COMEX 5, September 16th 2015, Krakow

Effect of thermal fluctuations in the pairing field on the width of giant dipole resonance

Nguyen Dinh Dang
RIKEN Nishina center (Saitama, Japan)
Institute of nuclear science and techniques (Hanoi, Vietnam)

Contents

1) Effect of thermal pairing on the GDR width:

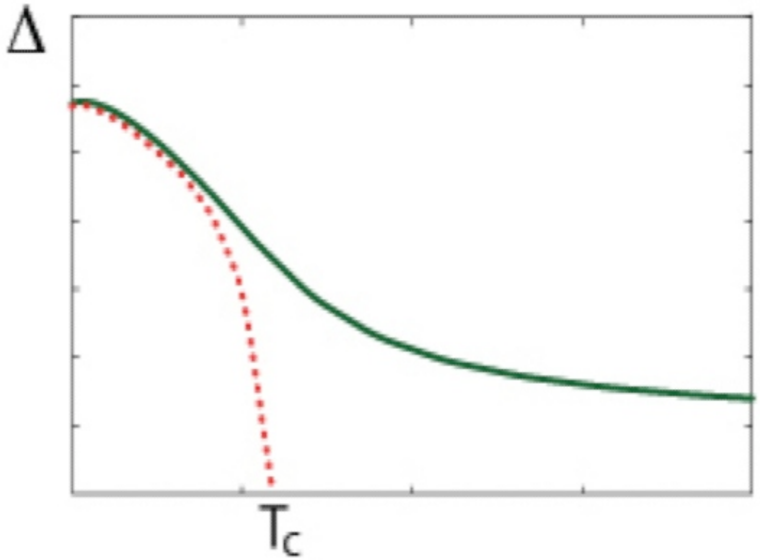
- thermal pairing
- within the Phonon Damping Model (PDM)
- within Thermal Shape Fluctuations Model (TSFM) that includes pairing fluctuations

2) PDM for the description of GDR in hot rotating nuclei

- All the theoretical predictions are compared with the most recent experimental systematics.

Thermal pairing

In finite systems such as nuclei large thermal fluctuations smooth out the sharp superfluid-normal (SN) phase transition. As the result, pairing does not collapse at $T_c \approx 0.57\Delta(T=0)$, but remains finite even at $T >> T_c$.



This has been shown within the following approaches:

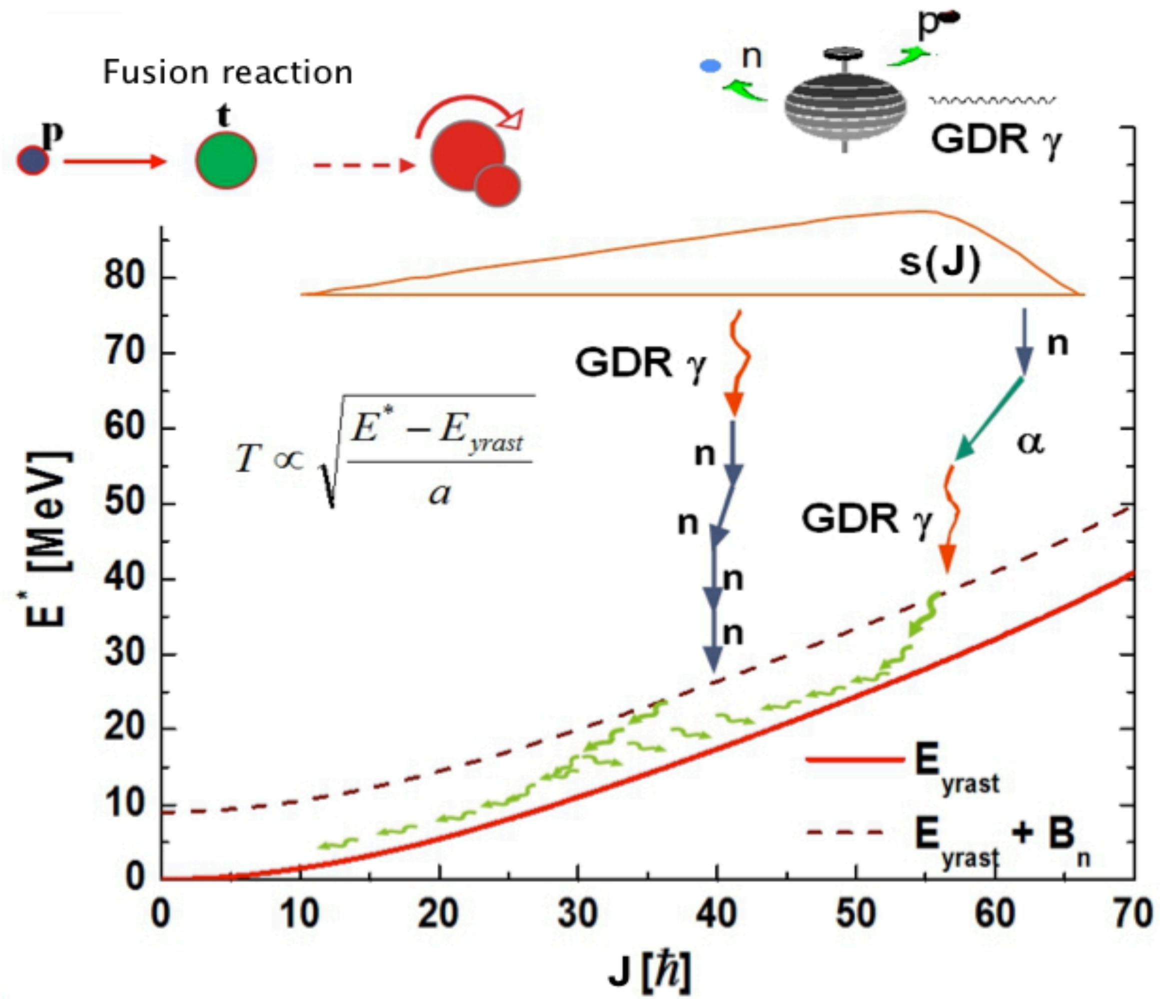
1) Fluctuations of pairing field (Moretto, 1972)
2) SPA (Dang, Ring, Rossignoli, 1992)
3) SM (Zelevinsky, Alex Brown, Frazier, Horoi, 1996)
4) MBCS (Dang, Zelevinsky, 2001)
5) FTBCS1 (Dang, Hung, 2008)
6) Exact solutions of pairing problem (Volya, Alex Brown, Zelevinsky, 2001) embedded in the GCE, CE, and MCE (Dang, Hung, 2009)

$$H = \sum_{jm} \epsilon_j \hat{N}_j - G \sum_{jj'} \hat{P}_j^\dagger \hat{P}_{j'}, \quad (1)$$

where the particle-number operator $\hat{N}_j$ and pairing operator $\hat{P}_j$ are given as

$$\hat{N}_j = \sum_m a_{jm}^\dagger a_{jm}, \quad \hat{P}_j^\dagger = \sum_{m>0} a_{jm}^\dagger a_{j\widetilde{m}}^\dagger, \quad \hat{P}_j = (\hat{P}_j^\dagger)^\dagger, \quad (2)$$

Decaying scheme of a highly-excited compound nucleus



1) GDR photons are emitted in the early stage in competition with neutrons.
2) When E* becomes lower than B_n slower γ transitions take place.
3) Most of the angular momentum is carried off at the final stage of the decay by quadrupole radiation.

