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Investigating finite-temperature dependence of electromagnetic dipole transitions in nuclei

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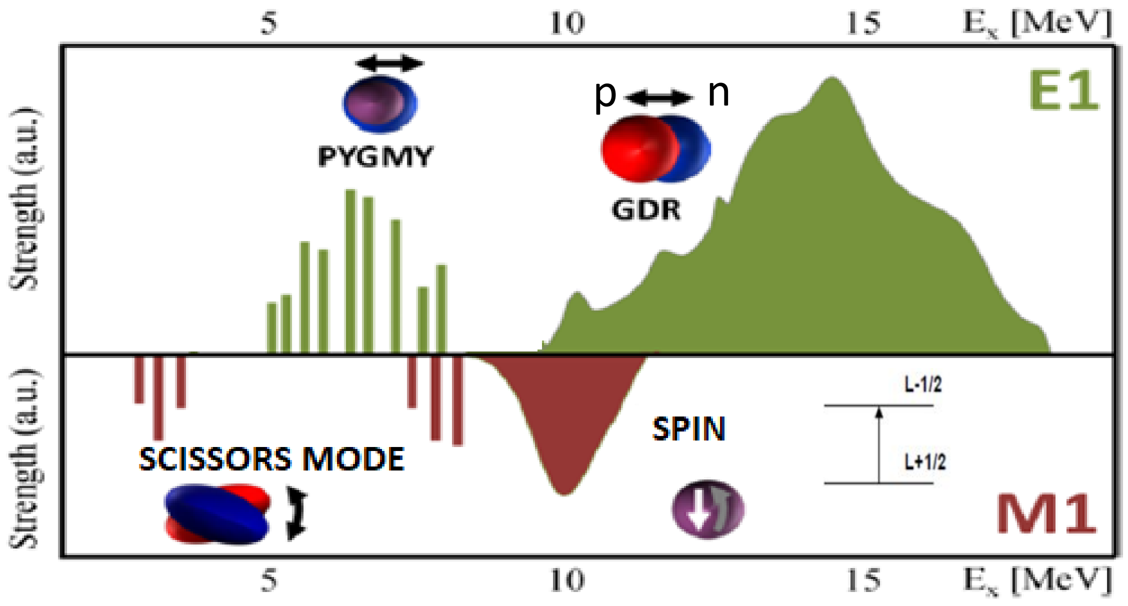
Electromagnetic dipole response of a nucleus

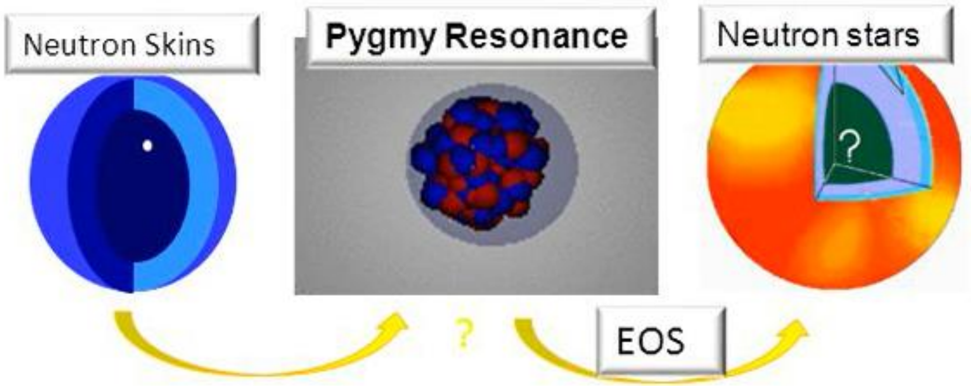


D. Budker et al. https://onlinelibrary.wiley.com/doi/full/10.1002/andp.202100284

- ✓ *Give information on the fundamental properties of nuclei.*
- ✓ *Provide insight into the behaviour of nuclear matter under extreme conditions.*

Astrophysical Interest

- ✓ *Pygmy E1 strengths → Provides information about neutron skin and symmetry energy in EOS → Relevant for modelling of neutron stars.*
- ✓ *Impact the gamma strength functions, reaction rates and r-process nucleosynthesis in the stellar environment.*



Electromagnetic dipole response of a nucleus

- ✓ Nuclei exist at high temperatures in stellar environments.
- ✓ Experimental studies are available on GDR at finite temperature mainly using fusion-evaporation reaction forming hot and rotating compound nucleus (CN).
- ✓ No experiments so far have searched the PDR mode at finite temperature.

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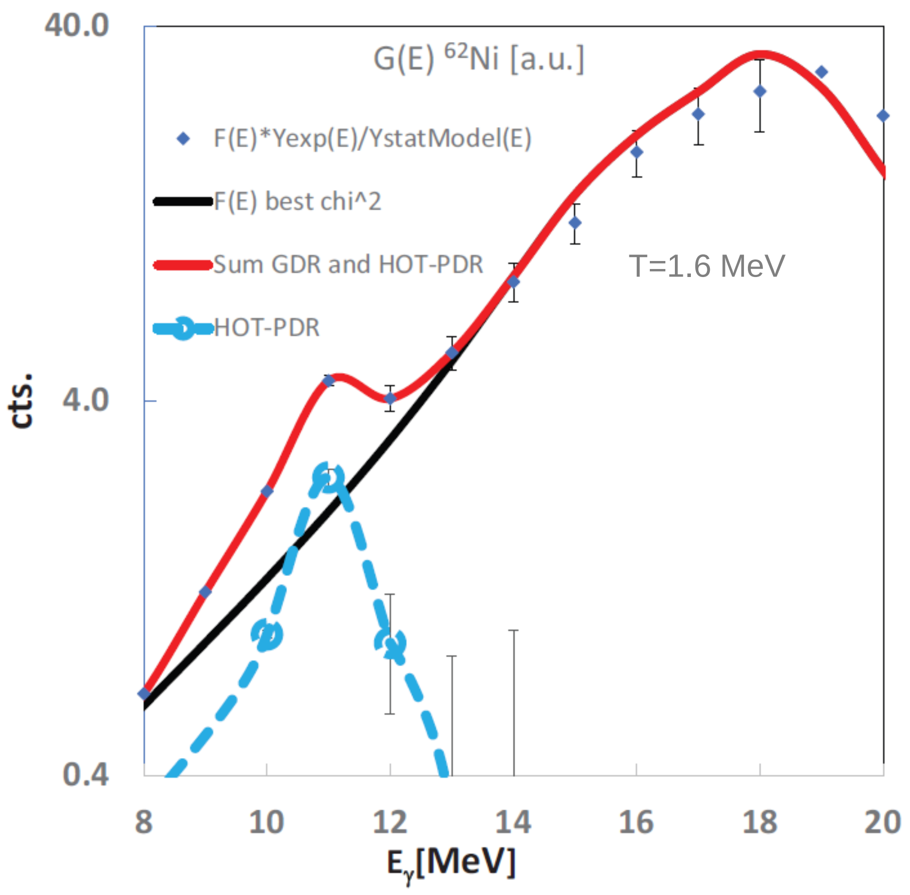
Recent Experimental Work in Progress in Ni isotopes

O. Wieland, Comex7; (https://agenda.infn.it/event/21964)

- ✓ Some evidence of a possible extra strength is observed in neutron-rich nucleus.
- ✓ Appears not in N=Z nucleus but (only) in N=Z+xn nucleus at high excitation energy (CN temperature up to ≈2 MeV).
- ✓ Located below GDR and with Strength around 2-4% of total GDR-EWSR.
- ✓ Not from deformation (angular momentum) effects.

