Workshop on "Vortex states in nuclear and particle physics",
Zhuhai, Guangdong, April 24th-28th, 2024

A novel way to study nuclear giant resonances with vortex gamma photons

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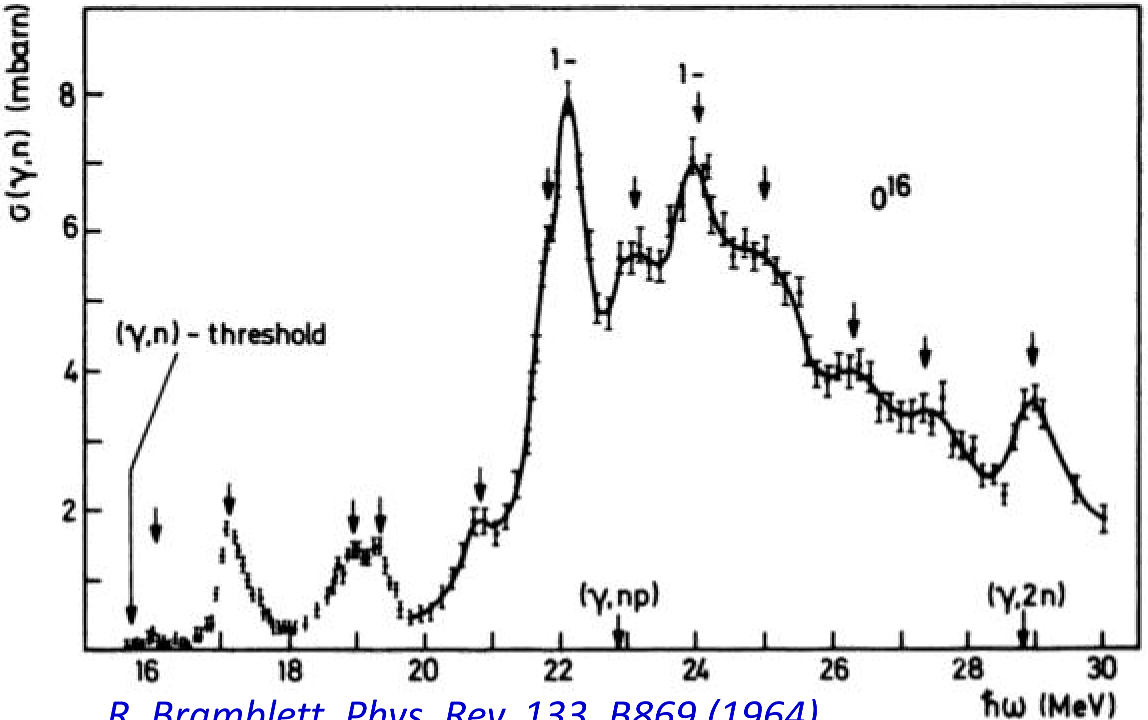
Outline

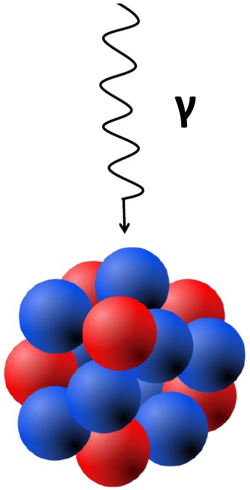
- **Introduction**
- **Nuclear Giant Resonances studied by QPVC approach**
- **Nuclear Giant Resonances excited by vortex photon**
- **Summary and Perspective**

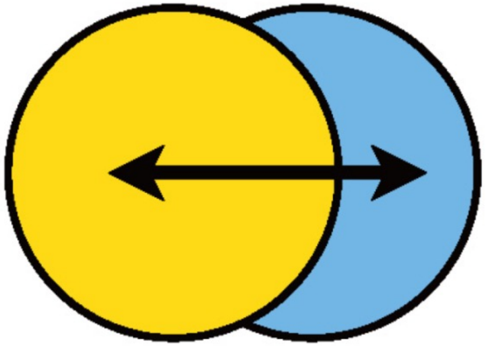
Nuclear Giant Resonances

- **Giant Dipole Resonance in ^{16}O**



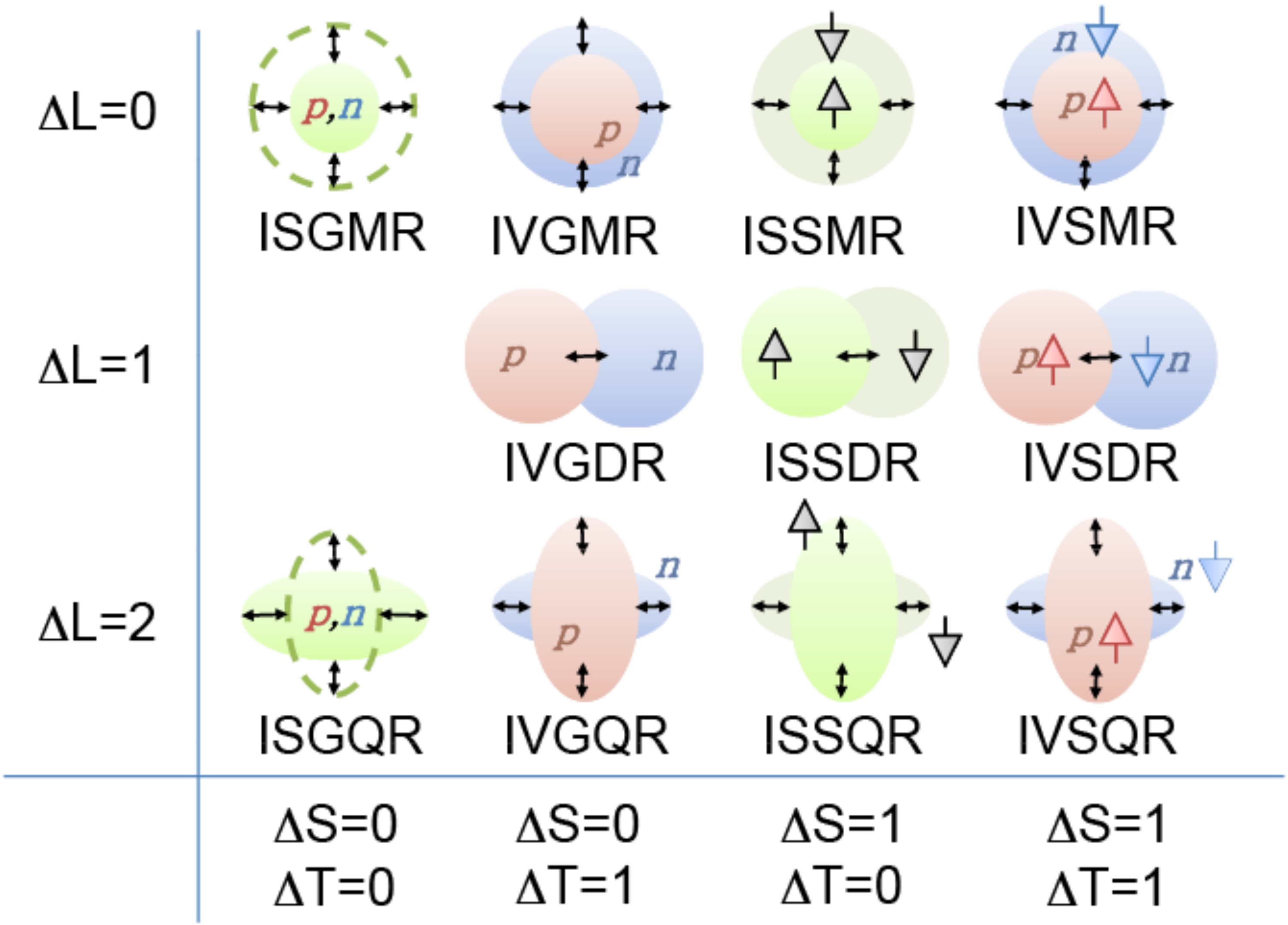
R. Bramblett, Phys. Rev. 133, B869 (1964)





