Continuum E1 and M1 response in Ni isotopes

Applications to neutron-capture rates

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Outline

01 **Introduction**

Neutron capture, related experiments

02 **Theoretical framework**

From Skyrme–HFB to the CQRPA response

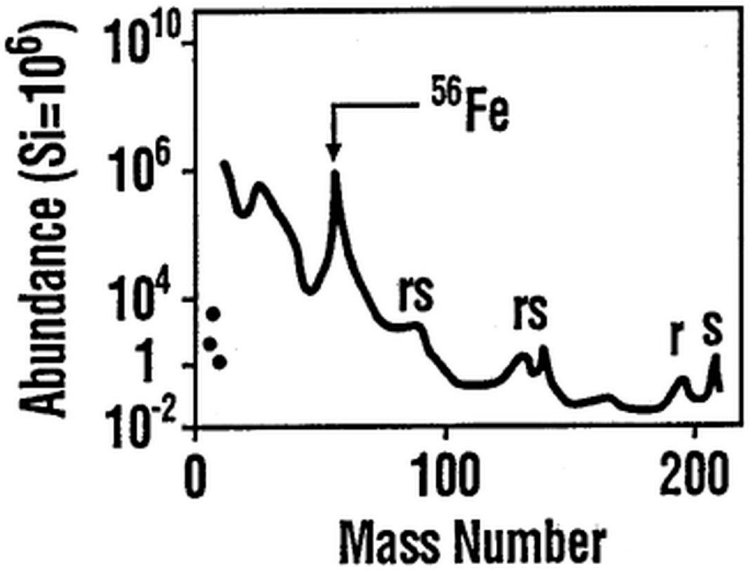
03 **Numerical results**

E1, M1, γ strength and neutron-capture rates

04 **Summary**

Neutron capture and dipole transition

Neutron-capture nucleosynthesis



Slow neutron-capture process

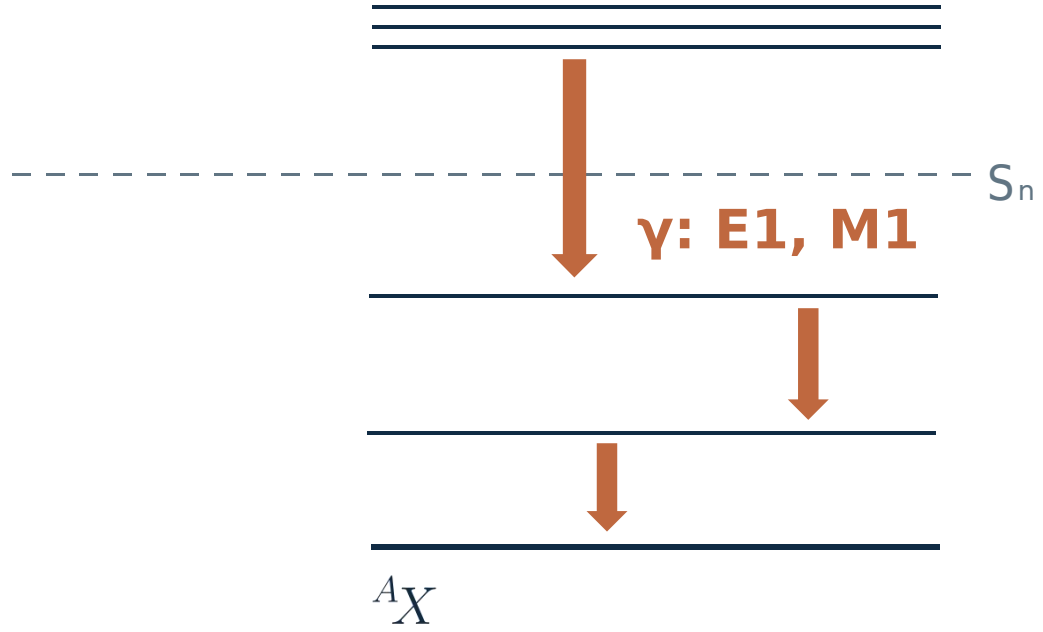
F. Käppeler, R. Gallino, S. Bisterzo, and W. Aoki,
Rev. Mod. Phys. 83, 157 (2011)