Phonon Damping Model (PDM)

NDD & Arima, PRL 80 (1998) 4145

$$H = \sum_s E_s a_s^\dagger a_s + \sum_q \omega_q Q_q^\dagger Q_q + \sum_{ss'q} F_{ss'}^{(q)} a_s^\dagger a_{s'} (Q_q^\dagger + Q_q)$$

Topical conference on giant resonances, Varenna, May 1998

$$G_q(E) = \frac{1}{2\pi}[E - \omega_q - P_q(E)]^{-1}$$

$$P_q(E) = \sum_{ss'} F_s^{(q)} F_{s'}^{(q)} \frac{f_s - f_{s'}}{E - E_{s'} + E_s} ,$$

$$\gamma_q(\omega) = \Im m P_q(\omega \pm i\varepsilon) .$$

Quantal: *ss' = ph*

Thermal: *ss' = pp'*, *hh'*

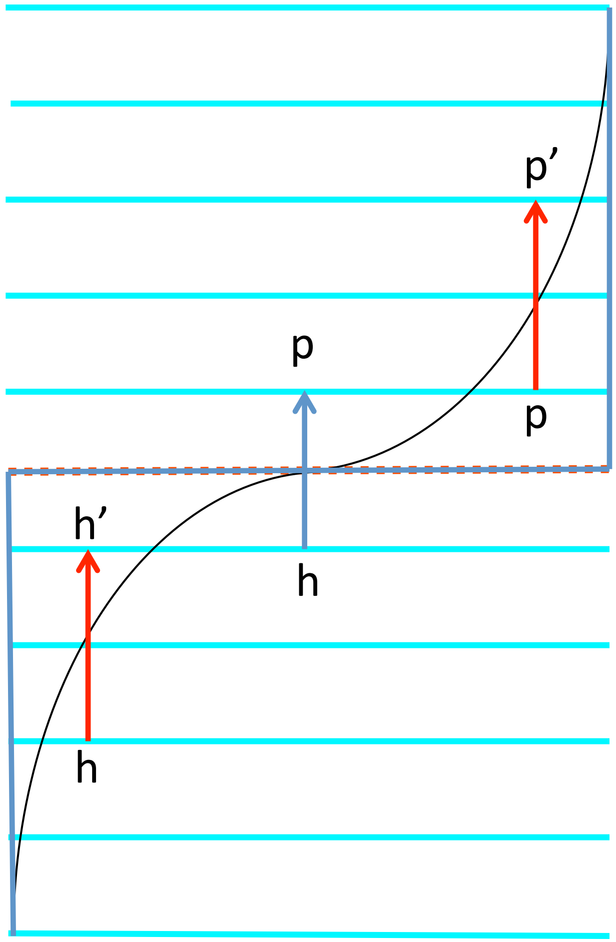
$$\Gamma = \Gamma_Q + \Gamma_T = 2\gamma_q(E_{GDR})$$

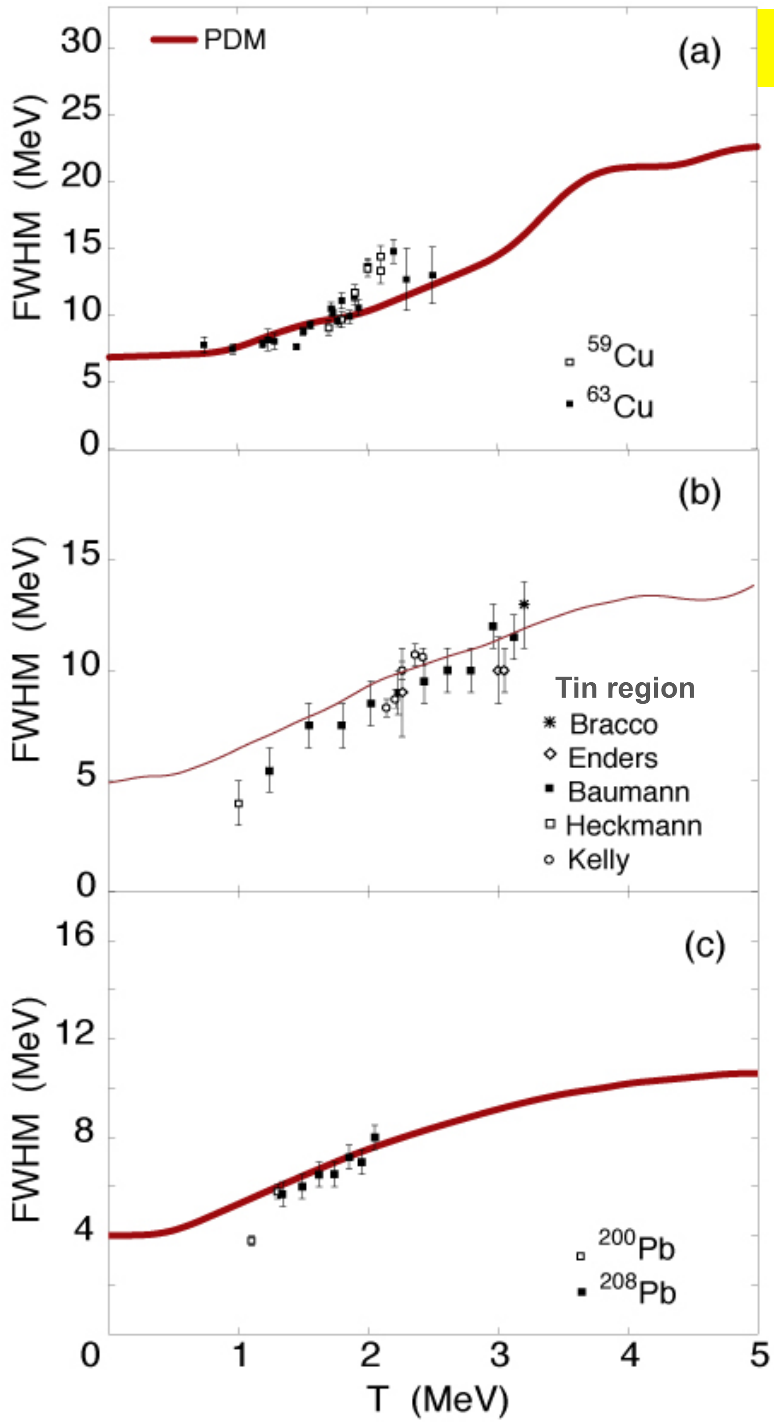
$$E_{GDR} - \omega_q - P_q(E_{GDR}) = 0 , \quad f_s = \{\exp[(\varepsilon_s - \lambda)/T] + 1\}^{-1}$$

GDR strenght function:

$$S_q(\omega) = \frac{1}{\pi} \frac{\gamma_q(\omega)}{[\omega - E_{GDR}]^2 + \gamma_q^2(\omega)} .$$

ph (T = 0 & T ≠ 0), pp’ & hh’ (T ≠ 0)





GDR width as a function of T

^{63}Cu

NDD, PRC 84 (2011) 034309

^{120}Sn & ^{208}Pb

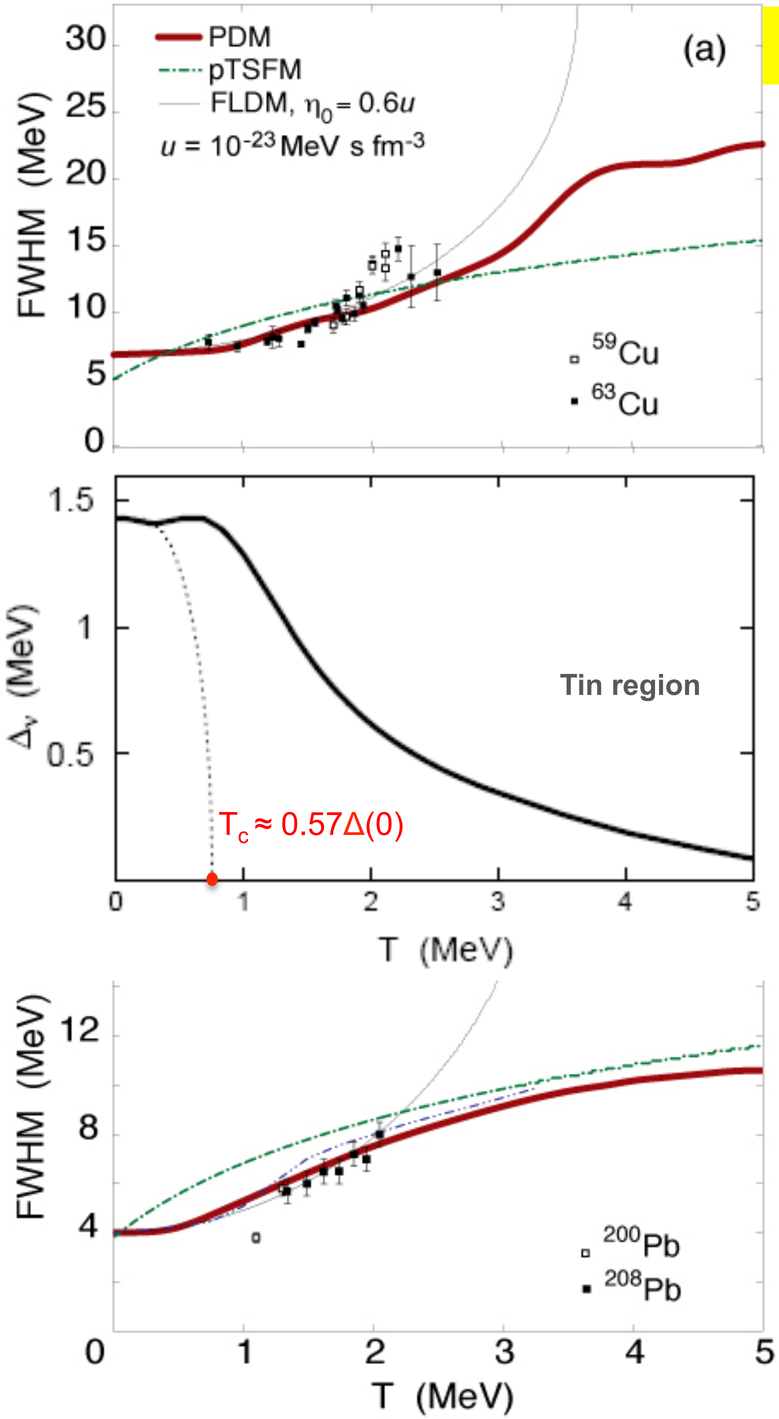
NDD & Arima, PRL 80 (1998) 4145

GDR width as a function of T

pTSFM
(Kusnezov, Alhassid, Snover)