- **Characteristics**
  - Broad resonance width ~ 5 MeV
  - Larger transition probabilities than s.p.
  - Excitation energy varies slowly and smoothly with mass number

Different modes of giant resonances



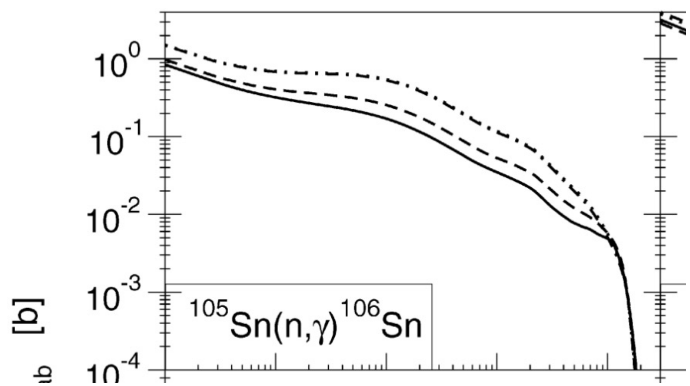
IS = Iso-Scalar
IV = Iso-Vector
S = Spin
G = Giant
M = Monopole
D = Dipole
Q = Quadrupole

reactions:
(α, α'),
(p,p') …
(γ, γ'),
(γ, n) ,
(e, e') …

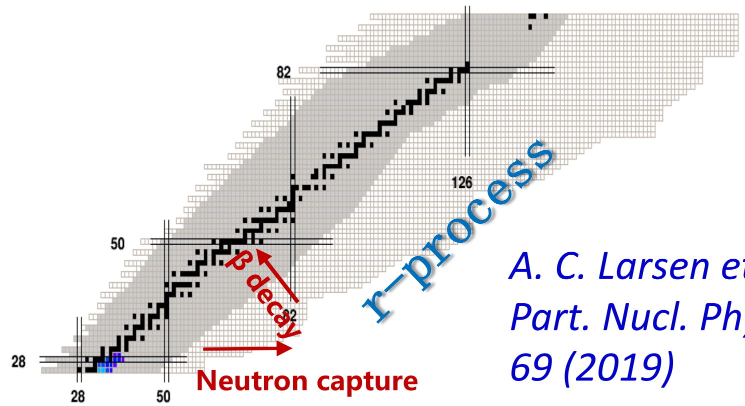
L : orbital angular momentum S: spin T: isospin

Giant Resonances Provide Insight to

- ***How were the heavy elements from iron to uranium made?***



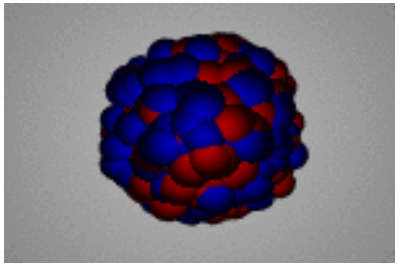
E. Litvinova et al., NPA 823, 26 (2009)



A. C. Larsen et al., Prog. Part. Nucl. Phys. 107, 69 (2019)

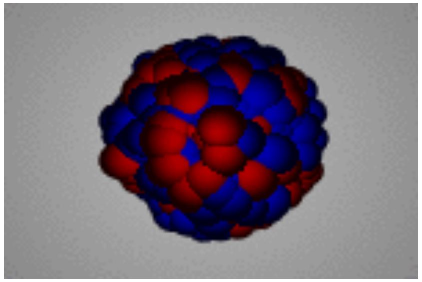
- ***What is the equation of state (EOS) of nuclear matter?***

  - **Giant monople resonance (GMR)**
  - **Giant dipole resonance (GDR)**



Nuclear incompressbility K

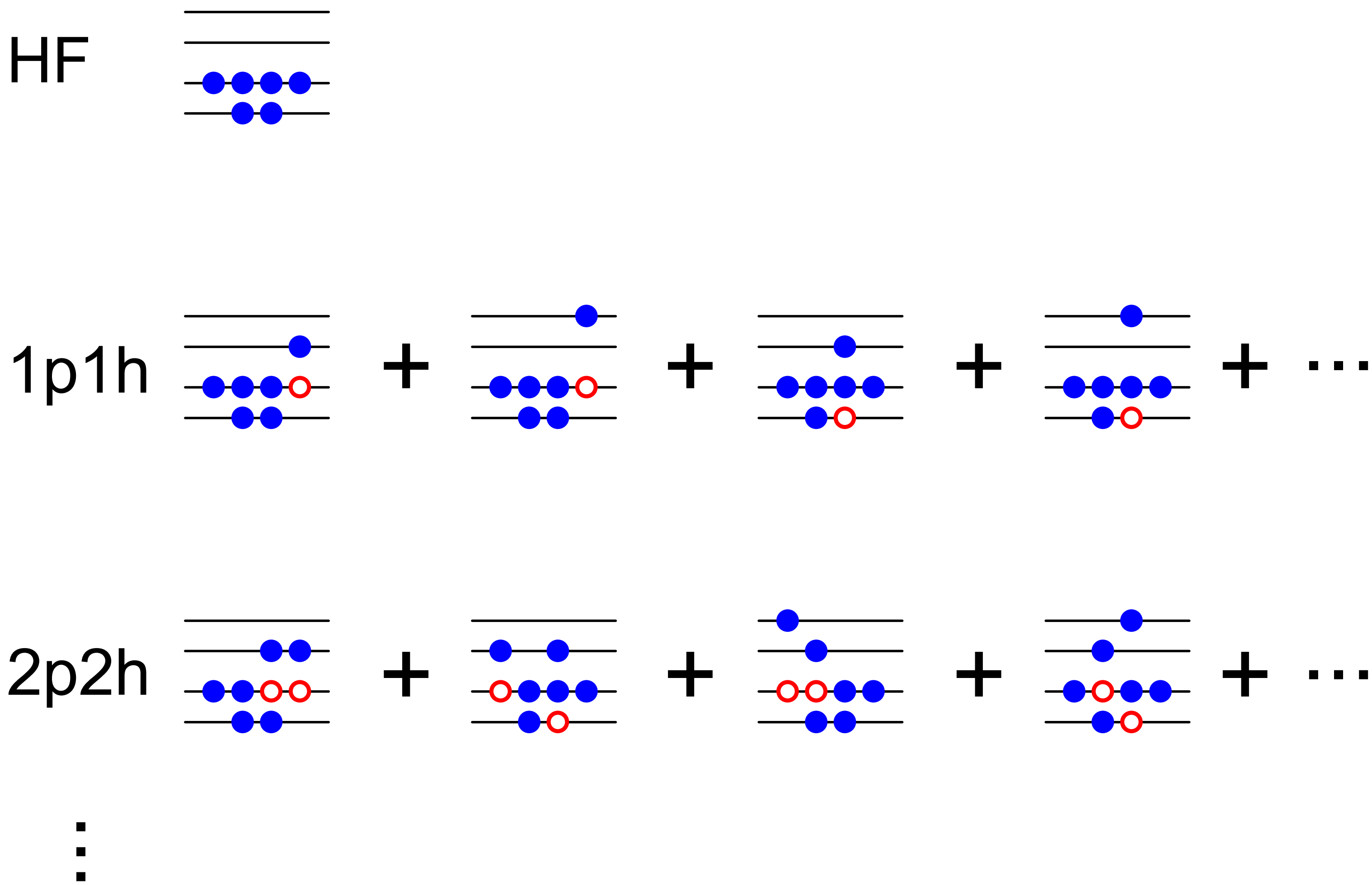
Garg and Colo, PPNP 101, 55 (2018)