Rapid neutron-capture process

J. J. Cowan, C. Sneden, J. E. Lawler, et al.,
Rev. Mod. Phys. 93, 015002 (2021)

Compound-nucleus reaction

$^{A-1}X + n \longrightarrow {}^{A}X^{*} \qquad E^{*} \simeq S_n + E_n$



Constraints on neutron capture in Ni isotopes

Direct measurement of $^{63}Ni(n,\gamma)^{64}Ni$

$t_{1/2} = 100.8 \pm 1.5$ yr

$^{63}Ni \xrightarrow{(n,\gamma)} {}^{64}Ni$

$^{63}Ni \xrightarrow{\beta^-} {}^{63}Cu$

Maxwellian-averaged cross sections (kT=30keV) :

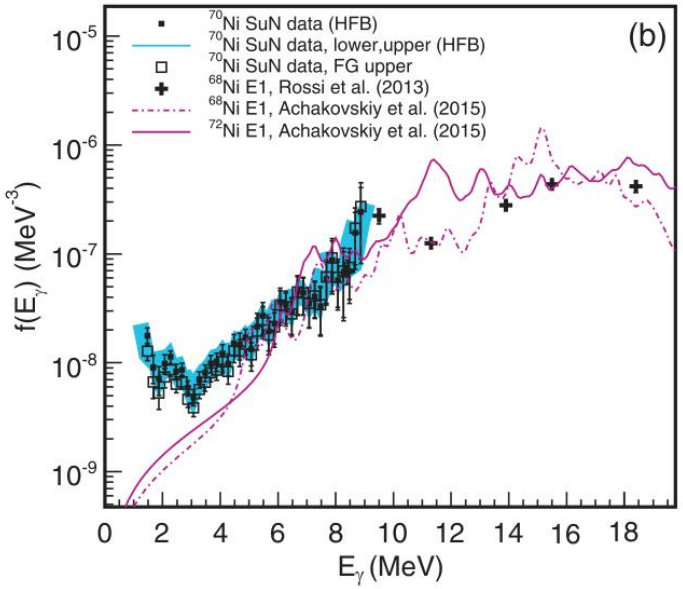
Exp. : **66.7 ± 5.4 (stat) ± 13.3 (sys) mb**

The. : 31 ± 6 mb

C. Lederer et al., Phys. Rev. Lett. 110, 022501 (2013)

Indirect measurement of $^{69}Ni(n,\gamma)^{70}Ni$

$^{70}Co \xrightarrow{\beta^-} {}^{70}Ni^* \rightarrow \gamma$ cascades



S. N. Liddick et al., Phys. Rev. Lett. 116, 242502 (2016)

Continuum coupling for nuetron-rich open-shell nuclei

Contribution to the resonance width

$$\Gamma_{\mathrm{tot}} \simeq \underbrace{\Gamma_{\mathrm{frag}}}_{\text{fragmentation}} + \underbrace{\Gamma^{\uparrow}}_{\text{particle escape}} + \underbrace{\Gamma^{\downarrow}}_{\text{complex configurations}}$$

Above threshold, particle emission gives an escape width $\Gamma\uparrow$.

