Gamma strength functions for (n,γ) reactions based on relativistic density-dependent point coupling interaction

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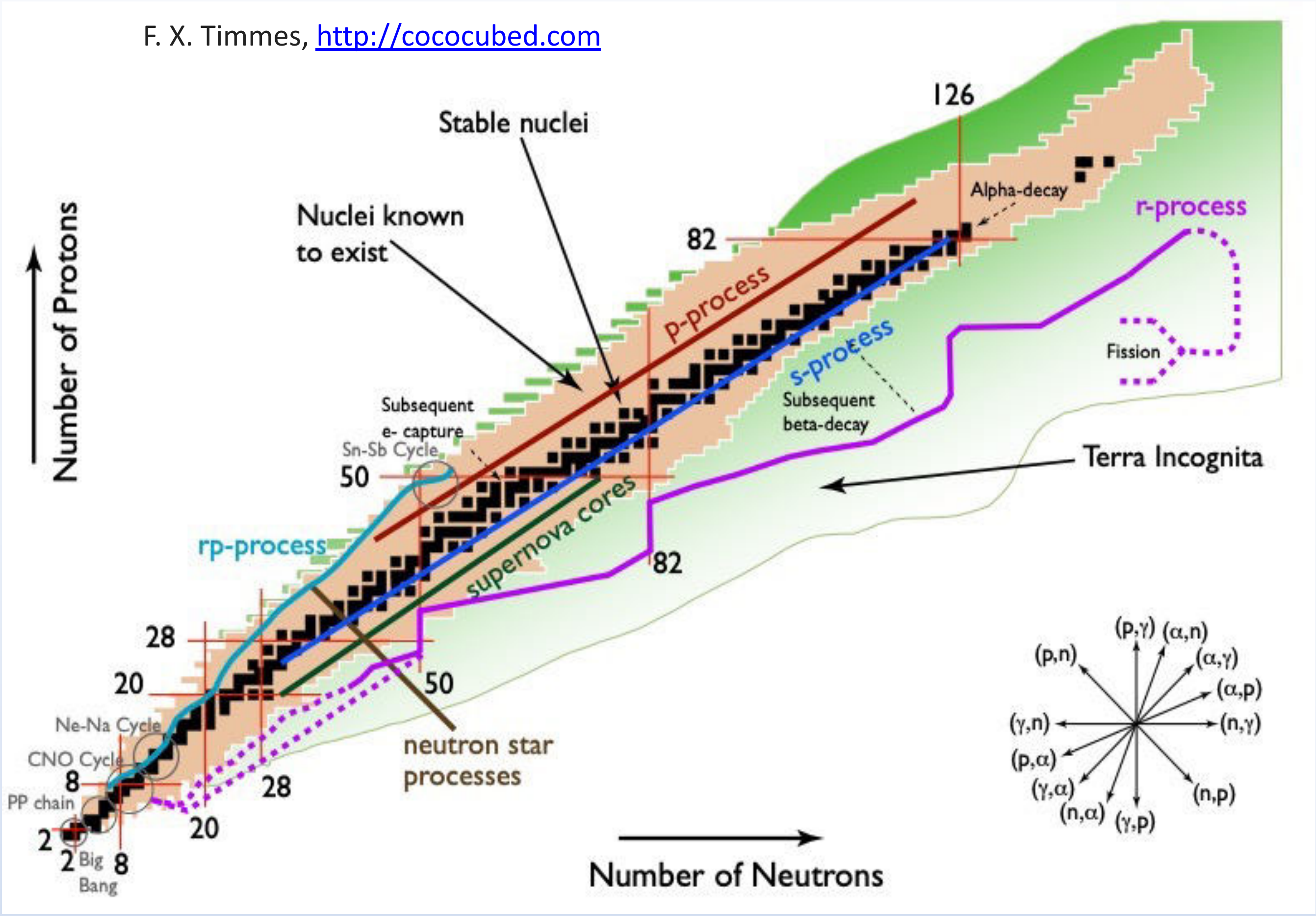
- ***Motivation***
- ***Cross section***
- ***FT-RQRPA***
- ***Calculation of strength function***
- ***Strength functions comparison with different models***
- ***Conclusions***