Symmetry energy slope L

Roca-Maza and Paar, PPNP 101, 96 (2018)

Schematic picture for collective excitations



Microscopic theories

☐ Configuration Interaction Shell Model

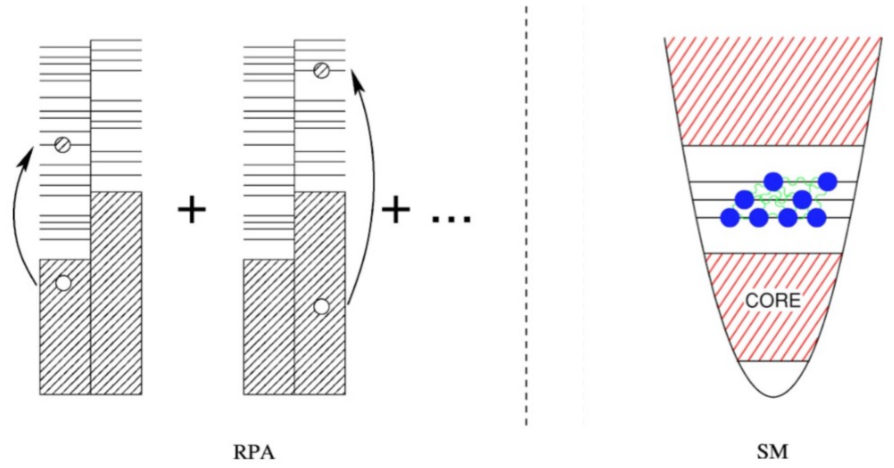
light nuclei or nuclei near magic number

S. E. Koonin et al., Phys. Rep. **278**, 1, 1997
E. Caurier, et al., Rev. Mod. Phys. **77**, 427, 2005

☐ Random Phase Approximation (RPA) based on density functionals

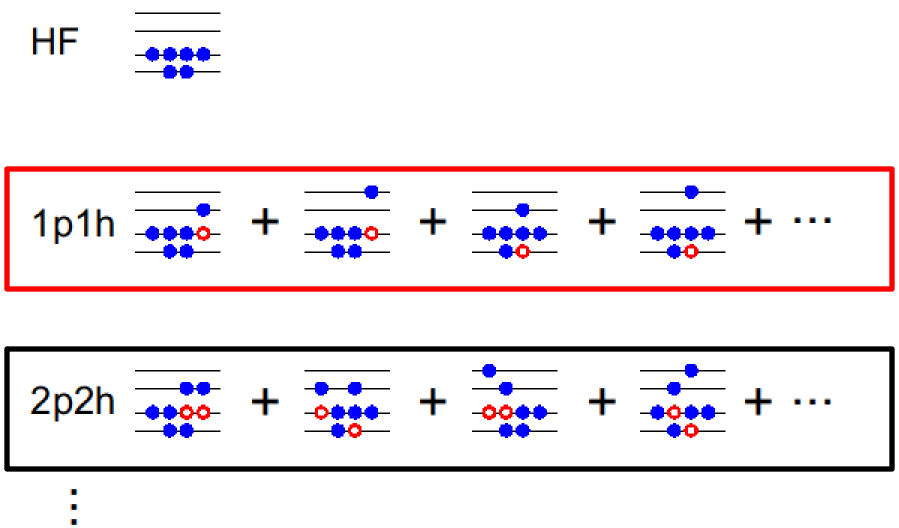
- Non-relativistic density functional
- Relativistic density functional

G. Colo, et al., Comp. Phys. Comm. 184, 142, 2013
N. Paar, et al., Rep. Prog. Phys. 70, 691, 2007



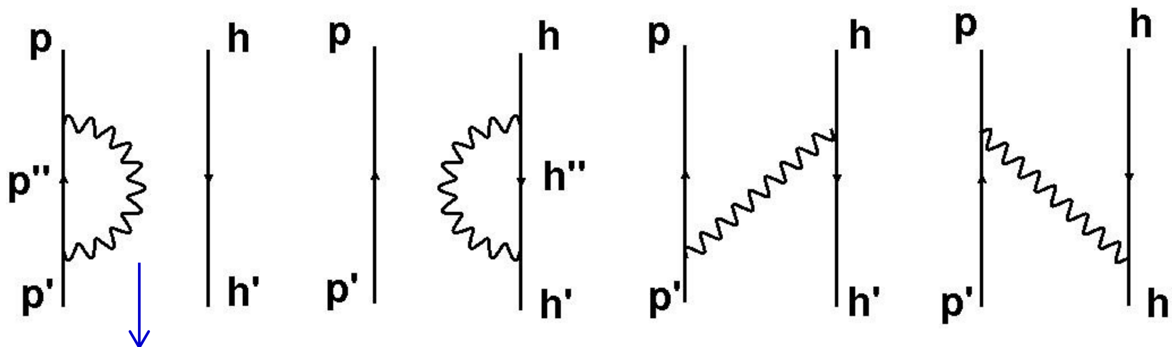
from K. Langanke et al., Rev. Mod. Phys. **75**, 819, 2003