Skyrme–HFB + CQRPA: spin-dependent residual channels omitted (E1)

K. Mizuyama, M. Matsuo, and Y. Serizawa, Phys. Rev. C 79,024313 (2009).

RMF + CQRPA

I. Daoutidis and P. Ring, Phys. Rev. C 83, 044303 (2011).

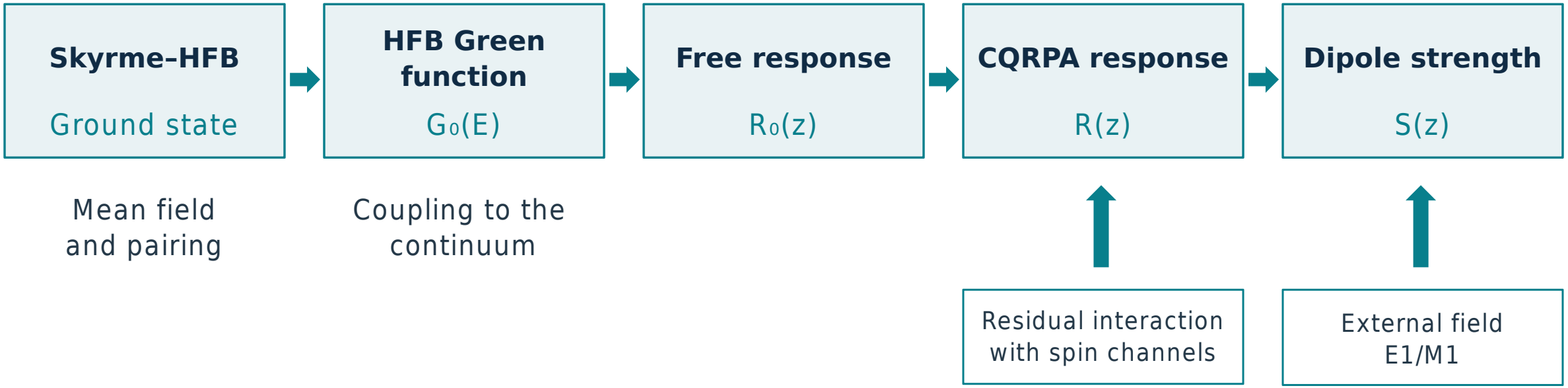
Coupled cluster + Berggren continuum

Acharya et al., Phys. Rev. Lett. 132, 232504 (2024)

Our work:

Skyrme–HFB + CQRPA : spin-independent and **spin-dependent terms** can calculate both E1 and M1

Workflow of coordinate-space HFB + CQRPA:



M. Matsuo, Nucl. Phys. A 696, 371 (2001) ;

K. Mizuyama, M. Matsuo, and Y. Serizawa, Phys. Rev. C 79,024313 (2009).

Continuum coupling

Skyrme interaction

$$v_{12} = t_0(1 + x_0 P_\sigma)\delta + \frac{1}{2}t_1(1 + x_1 P_\sigma)\left(\mathbf{k}'^2\delta + \delta\mathbf{k}^2\right) + t_2(1 + x_2 P_\sigma)\mathbf{k}'\cdot\delta\mathbf{k}$$
$$+ \frac{1}{6}t_3(1 + x_3 P_\sigma)\rho^\alpha\delta + iW_0(\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2)\cdot\left(\mathbf{k}'\times\delta\mathbf{k}\right)$$

T. H. R. Skyrme, Nucl. Phys. 9, 615 (1959).

Ground state: HFB potential

$$\mathcal{H}_{lj}\phi_{lj} = E\phi_{lj}, \qquad \phi_{lj} = \begin{pmatrix}\varphi_{1,lj}\\ \varphi_{2,lj}\end{pmatrix}$$

$$h_q = \frac{\delta\mathcal{E}}{\delta\rho_q}, \qquad \Delta_q = \frac{\delta\mathcal{E}}{\delta\tilde{\rho}_q}$$