AM
(Ormand, Bortignon, Broglia, Bracco)

FLDM
(Auerbach, Shlomo)



^{63}Cu

NDD, PRC 84 (2011) 034309

Effect of thermal pairing

NDD & Arima, PRC 68 (2003) 044303

^{120}Sn & ^{208}Pb

NDD & Arima, PRL 80 (1998) 4145

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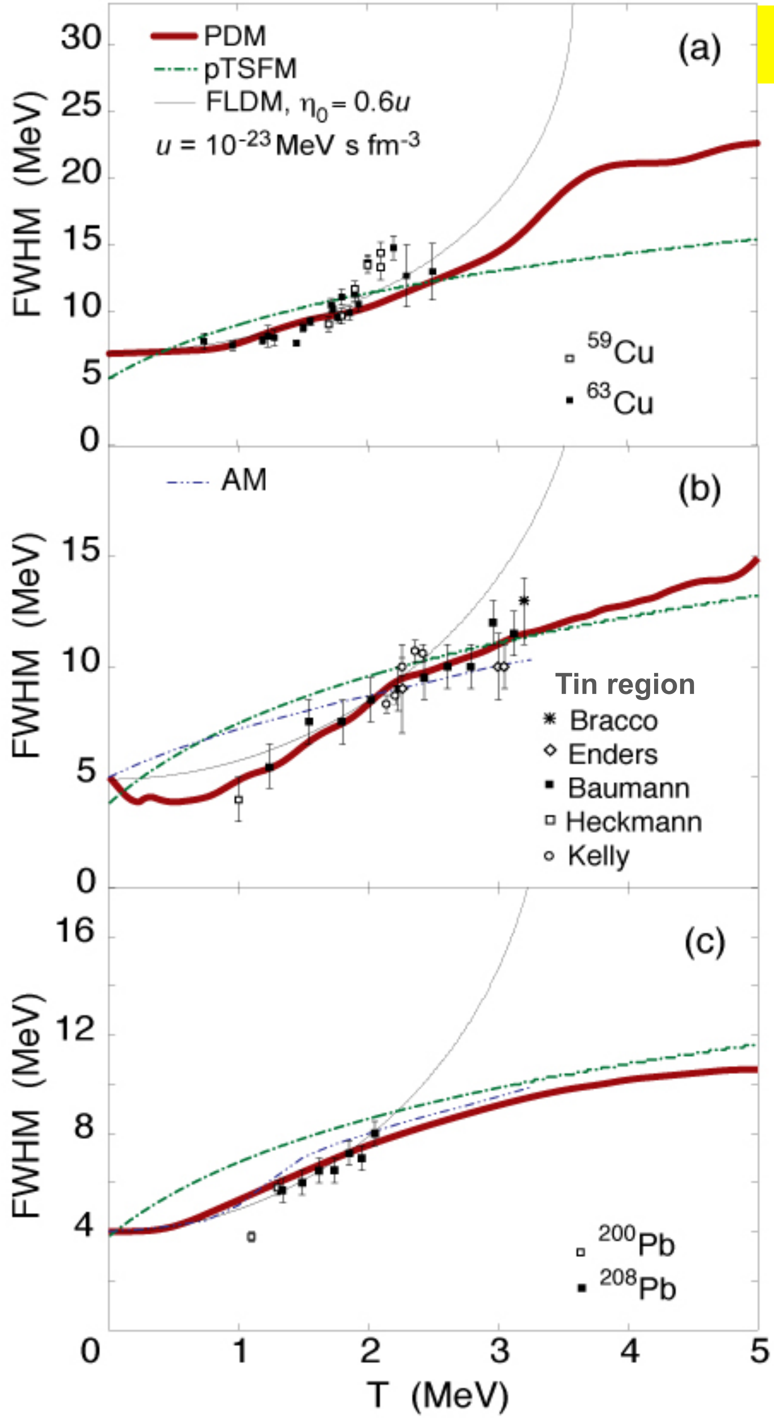

GDR width as a function of T

^{63}Cu

NDD, PRC 84 (2011) 034309

Effect of thermal pairing

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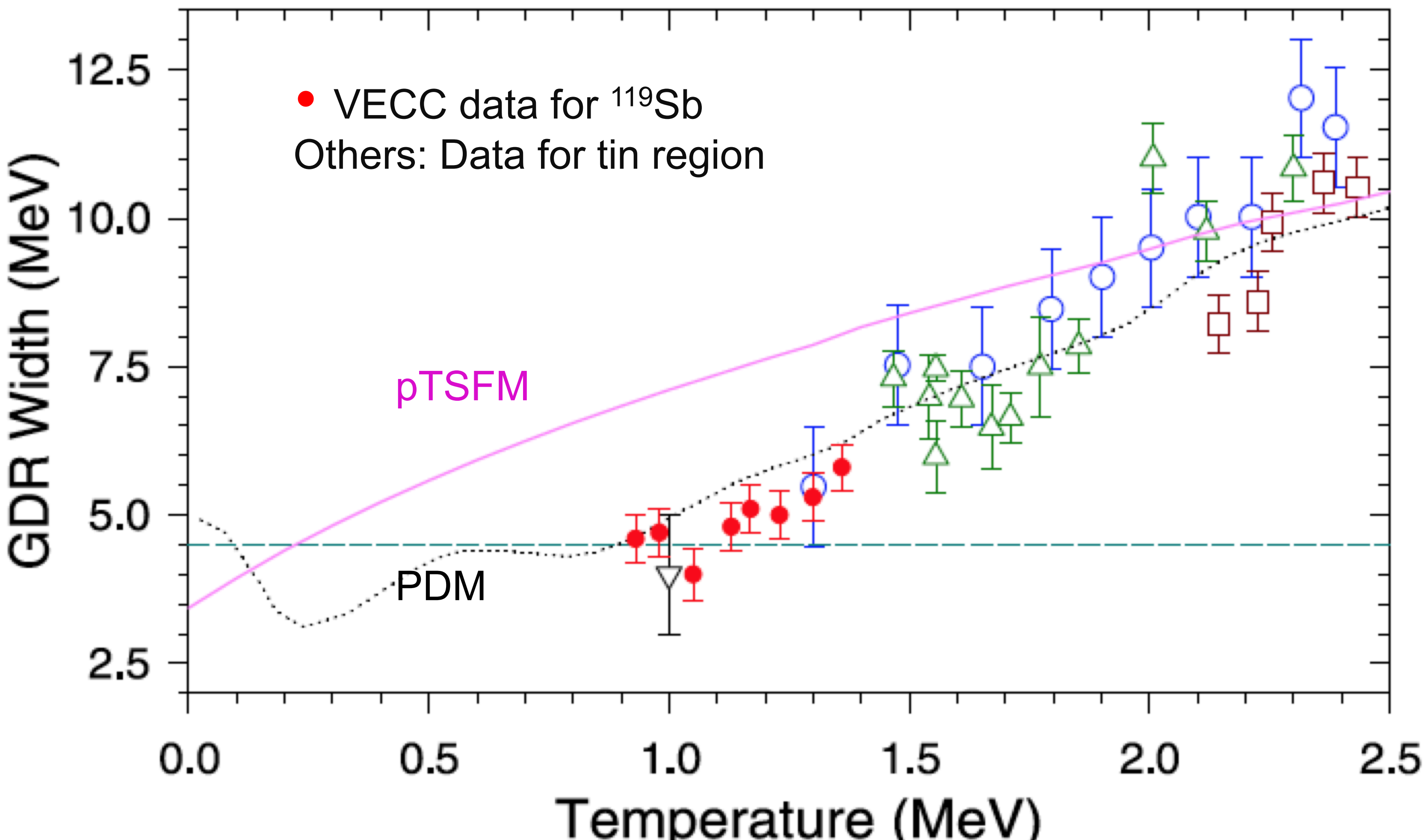
NDD & Arima, PRL 80 (1998) 4145