Something in between? --- RPA+PVC model



RPA

- **Second RPA** *drozdz et al., PR 197, 1 (1990)*
  Gambacurta et al., PRC 81, 054312 (2010)
  Yang et al., PRC 106, 014319 (2022)
- **RPA + PVC (particle vibration coupling)**



Low-lying vibration phonons |N>

$$W^{\downarrow}_{ph,p'h'}(\omega) = \sum_N \frac{\langle ph|V|N\rangle\langle N|V|p'h'\rangle}{\omega - \omega_N}$$

- RPA+PVC model based on Skyrme DFT
  Colo et al., PRC 50, 1496 (1994); Niu et al., PRC 85, 034314 (2012)
- RPA+PVC model based on relativistic DFT *Litvinova et al., PRC 75,064308 (2007)*

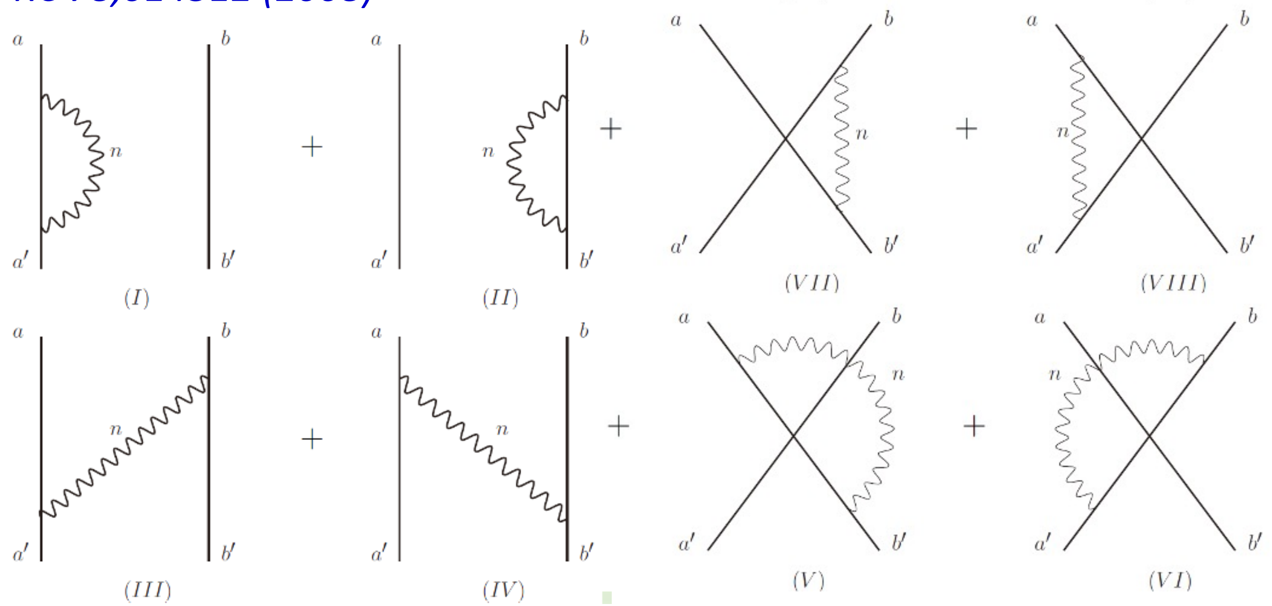
QRPA+QPVC model

- To include pairing correlations for open-shell nuclei
  - Quasiparticle RPA + quasiparticle vibration coupling
    (**QRPA**) + (**QPVC**)
    - based on relativistic DFT
      Litvinova et al., PRC 78,014312 (2008)
    - based on Skyrme DFT

✓ QPVC effect

2 qp ⊗ phonons

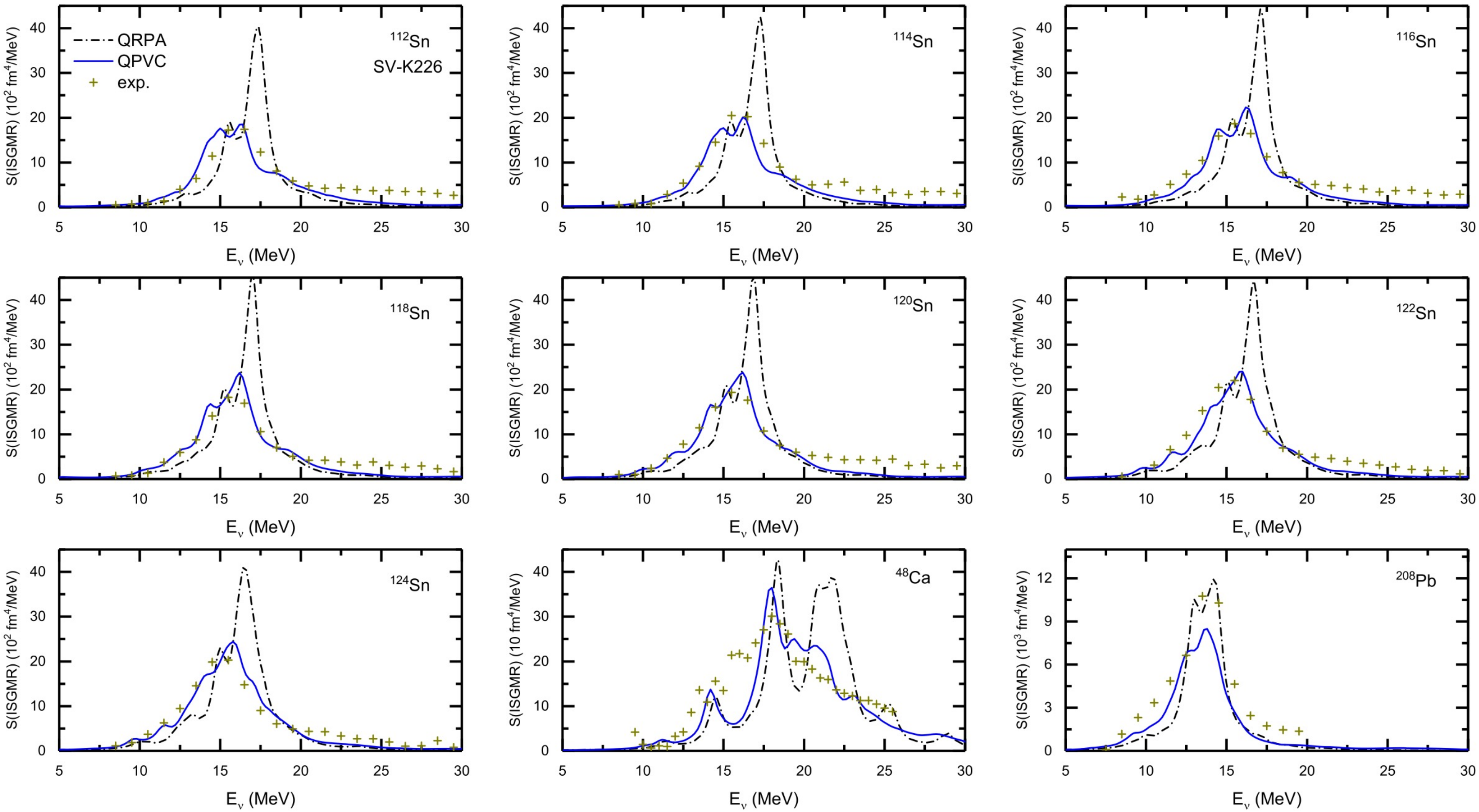
2 quasiparticles(qp)



