GDR and charged particle decay of highly excited compound nucleus - ^{88}Mo

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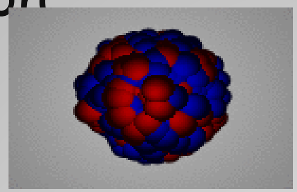
COMEX5

Outline

- GDR gamma-ray decay, from highly excited nuclei.
- Experimental setup and data analysis.
- Calculations within statistical model.
- Comparison of obtained experimental results with TFM with Lublin Strasbourg Drop (LSD) and Phonon Damping Model (PDM).
- Conclusions

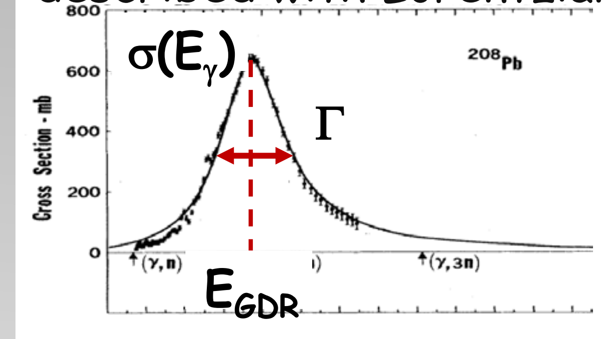
Giant Dipole Resonance

- Collective nucleus excitation



- In macroscopic approach described as oscillations of neutrons against protons
- Microscopically as superposition of particle-hole excitations

described with Lorentzian:



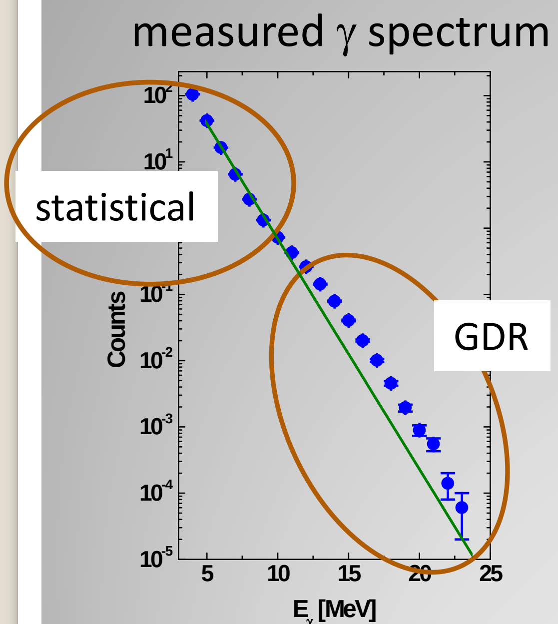
$$\sigma(E_\gamma) = \frac{\sigma_0 \Gamma_{GDR}^2 E_\gamma^2}{\left(E_\gamma^2 - E_{GDR}^2\right)^2 + \Gamma_{GDR}^2 E_\gamma^2}$$

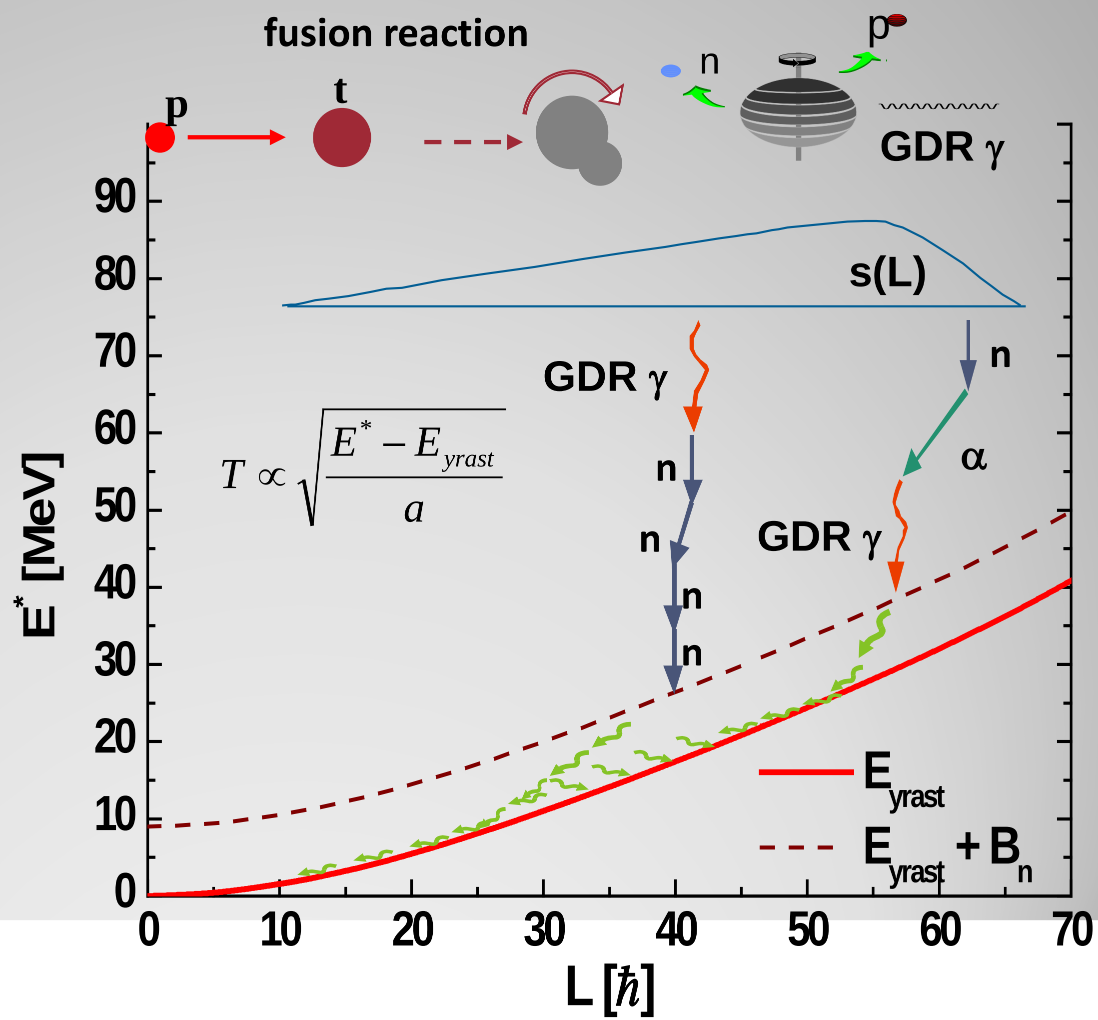
- ❑ **Strength σ_0=1 (S_{GDR})**
  (maximum corresponding to 100% of nucleons participating in oscillations
  calculated from Energy Weighted Sum Rule
  – **giant vibration, large collectivity**)

- ❑ **Energy – centroid (E_{GDR})**
  energy of oscillations ~ 1/R

- ❑ **Width (Γ_{GDR})** **Γ ~ -1/t**

Gamma rays from hot nuclei

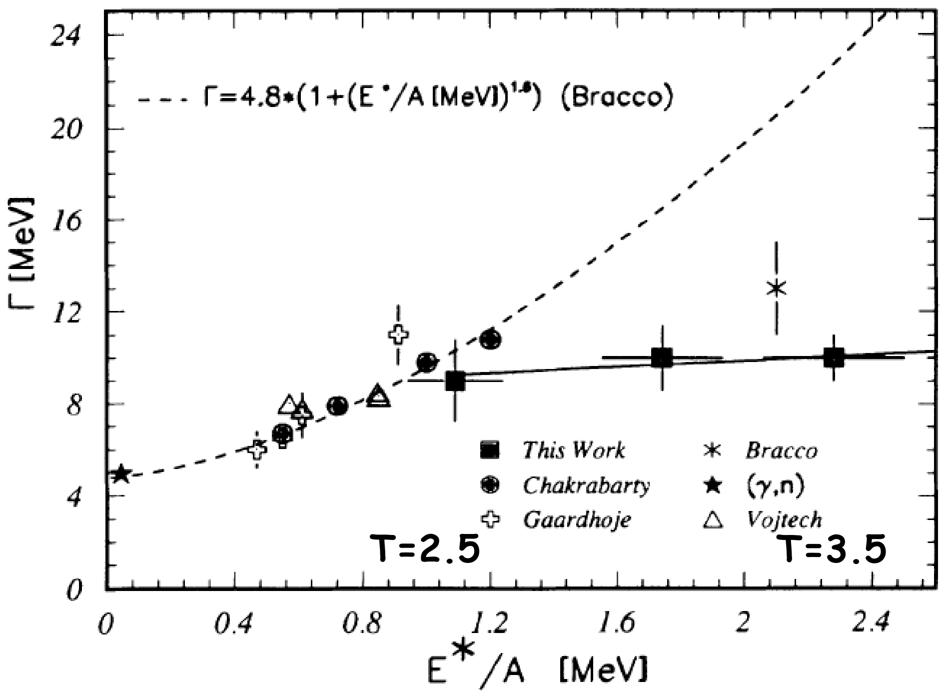




Does the GDR width saturate?