J. Dobaczewski, H. Flocard and J. Treiner, Nucl. Phys. A 422, 103 (1984)

Regular and outgoing solutions

$$\phi_{lj}^{(\mathrm{r}1)} \xrightarrow{r\to 0} \begin{pmatrix} r^{l+1}\\ 0\end{pmatrix} \qquad \phi_{lj}^{(\mathrm{r}2)} \xrightarrow{r\to 0} \begin{pmatrix} 0\\ r^{l+1}\end{pmatrix}$$

$$\phi_{lj}^{(+1)} \xrightarrow{r\to\infty} \begin{pmatrix} e^{ik_+ r}\\ 0\end{pmatrix} \qquad \phi_{lj}^{(+2)} \xrightarrow{r\to\infty} \begin{pmatrix} 0\\ e^{ik_- r}\end{pmatrix}$$

$$k_\pm(E) = \frac{\sqrt{2m(\lambda \pm E)}}{\hbar}, \qquad \mathrm{Im}\, k_\pm \geq 0$$

Green function, response function and dipole strength

Construction of the HFB Green function

$$\big(E-\mathcal{H}_{lj}\big)\mathcal{G}_{0,lj}=\delta$$

$$\mathcal{G}_{0,lj}(r,r',E)=\sum_{s,s'=1,2}c_{lj}^{ss'}(E)\Big[\theta(r-r')\phi_{lj}^{(+s)}(r,E)\phi_{lj}^{(\mathrm{r}s')\mathrm{T}}(r',E)+\theta(r'-r)\phi_{lj}^{(\mathrm{r}s')}(r,E)\phi_{lj}^{(+s)\mathrm{T}}(r',E)\Big]$$

Free response function

$$R_0^{\alpha\beta}(z)=\frac{1}{4\pi i}\oint_C dE\,\mathrm{Tr}[A_\alpha\mathcal{G}_0(E+z)B_\beta\mathcal{G}_0(E)+A_\alpha\mathcal{G}_0(E)B_\beta\mathcal{G}_0(E-z)]$$

Residual interaction

$$V_{\alpha\beta}(\mathbf{r},\mathbf{r}')=\frac{\delta^2\mathcal{E}}{\delta\rho_\alpha(\mathbf{r})\,\delta\rho_\beta(\mathbf{r}')}$$

CQRPA response function

$$R(z)=\big[1-R_0(z)V_{\mathrm{res}}\big]^{-1}R_0(z)$$

ph channel pp channel

External dipole operators

$$\hat{F}_{E1,\mu}=e\frac{N}{A}\sum_p r_pY_{1\mu}(\hat{r}_p)-e\frac{Z}{A}\sum_n r_nY_{1\mu}(\hat{r}_n)$$

$$\hat{F}_{M1,\mu}=\sqrt{\frac{3}{4\pi}}\mu_N\sum_i\big(g_l^{(i)}\mathbf{l}_i+g_s^{(i)}\mathbf{s}_i\big)_{1\mu}$$