New measurements at VECC (Kolkata):

α induced fusion reactions $^{4}He + ^{115}In \rightarrow ^{119}Sb^*$

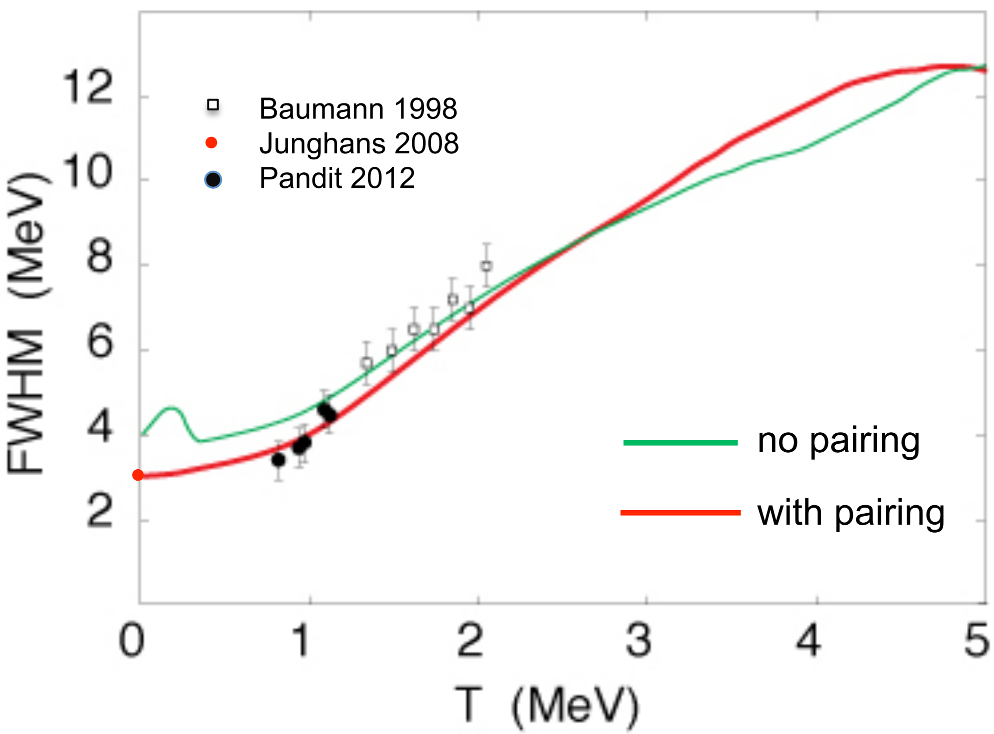
at beam energies of 30, 35, and 42 MeV

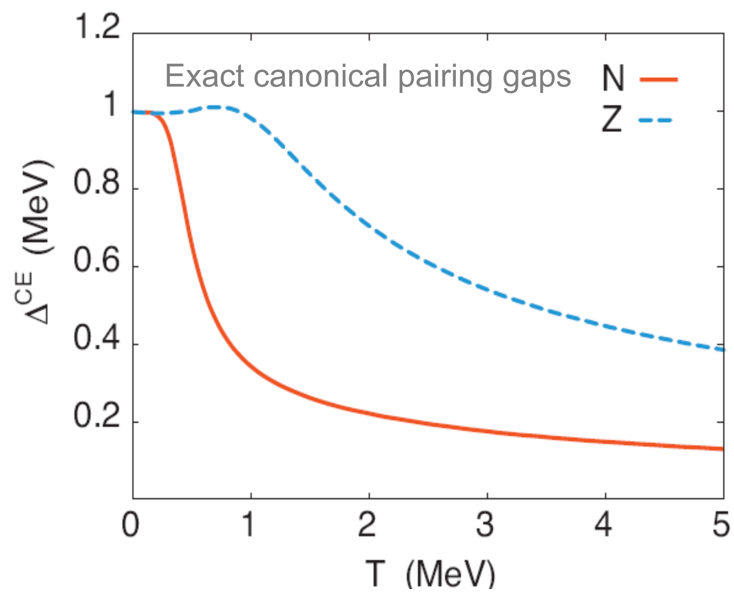
Mukhopadhyay et al. PLB 709 (2012) 9



^{201}Tl

New data at low *T*:
D. Pandit et al. PLB 713 (2012) 434

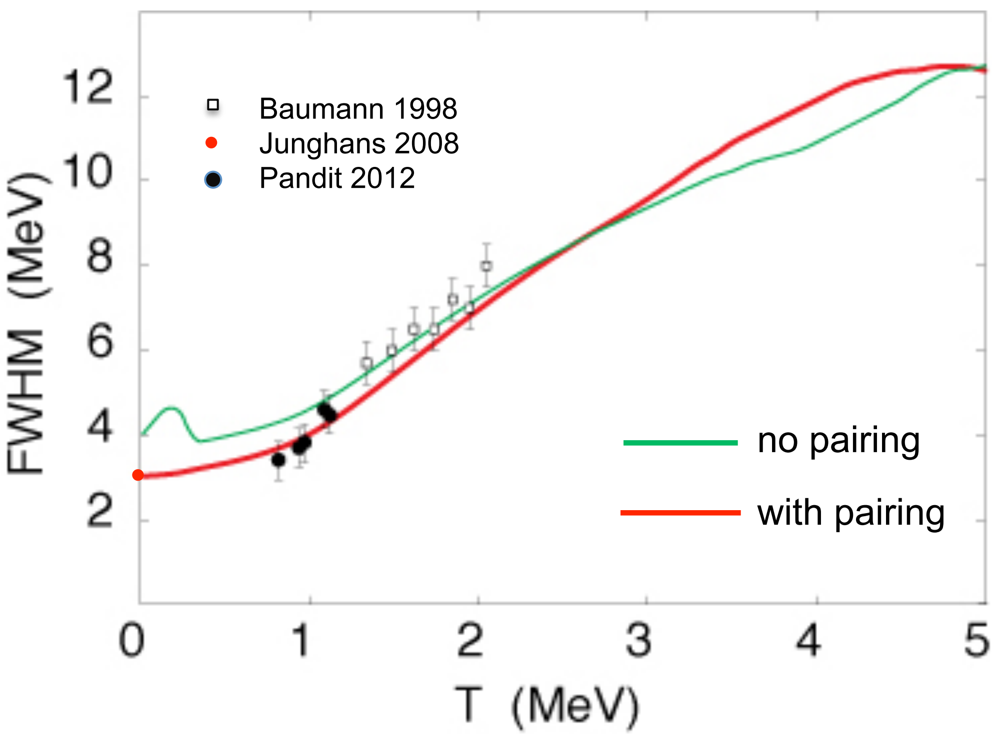


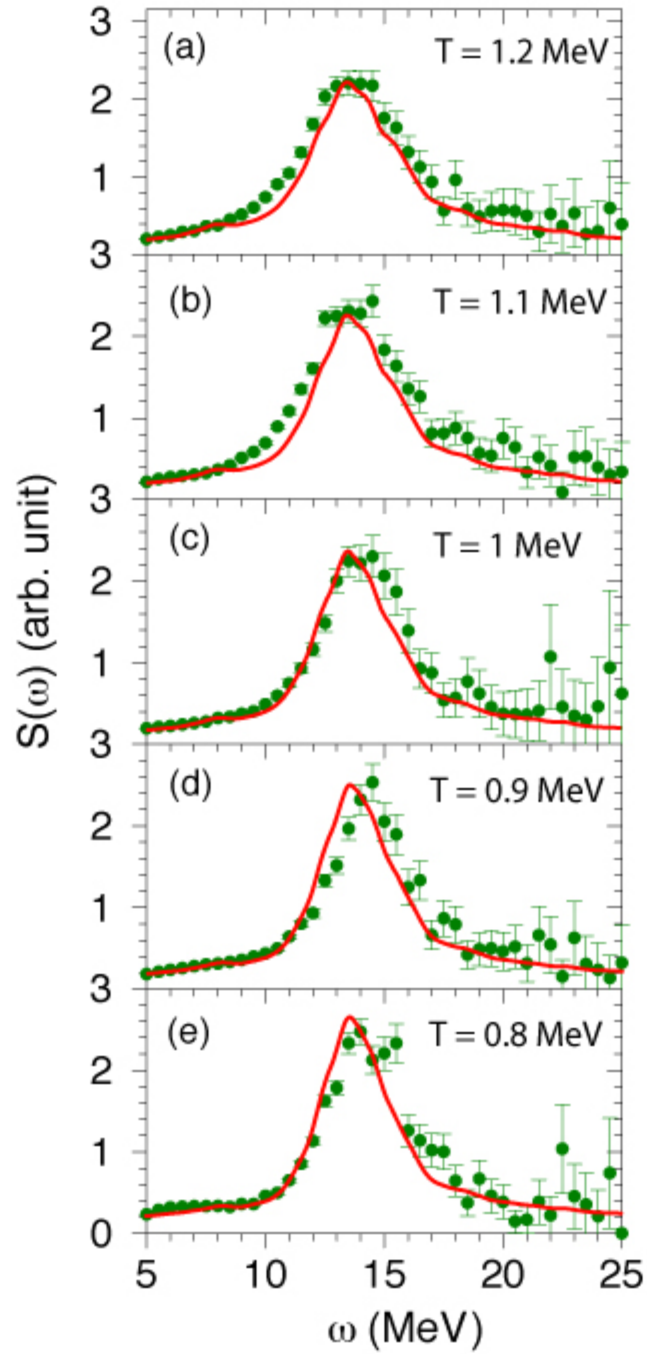


NDD & N. Quang Hung PRC 86 (2012) 044333

^{201}Tl

New data at low *T*:
D. Pandit et al. PLB 713 (2012) 434





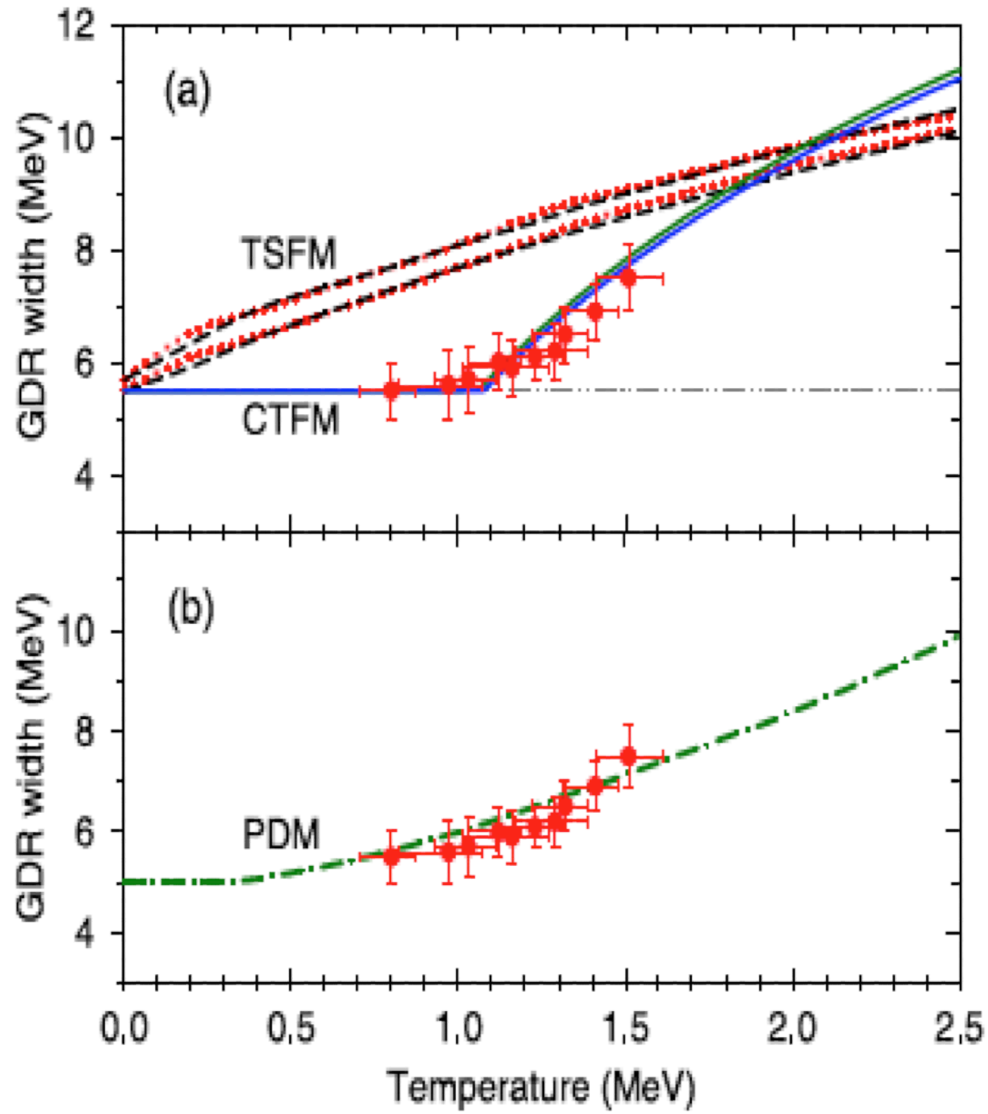
NDD & N. Quang Hung PRC 86 (2012) 044333

Dey, Mondal, Pandit, Mukhopadhyay, Pal, Bhattacharya, De, K. Banerjee, NDD, Quang Hung, S.R. Banerjee
PLB 731 (2014) 92

^{97}Tc

Sudhee Banerjee's group at VECC Kolkata

N. Quang Hung
(TanTao U.)



Pairing effect in the TSFM on the GDR width

Rhine Kumar, Arumugam, NDD, PRC 90 (2014) 044308, PRC 91 (2015) 044305

(Indian Institute of Technology Roorkee)

Total free energy at a fixed deformation = Liquid-drop energy + Nillson-Strutinsky shell correction:

$$F_{\rm TOT} = E_{\rm LDM} + \sum_{p,n} \delta F \ , \qquad \delta F = F - \tilde{F}$$