A. Bracco et al., PRL 62 (1989) 2080

G. Enders et al., PRL 69 (1992) 249



Possible explanations:

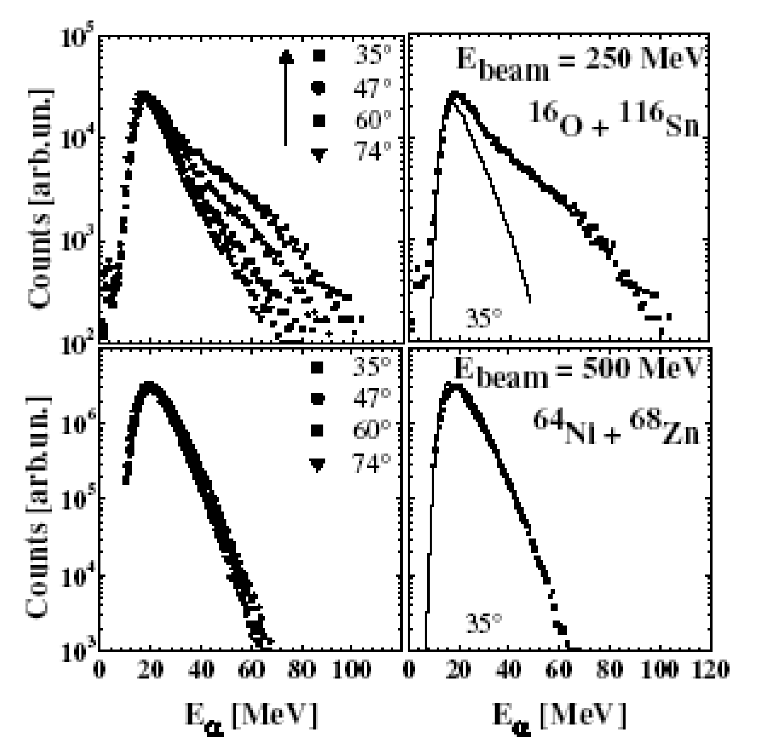
- saturation of the transferred angular momentum
- onset of multifragmentation
- preequilibrium emission

P.M.Kelly et al. PRL82 (1999) 3404

The width of GDR at high temperature

(HECTOR+ GARFIELD experiment with ^{132}Ce,
γ rays and charged particles measured)

O. Wieland et al., Phys. Rev. Lett. 97, 012501 (2006)



α particle spectra
from 132Ce produced in reactions:

^{16}O + ^{116}Sn → ^{132}Ce

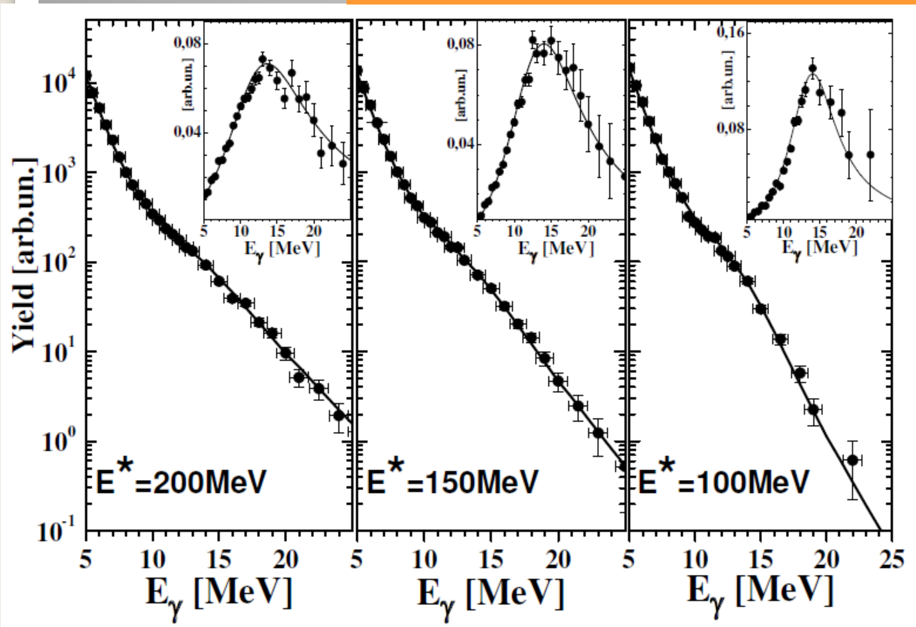
- Strong preequilibrium effects for mass-asymmetric reaction

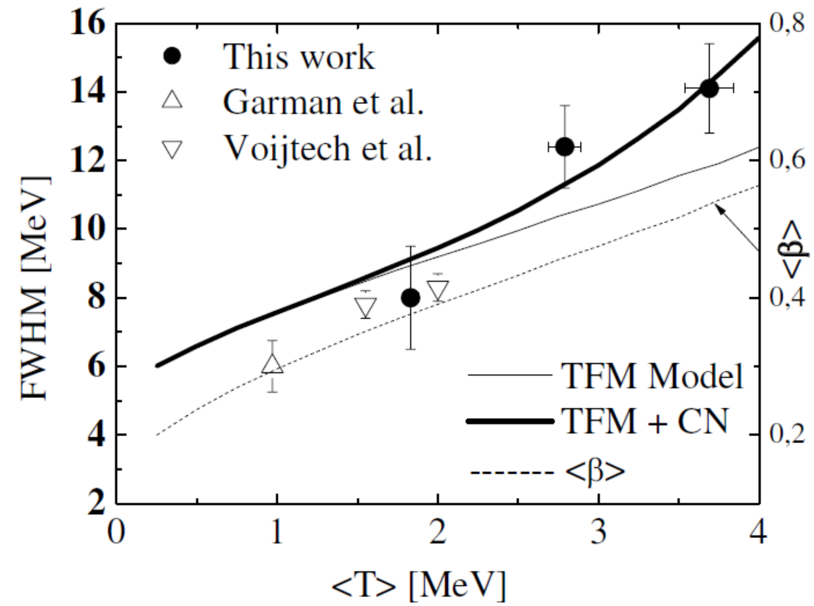
^{64}Ni + ^{68}Zn → ^{132}Ce

- Preequilibrium effects negligible for mass-symmetric reaction

The width of GDR at high temperature

<I> = 45 $\hbar$ **temperature dependence studied** *O. Wieland et al., Phys. Rev. Lett. 97, 012501 (2006)*





The GDR width increases with temperature (up to 4 MeV).

The results are in agreement with calculations based on thermal shape fluctuation model including compound nucleus life time (no room for intrinsic width increase!).

Experiment – ^{88}Mo, reaction parameters

^{48}Ti + ^{40}Ca -> ^{88}Mo* at 300 and 600 MeV beam energies
Target thickness: 500 ug/cm^2

Compound nucleus ^{88}Mo E* = 124, 261 MeV
Corresponding temperatures of compound nucleus T_{CN} = 3.2 and 4.8 MeV

Maximum of angular momentum of CN (> $L_{fission}$) = 78 and 84 hbar

Experiment performed by HECTOR-GARFIELD collaboration at LNL Legnaro, Italy.