Result on search of Hot Pygmy in ^{62}Ni



*O. Wieland et al., IL NUOVO CIMENTO **47 C** (2024) 24*

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Electromagnetic transitions are sensitive towards the extreme conditions of

- ➢ **Temperature**
- ➢ **Isospin**

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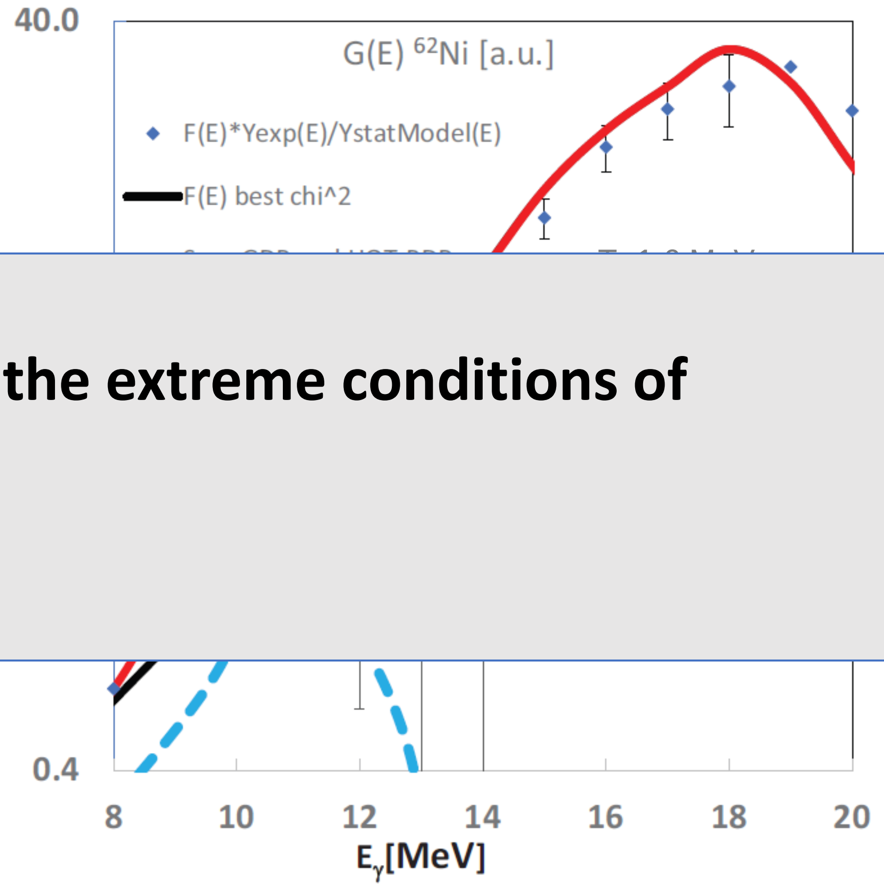


*O. Wieland et al., IL NUOVO CIMENTO **47 C** (2024) 24*

Relativistic nuclear energy density functional (RNEDF)

The point-coupling RNEDF determined from the Lagrangian density

$$\mathcal{L}_{PC} = \bar{\psi}(i\gamma.\partial \ - m)\psi\ n$$
$$-\frac{1}{2}\alpha_S(\rho)(\bar{\psi}\psi)(\bar{\psi}\psi) - \frac{1}{2}\alpha_V(\rho)(\bar{\psi}\gamma^{\mu}\psi)(\bar{\psi}\gamma_{\mu}\psi)$$
$$-\frac{1}{2}\alpha_{TV}(\rho)(\bar{\psi}\ \vec{\tau}\gamma^{\mu}\psi)(\bar{\psi}\vec{\tau}\gamma_{\mu}\psi)$$
$$-\frac{1}{2}\delta_S(\partial_{\nu}\bar{\psi}\psi)(\partial^{\nu}\bar{\psi}\psi)$$
$$- e\bar{\psi}\ \gamma.\mathrm{A}\frac{1-\tau_3}{2}\psi$$

- ❑ *Free nucleon terms*
- ❑ *Isoscalar-scalar, isoscalar-vector, isovector-vector interaction terms*
- ❑ *Derivative term (effects of finite range interaction)*
- ❑ *Electromagnetic interaction*

- By integrating the Hamiltonian density over the r-space we obtain the total energy

$$E_{RMF} = \int d^3r\mathcal{H}(r)$$

[T. Nikšić et al., Comput. Phys. Commun. 185, 1808 (2014)]
[DD-PCX: E. Yüksel et al., Phys. Rev. C 99, 034318 (2019)]

- **Nuclear state properties** are described within finite temperature Hartree-Bardeen-Cooper-Schrieffer (FT-HBCS) framework supplemented with pairing correlations (Separable Pairing force)

[A. L. Goodman, Nucl. Phys. A 352, 30 (1981)]

- **Collective excitations in Nuclei**: Relativistic Quasiparticle Random Phase Approximation (RQRPA)

HBCS+RQRPA are prominent tools for calculations.
Finite temperature calculations needs extra work!

- At finite temperature (FT), the occupation probabilities of single particle states are given by

$$n_i = v_i^2(1 - f_i) + u_i^2 f_i$$

- The T-dependent Fermi-Dirac distribution function is obtained as

$$f_i = [1 + \exp(E_i/k_B T)]^{-1}$$

Finite temperature RQRPA

- The starting point in the Equation of Motion method is definition of a suitable Excitation operator

$$\Gamma_\nu^\dagger = \sum_{a\geq b} X_{ab}^\nu a_a^\dagger a_b^\dagger - Y_{ab}^\nu a_b a_a + P_{ab}^\nu a_a^\dagger a_b - Q_{ab}^\nu a_b^\dagger a_a$$

Red terms contribute at T>0

two-quasiparticle creation/destruction and one-quasiparticle creation/destruction operators.

- With $|BCS\rangle$ as the approximate thermal vacuum the equation of motion can be written as

$$\langle BCS|[\delta\Gamma, H, \Gamma_\nu^\dagger]|BCS\rangle = E_\nu \langle BCS|[\delta\Gamma, \Gamma_\nu^\dagger]|BCS\rangle$$

$$f_{a(b)} = [1+\exp(E_{a(b)}/k_B T)]^{-1}$$

- The FT-RQRPA equations are derived as

$$\tilde{A}_{abcd} = \sqrt{1-f_a-f_b} A'_{abcd} \sqrt{1-f_c-f_d} + (E_a+E_b)\delta_{ac}\delta_{bd}$$

$$\tilde{B}_{abcd} = \sqrt{1-f_a-f_b} B_{abcd} \sqrt{1-f_c-f_d}$$

$$\tilde{C}_{abcd} = \sqrt{f_b-f_a} C'_{abcd} \sqrt{f_d-f_c} + (E_a-E_b)\delta_{ac}\delta_{bd}$$

$$\tilde{D}_{abcd} = \sqrt{f_b-f_a} D_{abcd} \sqrt{f_d-f_c}$$

$$A'_{abcd} = (u_a u_b u_c u_d + v_a v_b v_c v_d) V^{pp}_{abcd} + (u_a v_b u_c v_d + v_a u_b v_c u_d) V^{ph}_{a\bar{d}\bar{b}c} - (-1)^{j_c+j_d+J}(u_a v_b v_c u_d + v_a u_b u_c v_d) V^{ph}_{a\bar{c}\bar{b}d}$$

$$C'_{abcd} = (u_a v_b u_c v_d + v_a u_b v_c u_d) V^{pp}_{a\bar{b}c\bar{d}} + (u_a u_b u_c u_d + v_a v_b v_c v_d) V^{ph}_{adbc} + (-1)^{j_c+j_d+J}(u_a u_b v_c v_d + v_a v_b u_c u_d) V^{ph}_{a\bar{c}\bar{b}\bar{d}}$$