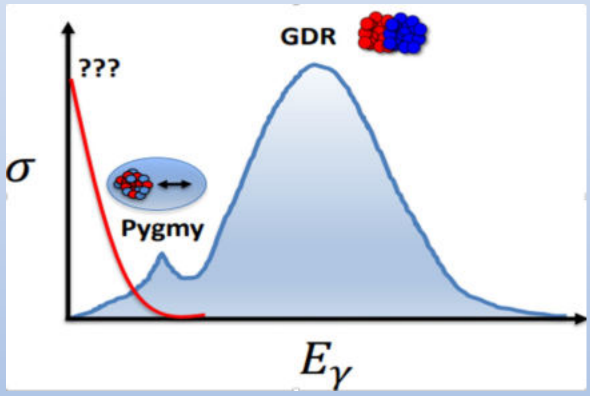
Synthesis of Chemical Elements in the Universe

- r-process
- Electromagnetic excitation

- (n,γ) reaction rates depend on electromagnetic transitions

Giant Dipole Resonance (GDR)





- Neutron rich nuclei: low-energy Pygmy Dipole Strength

Photon Strength Function

Photon Strength Function (PSF) is essential for description of (n,$\boldsymbol{\gamma}$) and ($\boldsymbol{\gamma}$,n) reactions.

$f_{Xl}(E_\gamma) \longrightarrow$

- Photon strength function of transmission of gamma ray at an energy $\mathbf{E_\gamma}$

$X \longrightarrow$

- E(Electric) or M(Magnetic) transition

$l \longrightarrow$

- Transition multipolarity. For dipole *l*=1

$f_{E1}(E_\gamma) >> f_{E2}(E_\gamma)$ $\qquad$ $f_{E1}(E_\gamma) >> f_{M1}(E_\gamma)$

PSF

Upwards $\vec{f}_{E1}(E_\gamma)$

Downward $\overleftarrow{f}_{E1}(E_\gamma)$

- **Gamma absorption : (γ,n)**
- **$E_\gamma > S_n$**

- **Gamma emission : (n,γ)**
- **$E_\gamma < S_n$**

Essential relation for the upward PSF

$$\vec{f}_{Xl}(E_\gamma) = \kappa_{Xl} \frac{\sigma_{Xl}}{E_\gamma^{2l-1}}$$

$$\kappa_{Xl} = \frac{1}{(2l+1)\pi^2\hbar^2c^2}$$

- Determined by experimental photo absorption cross section σ_{xl} (summed over all spins and parities).

Relation between photon transmission coefficient and downward PSF

- Statistical Hauser-Feshbach model includes photon transmission coefficients, for the determination of the competition photon emission with emission of particles.

$$\sigma_{(n,\gamma)}^{\mu\nu}(E_{i,n}) = \frac{\pi\hbar^2}{2M_{i,n}E_{i,n}} \frac{1}{(2J_i^{\mu}+1)(2J_n+1)} \sum_{J,\pi}(2J+1)\frac{T_n^{\mu}T_{\gamma}^{\nu}}{T_{\text{tot}}},$$

$$T_{\gamma}(E,J,\pi) = \sum_{\nu=0}^{\kappa} T_{\gamma}\left(E,J,\pi;E_m^{\nu},J_m^{\nu},\pi_m^{\nu}\right) + \int_{E_m^{\kappa}}^{E} \sum_{J_m,\pi_m} T_{\gamma}(E,J,\pi;E_m,J_m,\pi_m)\rho(E_m,J_m,\pi_m)\,dE_m,$$

Hauser–Feshbach

$$T_{\text{XL}}\left(E,J,\pi,E^{\nu},J^{\nu},\pi^{\nu}\right) = T_{\text{XL}}(E,E_{\gamma}) = 2\pi E_{\gamma}^{2L+1} f_{\text{XL}}(E,E_{\gamma}).$$

In general, the strength function depends on the initial and final states. However, in practical it is adopted "Brink-Axel Hypothesis" assumes strength function is independent of the detailed structure of initial state.