PHYSICAL REVIEW C **91**, 054313 (2015)

Giant dipole resonance built on hot rotating nuclei produced during evaporation of light particles from the ^{88}Mo compound nucleus

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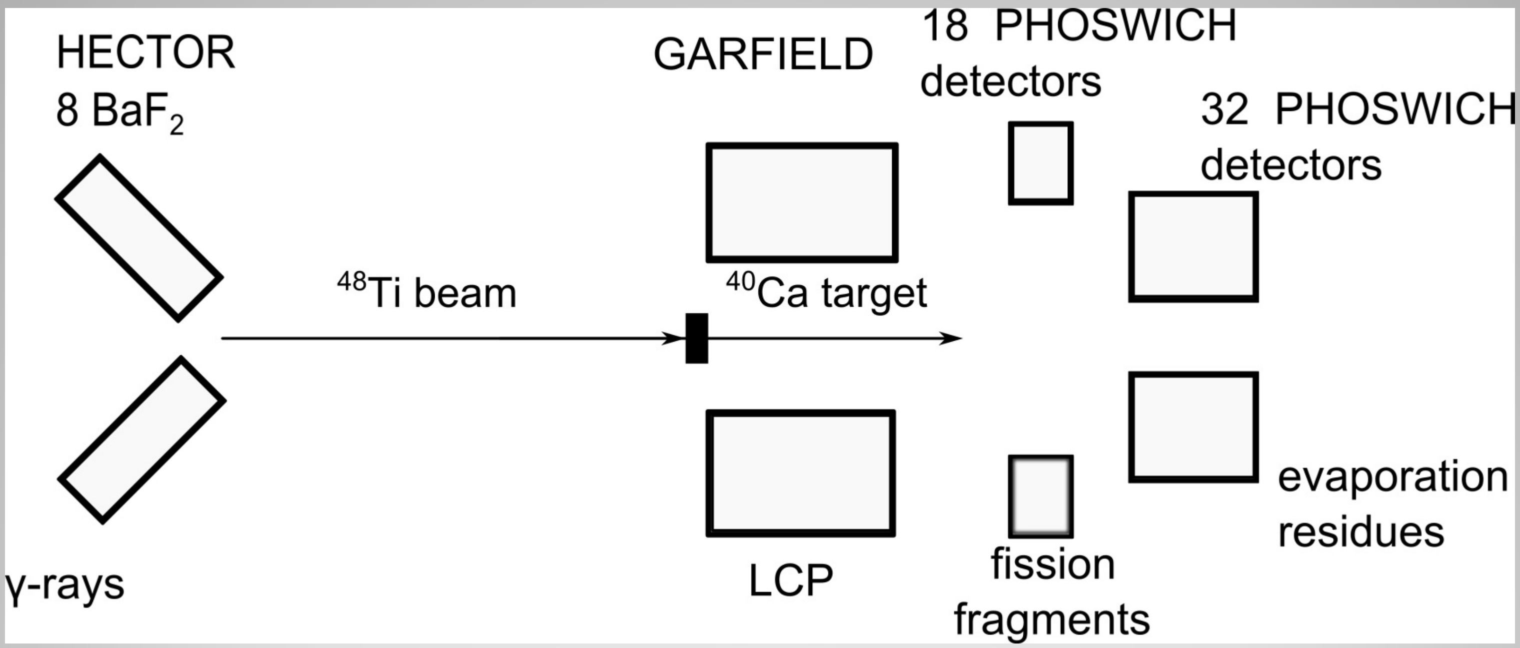
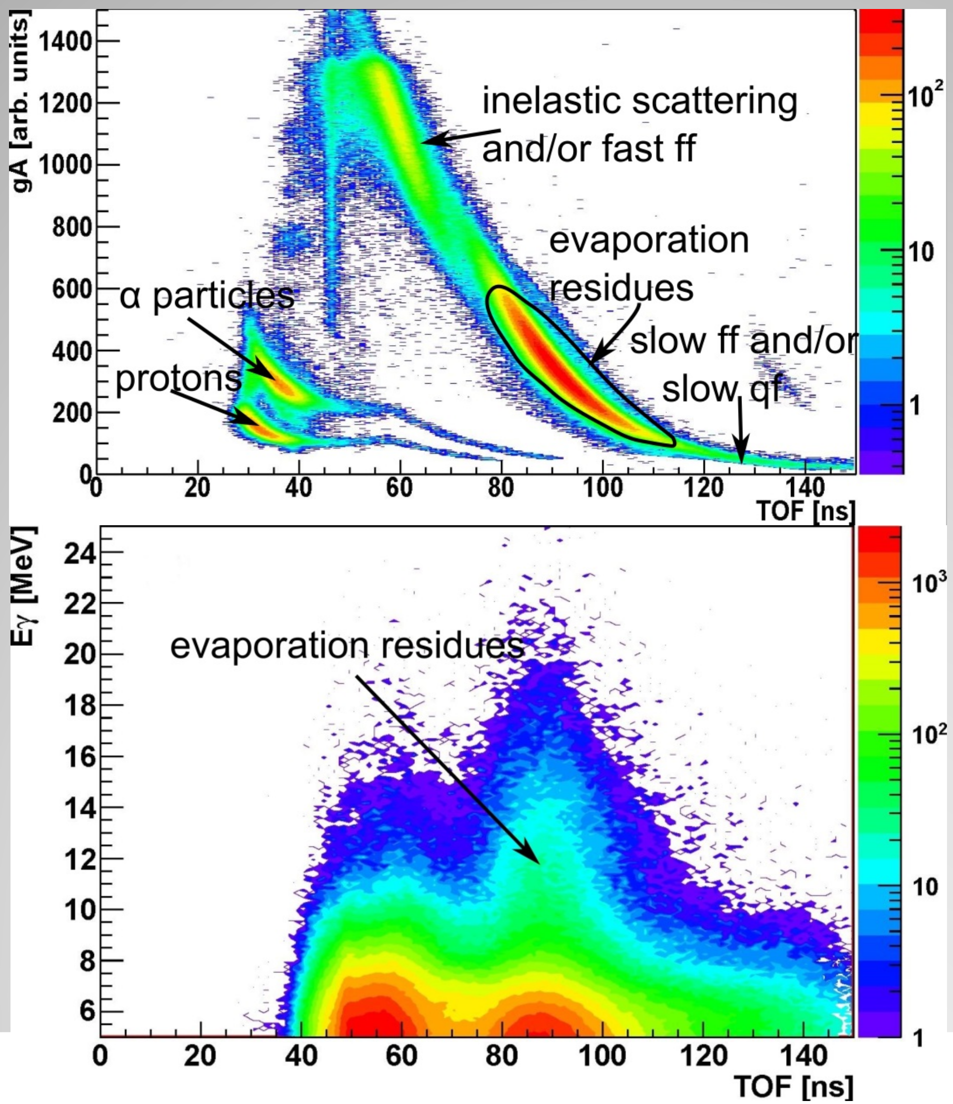
Experiment – ^{88}Mo, setup



Experiment – ^{88}Mo, phoswich



Good selection of the residues, with no A identification

High energy gamma rays come mainly from residues.

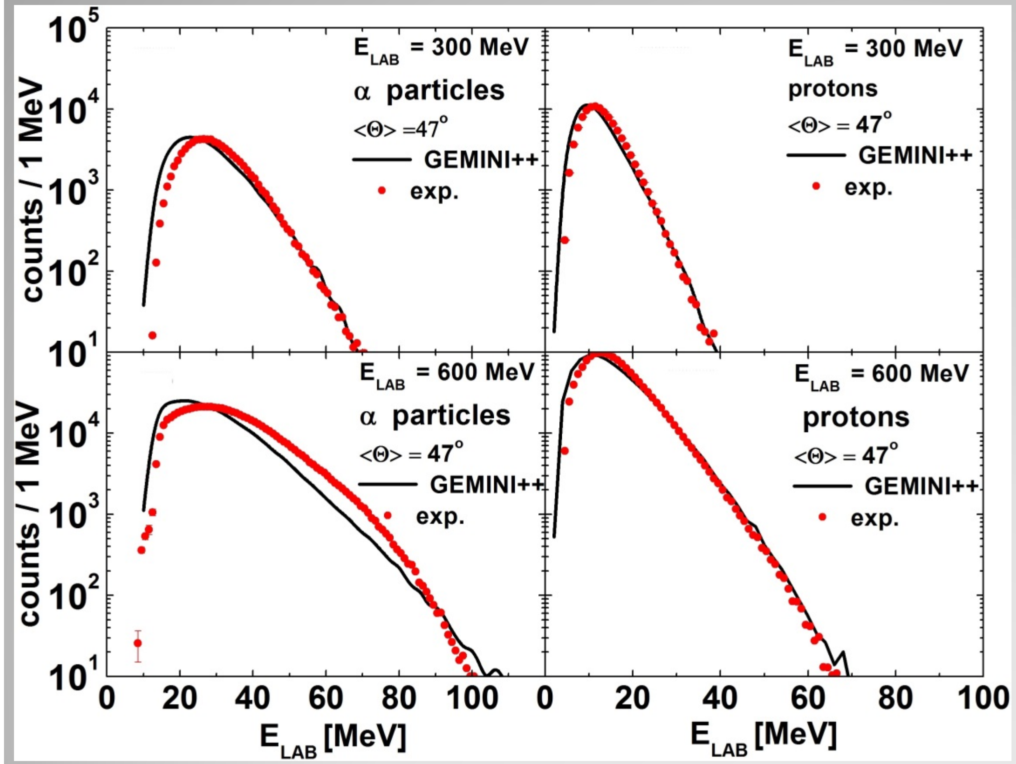
Analysis – statistical model – GEMINI++

To extract the GDR strength function from gamma-ray spectra, use of statistical code is necessary.

