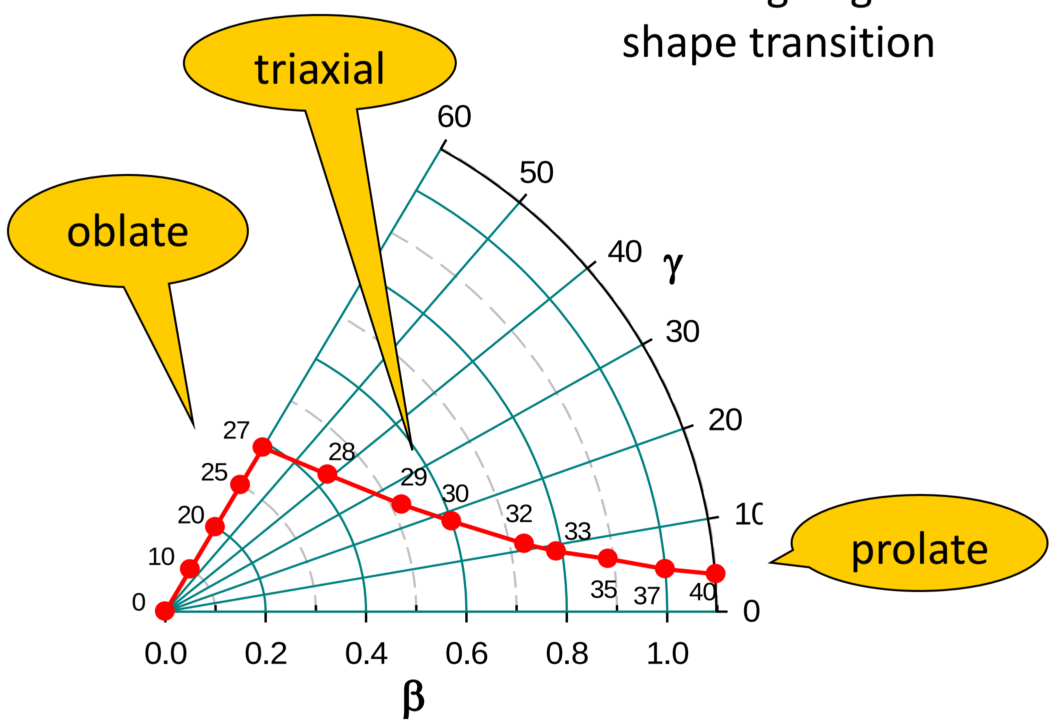


Free energy surfaces were computed in the range, $0 < \beta < 1$ and $0^o < \gamma < 60^o$

and the minimum of the free energy surfaces corresponds to the equilibrium shape (β,γ) at a particular J and T.

^{47}V nucleus undergoing a shape transition





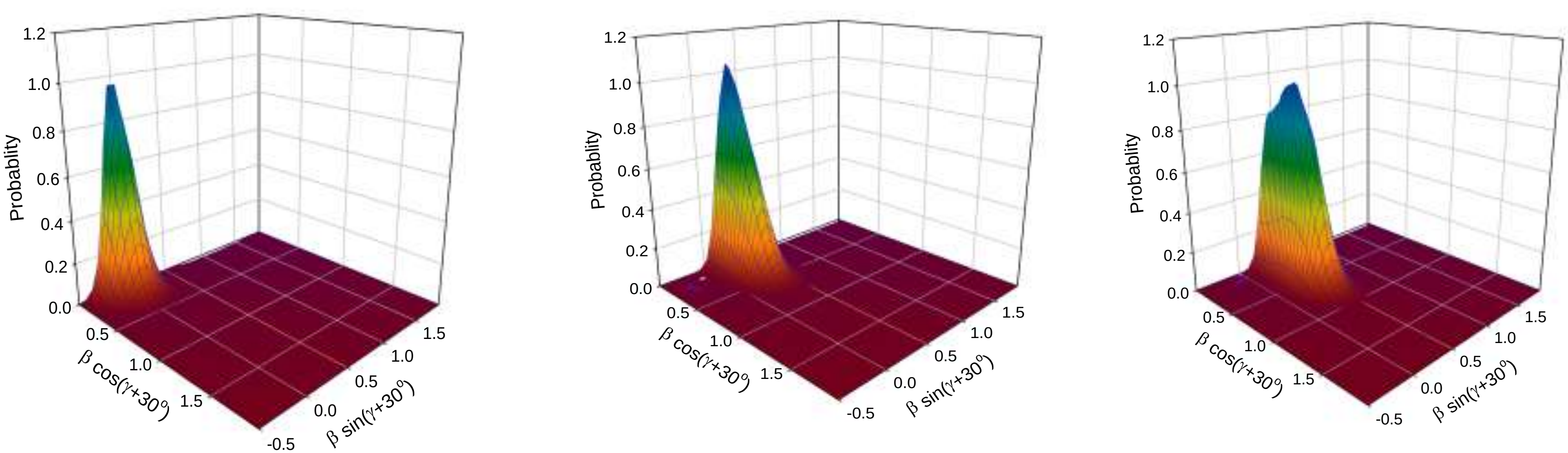
Thermal Fluctuations superimposed

GDR vibration samples an ensemble of shapes around equilibrium shape

An averaging is done around the equilibrium shape with
the Boltzman probability exp(-F/T)

The averaged GDR strength function due to thermal fluctuations is calculated

$$\left\langle \sigma(E_\gamma;T,J)\right\rangle = \frac{\int e^{-F(\beta,\gamma,T,J)/T}\sigma(E_\gamma;\beta,\gamma,T,J).\beta^4\left|\sin 3\gamma\right|d\beta.d\gamma}{\int e^{-F(\beta,\gamma,T,J)/T}.\beta^4\left|\sin 3\gamma\right|d\beta.d\gamma}$$



Calculation of GDR strength functions

Once we know the equilibrium shape, we can calculate the GDR strength function corresponding to that shape (β_{eq}, γ_{eq}) of the nucleus.

We know from the systematics, $E_{GDR} = \hbar\omega_{GDR} = 31.2A^{-1/3} + 20.6A^{-1/6}$

and since $\omega_{GDR} \propto 1/R$, we have from Hill-Wheeler parametrization

$$\hbar\omega_x = \hbar\omega_{GDR}\exp\left(-\sqrt{\frac{5}{4\pi}}\beta_{eq}\cos\left(\gamma_{eq} - \frac{2\pi}{3}\right)\right)$$

$$\hbar\omega_y = \hbar\omega_{GDR}\exp\left(-\sqrt{\frac{5}{4\pi}}\beta_{eq}\cos\left(\gamma_{eq} + \frac{2\pi}{3}\right)\right)$$

$$\hbar\omega_z = \hbar\omega_{GDR}\exp\left(-\sqrt{\frac{5}{4\pi}}\beta_{eq}\cos\gamma_{eq}\right)$$

The individual widths are given by,

$$\Gamma_i = \Gamma_0\left(\frac{E_i}{E_0}\right)^{\lambda} = 0.026\cdot E_i^{1.9}$$

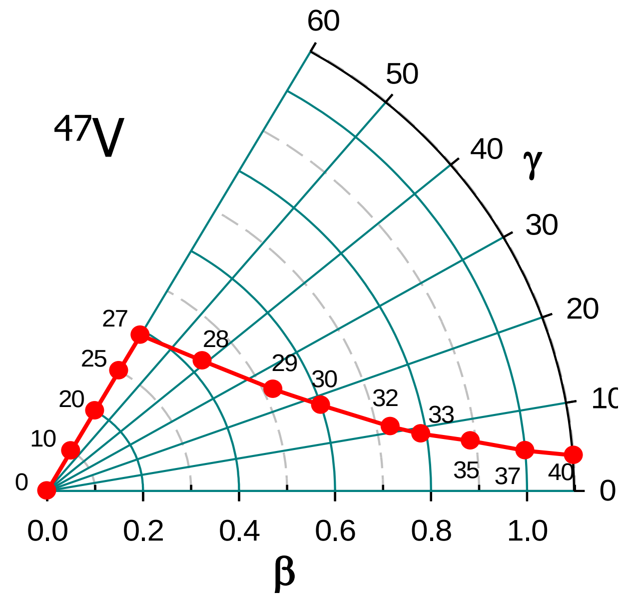
The resultant total strength function then becomes,

$$\boldsymbol{\sigma_{TOTAL}} = \sum_i \frac{\boldsymbol{E_\gamma^2\cdot\Gamma_i}}{\boldsymbol{\left(E_\gamma^2 - E_i^2\right)^2 + E_\gamma^2\cdot\Gamma_i^2}}$$