Brink-Axel hypothesis

$$f_{E1}(E_\gamma) = \vec{f}_{E1}(E_\gamma) = \overleftarrow{f}_{E1}(E_\gamma)$$

Models For PSF

Phenomenological Approaches

1. Brink-Axel

$$f_{Xl}(E_\gamma) = \kappa_{Xl} \frac{\sigma_{Xl} E_\gamma \Gamma_{Xl}^2}{(E_\gamma^2 - E_{Xl}^2)^2 + E_\gamma^2 \Gamma_{Xl}^2}$$

σ_{xl}: Strength of giant resonance,

E_{xl}: Energy of giant resonance,

Γ_{xl}: width of giant resonance

2. Kopecky-Uhl

$$f_{E1}(E_\gamma, T) = \kappa_{E1}\left[\frac{E_\gamma \tilde{\Gamma}_{E1}(E_\gamma)}{(E_\gamma^2 - E_{E1}^2)^2 + E_\gamma^2 \tilde{\Gamma}_{E1}(E_\gamma^2)} + \frac{0.7\Gamma_{E1} 4\pi^2 T^2}{E_{E1}^3}\right]\sigma_{E1}\Gamma_{E1}$$

Energy dependent damping width

$$\tilde{\Gamma}_{E1}(E_\gamma) = \Gamma_{E1} \frac{E_\gamma^2 + 4\pi^2 T^2}{E_{E1}^2}$$

Temperature

$$T = \sqrt{\frac{E_n + S_n - \Delta - E_\gamma}{\alpha(S_n)}}$$

S_n: neutron separation en E_n:neutron incident energy

Δ: parity correction (level density)

α: level density parameters at S_n

Microscopic Approceses

3. HF-BCS Khan-Goriely 2002

$$f_L(E, E_i, \gamma_i) = \frac{2}{\pi} \frac{\gamma_i E^2}{(E^2 - E_i)^2 - \gamma_i^2 E^2}$$

4. HFB Khan-Goriely 2004

$$f_L(E, E^{'}) = \frac{1}{2\pi} \frac{\Gamma(E)}{(E' - E - \Delta(E))^2 + \frac{\Gamma(E)}{4}}$$

5. RMF-T Daoutidis-Goriely 2012

$$f_L(E, E^{'}) = \frac{2}{\pi} \frac{\Gamma(E)E^2}{[E^2 - (E' - \Delta(E'))^2]^2 + \Gamma(E)^2 E^2}$$

6. Gogny HFB Goriely 2018

$$L(E, W) = \frac{1}{\pi} \frac{\Gamma(E)E^2}{[E^2 - (W - \Delta^2)]^2 + \Gamma(E)^2 E^2}$$

7. FT-QRPA

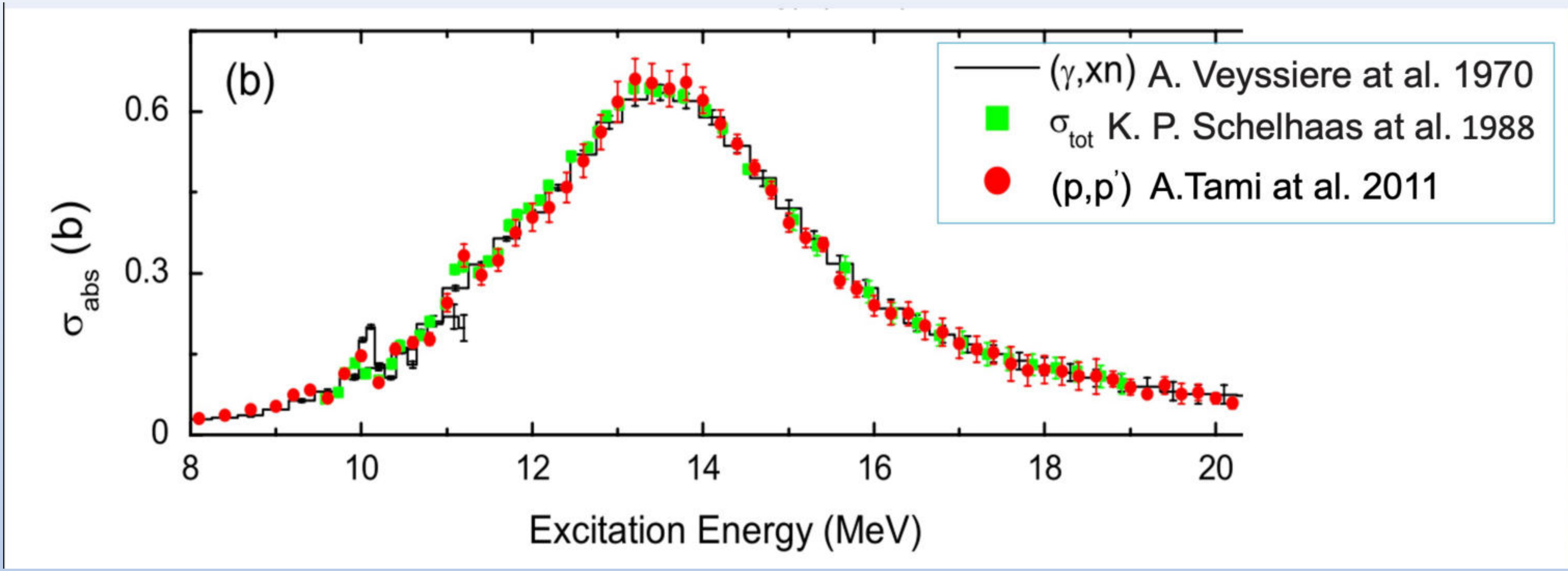
$$f_L(E, E^{'}) = \frac{2}{\pi} \frac{\Gamma(E)E^2}{[E^2 - (E' - \Delta(E'))^2]^2 + \Gamma(E)^2 E^2}$$