The GEMINI++ (re-written in C++ GEMINI maintained by R. Charity), a newer Monte Carlo simulation code based on statistical model, has been successfully used for the description of charged particle decay and fission fragments emission following the heavy-ion fusion-reactions in wide mass and excitation energy regions. [R.J. Charity, Phys. Rev. C82, 014610 (2010)]

In the present studies, the statistical code GEMINI++ with an option allowing to treat explicitly the GDR emission [Ciemala et al. Acta Phys. Pol B44, 611 (2013)] was employed for the first time for such an analysis.

Experimental results and GEMINI++ calculations



GEMINI++ model parameters were tested by comparison of calculated and experiemtnal LCP energy spectra.

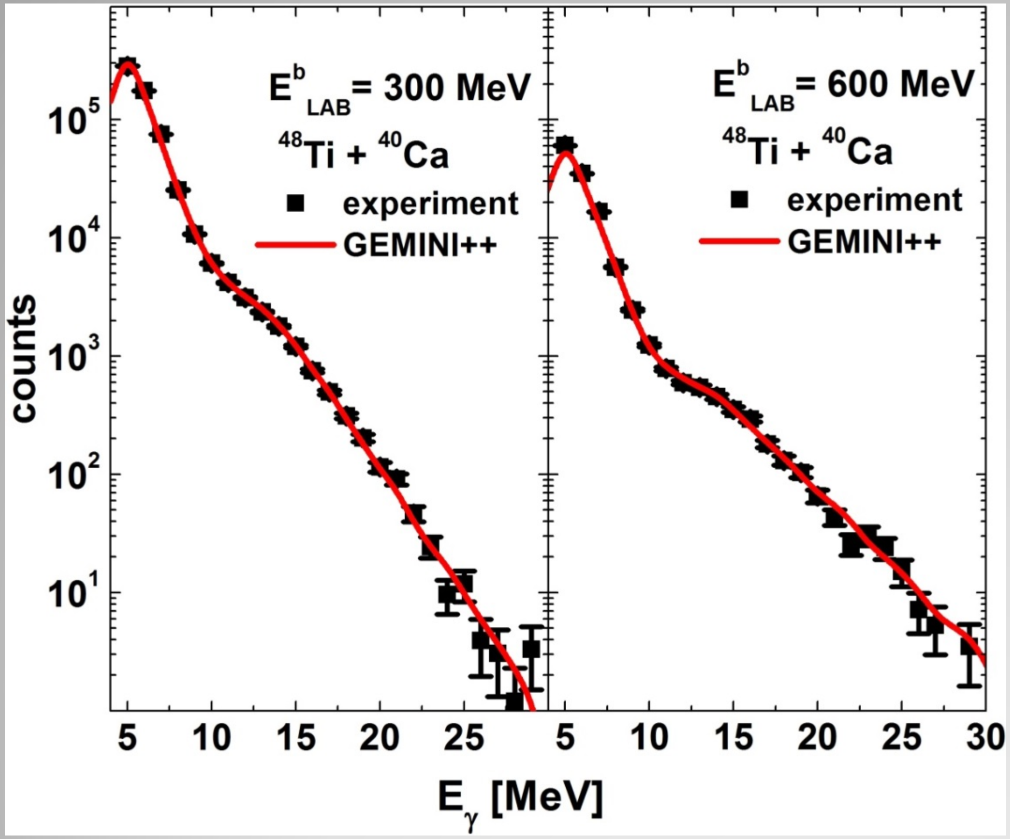
Als it demonstrates that the pre-equilibrium emissions are almost absent even at the highes bombargin energy.

The charged-particle and gamma-ray events generated by the statistical code were sorted using the same conditions as in the experiment

For the calculations, the RLDM Yrast line parametrization was used (instead of standard GEMINI++ - Sierk one).

More:
Simone Valdre talk today.

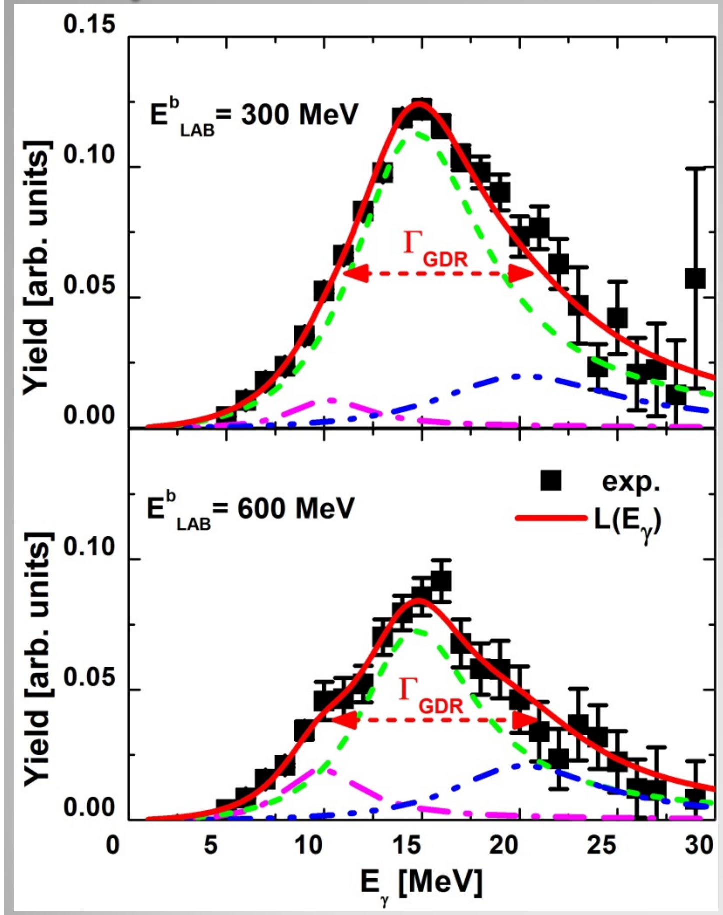
Experimental results and GEMINI++ calculations



The first iteration of the model gamma-ray spectrum was obtained using certain starting-value parameters compared with the experimental one and the corresponding chi^2-value was calculated (8-24 MeV range).

Then, a new trial GDR function inserted to GEMINI++ and new spectrum calculated, and compared with the experimental one.
In such a process, parameters of the GDR are being fitted in order to match the experimental spectra in the GDR region (best chi^2).

Experimental results



The experimental (points), and fitted, (lines) GDR strength functions.

Three Lorentzian functions were used for the fit.