- H. Sommermann, Ann. of Phys. 151, 163 (1983)
- E. Yüksel et al., Phys. Rev. C 96, 024303 (2017)
- A. Kaur, E. Yüksel, N. Paar, Phys. Rev. C 109, 014314 (2024)

Finite temperature RQRPA

- The FT-RQRPA equations can be combined into a single matrix

Red terms contribute at T>0

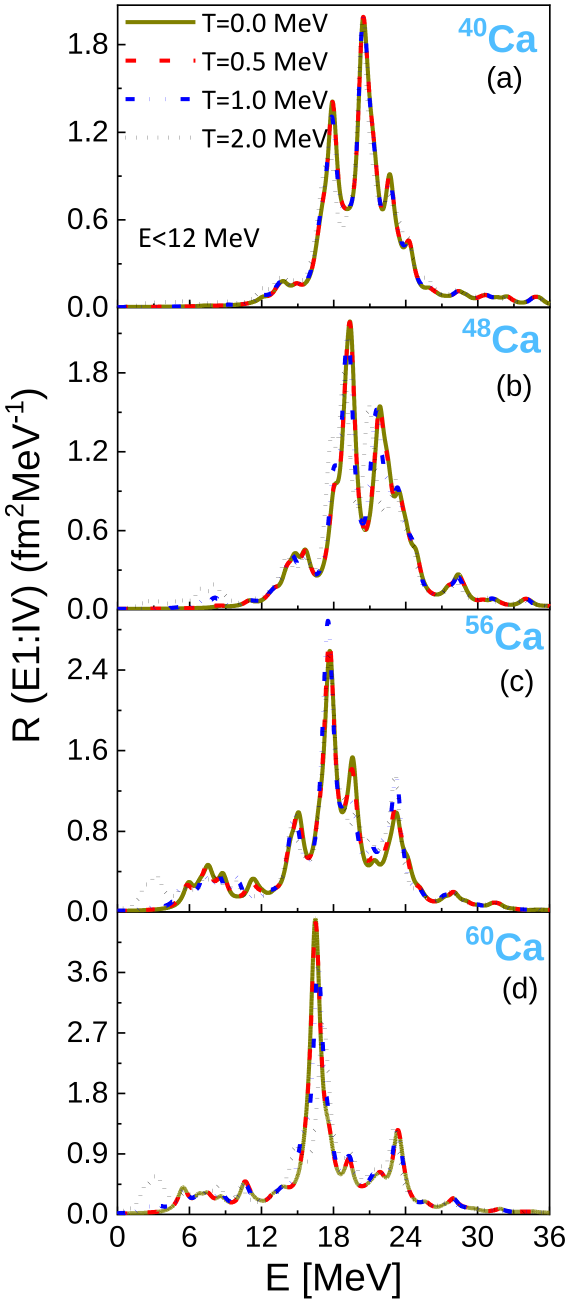
$$\begin{pmatrix} \tilde{C} & \tilde{a} & \tilde{b} & \tilde{D} \\ \tilde{a}^{+} & \tilde{A} & \tilde{B} & \tilde{b}^{T} \\ -\tilde{b}^{+} & -\tilde{B}^{*} & -\tilde{A}^{*} & -\tilde{a}^{T} \\ -\tilde{D}^{*} & -\tilde{b}^{*} & -\tilde{a}^{*} & -\tilde{C}^{*} \end{pmatrix} \begin{pmatrix} \tilde{P} \\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

In the limit $T \to 0$
FT-RQRPA $\to$ RQRPA

- The reduced transition probability is

$$B(TJ) = \left|\langle \omega \| \hat{F}_J \| \tilde{0} \rangle\right|^2$$
$$= \left| \sum_{c \geq d} \left\{ \begin{aligned} &\left(\tilde{X}^{\omega}_{cd} + (-1)^{j_c - j_d + J} \tilde{Y}^{\omega}_{cd}\right)\left(u_c v_d + (-1)^J v_c u_d\right)\sqrt{1 - f_c - f_d} \\ &+ \left(\tilde{P}^{\omega}_{cd} + (-1)^{j_c - j_d + J} \tilde{Q}^{\omega}_{cd}\right)\left(u_c u_d - (-1)^J v_c v_d\right)\sqrt{f_d - f_c} \end{aligned} \right\} \langle c \| \hat{F}_J \| d \rangle \right|^2$$

Isovector E1 response at finite temperature



Calculations are performed using DD-PCX interaction

At T=0 MeV

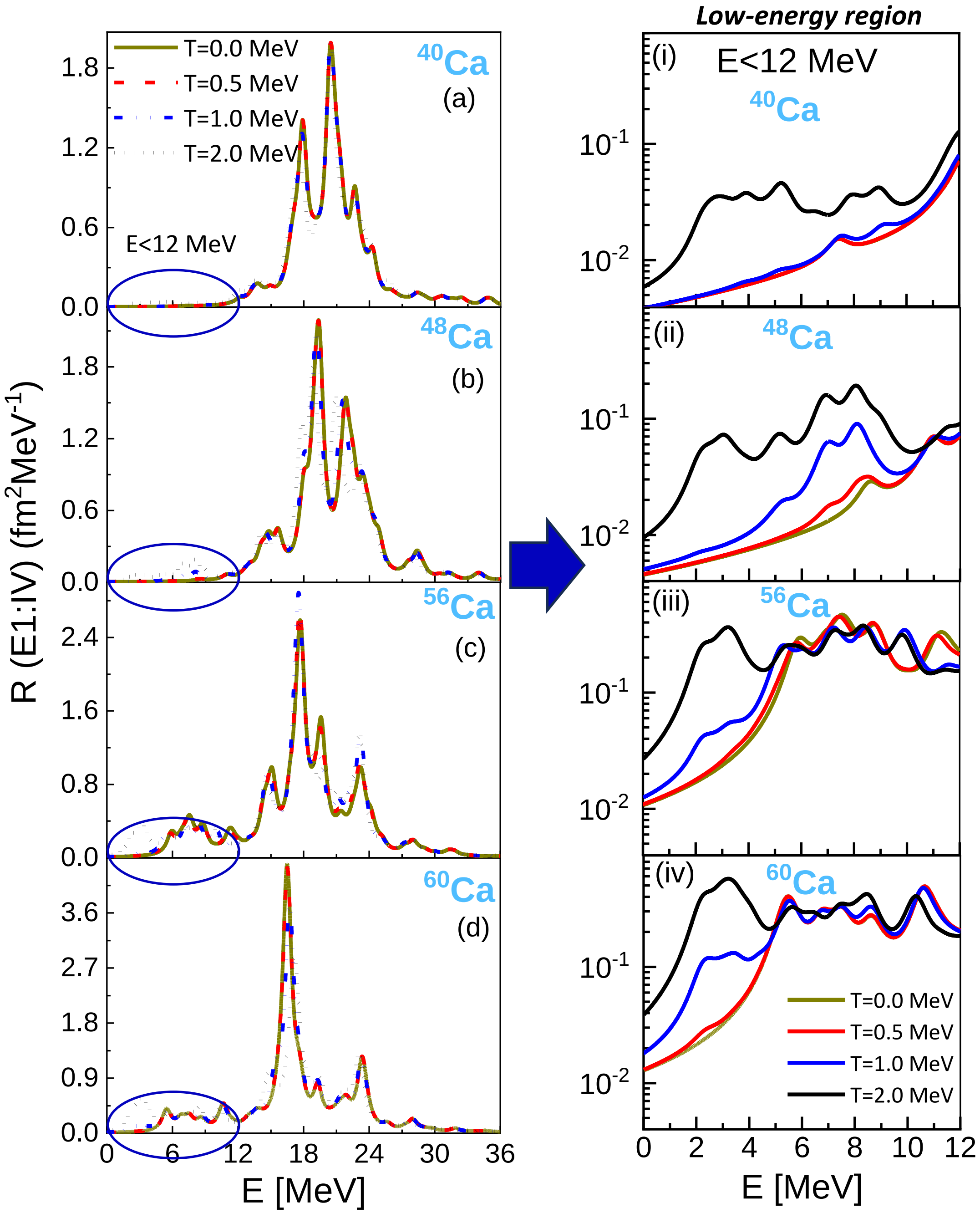
- *Low-energy excited states begin to emerge, as neutron number of Ca isotopes increases.*