Photo-absorption cross section

$$\sigma(E) = \frac{16\pi^3 e^2}{9\hbar c} E\, S_{\mathrm{RPA}}(E)\ [\mathrm{fm}^2]$$
$$= 4.022\, E\, S_{\mathrm{RPA}}(E)\ [\mathrm{mb}].$$

$$f_L(E, E') = \frac{2}{\pi} \frac{\Gamma(E) E^2}{[E^2 - (E' - \Delta(E')^2]^2 + \Gamma(E)^2 E^2}$$

$$S(E) = \int_0^\infty dE' S_{\mathrm{RPA}}(E') f_L(E, E')$$

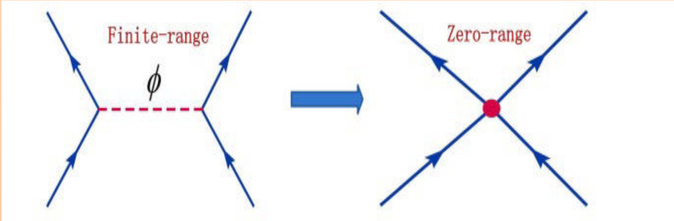


A, Tami at al. PRL 107, 062502 (2011)

- To study electric dipole transitions we used Finite Temperature Relativistic Quasiparticle Random Phase Approximation (FT-RQRPA) (A.Kaur at al. PRC **109**, 014314, 2024) based on EDF.

FT-RQRPA

- FT-RQRPA is used to describe to ground state and excitation properties of nuclei.