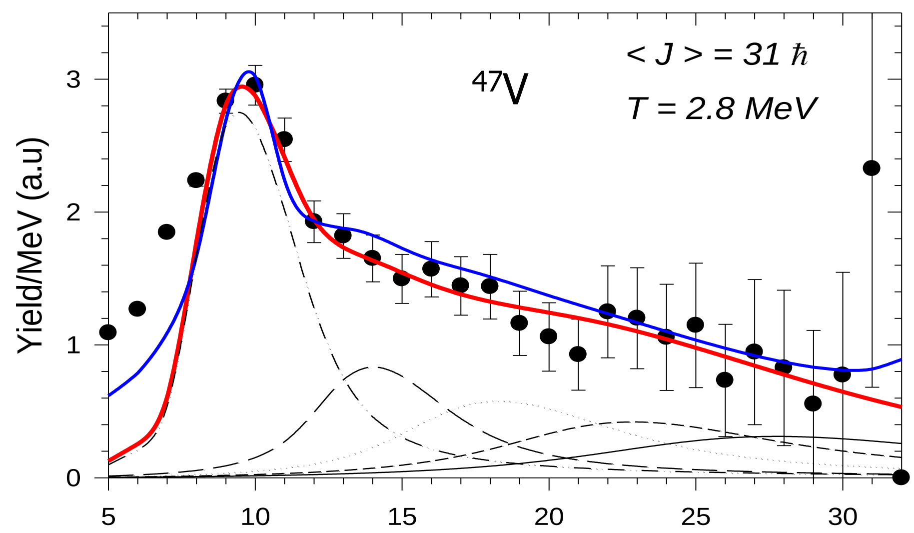
Jacobi shape transition in ^{47}V

^{20}Ne (160 MeV) + ^{27}Al

Gradual evolution of shape from spherical to oblate to triaxial to extended prolate with increasing rotation



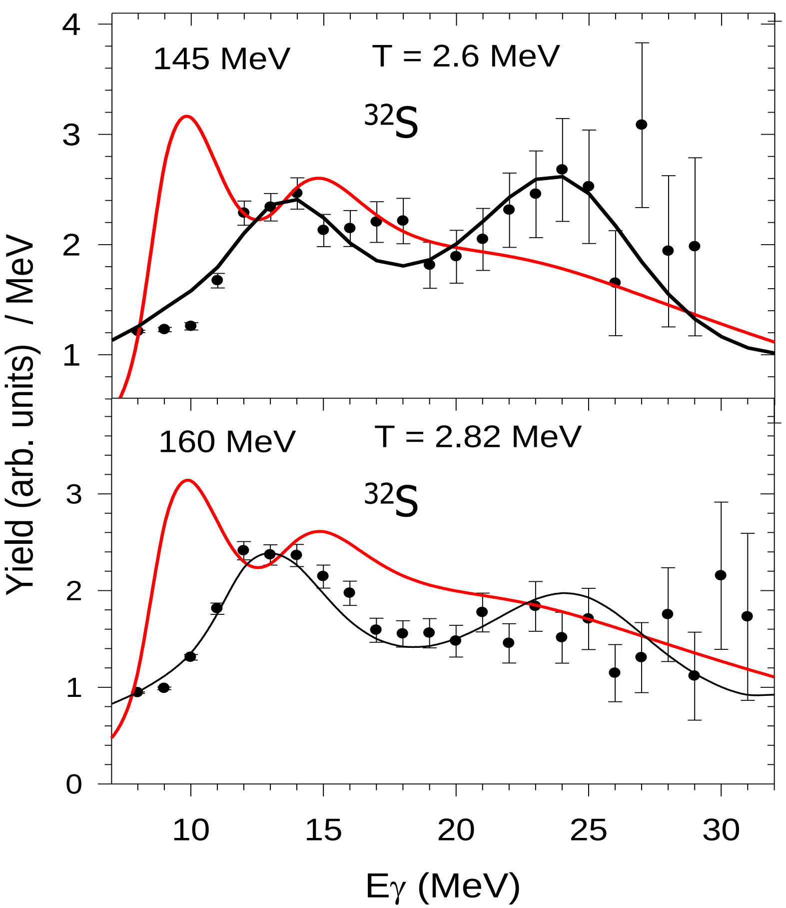
GDR vibration couples with the rotation and the strength fn. splits – in general into 5 components (Coriolis splitting at high rotation)



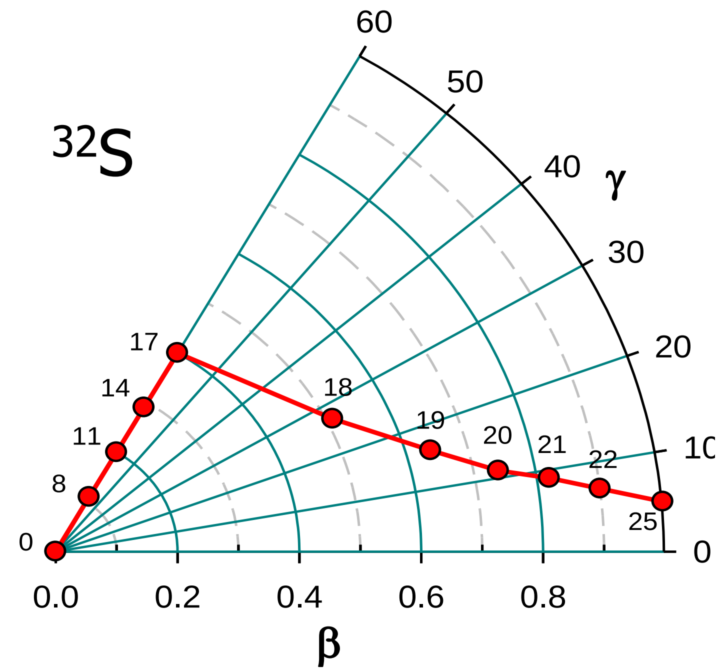
PRC 81 (2010) 061302 (Rapid comm.)

Orbiting di-nuclear complex seen directly via GDR

$^{20}Ne + ^{12}C \rightarrow ^{32}S$



Phys. Rev. C 81 (2010) 061302 (Rapid comm.)