At finite temperature

- *Giant dipole resonance (GDR) region exhibits only minor changes up to T=2 MeV.*

*A. Kaur, E. Yüksel, N. Paar, Phys. Rev. C **109**, 014314 (2024)*

Isovector E1 response at finite temperature



- *New low-energy excited states start to emerge below E<5 MeV.*
- *At T=2 MeV, Its influence become more pronounced in the low-energy region of neutron-rich nuclei.*
- *Thermal unblocking effects → open new excitation channels*
- *These newly formed states at low energies are created through single quasiparticle transitions and do not exhibit collectively.*

*A. Kaur, E. Yüksel, N. Paar, Phys. Rev. C **109**, 014314 (2024)*

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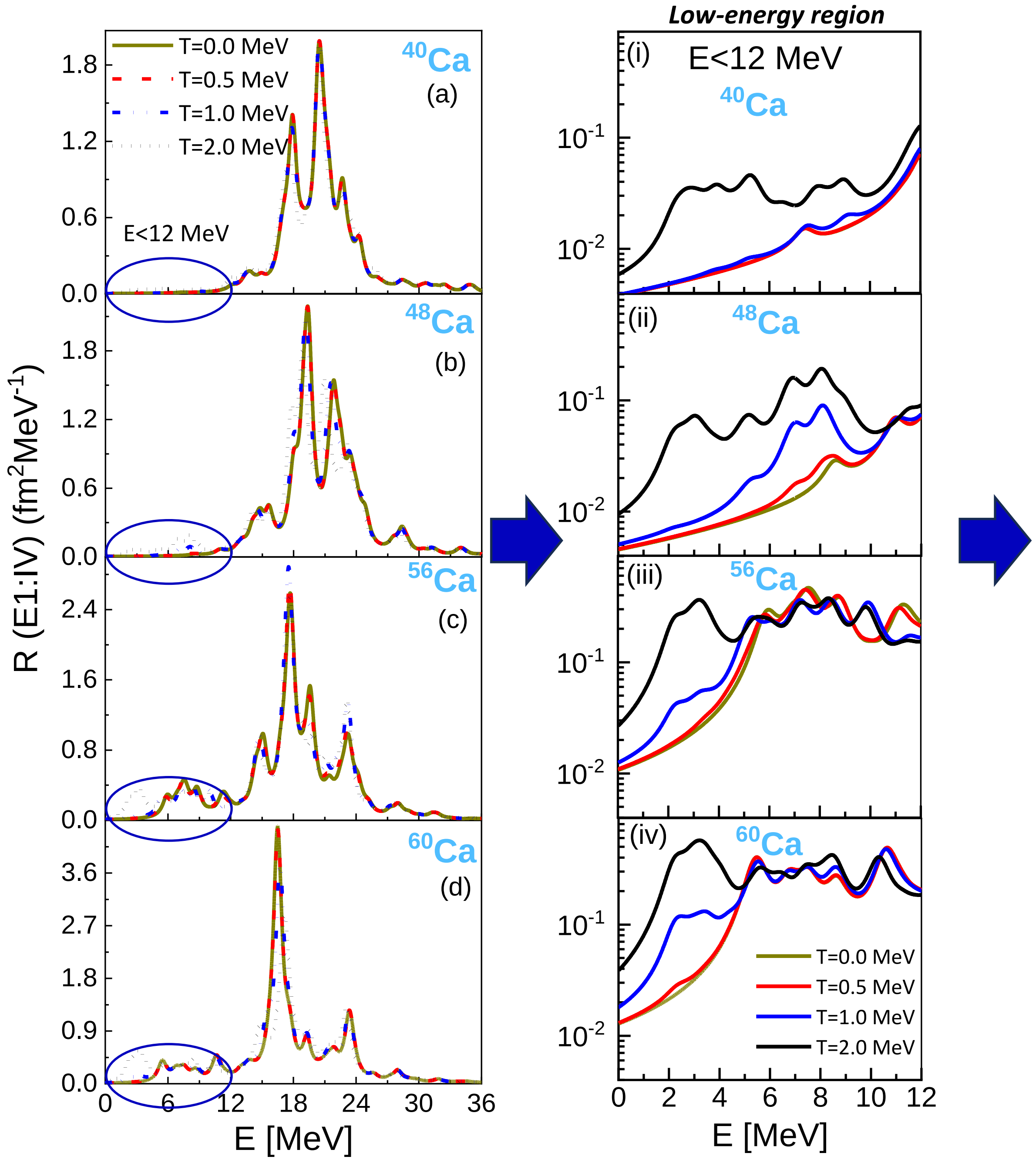
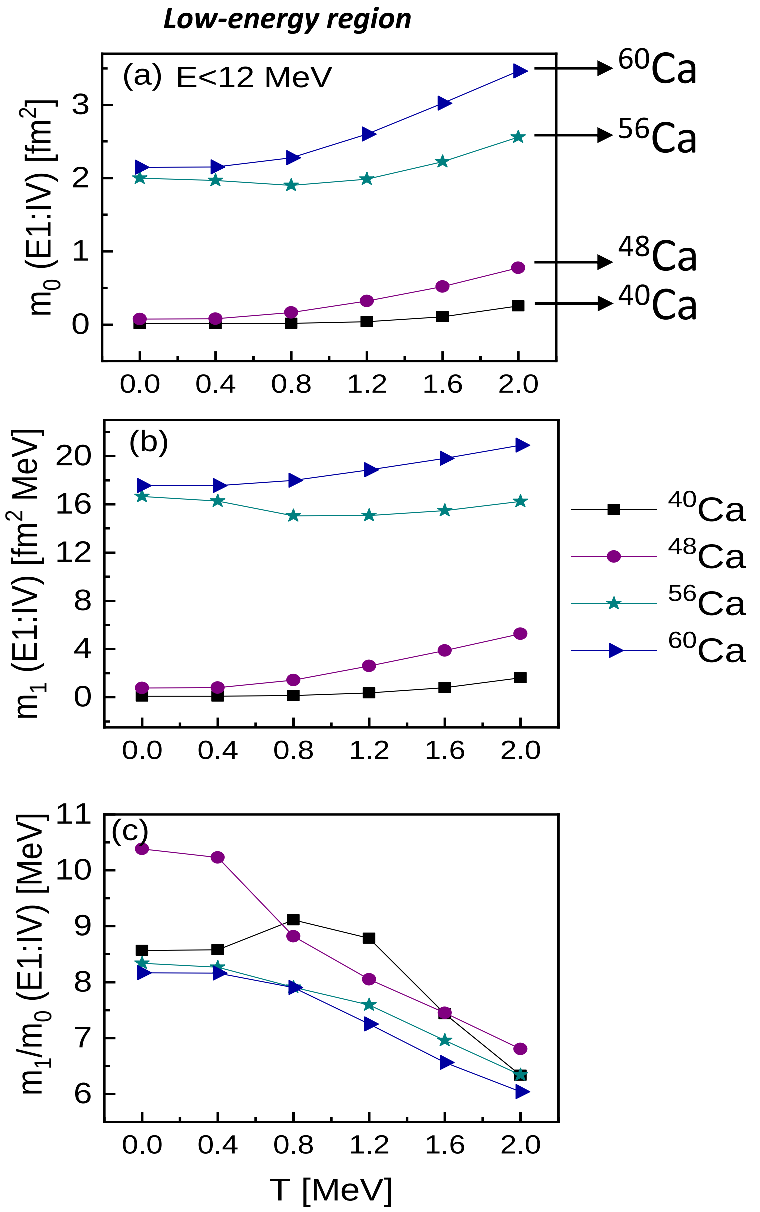
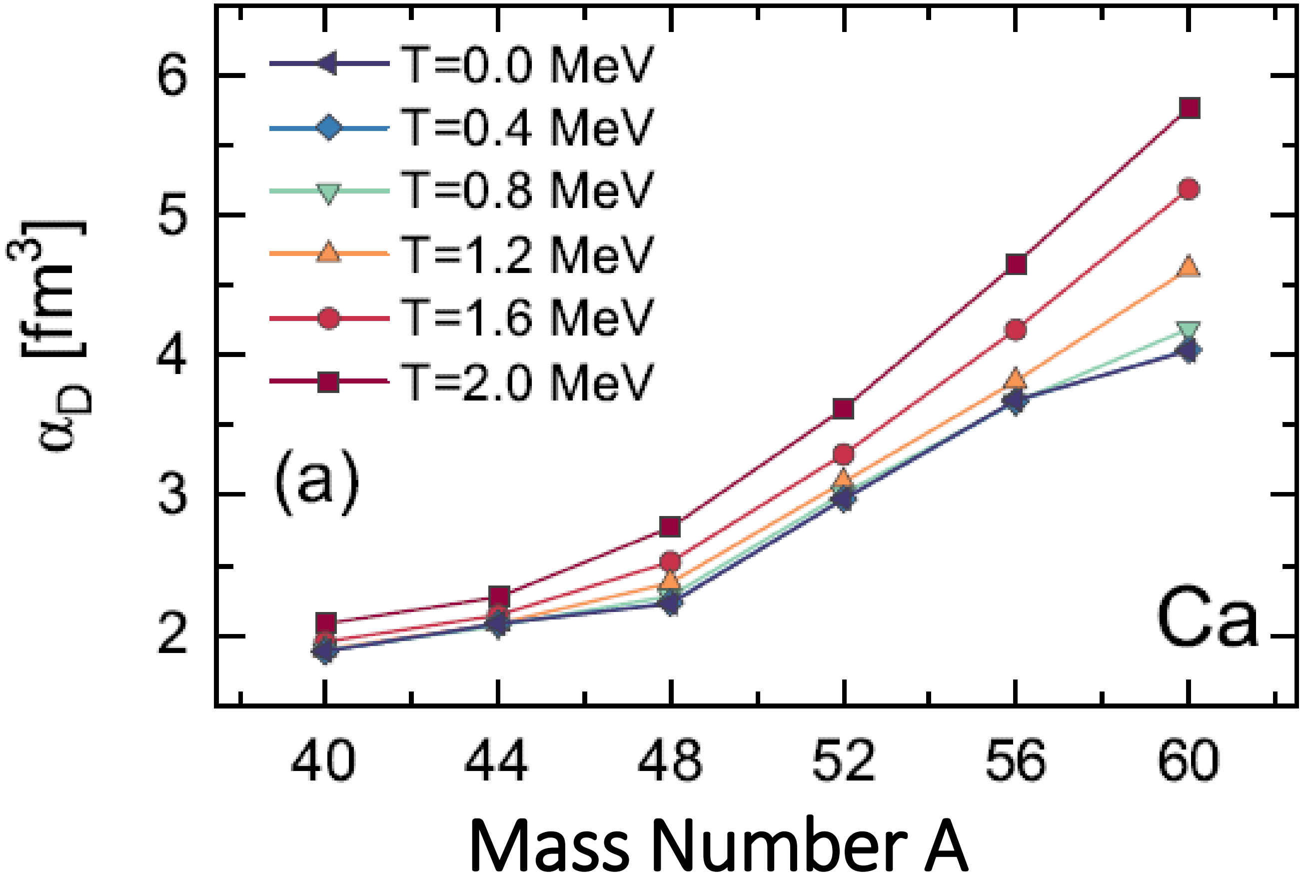