E [MeV]	FWHM [MeV]	E_{GDR} [MeV]	S
300	9.9(7)	14.9(2)	1.19(5)
600	10.3(9)	14.7(2)	0.80(5)

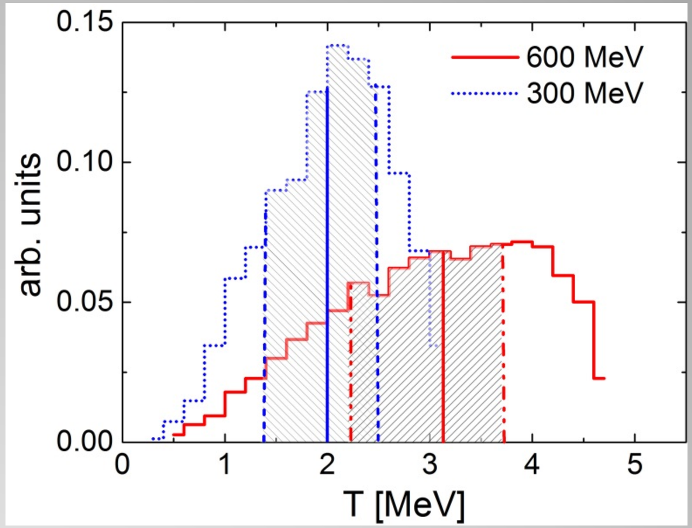
Onset on the GDR strength quenching at high excitation energy.
Santocito et al., Phys. Rev. C 90, 054603 (2014)

Temperature distributions - calculations

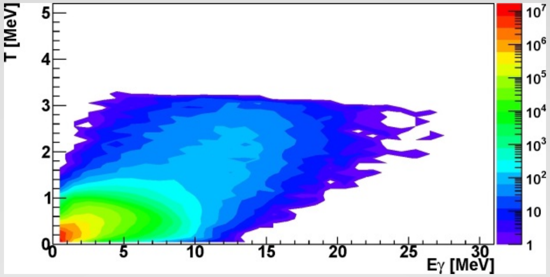
GEMINI++ calculations for $^{48}Ti + ^{40}Ca \rightarrow ^{88}Mo$

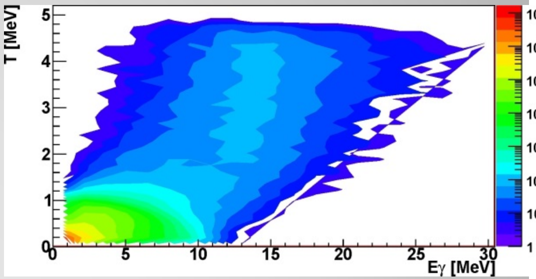
$$T = \left(\frac{1}{\rho}\frac{d\rho}{dU}\right)^{-1}$$

$$T = [(E^* - E_{rot} - E_{GDR})/a(T)]^{1/2}$$



Temperature after γ decay and gated by experimental residue events

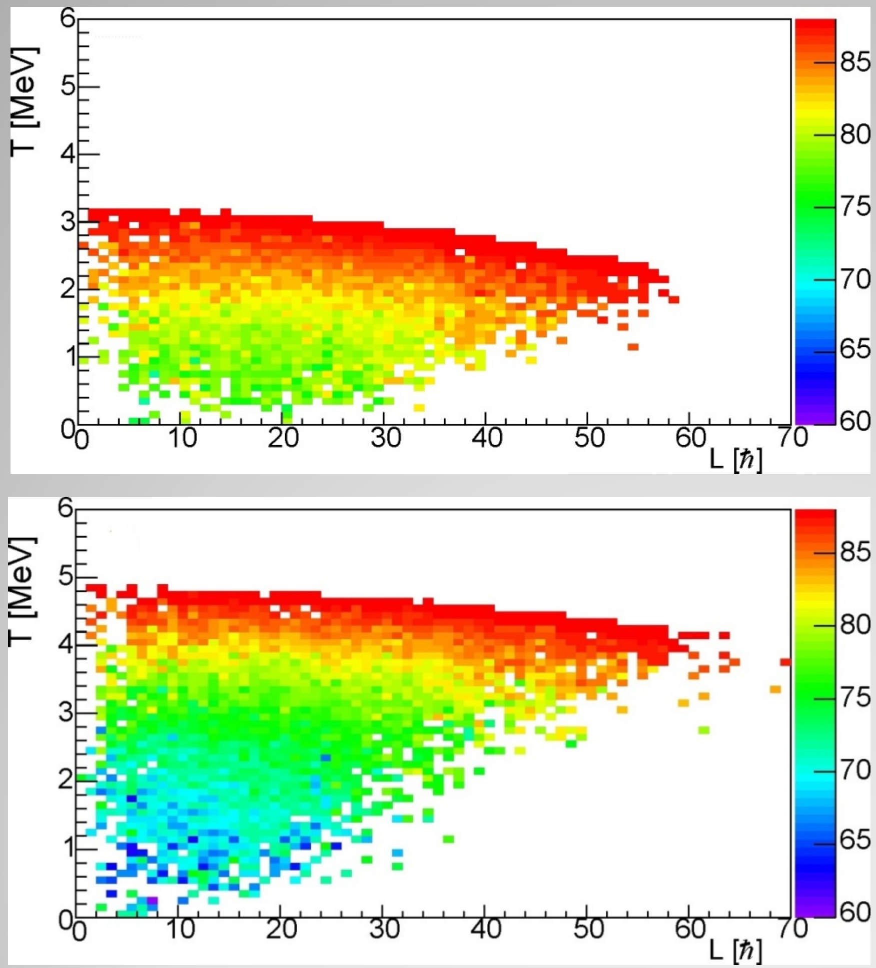




300 MeV
<T_{CN}> = 3.2 MeV
T_{eff_GDR} = 2.0 (6)MeV

600 MeV
<T_{CN}> = 4.8 MeV
T_{eff_GDR} = 3.1 (9) MeV

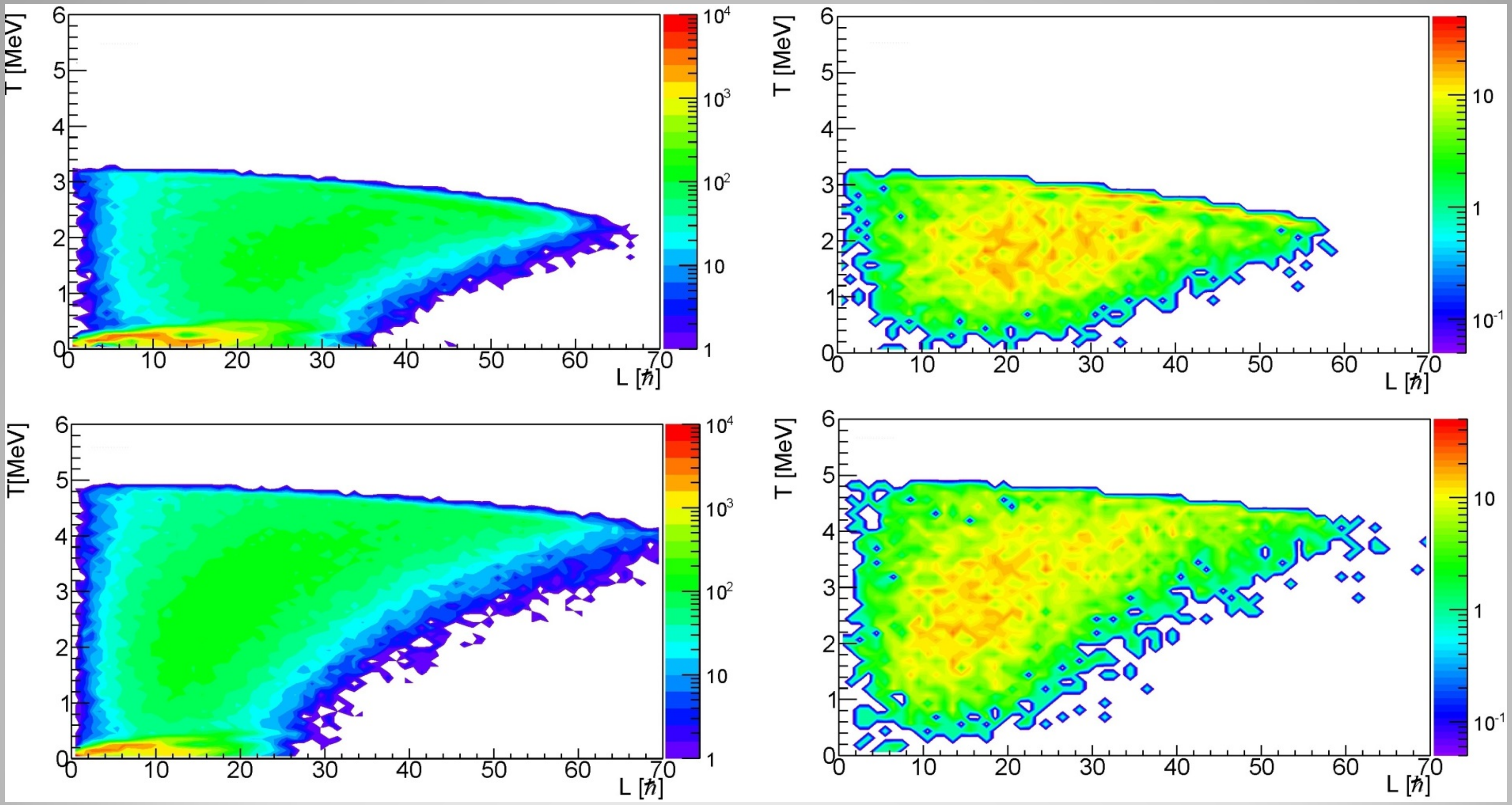
GDR deay nuclei mass distributions (calc.)