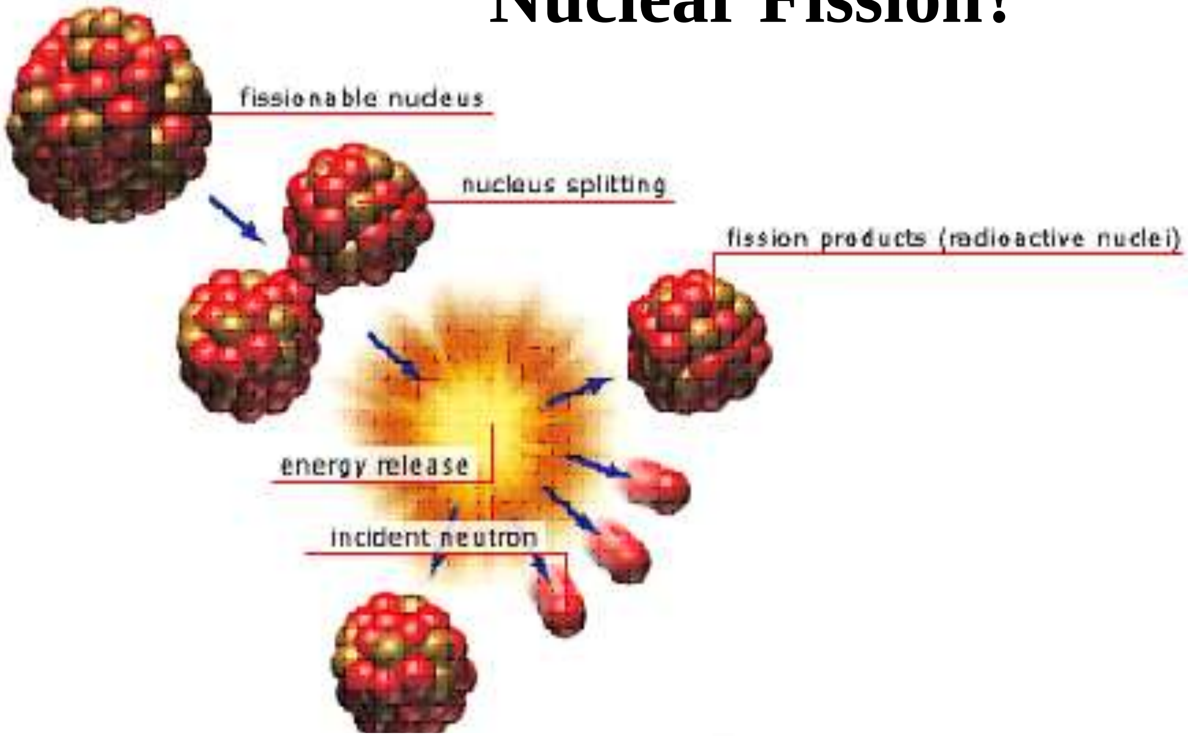


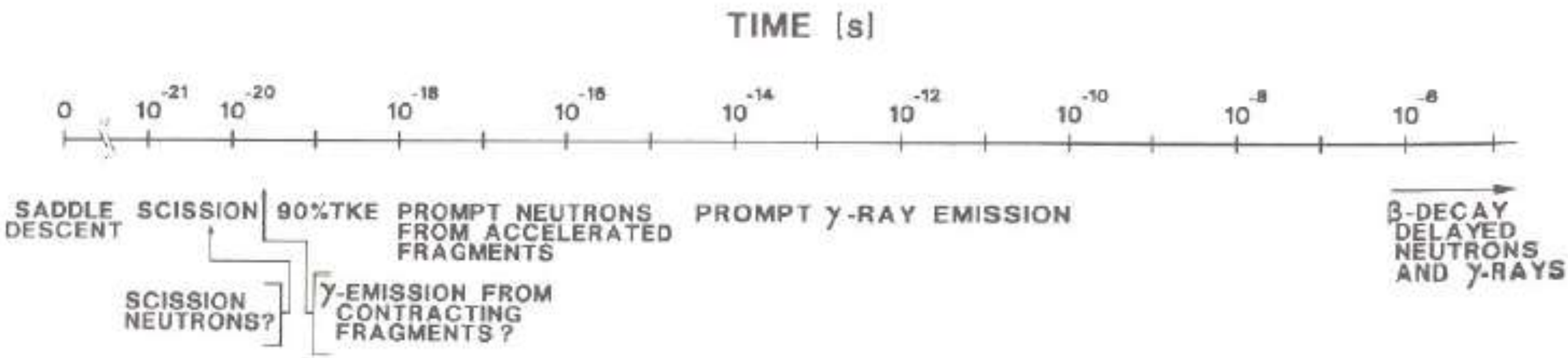
Odd nuclear shape
(prolate, super-deformed)
β ≈ 0.75 , axis ratio ≈ 2:1

Hot & rotating Liquid drop calculations fail miserably to describe the GDR strength fn.

Indicates a different reaction mechanism
---- Orbiting !!!

Can bremsstrahlung radiation be observed in Nuclear Fission?





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

J. D. Jackson

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

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

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

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

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

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

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

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

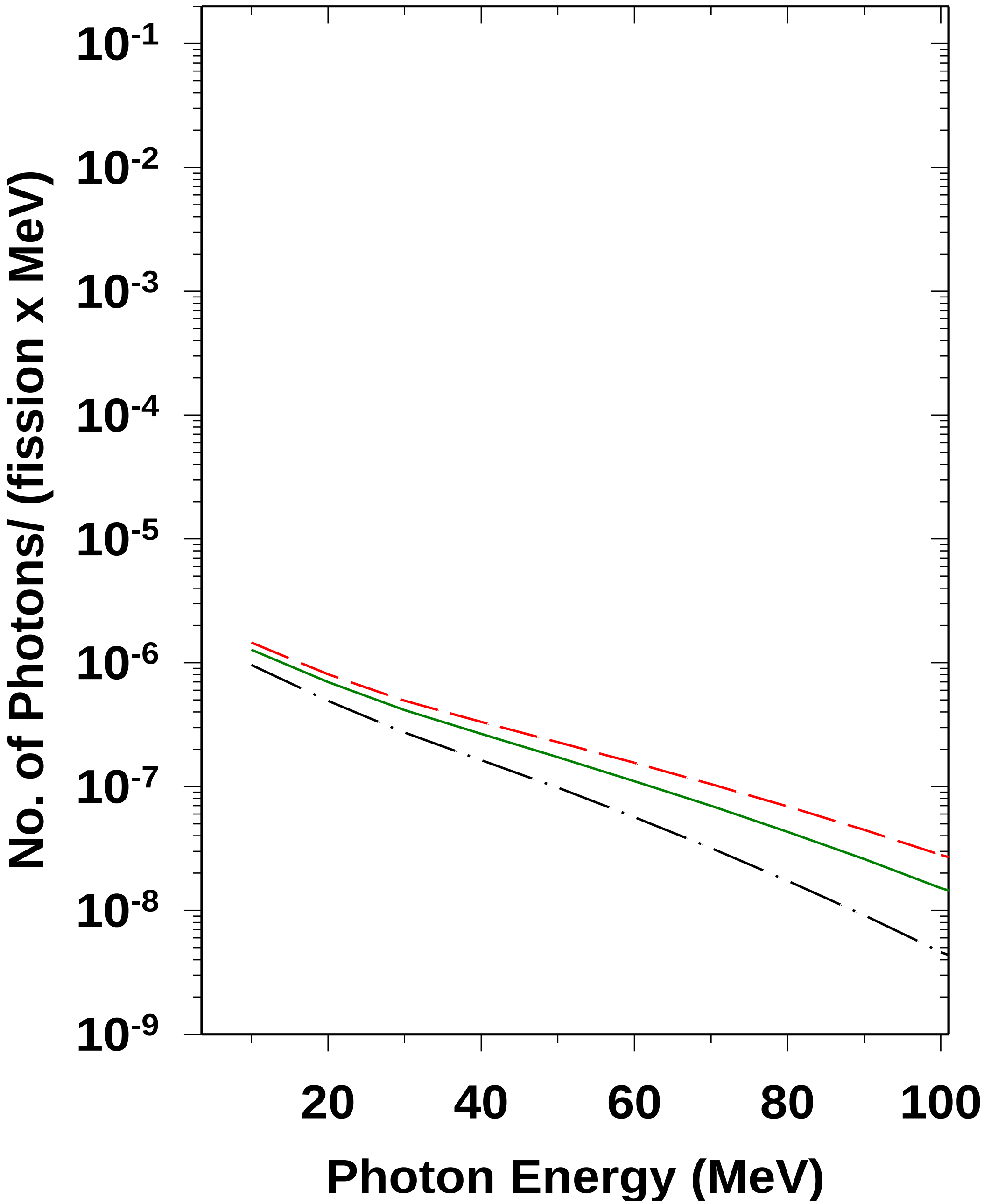
μ is the reduced mass

$k = z_1 z_2 e^2$

$\dot{r}$ is the relative velocity

E is the energy of the system

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



Classical Coulomb acceleration model (non-relativistic)