$$F = \langle H_0 \rangle - \lambda N - TS = \sum_i (e_i - \lambda - E_i) - 2T \sum_i \ln[1 + \exp(-E_i/T)] + \frac{\Delta^2}{G},$$

$$\tilde{F} = 2\sum_i (e_i - \lambda)\tilde{n}_i - 2T\sum_i \tilde{s}_i + 2\gamma_s \int_{-\infty}^{\infty} \tilde{f}(x) x \sum_i n_i(x) dx - \frac{\Delta^2}{G}$$

$$\tilde{f}(x) = \frac{1}{\sqrt{\pi}} \exp(-x^2) \sum_{m=0}^{p} C_m H_m(x);$$

$$C_m = \frac{(-1)^{m/2}}{2^m (m/2)!} \text{ if } m \text{ is even} , \ 0 \text{ if } m \text{ is odd} ,$$

$$\mathrm{x} = \frac{e - e_i^{\omega}}{\gamma_s} , \quad \gamma_s \text{ is defined from } d\tilde{F}/d\gamma_s = 0 .$$

$$\tilde{n}_i = \int_{-\infty}^{\infty} n_i \tilde{f}(x) dx \ , \ \ n_i = \left[1 + \exp(\beta E_i)\right]^{-1}, \ \ \tilde{s}_i = \int_{-\infty}^{\infty} s_i \tilde{f}(x) dx \ , \ \ s_i = -2\left[n_i \ln n_i + (1 - n_i)\ln(1 - n_i)\right], \ \ S = \sum_i s_i$$

Averaged cross-section

GDR Hamiltonian:

$$H = H_{\text{osc}} + \eta\, D^\dagger D + \chi\, P^\dagger P$$

$$\sigma(E_\gamma) = \sum_i \frac{\sigma_{mi}}{1 + \left(E_\gamma^2 - E_{mi}^2\right)^2 / E_\gamma^2 \Gamma_i^2}$$