Average mass <A>(z-axis) of a nucleus emitting GDR gamma-rays during the decay of the ^{88}Mo CN as functions of temperature and spin.

<A> for 300 MeV beam = 84
<A> for 600 MeV beam = 80

Angular momentum distributions (calc.)



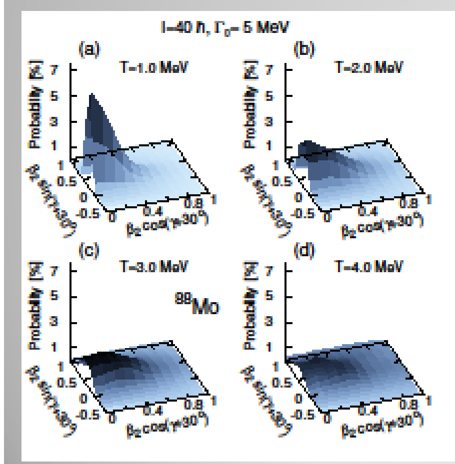
Population matrices in L vs. T space of all nucleus in evaporation process of ^{88}Mo.

Matrice of L vs. T for gamma-GDR decaying nuclei:
300 MeV: <L> = 24 hbar
600 MeV: <L> = 20 hbar

LSD with TFM and PDM

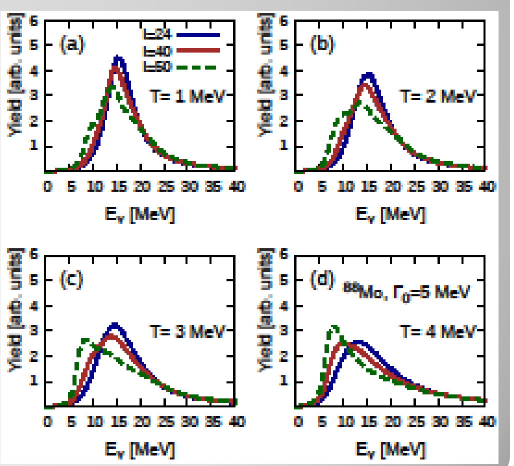
In order to interpret the experimental information on the GDR strength functions and on the effective GDR widths, theoretical approaches using two techniques of modeling the giant resonance were employed: LSD with TFM and PDM.

For both models the GDR strength functions were averaged over all possible spins and temperatures (using population matrices produced by GEMINI++) with the corresponding values of the GDR strength functions.

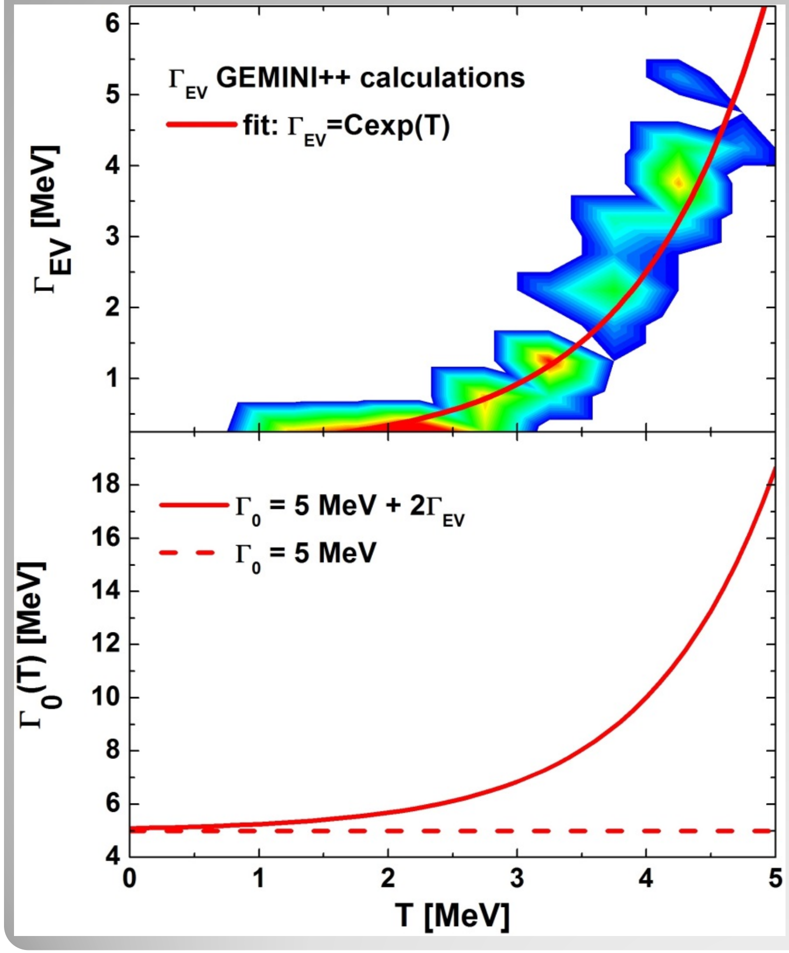


LSD with TFM:

GDR strength functions at various temperatures and spins for the ^{88}Mo nucleus (right), averaged using the shape probability distributions (left).



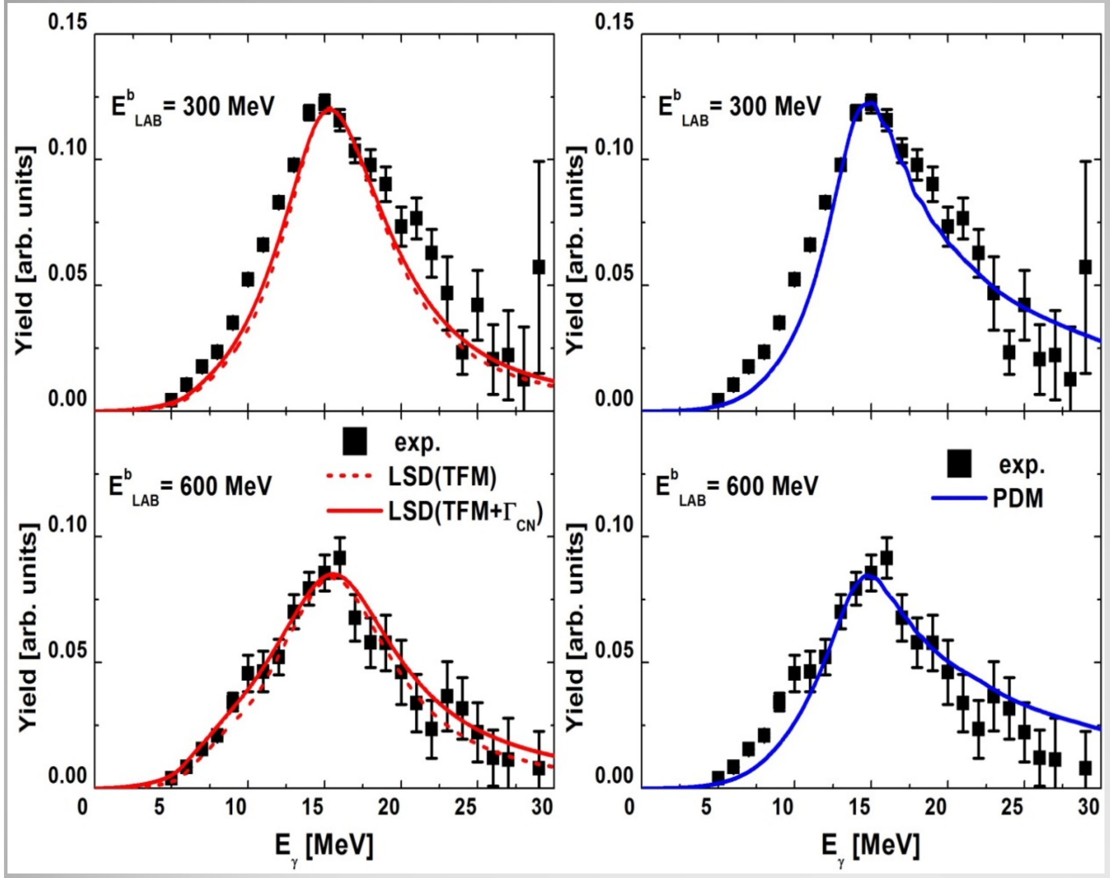
Compound nucleus lifetime



Thelifetime of the compound nucleus, as well as the lifetimes of nuclei during the evaporation process, may play an important role at very high temperatures and this mechanism generally needs to be taken into account for the GDR width modeling.