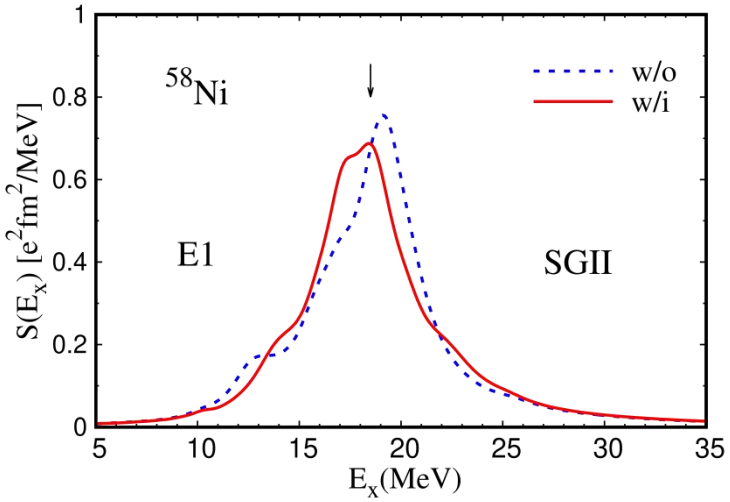
Strength function

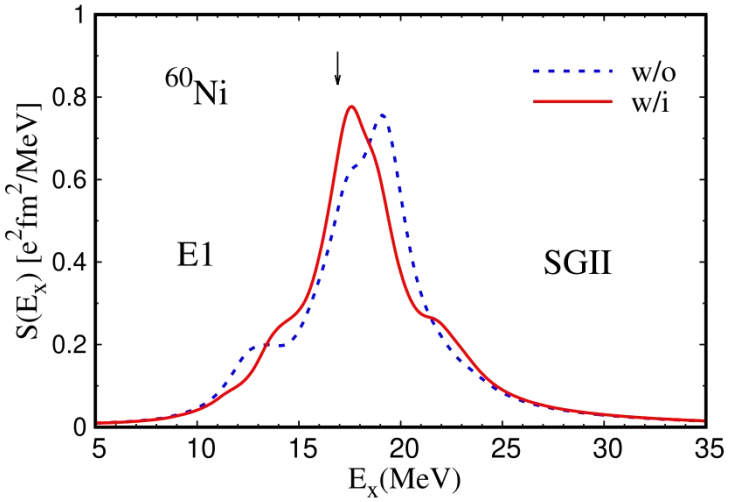
$$S(E)=-\frac{1}{\pi}\,\mathrm{Im}\big[F^\dagger R(E+i\epsilon)F\big]$$

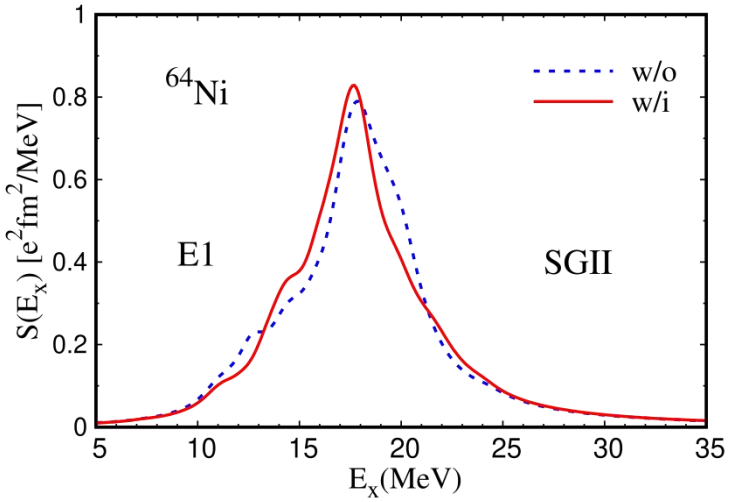
γ-ray strength

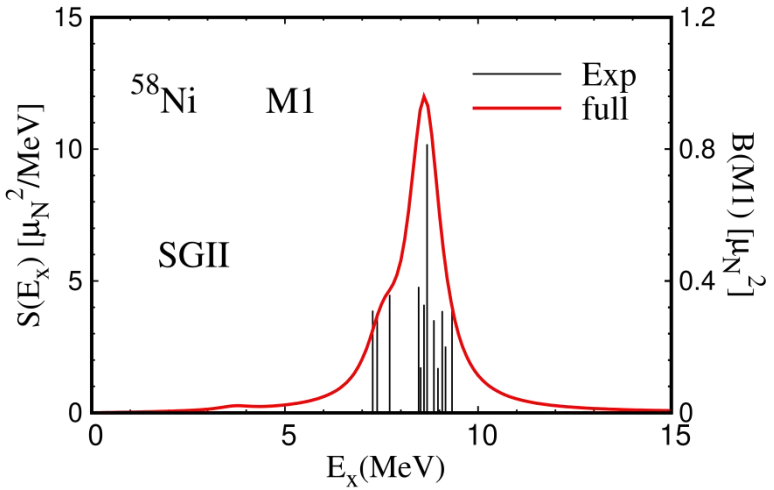
$$f_{X1}(E_\gamma)=\frac{16\pi}{27(\hbar c)^3}\,S_{X1}(E_\gamma),\qquad X=E,M$$