✓ Pairing effect

Giant Monopole Resonance studied by QPVC

- Achieved a unified description of GMR in Ca, Sn and Pb isotopes

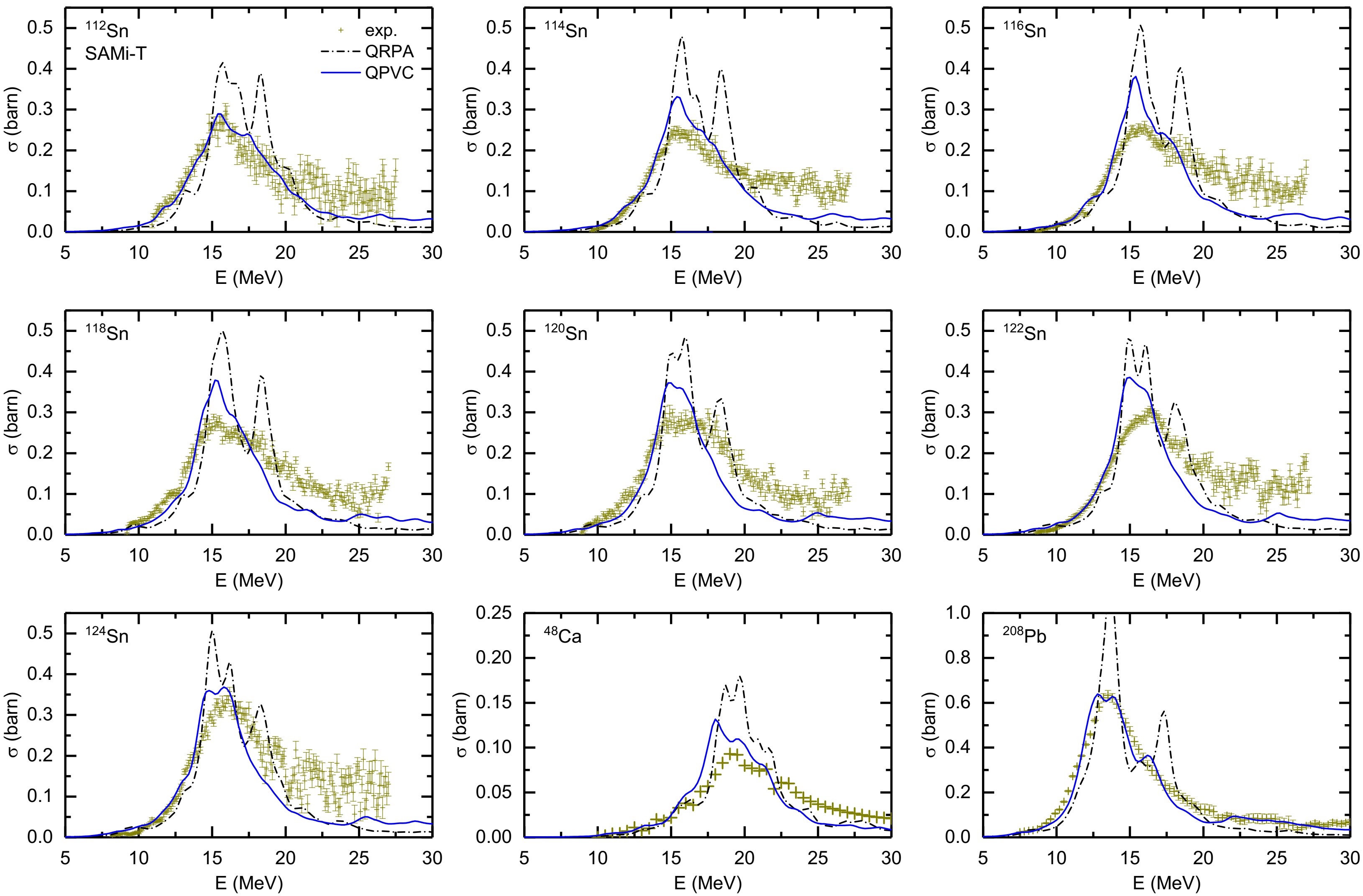


➢ Solved the famous puzzle in nuclear physics "Why are tins so soft? "

Z.Z. Li, Y.F. Niu and G. Colo, PRL 131, 082501 (2023)

Giant Dipole Resonance studied by QPVC

- Photoabsorption cross section is dominated by GDR
  - ✓ Unified descriptions of GDRs in Ca, Sn and Pb isotopes