Evaporation widths calculated for different temperatures were fitted with the exponential functions and then used in the TFM +LSD model to increase the intrinsic GDR width.

Experimental results compared to LSD and PDM

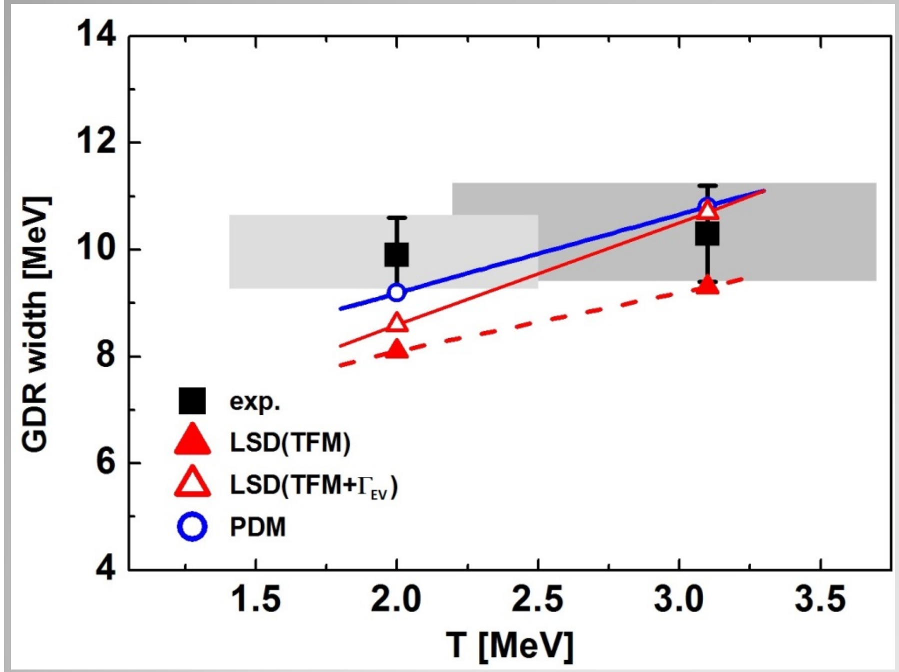


Effective GDR strength functions predicted by LSD with TFM and the PDM are found in rather good agreement with the experimental data.

For the lower energy both approaches produce a slightly narrower GDR strength function as compared to the experimental one.

LSD calculations with TFM done by K. Mazurek.
PDM calculations done by N. Dinh Dang.

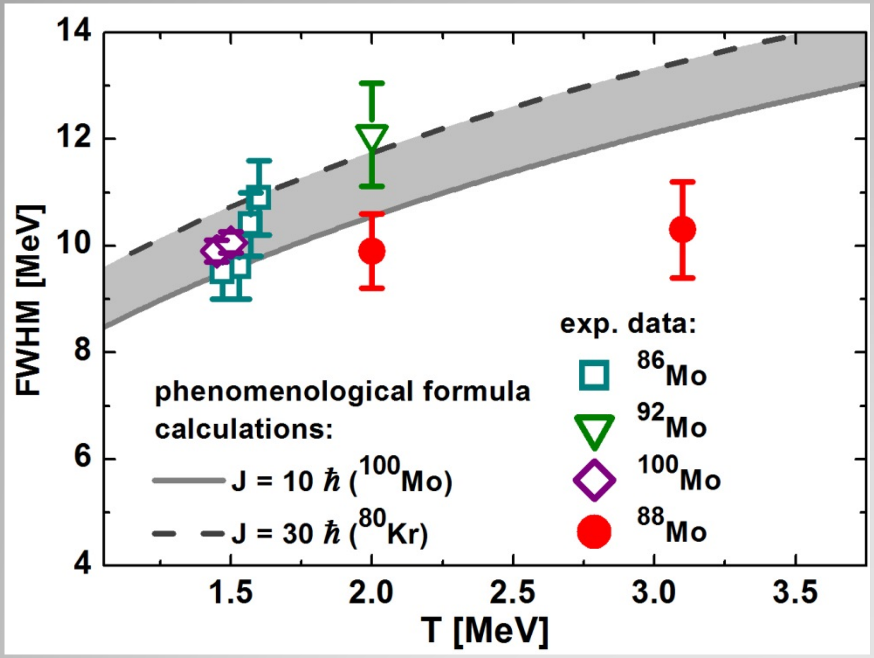
Experimental results compared to LSD and PDM



The small dependence of the GDR width on temperature (in contrast to the much stronger dependence deduced for the ^{132}Ce) may be explained (partly) with much higher (almost twice) rotational frequency for the same spin in ^{88}Mo than in ^{132}Ce. So, GDR width in ^{88}Mo is govern mainly by deformation effects induced by rotation (splitting of the GDR components), which are similar at both T, and not so much affected by T effects as in the case of ^{132}Ce.

The effective GDR (FWHM) of the experimental GDR strength functions were found within the error bars to be approximately the same.

GDR width evolution with temperature in Mo region



The indication of the onset of the GDR width saturation at high temperatures supported by examining measured GDR widths for ^{88}Mo together with the previously measured ones.

To compare these data with the ones of the present experiment, only the data points associated to the mean angular momentum in the interval between 18 and 25 hbar.

Obtained GDR width were compared with previously measured in nuclei from ^{88}Mo region.

^{86}Mo, S.K. Rathi et al., Phys. Rev. C 67 (2003) 024603

^{92}Mo, J. H. Gundlach et al., Phys. Rev. Lett 65, 2523 (1990)

^{100}Mo, M. Kicińska-Habior et al., Phys. Rev. C 45, 569 (1992)

Phenomenological formula: D. Kusnezov et al. Phys. Rev. Lett .81, 542 (1998)

Conclusions

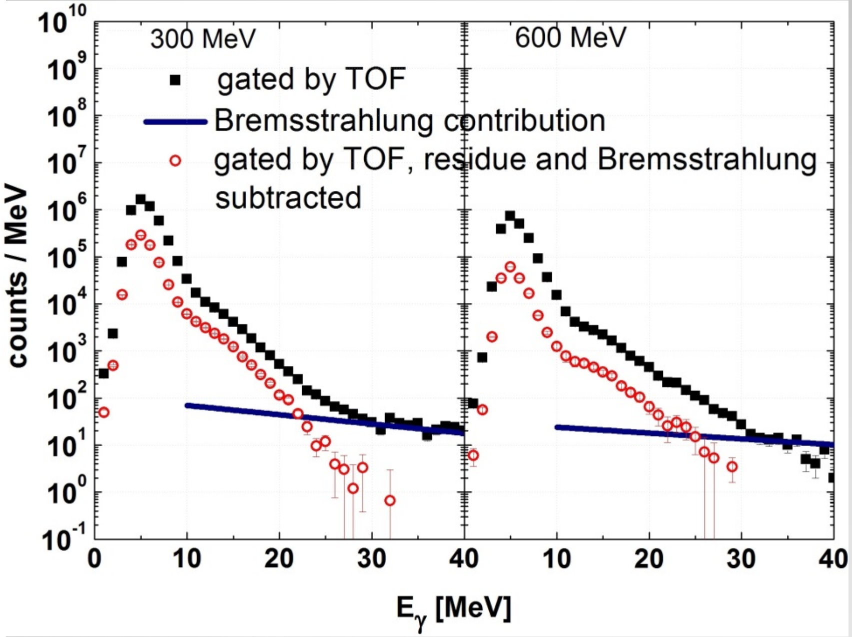
- New experimental results for the GDR width of the ^{88}Mo CN up to the T = 3 MeV were obtained. To extract the GDR width from the experimental data the statistical-model Monte Carlo GEMINI++ code was employed for the first time.
- Model calculations were performed using, TFM based on the LSD model and the PDM. The resulting GDR strength functions were convoluted, for the first time, with the population matrices of the evaporation process from the GEMINI++ code.
- Indications coming from the comparison with theoretical predictions, may suggest an onset of saturation of the GDR width at above temperature of 3 MeV, originating both from rotational and temperature effects.
- Measurements at high temperature not easy to perform (wide T distributions) – possible solution, differential technique [Maj et al., Nucl. Phys. A 571, 185 (1994)].