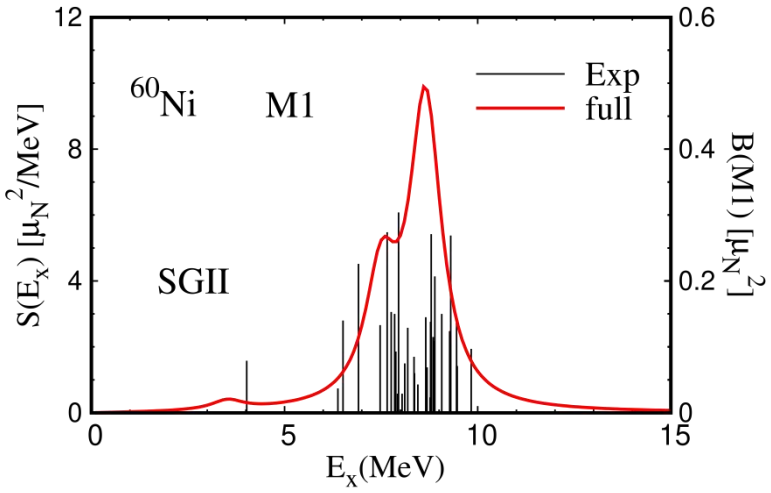
E1 and M1 response of ^{58,60,64}Ni within CQRPA