$$m_k = \sum_{\nu} B(EJ, \tilde{0} \to \nu) E_{\nu}^k.$$



Dipole Polarizability α_D at finite temperature



- *α_D is highly sensitive to the density dependence of the symmetry energy and is directly proportional to the inverse energy-weighted E1 sum rule m_{-1}.*

$$\alpha_D = \frac{8\pi e^2}{9} m_{-1}(E1)$$

- *In addition to the increase with the neutron excess, for all isotopes, the dipole polarizability systematically increases with temperature.*

*A. Kaur, E. Yüksel, N. Paar, Phys. Rev. C **109**, 014314 (2024)*

M1 response at finite temperature

- ✓ *M1 excitation at the leading one-body operator would take place between the spin-orbit partner orbits.*

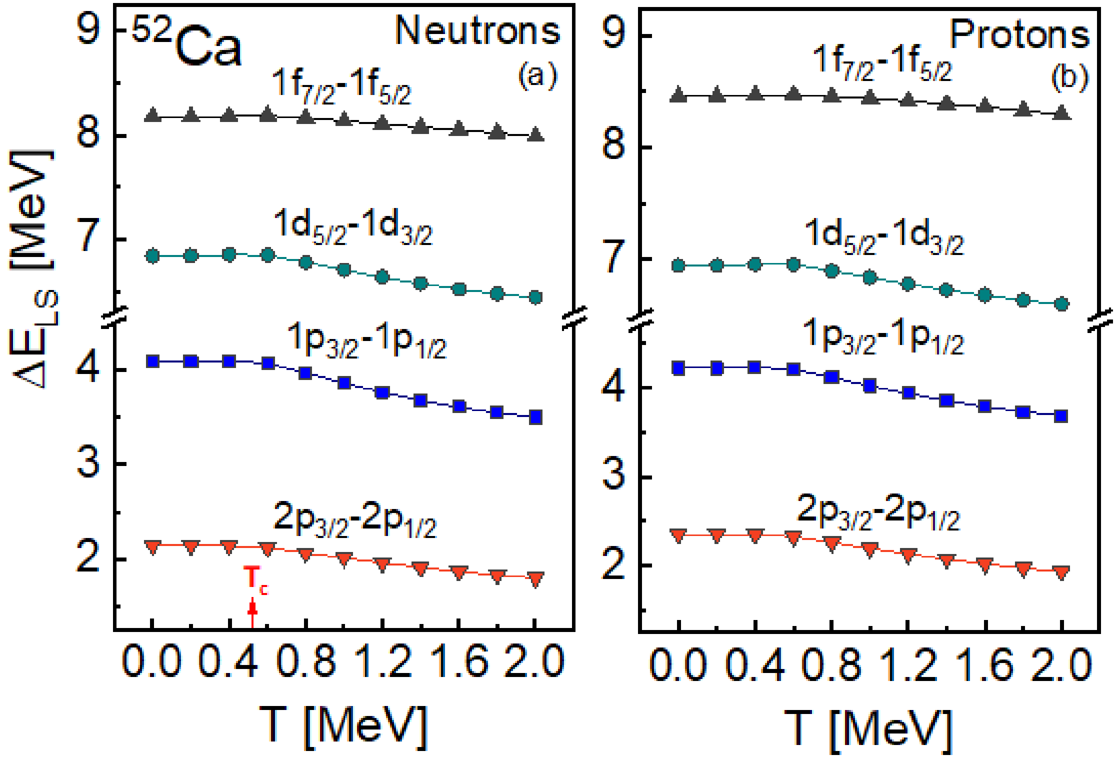
$$\hat{\mu}_{\nu}^{M1,IV} = \sqrt{\frac{3}{4\pi}}\mu_N \sum_{k\epsilon A}\left[g_s^{IV}\hat{s}_{\nu}(k) + g_l^{IV}\hat{l}_{\nu}(k)\right]\hat{\tau}_0(k)$$