Giant Quadrupole Resonance studied by QPVC

- Unified descriptions of GQRs in Ca, Sn and Pb isotopes

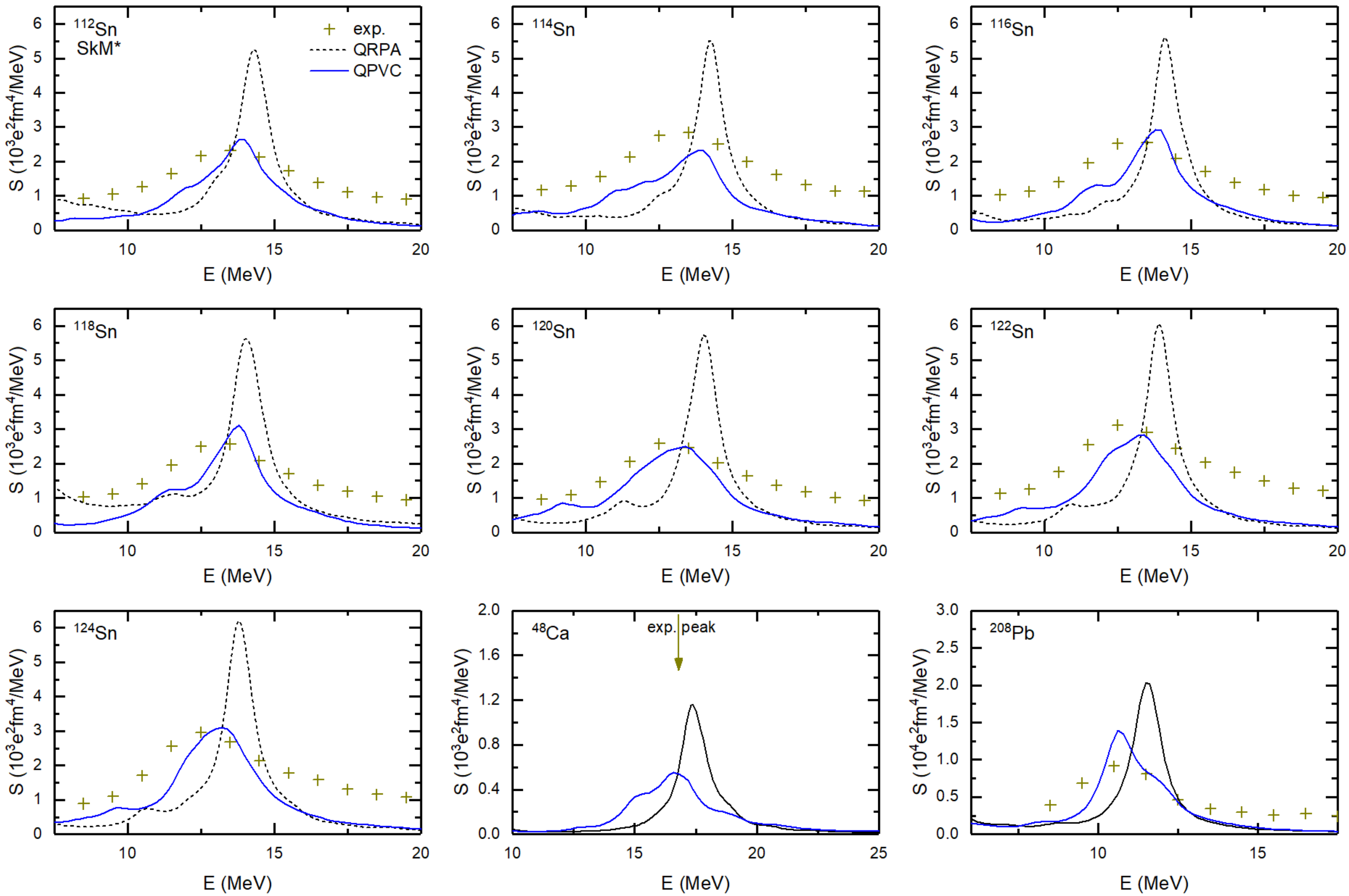


Photo-nuclear reaction

- **Advantages**

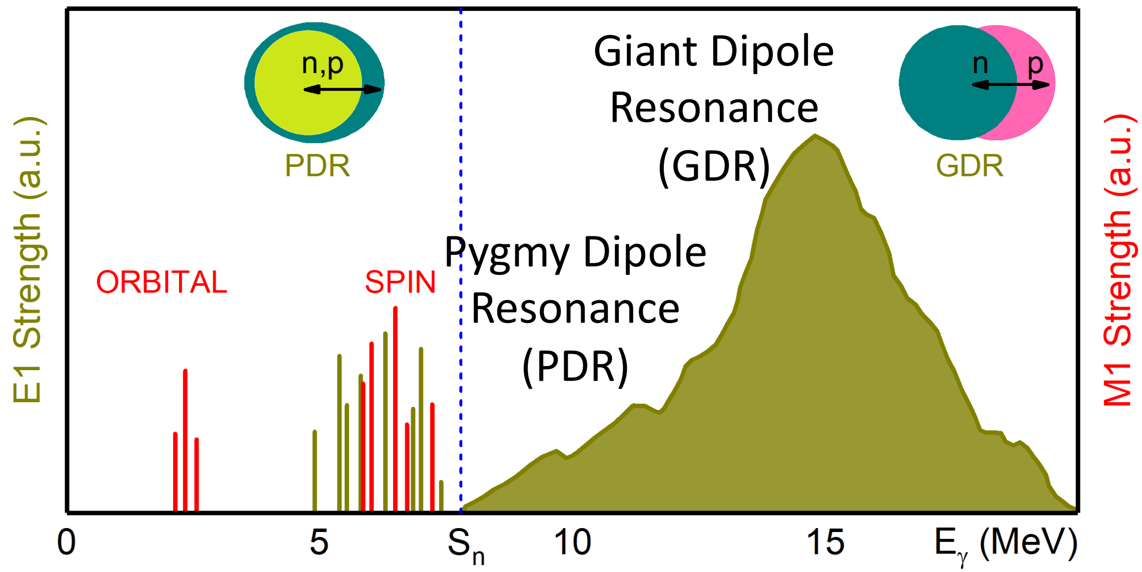
The transition strengths can be extracted in a model-independent way due to the well-known electromagnetic force

$$\sigma^{(pl)}_{\mu J}(E_\gamma) = \frac{8\pi^3 e^2}{3} \frac{(2J+1)(J+1)}{J((2J+1)!!)^2} \left(\frac{E_\gamma}{\hbar c}\right)^{2J-1} \boxed{S_{\mu J}(E_\gamma)}$$