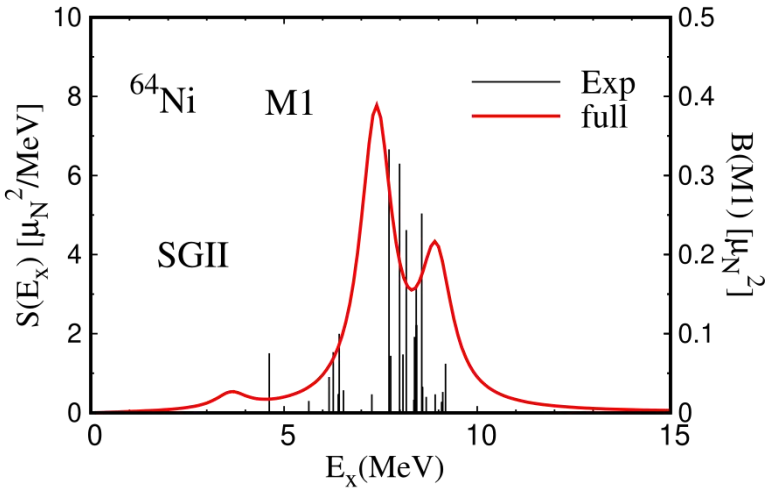










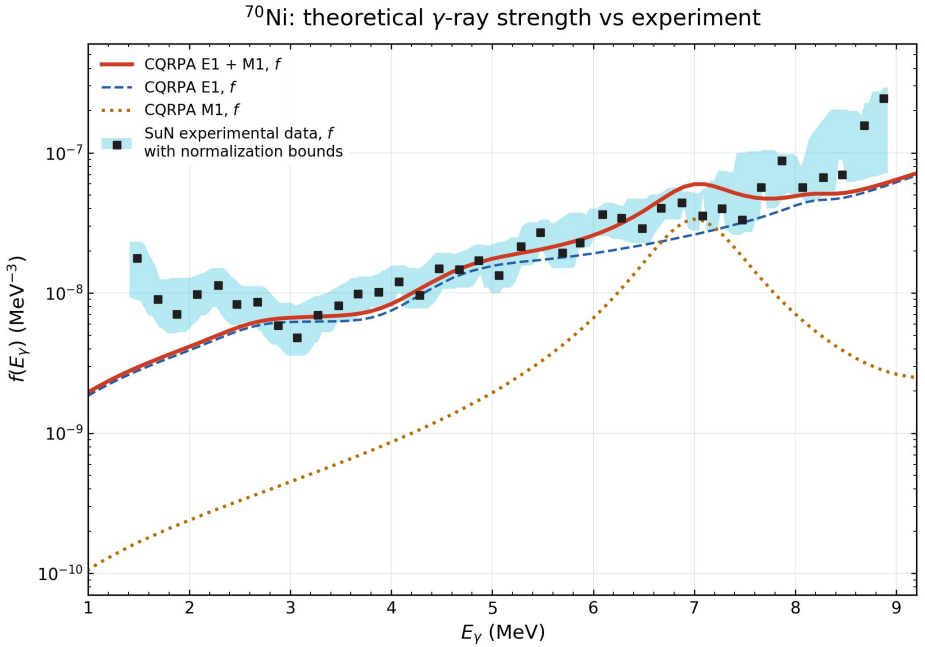


M1 uses separate axes for S(M1) and experimental B(M1).

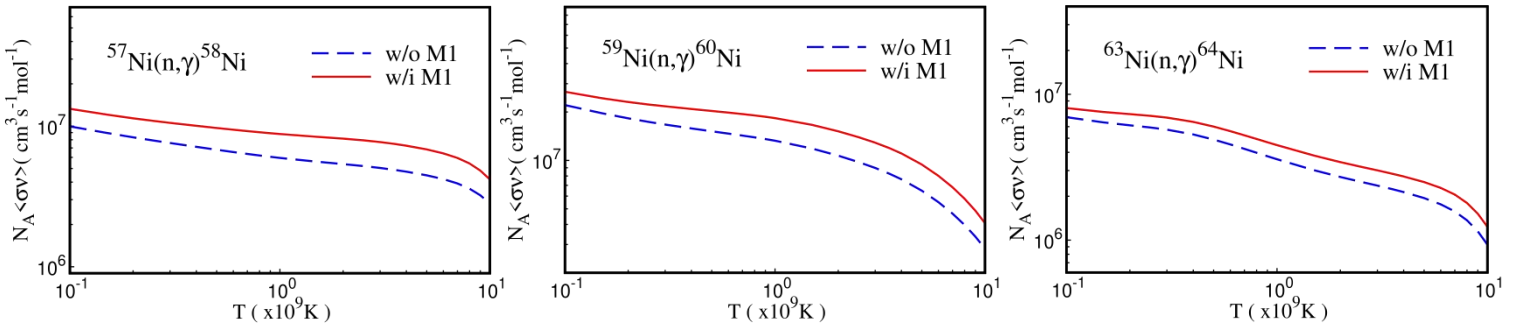
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γ-ray strength and neutron-capture rates

^{70}Ni γ-ray strength



Neutron-capture rates: E1 only versus E1 + M1, with other inputs unchanged.



Rates increase due to the inclusion of M1

Reaction	T_9 = 0.3	T_9 = 1.0
^{57}Ni(n,γ)^{58}Ni	≈ 39%	≈ 48%
^{59}Ni(n,γ)^{60}Ni	≈ 30%	≈ 38%
^{63}Ni(n,γ)^{64}Ni	≈ 21%	≈ 25%

^{63}Ni(n,γ)^{64}Ni MACS(kT=30keV)

	MACS (mb)
Experimental	66.7±5.4±13.3
CQRPA: E1	37.89
CQRPA: E1 + M1	46.03

W. H. Li, C. L. Bai, C. L. Zhang, H. Sagawa, and H. Q. Zhang, preparing.....

Summary

Framework A self-consistent Skyrme–HFB + CQRPA treatment of E1 and M1, including spin-dependent central channels.

Ni response E1 and M1 responses in ^{58},^{60},^{64}Ni, with a further comparison of the ^{70}Ni γ-ray strength.

Capture rates Adding M1 increases the calculated Ni capture rates over 20% at different thermal temperatures.

Thank you for your attention!