Nuclear spin and orbital g factors for the IV-M1 mode are $g_s = 4.706$ and $g_l = 0.5$

G. Kružic, T. Oishi, D. Vale, and N. Paar, Phys. Rev. C 102, 044315 (2020).

- ✓ *Thus, it can provide important information on the underlying SO splittings.*

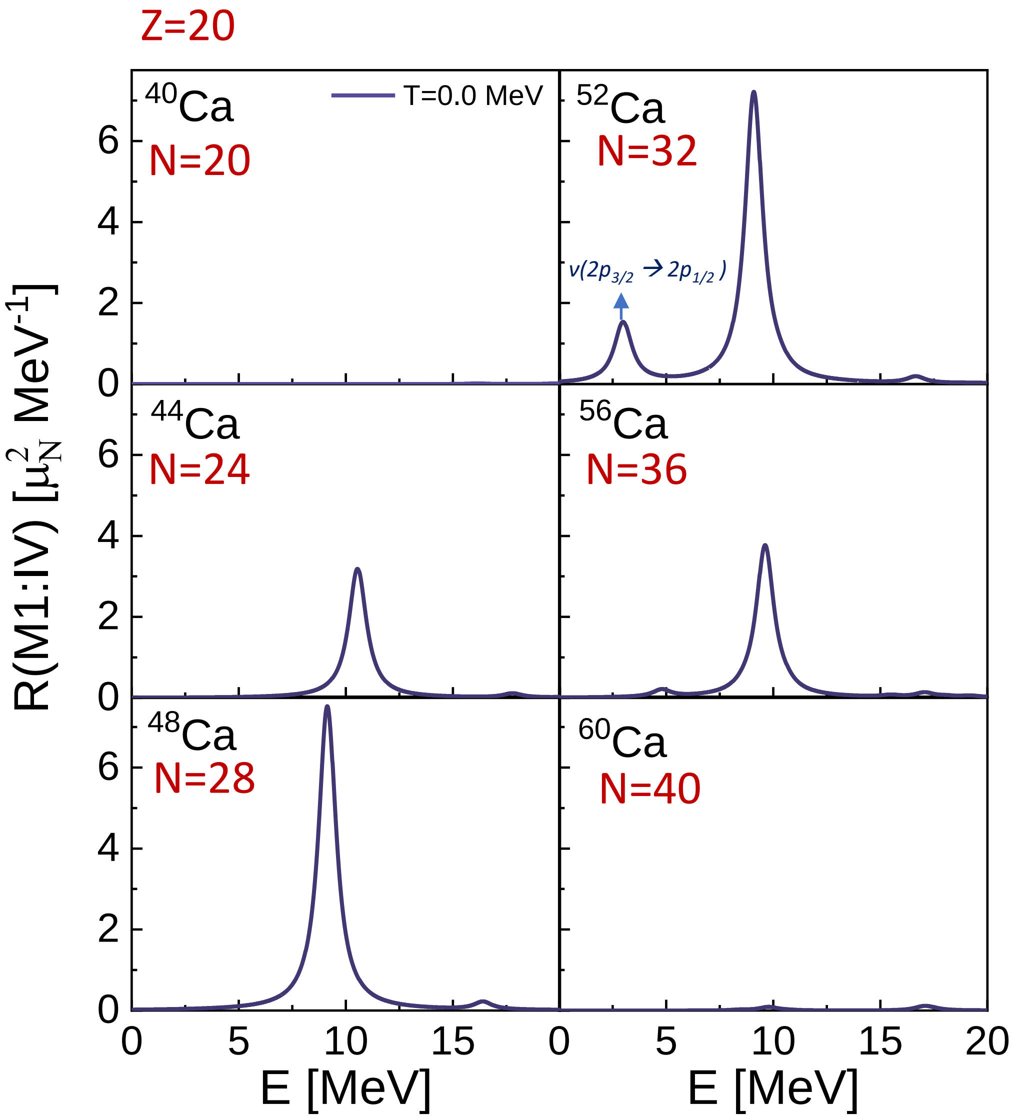
Spin-orbit (SO) gap energies (ΔE_{LS})



- ✓ *Gap between SO partners decreases with an enhancement in T especially above T_c.*
- ✓ *Because the pairing force reduces rapidly with increase in temperature and collapses above T_c.*
- ✓ *This reduction in SO gap energies above T_c will significantly modify the M1 response.*

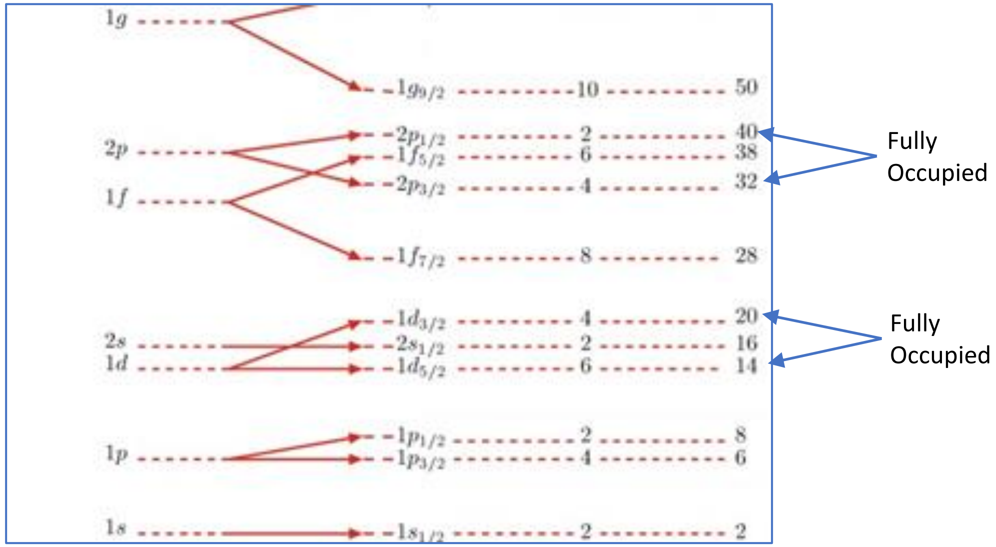
*A. Kaur, E. Yüksel, and N. Paar, Phys. Rev. C **109**, 024305 (2024)*