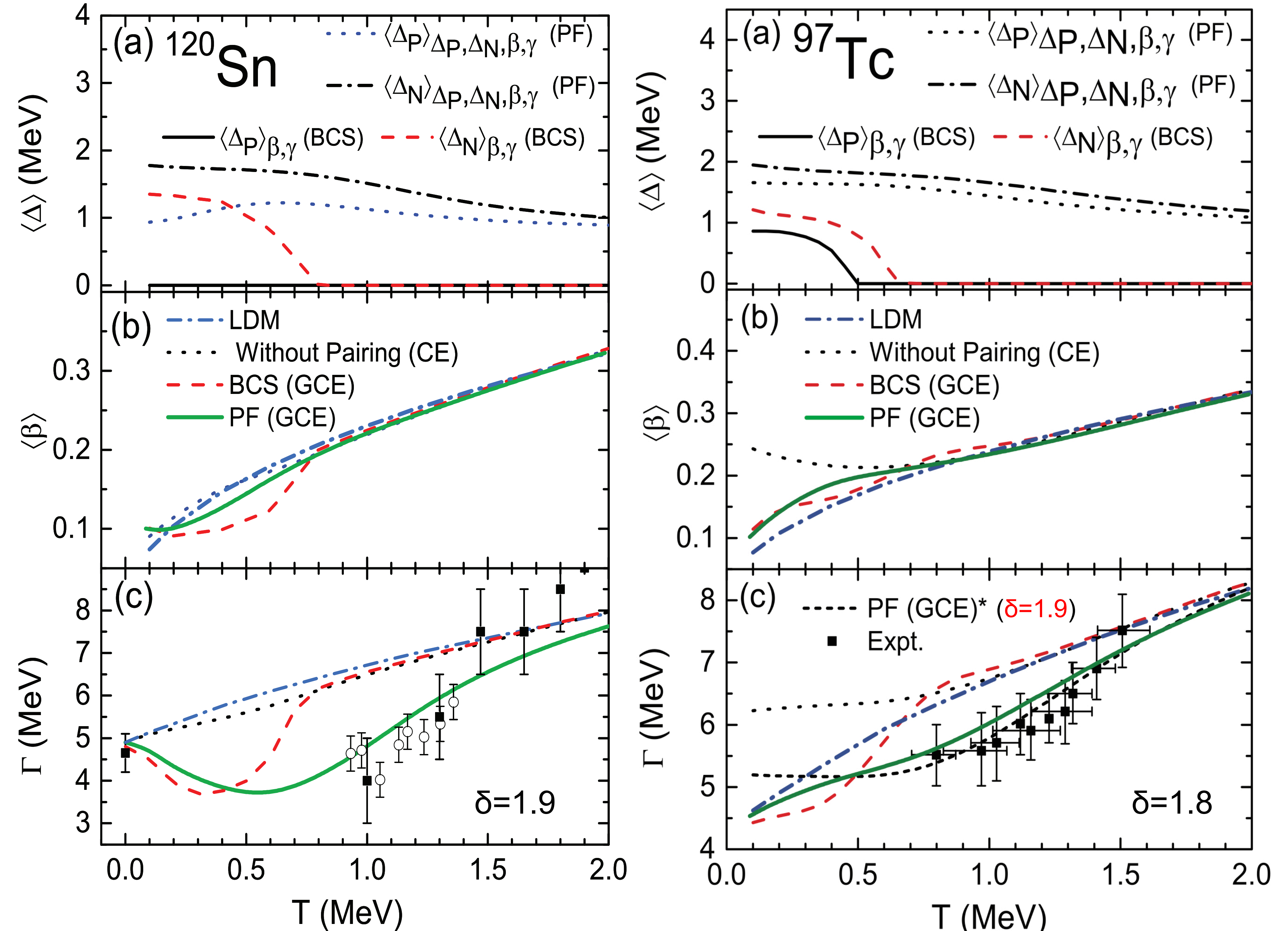
$$\Gamma_i \approx 0.026 E_i^{(1.8\sim 1.9)}$$

$$\sigma_m = 60 \frac{2}{\pi} \frac{NZ}{A} \frac{1}{\Gamma} (1+\alpha)$$

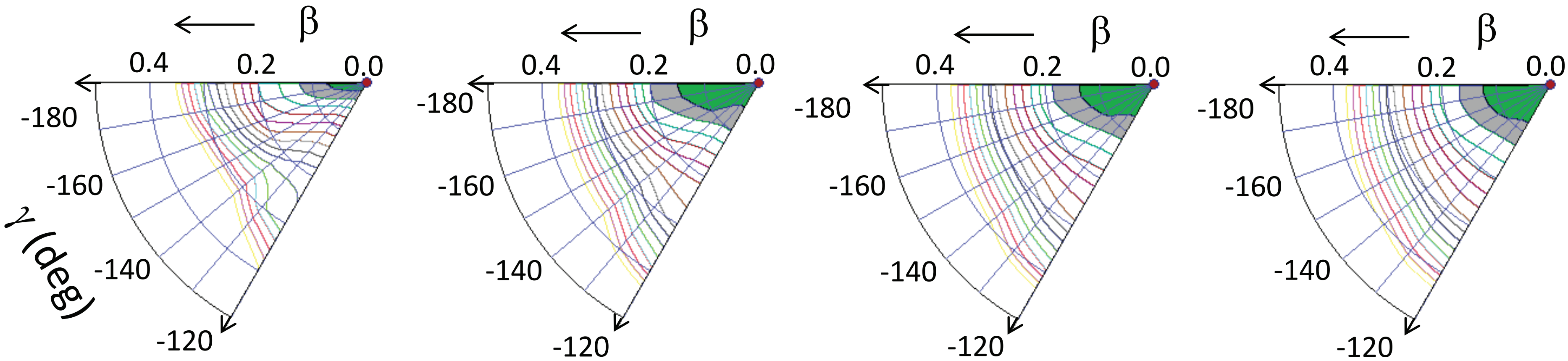
Expectation value of an observable including thermal shape and pairing fluctuations:

$$\langle \mathcal{O} \rangle_{\beta,\gamma,\Delta_P,\Delta_N} = \frac{\int \mathcal{D}[\alpha] \exp[-F_{\text{TOT}}(T;\beta,\gamma,\Delta_P,\Delta_N)/T]\mathcal{O}}{\int \mathcal{D}[\alpha] \exp[-F_{\text{TOT}}(T;\beta,\gamma,\Delta_P,\Delta_N)/T]}$$

$$\mathcal{D}[\alpha] = \beta^4 |\sin 3\gamma|\, d\beta\, d\gamma \;\; \Delta_P\, \Delta_N\, d\Delta_P\, d\Delta_N$$

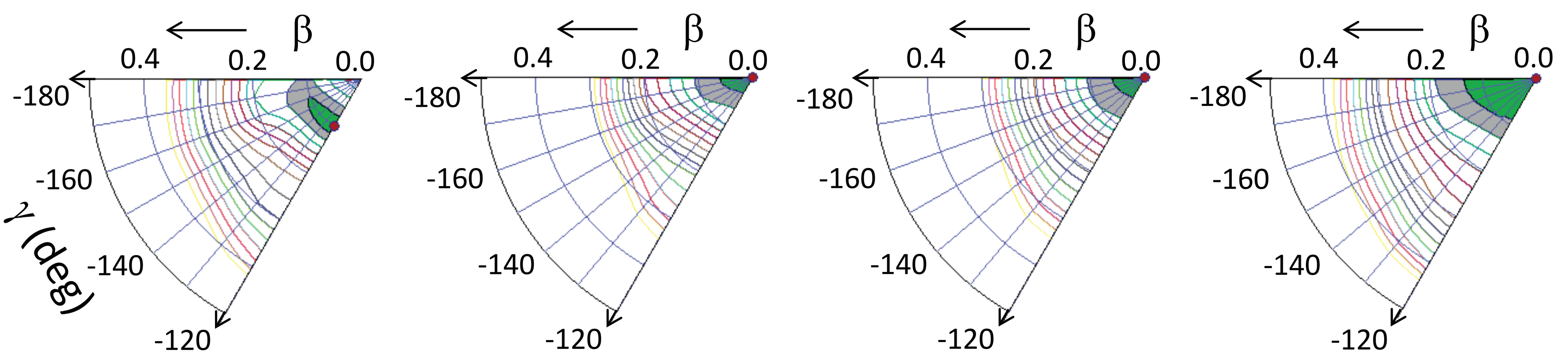


(a) 120Sn
⟨ΔP⟩ΔP,ΔN,β,γ (PF)
⟨ΔN⟩ΔP,ΔN,β,γ (PF)
⟨ΔP⟩β,γ (BCS)
⟨ΔN⟩β,γ (BCS)
⟨Δ⟩ (MeV)
(b)
LDM
Without Pairing (CE)
BCS (GCE)
PF (GCE)
⟨β⟩
(c)
δ=1.9
Γ (MeV)
T (MeV)
(a) 97Tc
⟨ΔP⟩ΔP,ΔN,β,γ (PF)
⟨ΔN⟩ΔP,ΔN,β,γ (PF)
⟨ΔP⟩β,γ (BCS)
⟨ΔN⟩β,γ (BCS)
⟨Δ⟩ (MeV)
(b)
LDM
Without Pairing (CE)
BCS (GCE)
PF (GCE)
⟨β⟩
(c)
PF (GCE)* (δ=1.9)
Expt.
δ=1.8
Γ (MeV)
T (MeV)