cross section

transition strengths

- **Main modes**

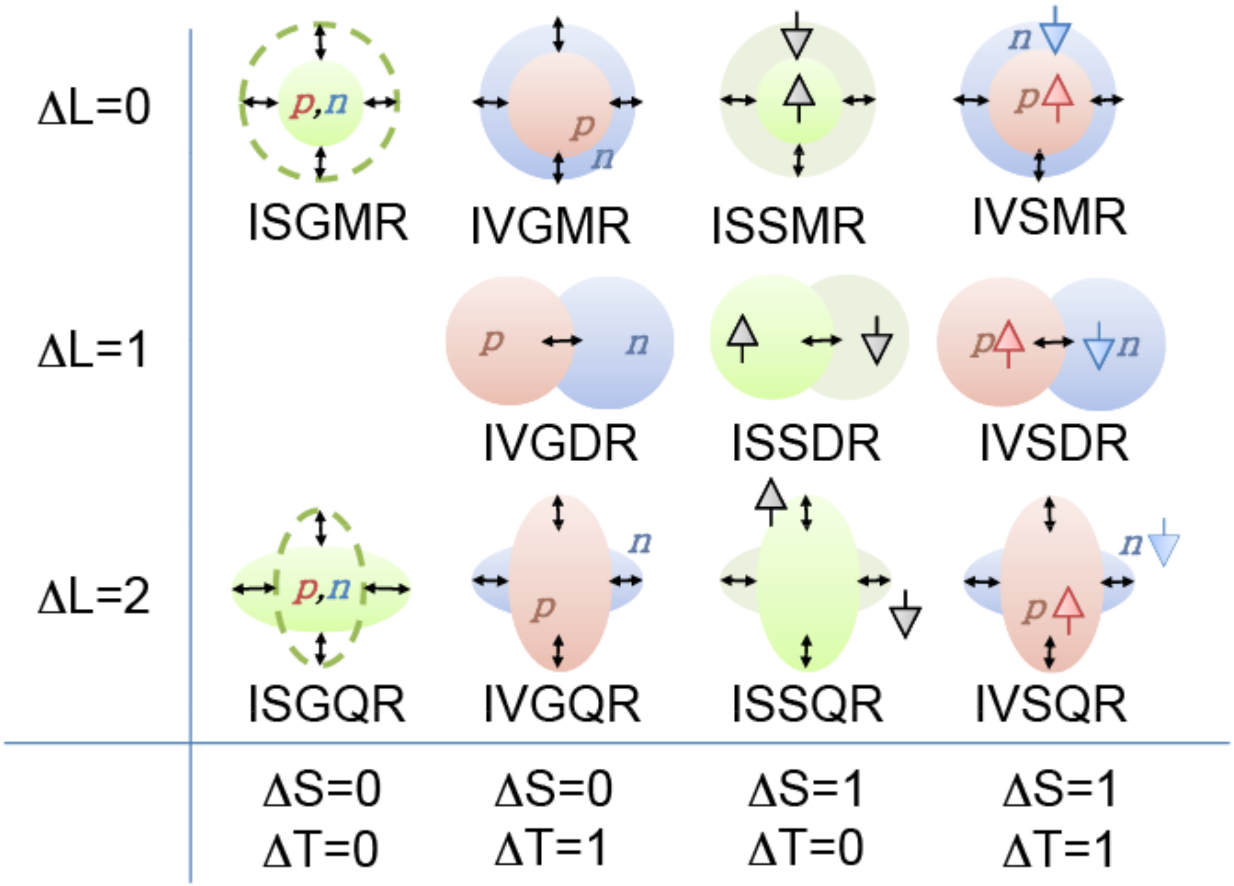


$$T_E(L+1)/T_E(L) \sim 10^{-3}$$
$$T_M(L+1)/T_M(L) \sim 10^{-3}$$
$$T_M(L)/T_E(L) \sim 10^{-3}$$

T: transition probability
E: electric
M: magnetic

Different modes of giant resonances

L : orbital angular momentum S: spin T: isospin



IS = Iso-Scalar
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S = Spin
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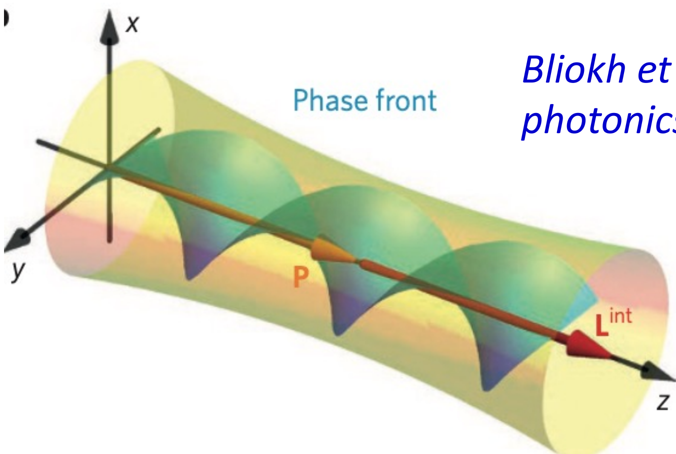
Q = Quadrupole

Is it possible to study giant resonances of higher multipolarity with photons?

New possibilities: vortex photon

- **Coordinate space**



Bliokh et al., Nature photonics 9, 796(2015)

- ✓ **Vortex wavefunction**:

$$\Psi_l(\boldsymbol{r},t) = u(\rho,z)e^{il\phi}e^{ik_z z}e^{-i\omega t}$$

Eigenfunctions for **OAM** operator

$L_z = -\frac{i\partial}{\partial\phi}$, carry OAM $m_l = l\hbar$

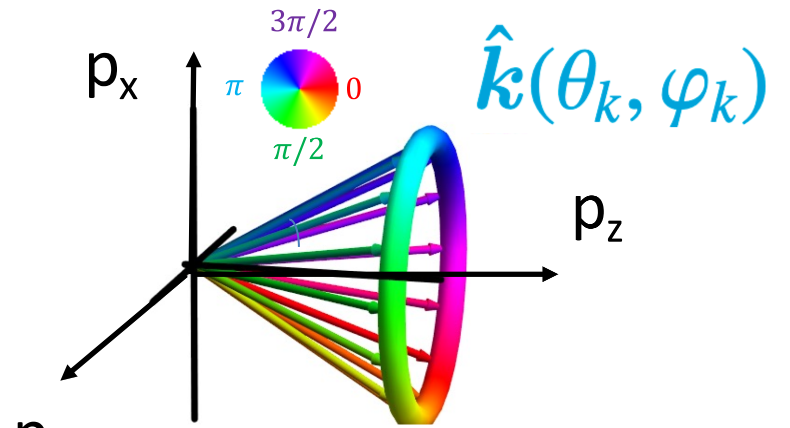
$$m_\gamma = m_l + m_s$$

Mode function: $u(\rho,z)$

(Bessel or LG beam modes)

Helical phase: $e^{il\phi}e^{ik_z z}$

- **Momentum space**



polar angle $\theta_k = \arctan(\varkappa/k_z)$

- ✓ **Superposition of plane waves**

$$\psi_{\varkappa m k_z}(\mathbf{r}) = \exp(ik_z z)\int a_{\varkappa m}(\mathbf{k}_\perp)\exp(i\mathbf{k}_\perp\boldsymbol{\rho})\frac{d^2k_\perp}{(2\pi)^2}$$

$$= \int a_{\varkappa m}(\mathbf{k}_\perp)\exp(i\mathbf{kr})\frac{d^2k_\perp}{(2\pi)^2},$$