Isovector M1 response at T=0 MeV



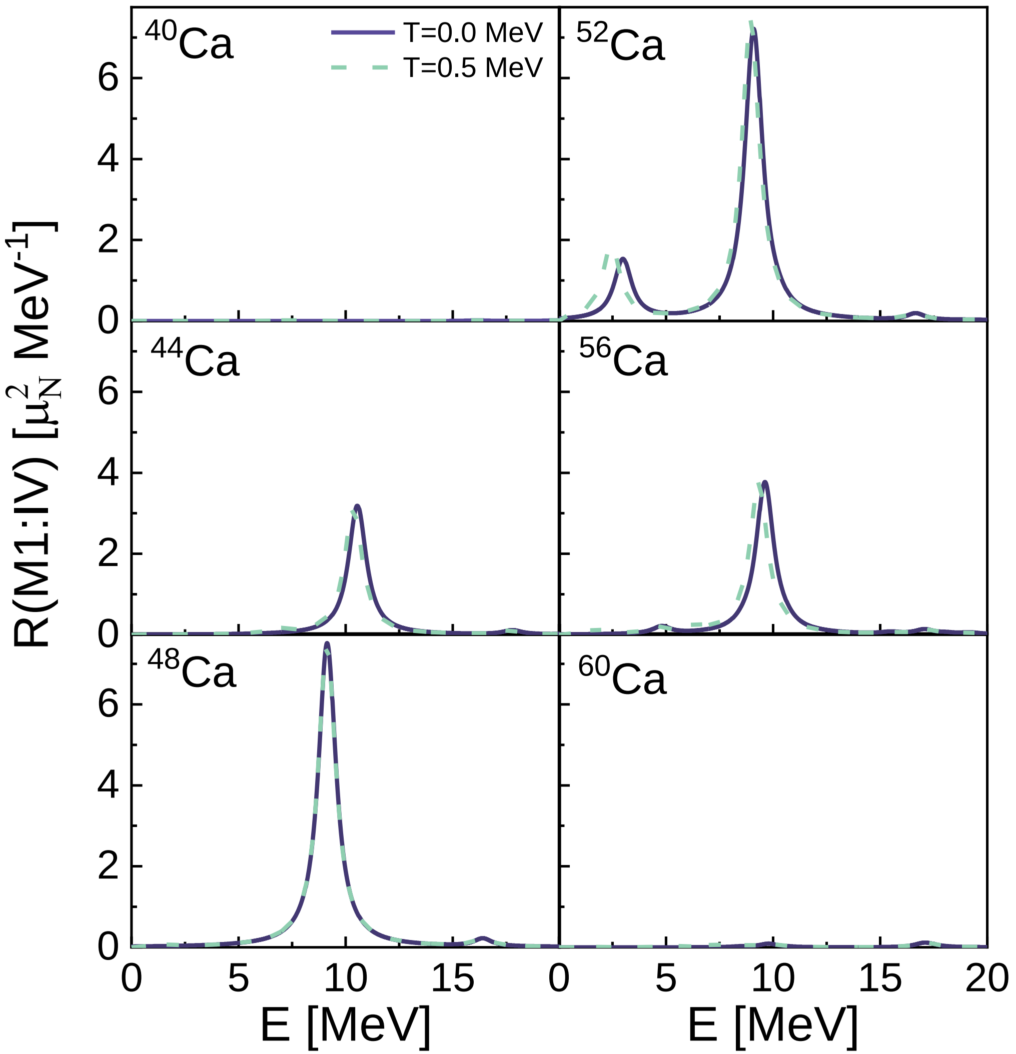
A. Kaur, E. Yüksel, and N. Paar, Phys. Rev. C **109**, 024305 (2024)

- *The M1 response does not appear when the SO-partner orbits are both occupied or empty.*
- *M1 transitions are not present for protons due to shell closure for Z=20.*
- *For ^{40}Ca and ^{60}Ca, the nucleon numbers 20 and 40 are the "M1-silence" points.*



- *For $^{44\text{-}56}$Ca nuclei, there is a strong peak in each isotope that attributes to the M1 excitation of valence neutron transitions $\nu(1f_{7/2} \rightarrow 1f_{5/2})$.*

M1 response at finite temperature



- *At T=0.5 MeV, the M1 strength does not change much.*

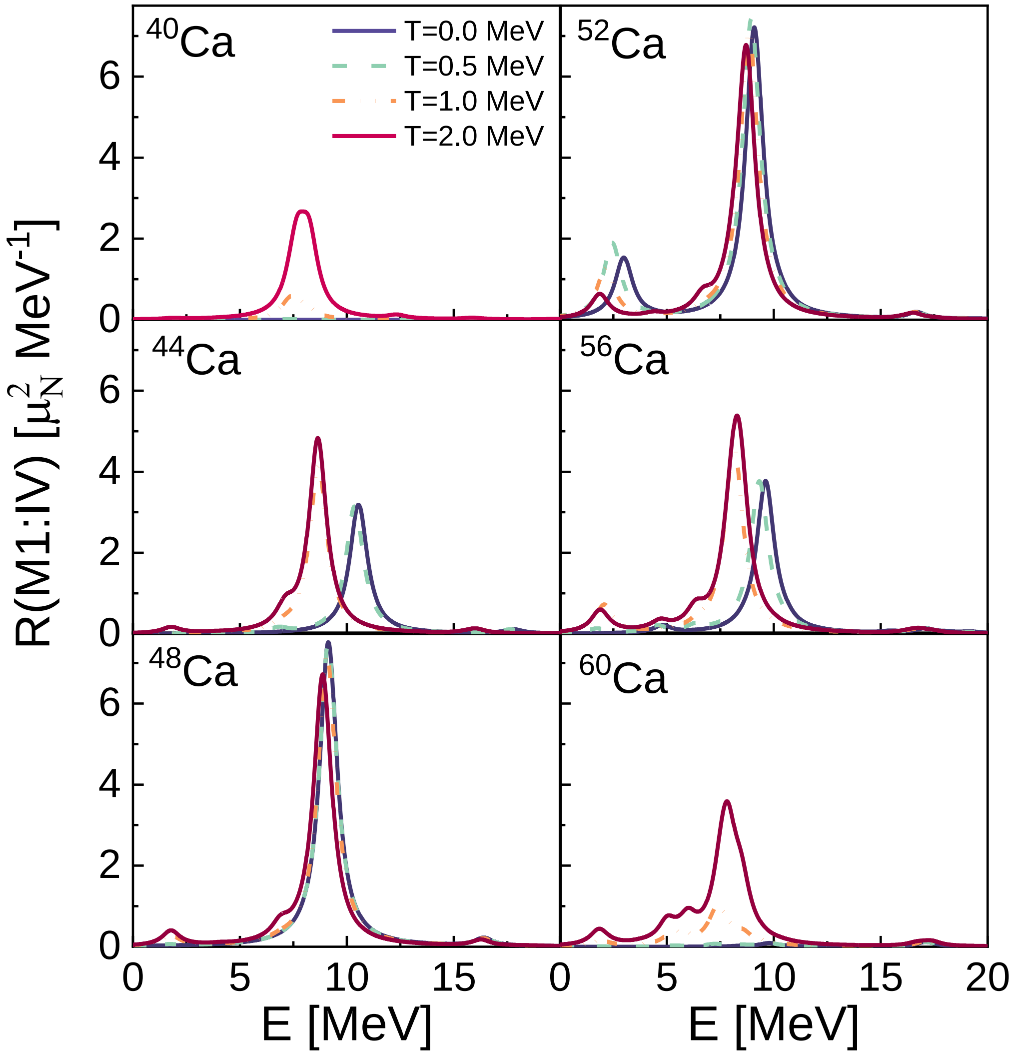
  At T=1 & 2 MeV
- *Due to thermal unblocking of forbidden transitions between ($1d_{5/2} \rightarrow 1d_{3/2}$) and ($1f_{7/2} \rightarrow 1f_{5/2}$) , M1 strength appears for ^{40}Ca and ^{60}Ca nuclei.*

- *Low-energy region E<5 MeV:*
  New smaller peak arises for neutron-rich nuclei as a result of major ν($2p_{3/2} \rightarrow 2p_{1/2}$) transition.