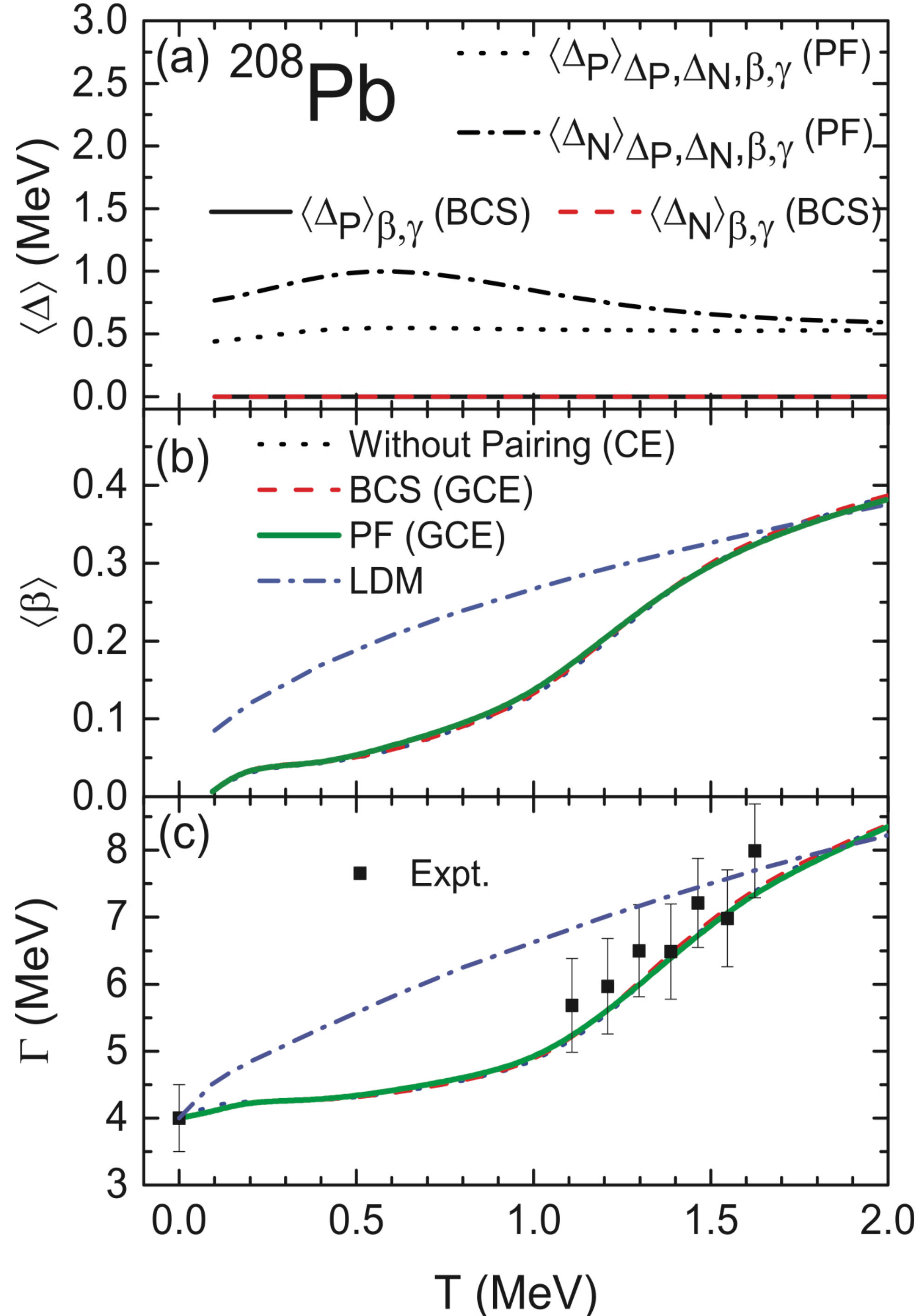
T = 0.1 MeV T = 0.4 MeV T = 0.6 MeV T = 0.8 MeV

^{120}Sn Without pairing



T = 0.1 MeV T = 0.4 MeV T = 0.6 MeV T = 0.8 MeV

^{120}Sn With pairing



(a) ^{208}Pb
$\langle\Delta_P\rangle_{\Delta_P,\Delta_N,\beta,\gamma}$ (PF)
$\langle\Delta_N\rangle_{\Delta_P,\Delta_N,\beta,\gamma}$ (PF)
$\langle\Delta_P\rangle_{\beta,\gamma}$ (BCS)
$\langle\Delta_N\rangle_{\beta,\gamma}$ (BCS)
$\langle\Delta\rangle$ (MeV)
(b)
Without Pairing (CE)
BCS (GCE)
PF (GCE)
LDM
$\langle\beta\rangle$
(c)
Expt.
Γ (MeV)
T (MeV)

PDM at T≠0 & J=M≠0

NDD, PRC 85 (2012) 064323

$$H = H_0 - \gamma \hat{M}, \quad \hat{M} = \sum_{k>0} m_k (N_k - N_{-k}), \quad \hat{N} = \sum_{k>0} (N_k + N_{-k}), \quad N_{\pm k} = a_{\pm k}^{\dagger} a_{\pm k},$$

$$H_0 = \sum_{k>0} (\varepsilon_k - \lambda) N_k + \sum_{k>0} (\varepsilon_k - \lambda) N_{-k} + \sum_q \omega_q Q_q^{+} Q_q + \sum_{k,k'>0,q} \mathcal{F}_{kk'}^{(q)} \left(a_k^{+} a_{k'} + a_{-k}^{+} a_{-k'} \right) \left(Q_q^{+} + Q_q \right)$$

$$G_q(E) = \frac{1}{2\pi} \frac{1}{E - \tilde{\omega}_q}, \quad \tilde{\omega} = \omega_q + P_q(E),$$

$$P_q(E) = \sum_{kk'} [\mathcal{F}_{kk'}^{(q)}]^2 \left[\frac{f_{k'}^{+} - f_k^{+}}{E - E_k^{-} + E_{k'}^{-}} + \frac{f_{k'}^{-} - f_k^{-}}{E - E_k^{+} + E_{k'}^{+}} \right].$$

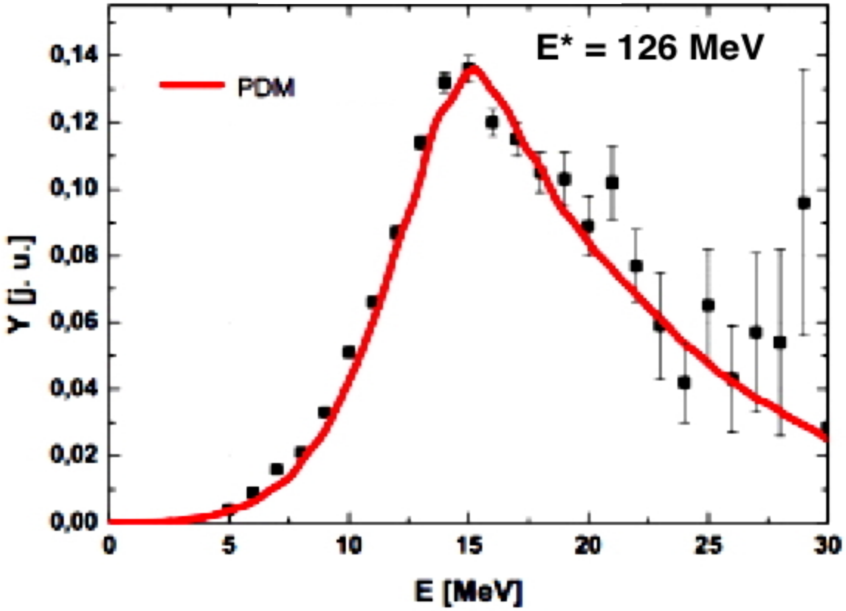
$$f_k^{\pm} = \left[\exp(E^{\mp}/T) + 1 \right]^{-1}, \quad E^{\mp} = \varepsilon_k - \lambda \mp \gamma m_k ,$$