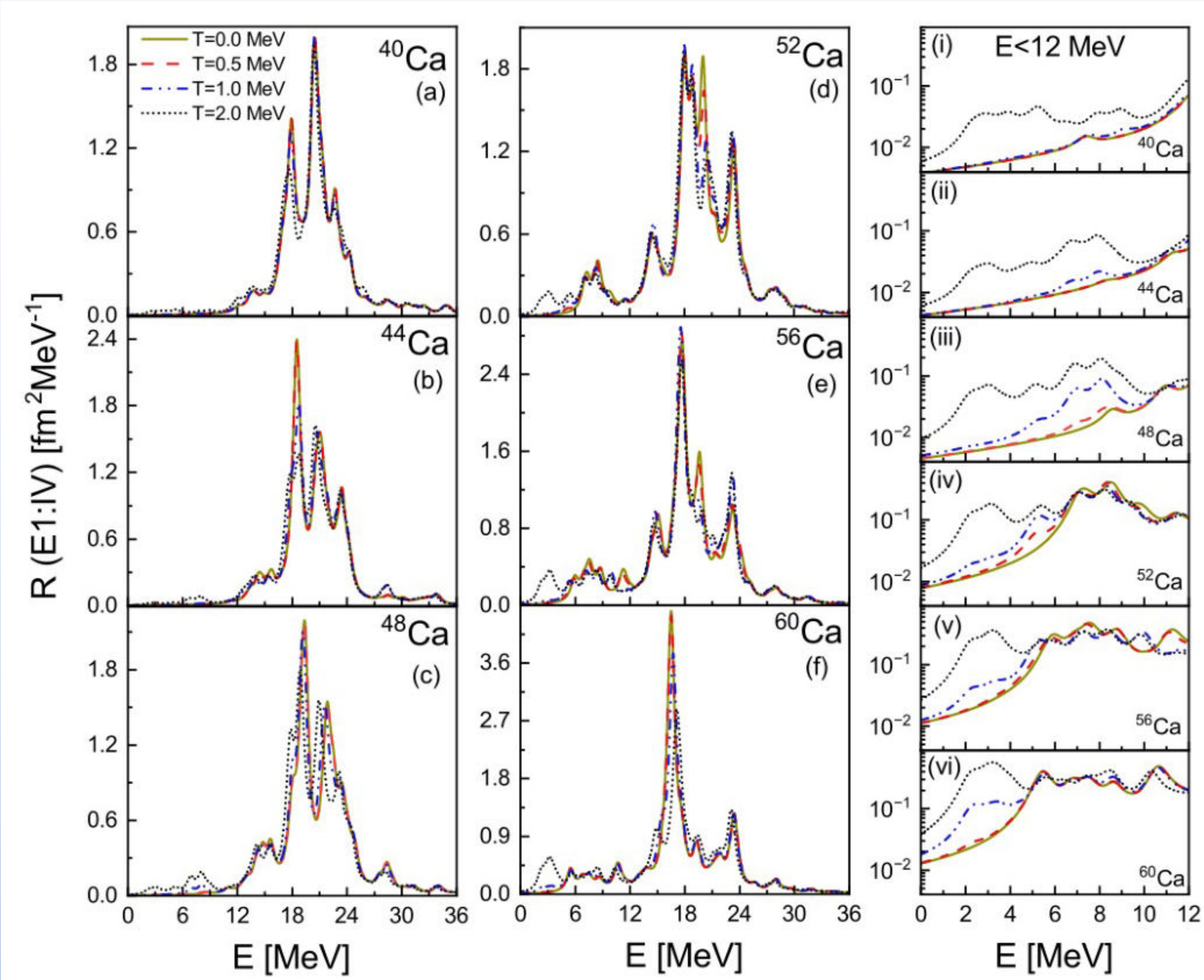
- Based on relativistic point-coupling interaction.

The finite temperature RQRPA matrix

$$\begin{pmatrix} \widetilde{C} & \widetilde{a} & \widetilde{b} & \widetilde{D} \\ \widetilde{a}^{+} & \widetilde{A} & \widetilde{B} & \widetilde{b}^{T} \\ -\widetilde{b}^{+} & -\widetilde{B}^{*} & -\widetilde{A}^{*} & -\widetilde{a}^{T} \\ -\widetilde{D}^{*} & -\widetilde{b}^{*} & -\widetilde{a}^{*} & -\widetilde{C}^{*} \end{pmatrix} \begin{pmatrix} \widetilde{P} \\ \widetilde{X} \\ \widetilde{Y} \\ \widetilde{Q} \end{pmatrix} = E_w \begin{pmatrix} \widetilde{P} \\ \widetilde{X} \\ \widetilde{Y} \\ \widetilde{Q} \end{pmatrix}$$

A.Kaur at al. PRC **109**, 014314 (2024)