Many thanks to

Adam Maj, Maria Kmiecik, Katarzyna Mazurek (Krakow), Angela Bracco, Franco Camera, Oliver Wieland (Milano), Sandro Barlini, Giovani Casini, Simone Valdre (Florenze), Vladimir Kravchuk, Fabiana Gramegna (Legnaro), Jerzy Dudek (Strasbourg), Nguyen Dinh Dang (RIKEN)

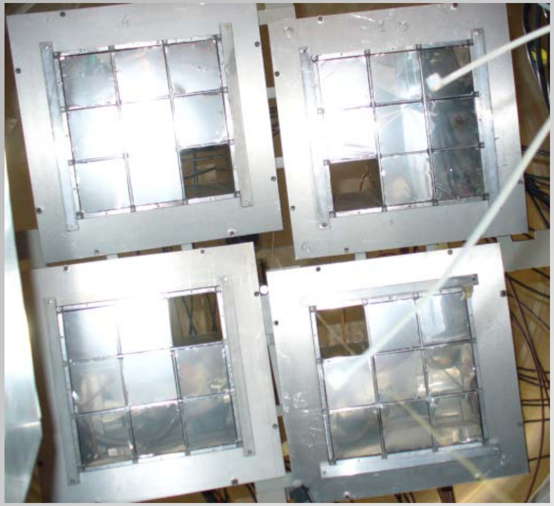
and HECTOR – GARFIELD collaboration

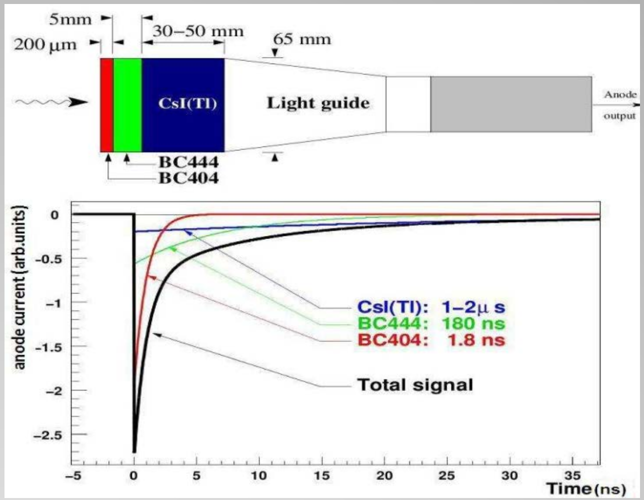
Experiment – ^{88}Mo, gamma spectra

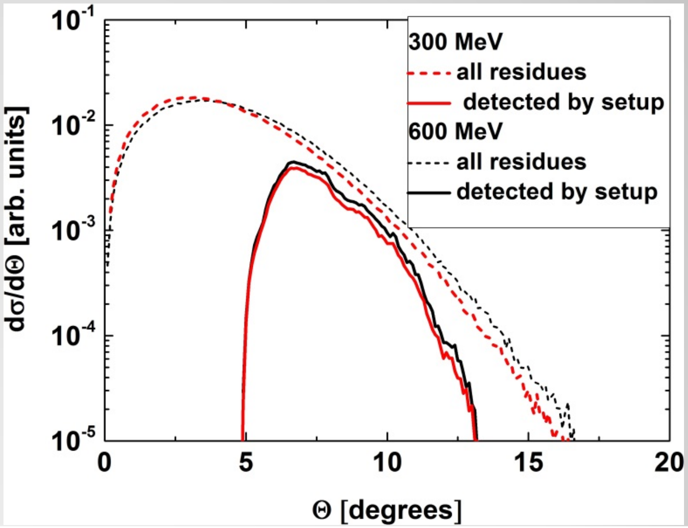


Energy-spectra obtained while gating on the HECTOR ToF (full squares) and on the residues after subtracting the cosmic-ray and Bremsstrahlung contributions.

Phoswich detectors



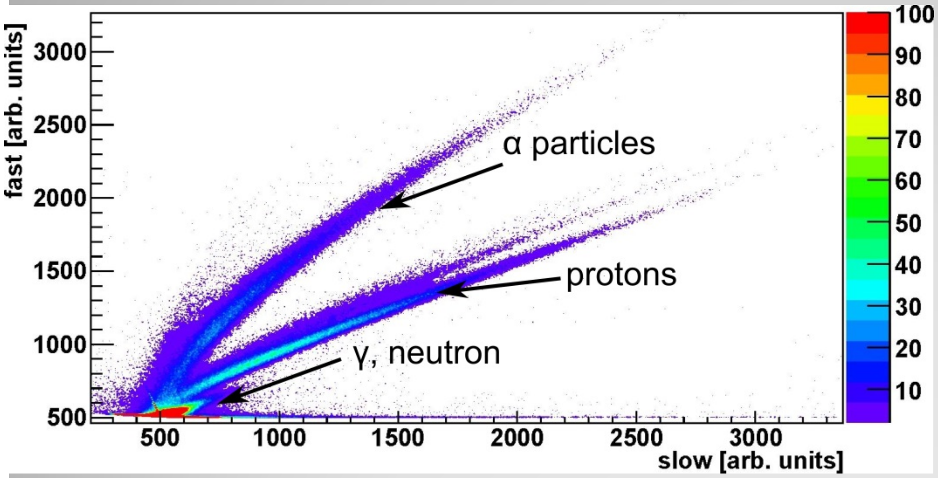


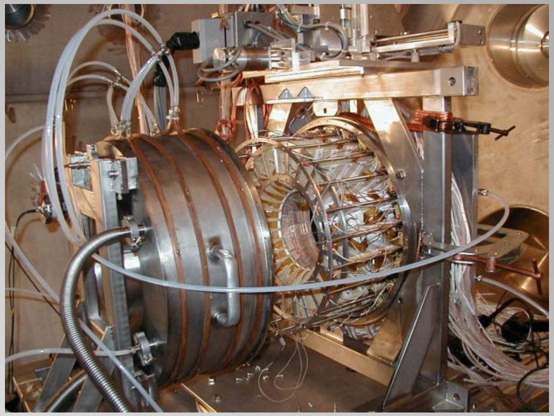


Angular coverage:
from 5 to 13 degree.

Experiment – ^{88}Mo, GARFIELD detectors

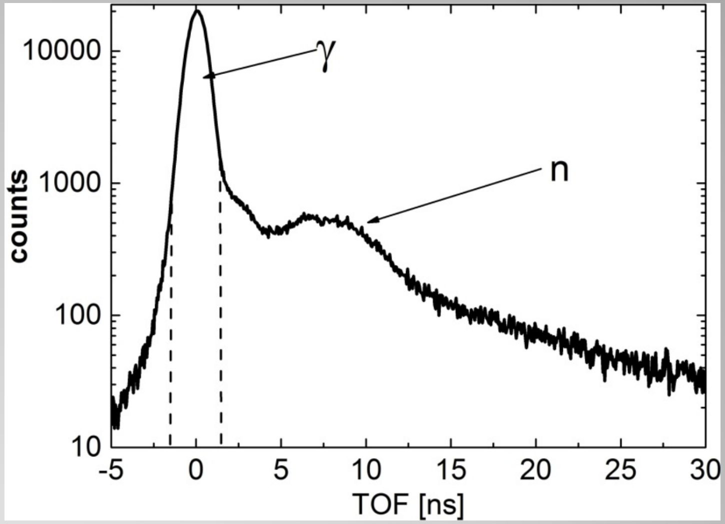
Angular coverage from 29.5 to 83 degrees.





LCP A,Z and energy identifiation.

Experiment – ^{88}Mo, HECTOR array



8 large volume (14.5 x 17 cm) BaF_2 Scintillation detectors, were placed at back angles regarding the beam direction (theta 129 to 160 degree).

All analyzed data were collected with the logical condition: (OR PHOS) AND (OR HECTOR above threshold). An additional gate - to remove neutron contributions - was set on ToF measured with the HECTOR detectors in respect to the RF-signal from the bunching system.