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

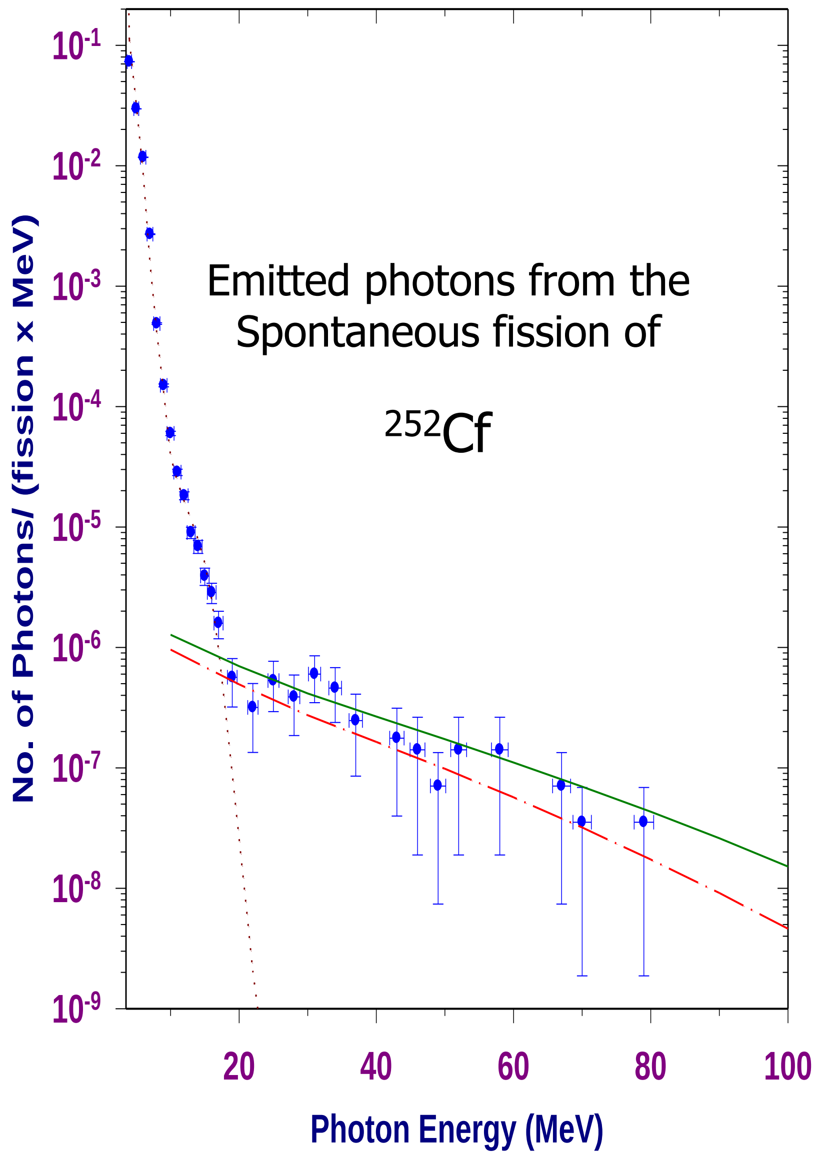
Pre-scission kinetic energy = 25-30 MeV

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

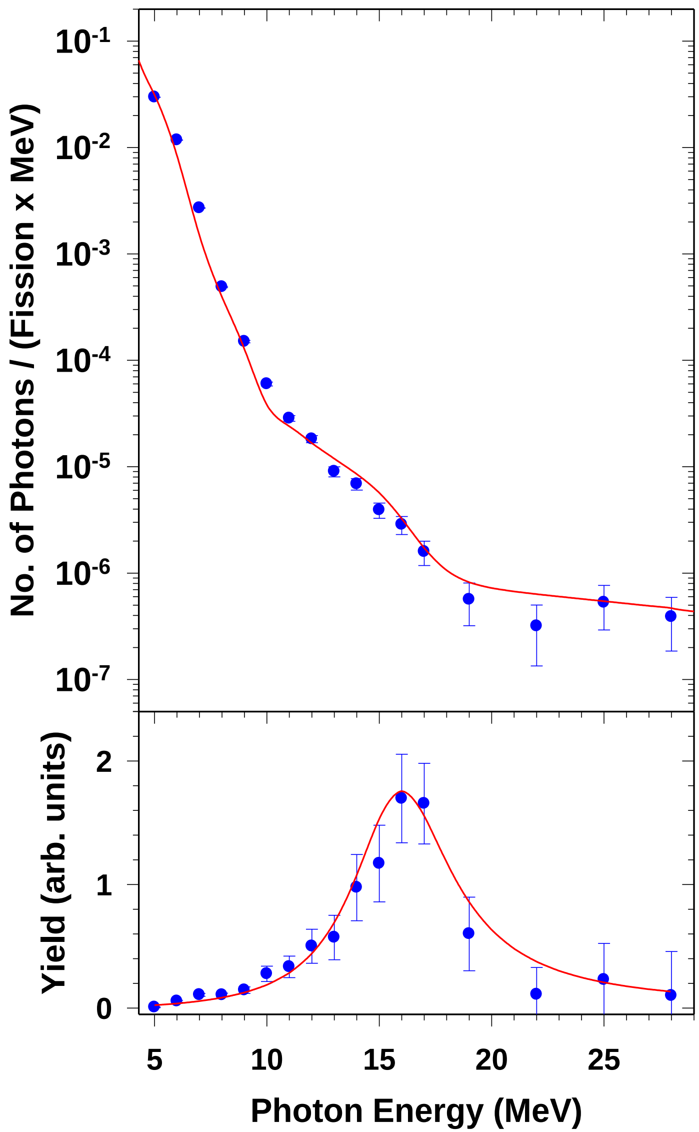
-- from the Coulomb accelerated fission fragments in spontaneous fission of ^{252}Cf

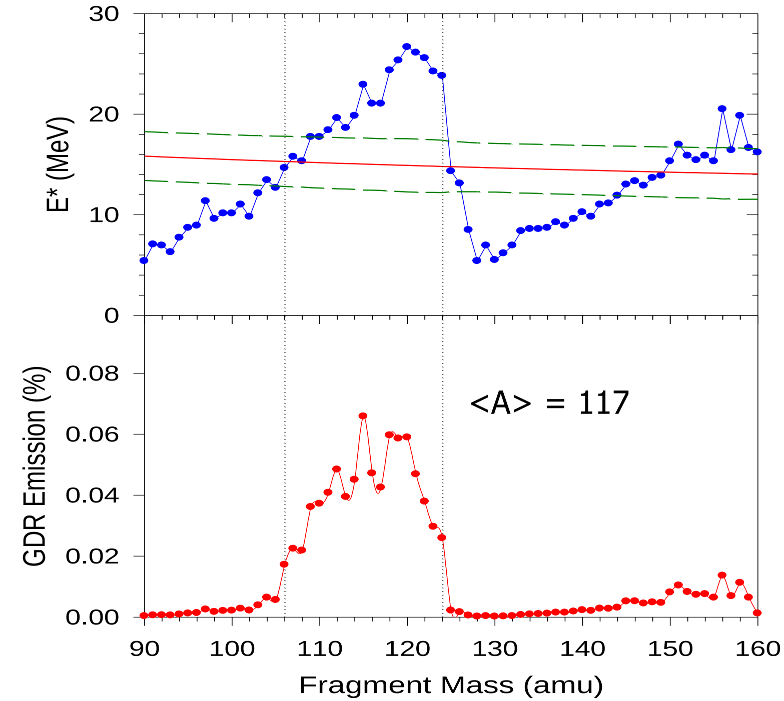
Classical bremsstrahlung considering the pre-scission kinetic energies of the fission fragments