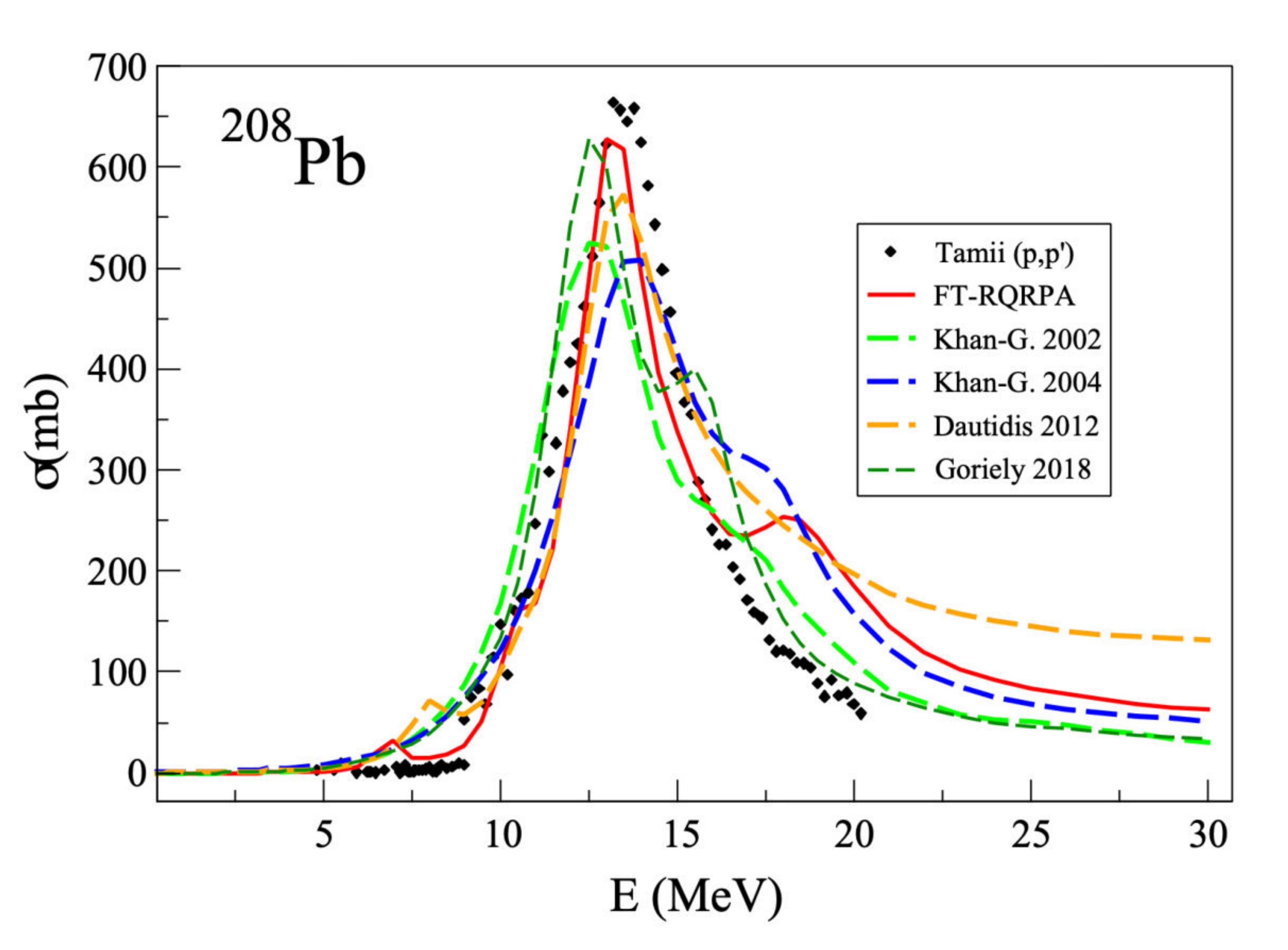
E_w : the excitation energies
$P^{\sim}, X^{\sim}, Y^{\sim}, Q^{\sim}$: *eigenvectors*



- The isovector dipole strength distributions for $^{40-60}$Ca isotopic chain. The calculations are performed using the FT-RQRPA with DD-PCX interaction at temperatures $T = 0$, 0.5, 1, and 2 MeV.