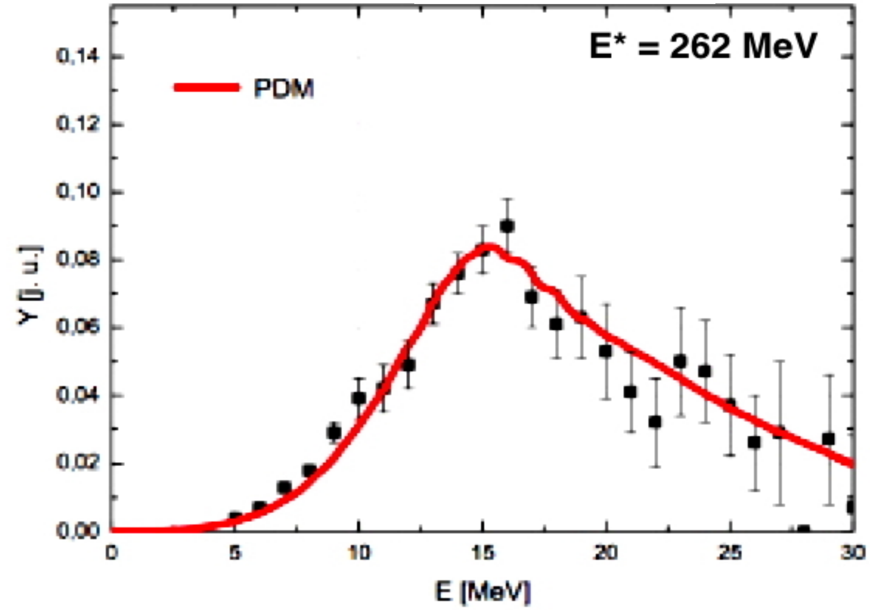
$$\gamma_q(\omega) = \pi \sum_{kk'} [\mathcal{F}_{kk'}^{(q)}]^2 [(f_{k'}^{+} - f_k^{+}) \delta(\omega - E_k^{-} + E_{k'}^{-}) + (f_{k'}^{-} - f_k^{-}) \delta(\omega - E_k^{+} + E_{k'}^{+})],$$

$\bar{T} = 2.04$ MeV
$\bar{J} = 38\,\hbar$

^{88}Mo

$\bar{T} = 3.06$ MeV
$\bar{J} = 38\,\hbar$



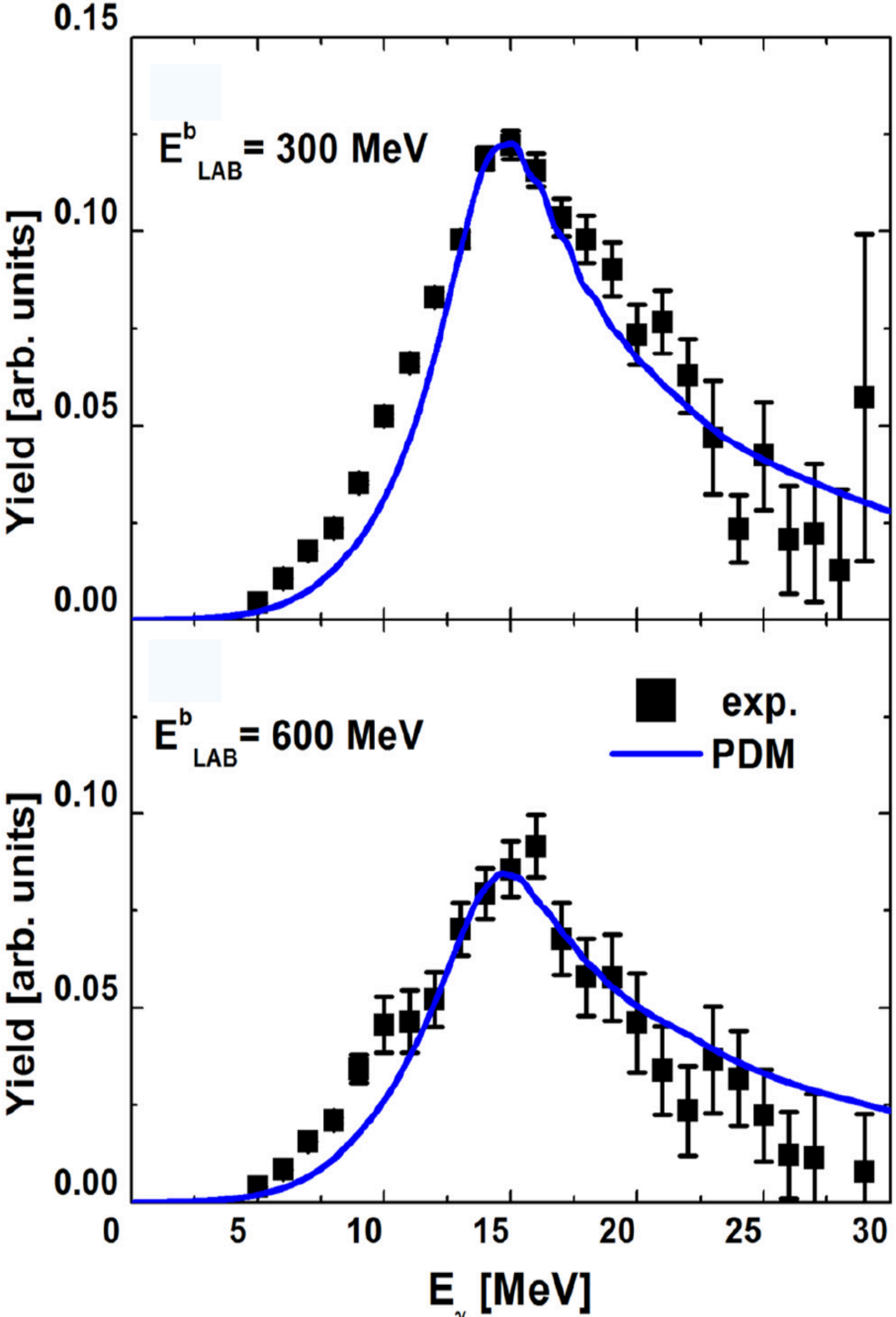


Ciemala, PhD thesis (2013)

M. Ciemala

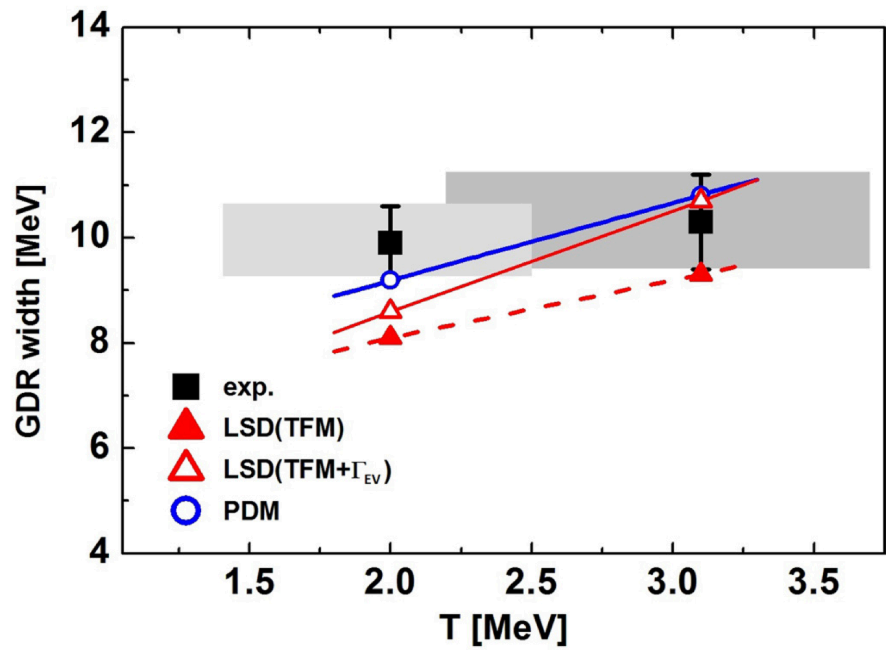
A. Maj

See alo NDD, Ciemala, Kmiecik, Maj, PRC 87 (2013) 054313



GDR in nuclei produced during evaporation from ^{88}Mo

Ciemala *et al.*, PRC 91 (2015) 0454313



Conclusions

1. Thermal pairing plays an important role in quenching the GDR width at low T, leading to a nealy constant GDR width at $T \leq 1$ MeV. This has been showed within the PDM and the TSFM that includes pairing fluctuations, whose predictions agree well with the most recent experimental systematics. This means the TSFM can describe correctly the GDR width at low T even in open shell nuclei if thermal pairing is properly included.

2. The fact that both models show the same effect of thermal paiting means that it is robust and model independent.

3. Shell effects is crucial to describe the GDR width at low T only in closed shell nuclei. In open shell nuclei shell effects are negligible.

4. The PDM also successfully describes the GDR in hot nuclei at high angular momentum when pairing effect vanishes or negligible.