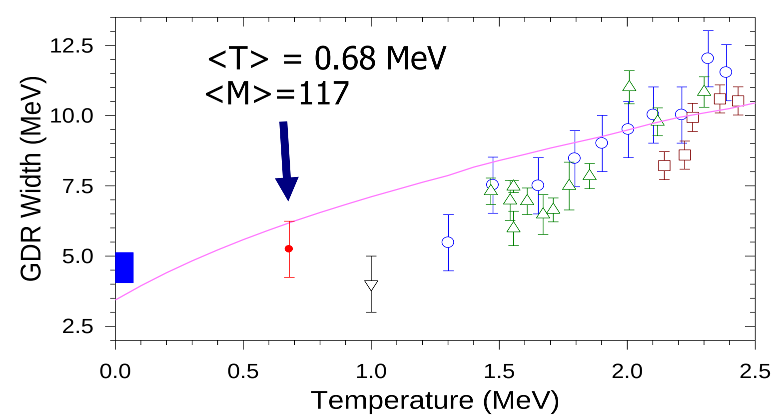
Physics Letters B 690 (2010) 473

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

GDR width from excited fragments of ^{252}Cf



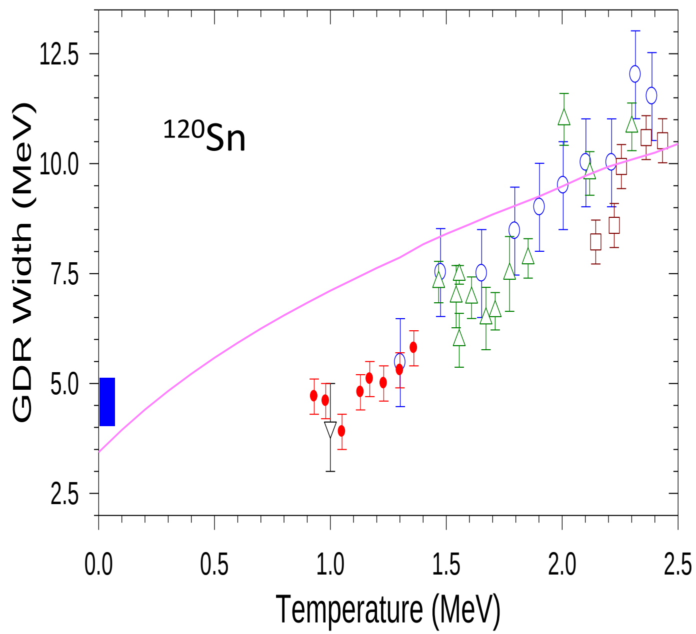


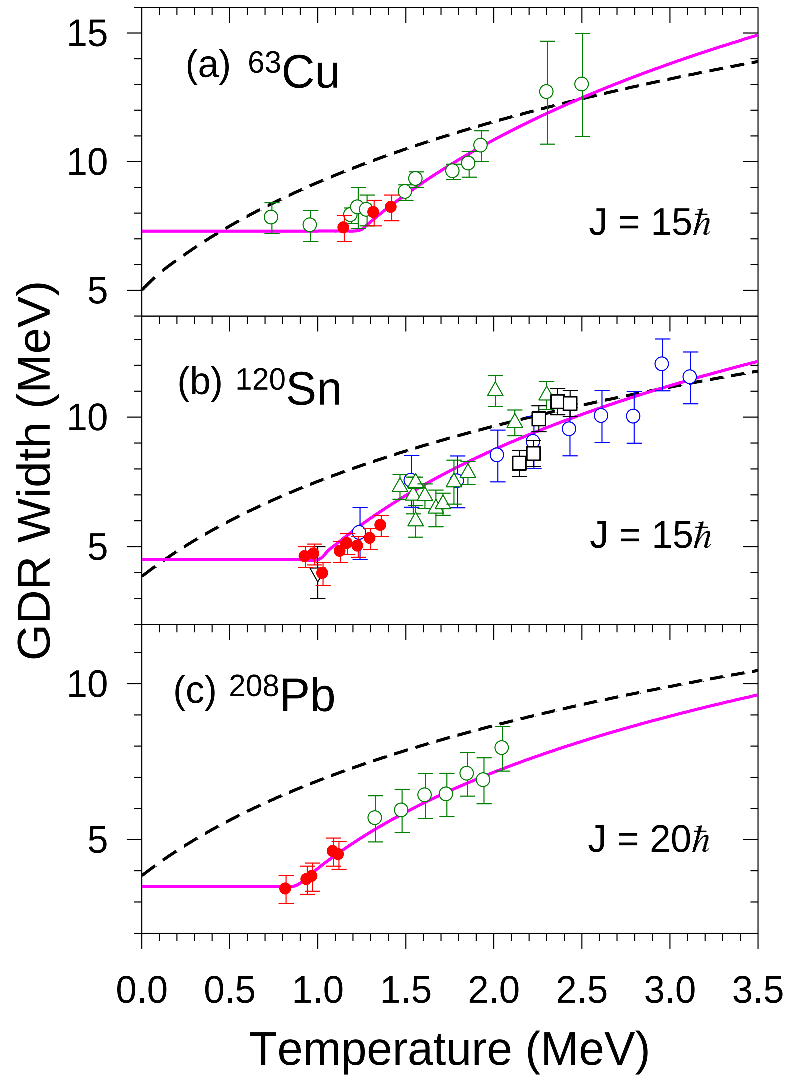


Phys Lett B 690 (2010) 473

Systematic study of the GDR width at low temperature

Critical Temperature Fluctuation Model (CTFM)



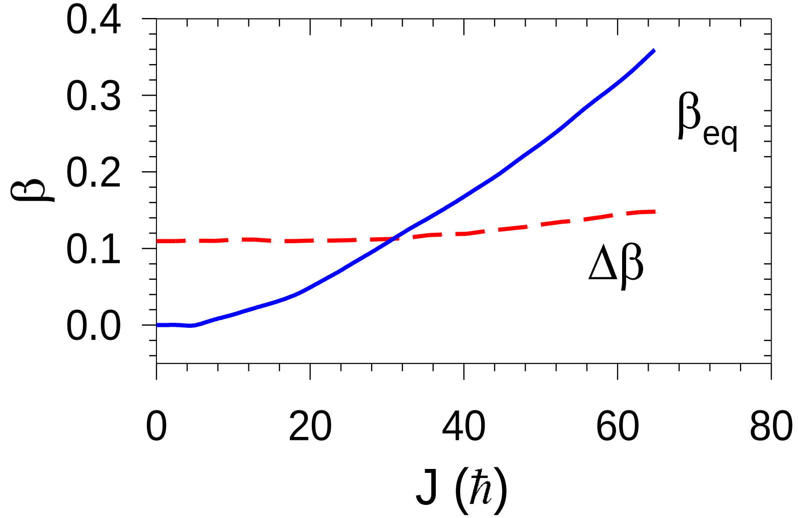


This critical behavior is seen for the first time and is explained in terms of the GDR induced quadruple deformation and its competition with the thermal fluctuations

Phys. Letts. B 709, 9, (2012)
Phys. Letts. B 713, 434, (2012)

Angular momentum dependence of GDR width

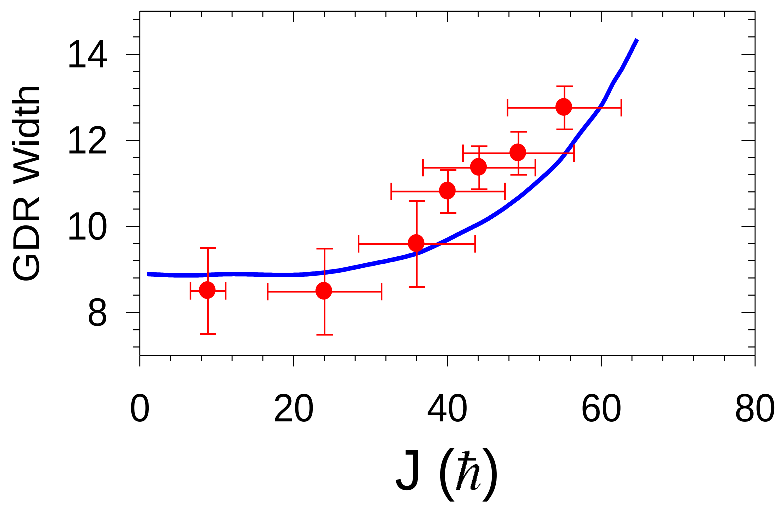
(Similar idea)



GDR width does not increase until equilibrium deformation becomes larger than the fluctuations of the deformation (TSF Model)