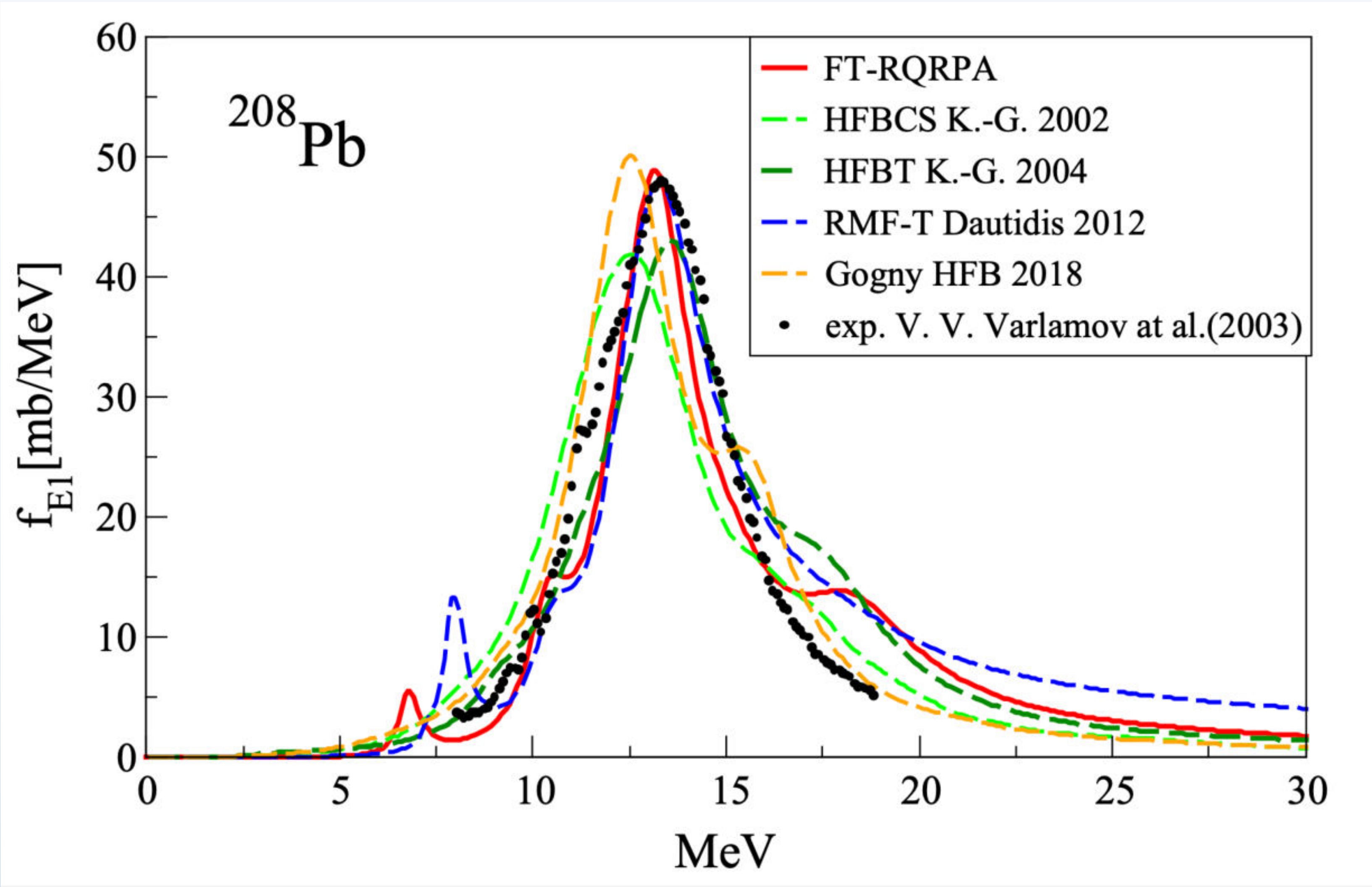
A. Kaur at al. P. R. C. **109**, 014314 (2024)