- *M1 transitions are considerably sensitive to changes in temperature.*

*A. Kaur, E. Yüksel, and N. Paar, Phys. Rev. C **109**, 024305 (2024)*

M1 response at finite temperature



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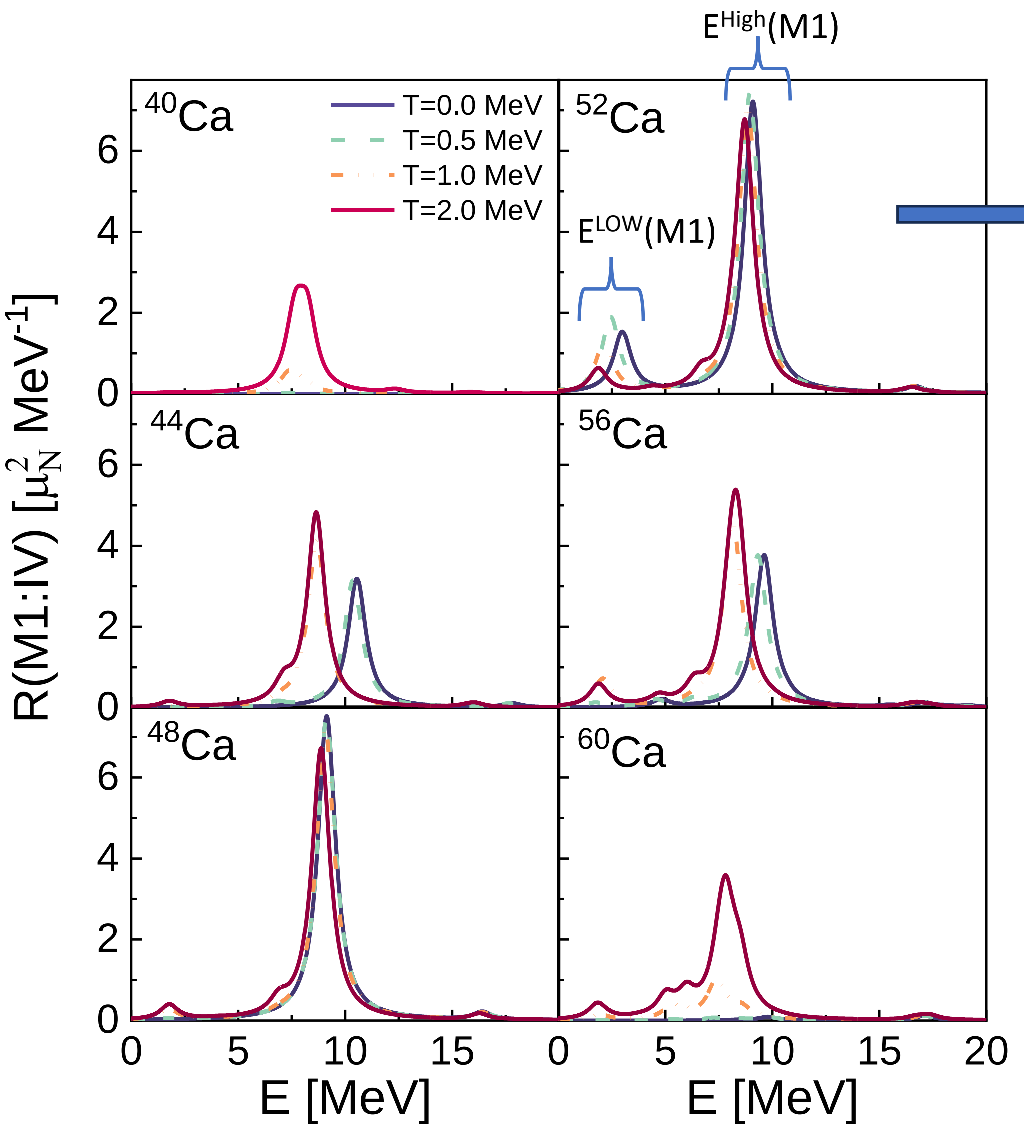

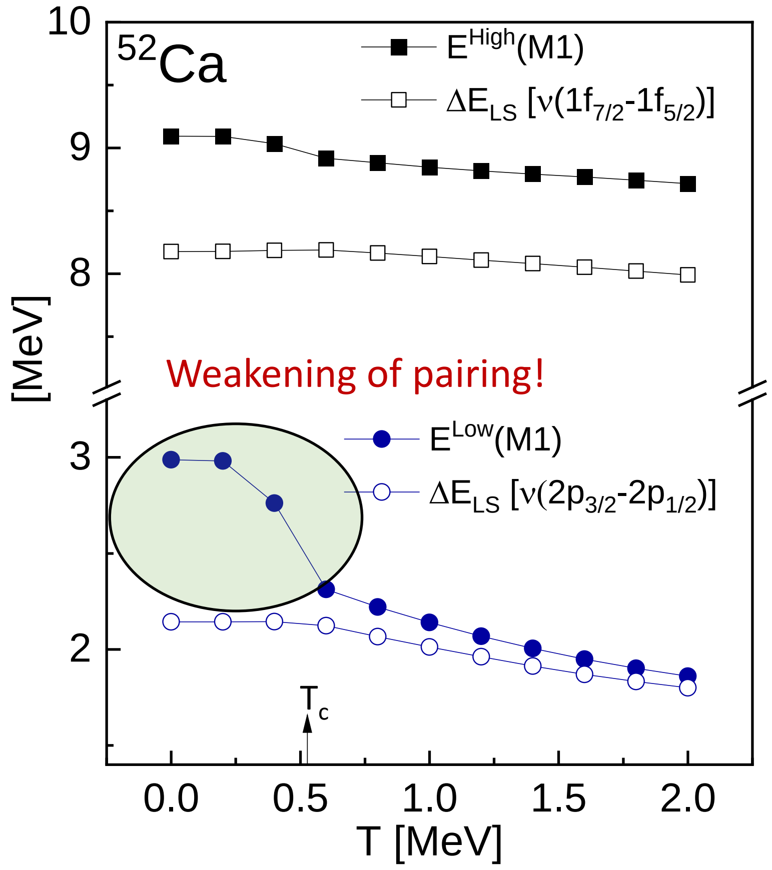

- *M1 response shifts to lower energies for ^{44,48,52,56}Ca nuclei with increasing temperature.*

✓ *Weakening and disappearance of pairing correlations*
✓ *Weakening of the residual interaction*
✓ *Decrement in SO splitting*

*A. Kaur, E. Yüksel, and N. Paar, Phys. Rev. C **109**, 024305 (2024)*

Summary

A self-consistent finite temperature relativistic QRPA (FT-RQRPA) framework is developed to study the finite temperature effects on E1 and M1 transitions.

- New excitation channels open due to thermal unblocking effects in the low and high energy region; especially in neutron-rich nuclei.
- The GDR region of E1 response is slightly modified for the considered range of temperature; however, the M1 response exhibits a considerable dependence on temperature.
- Temperature and pairing effects play a significant role below critical temperature T_c.

Future perspectives: Possible contributions of E1 and M1 transitions at finite temperature in γ strength functions.

Acknowledgments

Collaborators:

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Esra Yüksel

University of Surrey, UK

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