Critical spin $J_c \sim 0.6A^{5/6}$

Observed in entire the mass region

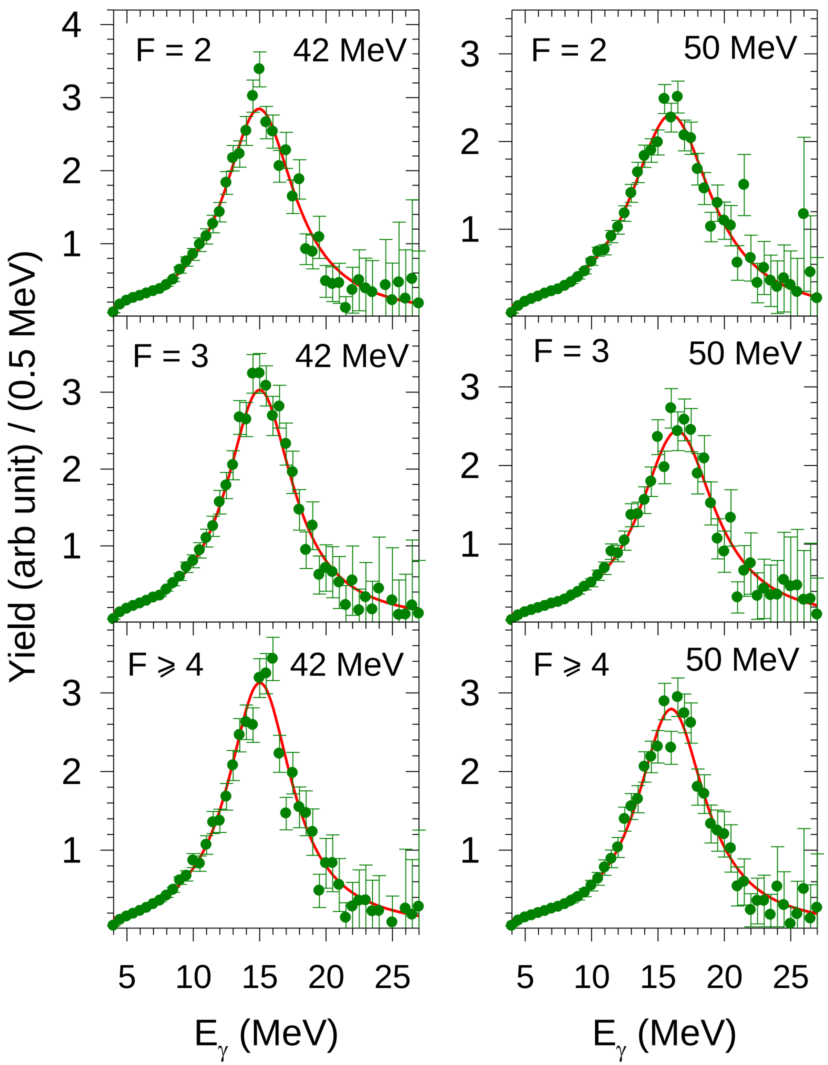


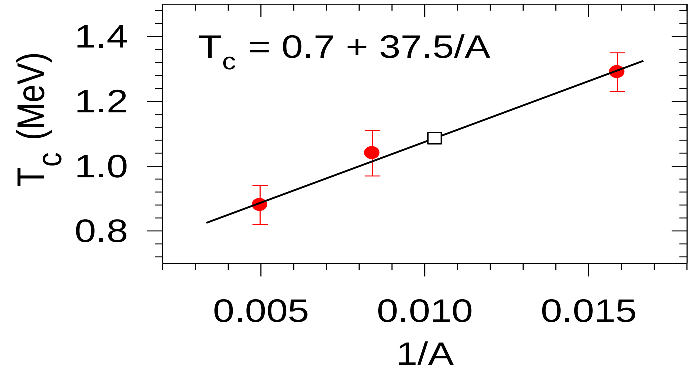
TSFM gives excellent description of GDR width as a function of J

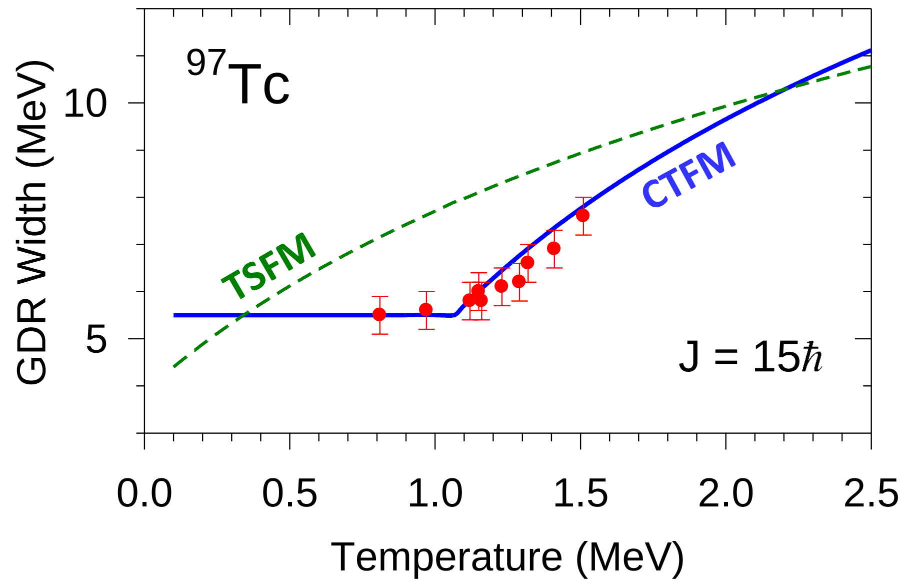
Further verification in different mass region

$^{4}He + ^{93}Nb \rightarrow ^{97}Tc^{*}$

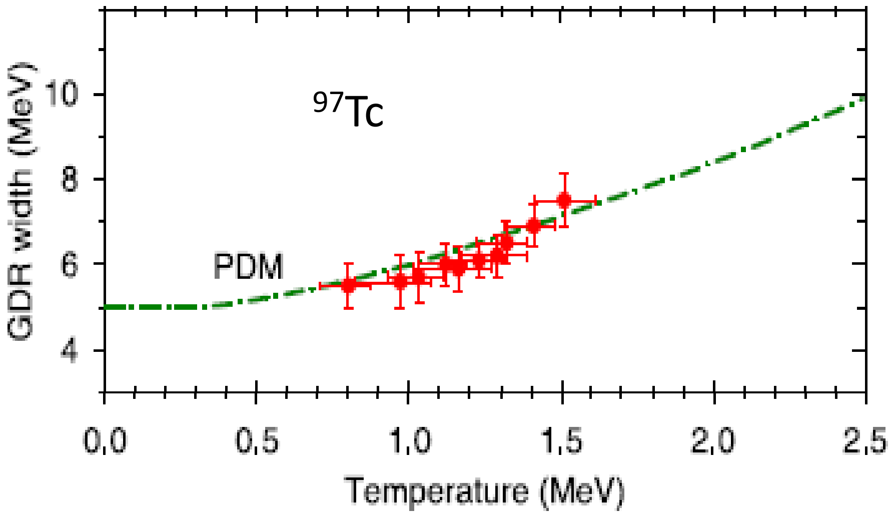
E_{lab} = (28, 35, 42, 50 MeV)





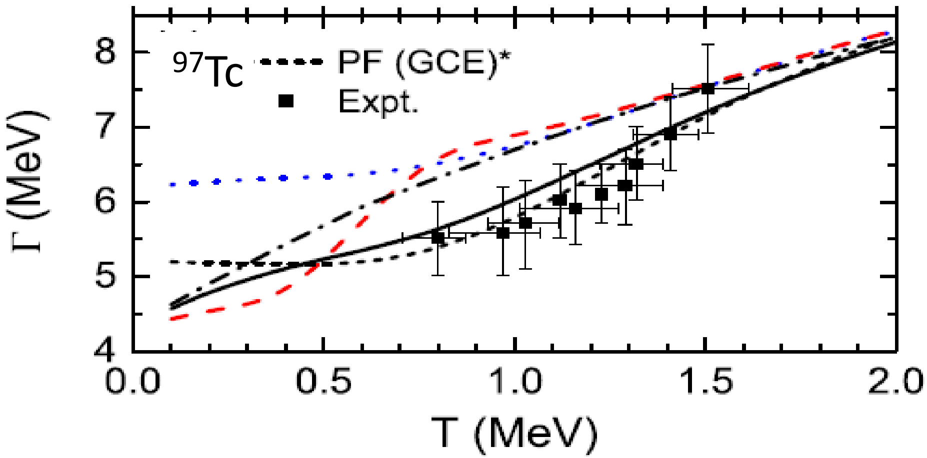


Experimental Signature for GDR – GQR Coupling at finite Temp --- ???