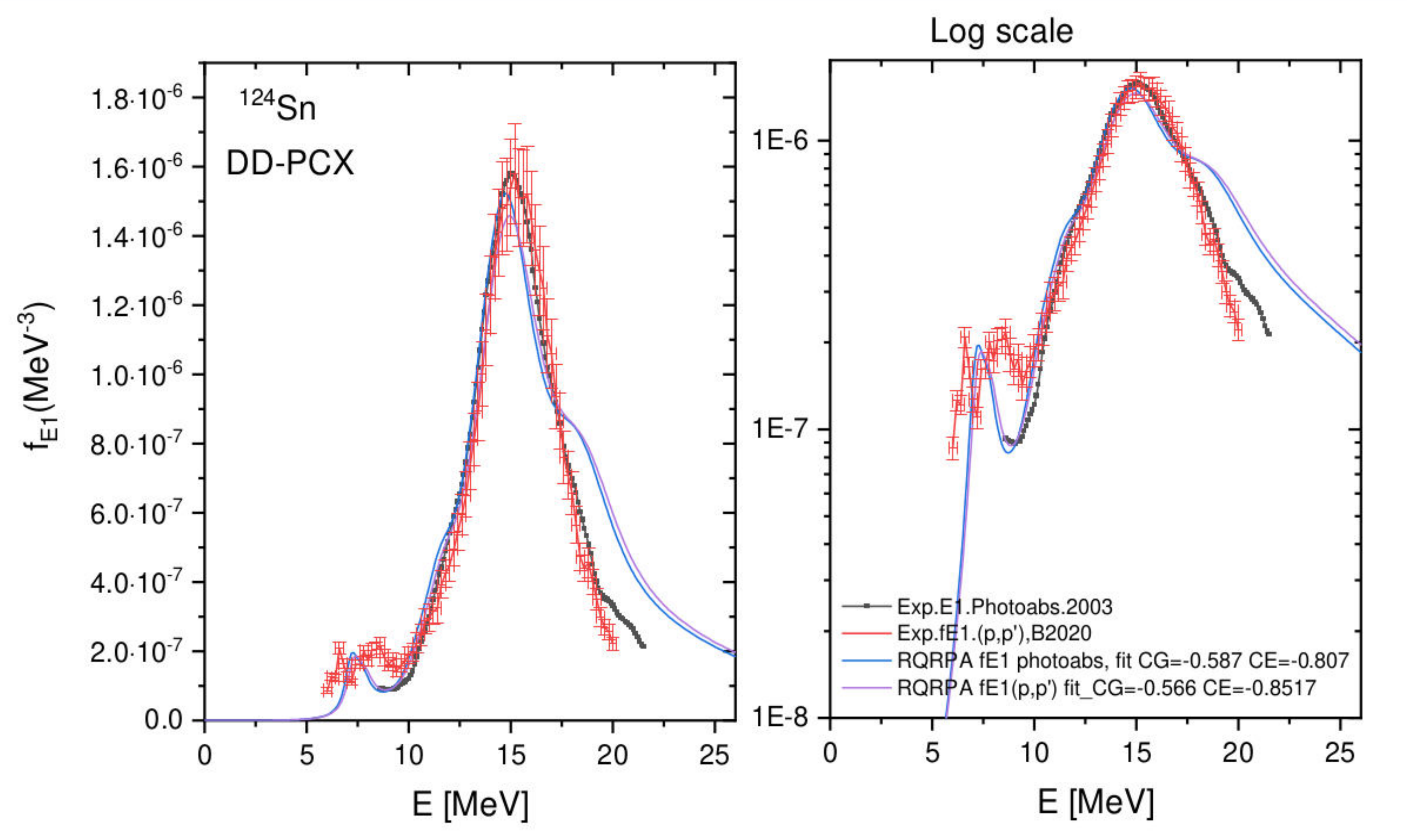
FT-RQRPA photo-absorption cross section



Comparison of strength functions

- T=0 limit to benchmark the model with experimental data.





Log scale
^{124}Sn
DD-PCX
f_{E1}(MeV^{-3})
1.8·10^{-6}
1.6·10^{-6}
1.4·10^{-6}
1.2·10^{-6}
1.0·10^{-6}
8.0·10^{-7}
6.0·10^{-7}
4.0·10^{-7}
2.0·10^{-7}
0.0
1E-6
1E-7
1E-8
0
5
10
15
20
25
E [MeV]
Exp.E1.Photoabs.2003
Exp.fE1.(p,p'),B2020
RQRPA fE1 photoabs, fit CG=-0.587 CE=-0.807
RQRPA fE1(p,p') fit_CG=-0.566 CE=-0.8517

A, Kaur (2024)

CONCLUSIONS

- We have developed microscopic model for gamma strength function based on REDF.
- The results of model calculations for the strength functions and cross sections are compared with experimental data and other theoretical approaches to validate present approach.
- Focusing on the intricate relationship between neutron-induced reactions and photon emission within the relativistic microscopic framework, this study will further investigate the temperature-dependent characteristics of the gamma strength functions.
- The implementation of a temperature-dependent gamma strength function in the nuclear reaction code (Talys) is considered for the future systematic calculations of (n,γ) reactions.

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