Phonon Damping Model
(included Thermal Pairing)

Physics Letters B 731 (2014) 92



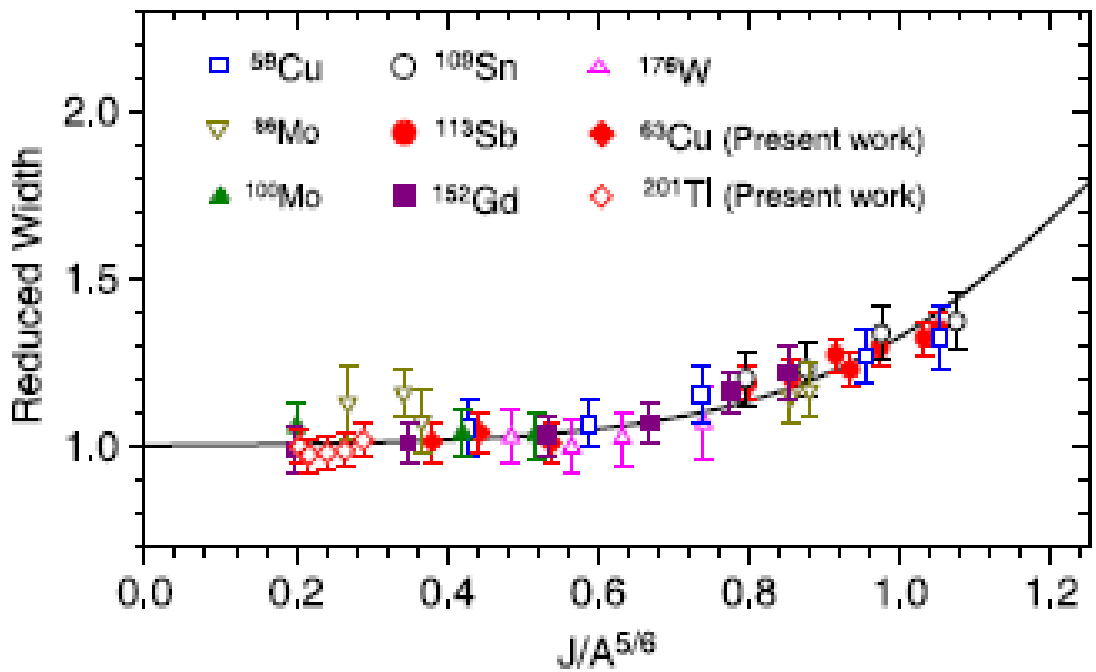
Thermal Shape Fluctuation Model
(with Pairing Fluctuations)

Physical Review C 91, 044305 (2015)

GDR width should vary continuously
From its G.S. value with increase in T

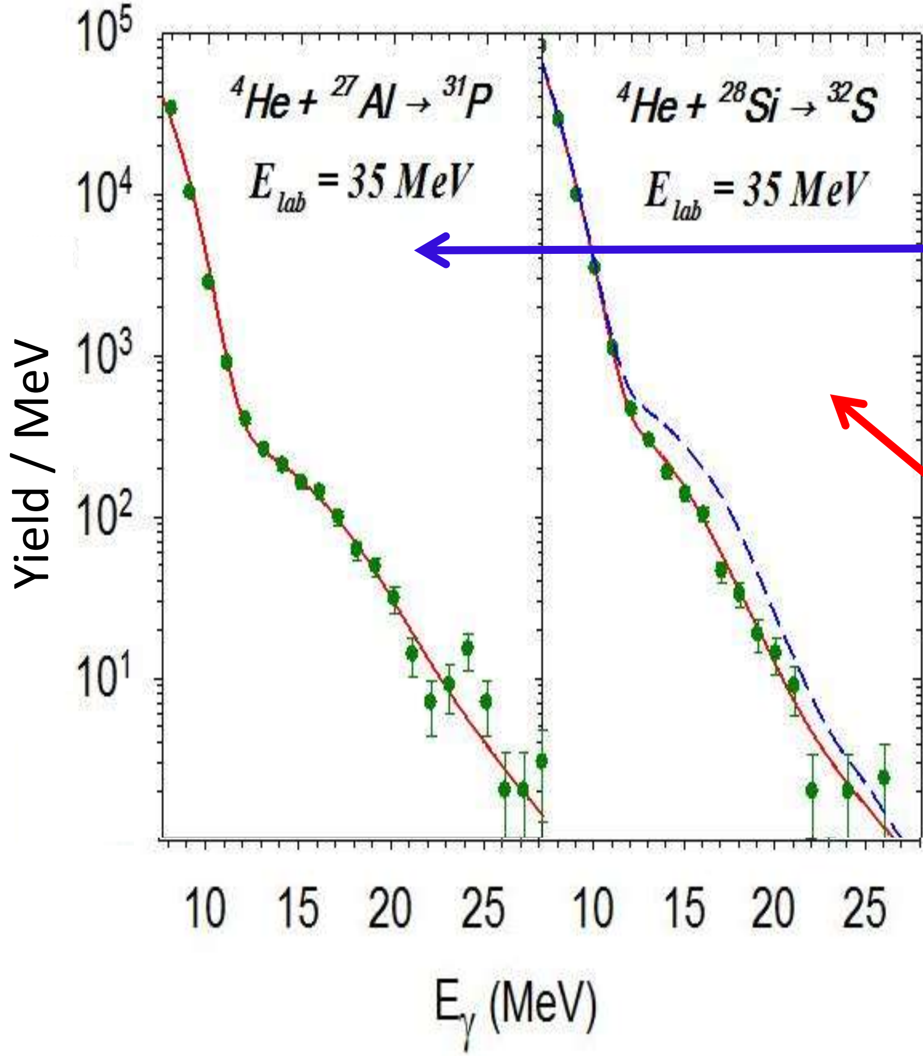
Ground state GDR widths are estimated with the Spreading Width Parameterization given by A. R. Junghans et al, Phys. Lett. B 670 (2008) 200 (0.05 * Egdr^1.6 MeV) and is consistent with the measured values

Modified Kusnezov parameterization with GDR – GQR coupling included



Universal macroscopic description for a complete range of T & J

Isospin symmetry breaking/restoration in excited nuclei



Degree of isospin mixing can be estimated by observing the isospin forbidden transitions.

$T_z \neq 0$, $\Delta T = 0,1$ allowed transitions

No suppression in IVGDR γ - yield.

Compared with CASCADE calculation with full mixing

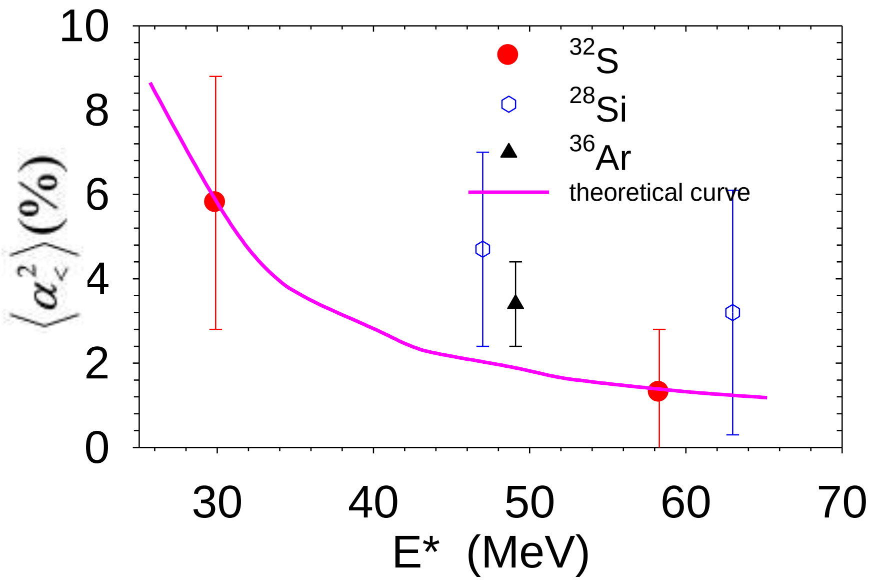
$T_z = 0$, $\Delta T = 0$ forbidden

IVGDR decay Suppressed

Blue-dashed line → CASCADE calculation with full mixing

Red line → CASCADE calculation with $\Gamma^{\downarrow}$ = 13 keV

Isospin symmetry breaking/restoration in excited nuclei



For ^{32}S at 30 MeV excitation

E* (MeV)	$\Gamma_>^{\downarrow}$ (KeV)	$\langle \alpha_<^2 \rangle$ %
29.9	13 ± 8	5.8 ± 3.0

The result shows mixing increases with a decrease in temperature in accordance with Wilkinson's prediction

Relative importance of the charge symmetry and charge independence breaking forces in nuclear phenomena

Correction in the transition matrix element for super-allowed Fermi β-decay. This helps in the proper estimation of the u-quark to d-quark transition matrix element in the Cabibo-Kobayashi-Maskawa (CKM) matrix whose unitarity validates the standard model.

Requires mixing at T = 0

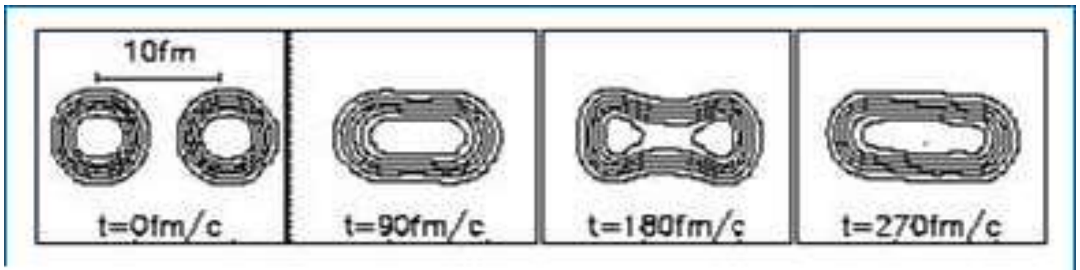
Plans for the VECC Super-conducting cyclotron

Plans with Super-conducting Cyclotron ---- At still higher energies

Pre-equilibrium GDR

Prompt dipole gamma emission due to entrance channel charge asymmetry

Charge asymmetric collisions → **forms large amplitude dipole collective motion before complete equilibration (charge)**



Density plots projected on reaction plane for central collisions (TDHF)

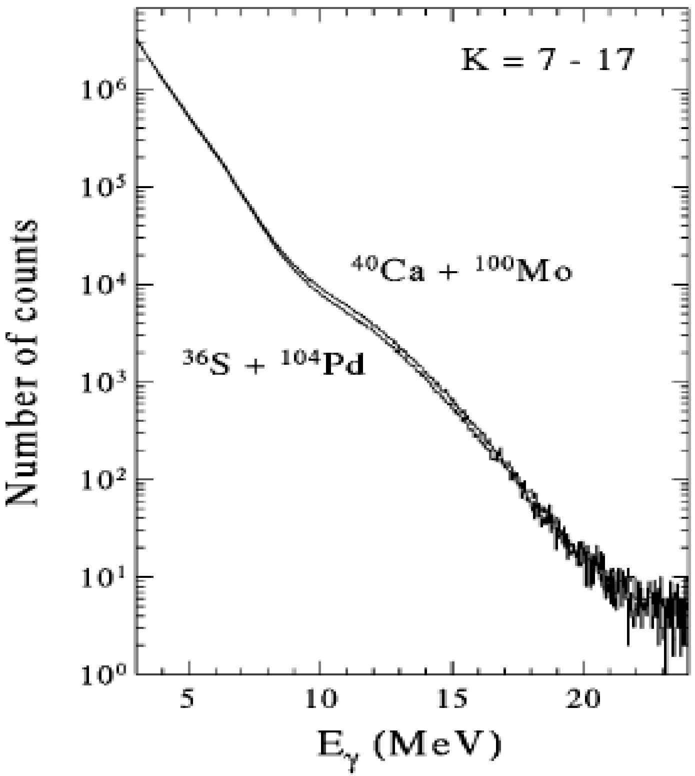
PRL 86 (2001) 2971.

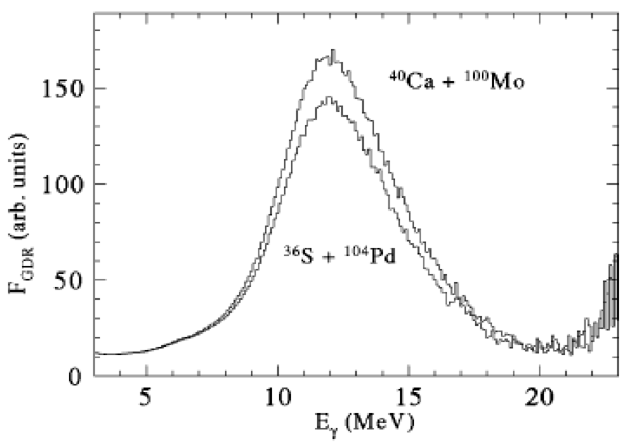
Initial dipole moment $D_0 = \frac{Z_1 Z_2}{A}\left(\frac{N_1}{Z_1} - \frac{N_2}{Z_2}\right)(R_1 + R_2)$ → **Dipole oscillation** → **Statistical CN - GDR**

Excess GDR photon yield – when compared with a similar but more charge symmetric system

Strong effect for very asymmetric target / projectile combination.

Pre-equilibrium GDR





^{40}Ca + ^{100}Mo → N/Z ratio -- 1 : 1.38

^{36}S + ^{104}Pd → N/Z ratio -- 1.25 : 1.26 ≈ 1:1

Same CN ^{140}Sm* (N/Z = 1.26) is formed

- information on the charge equilibration in relation to the reaction mechanism;
- information on the damping of the dipole mode;
- information on the symmetry energy of the nuclear matter at lower densities than the saturation one

Filbotte *et al*, PRL 77, 1448 (1996),
Pierroutsakou *et al.*,PR C71, 054605 (2005)

Near SHE population & their GDR characteristics

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

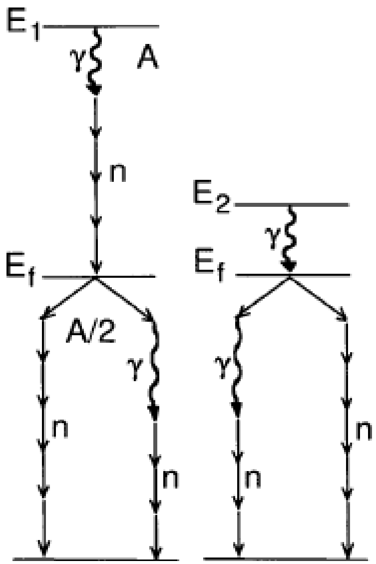
These are highly fissile systems

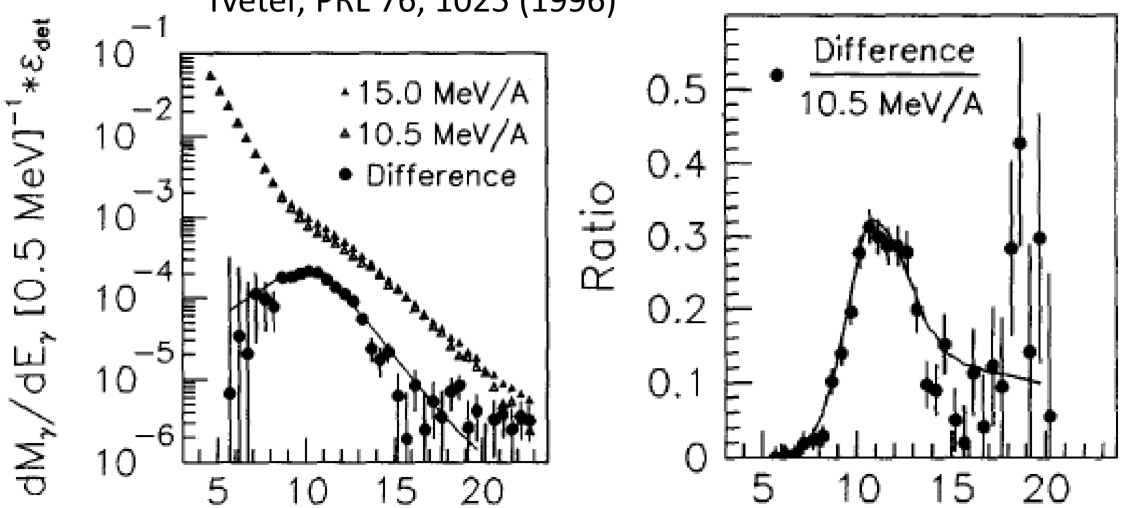
Fission process slows down as excitation increases – well known

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

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

Tveter, PRL 76, 1025 (1996)





Photon Energy (MeV)

Thank you
for your kind attention