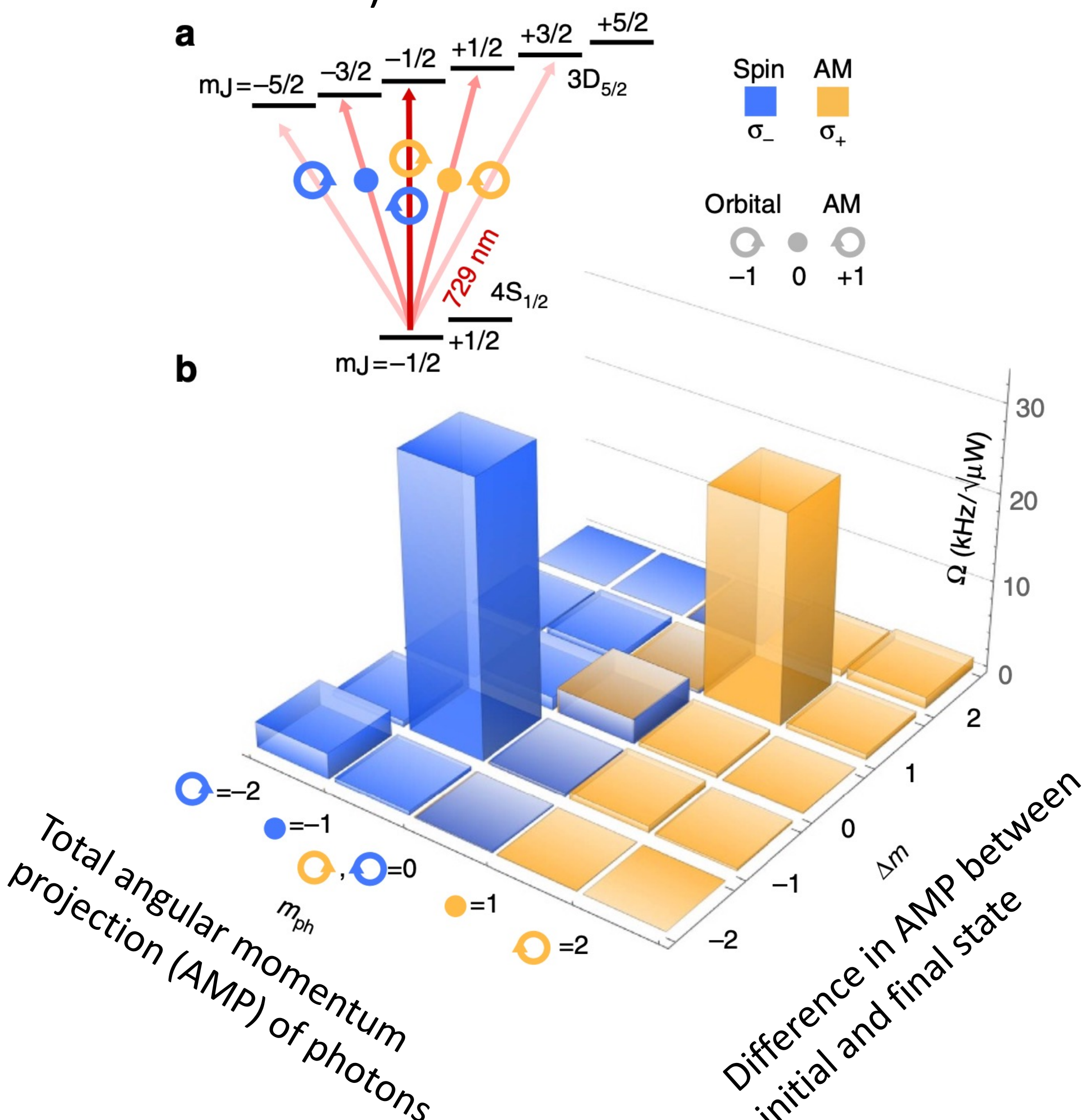
where the Fourier amplitude

$$a_{\varkappa m}(\mathbf{k}_\perp) = i^{-m}\exp(im\varphi_k)\frac{2\pi}{k_\perp}\delta(k_\perp - \varkappa)$$

Knyazev and Serbo, Physics uspekhi 61, 449 (2018)

Transfer of optical OAM to a bound electron

- Excite an atomic transition ($^{40}Ca^{+}$) with a vortex laser beam (Laguerre-Gaussian beam)



demonstrate the transfer of optical orbital angular momentum to the valence electron of a single trapped ion

Modification of transition selection rule

$$\Delta m = m_f - m_i = \sigma_{+/-}$$

$$\Downarrow$$

$$\Delta m = m_f - m_i = \sigma_{+/-} + m_l$$

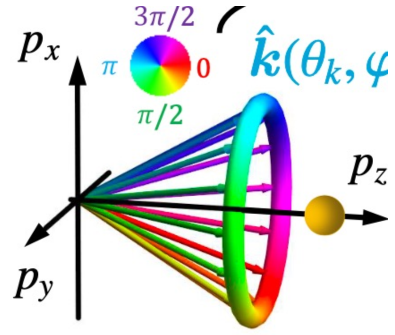
Schmiegelow et al., Nature Comm. 7, 12998 (2016)

Cross section for vortex photon absorption on nucleus

- Nuclear photo-absorption cross section for vortex gamma photon

$$\sigma^{(tw)} = \frac{2\pi\delta(E_\gamma - E_f + E_i)}{(2J_i+1)\bar{J}_z^{(tw)}} \sum_{M_i M_f} M^{(tw)}_{M_i M_f}(\mathbf{b}) M^{(tw)*}_{M_i M_f}(\mathbf{b}).$$

✓ Transition amplitude



$$M^{(tw)}_{M_i M_f} = -\frac{1}{c}\langle J_f M_f \mid \int \hat{\mathbf{j}}(\boldsymbol{r}) \cdot \boldsymbol{A}^{(tw)}_{\varkappa m_\gamma k_z \lambda}(\boldsymbol{r}, t) d\boldsymbol{r} \mid J_i M_i\rangle$$
$$= \int \frac{d^2 k_\perp}{(2\pi)^2} \alpha_{\varkappa m_\gamma}(\boldsymbol{k}_\perp) e^{-i\boldsymbol{k}_\perp b} M^{(pl)}_{M_i M_f}(\theta_k, \varphi_k),$$

By rotating the nucleus from the propagation axis to the ***k*** direction (plane-wave component)

$$M^{(pl)}_{M_i M_f}(\theta_k, \varphi_k) = e^{-i(M_f - M_i)\varphi_k} \sum_{M_i' M_f'} d^{J_i}_{M_i M_i'}(\theta_k) d^{J_f}_{M_f M_f'}(\theta_k) M^{(pl)}_{M_i' M_f'}(0).$$

Finally

$$M^{(tw)}_{M_i M_f}(\mathbf{b}) = -i^{M_f - M_i - 2m_\gamma} e^{i(m_\gamma + M_i - M_f)\varphi_b} J_{m_\gamma + M_i - M_f}(\varkappa b) \sum_{M_i' M_f'} d^{J_i}_{M_i M_i'}(\theta_k) d^{J_f}_{M_f M_f'}(\theta_k) M^{(pl)}_{M_i' M_f'}(0).$$

✓ Average flux density of vortex gamma beam: $\bar{J}_z^{(tw)} = k\cos\theta_k/(2\pi)$

Ratio of the vortex and plane-wave cross section

- The ratio of the vortex and plane-wave cross section

$$r^{(tw)} = \sigma^{(tw)}/\sigma^{(pl)} = \frac{\sum_{M_i M_f} |J_{m_\gamma + M_i - M_f}(\varkappa b) \sum_{M_i' M_f'} d^{J_i}_{M_i M_i'}(\theta_k) d^{J_f}_{M_f M_f'}(\theta_k) M^{(pl)}_{M_i' M_f'}(0)|^2}{\cos\theta_k \sum_{M_i' M_f'} |M^{(pl)}_{M_i' M_f'}(0)|^2}.$$

even-even nuclei

$$= \frac{\sum_{M_f} | J_{m_\gamma - M_f}(\varkappa b) d^{J_f}_{M_f \Lambda}(\theta_k) |^2}{\cos\theta_k}.$$

- Impact parameter b=0

The spherical Bessel function gives the selection rule

$$M_f - M_i = m_\gamma \qquad m_\gamma = m_l + m_s$$

the projection of total angular momentum on propagation axis

which reflects angular momentum conservation.

✓ For plane wave case, the selection rule is

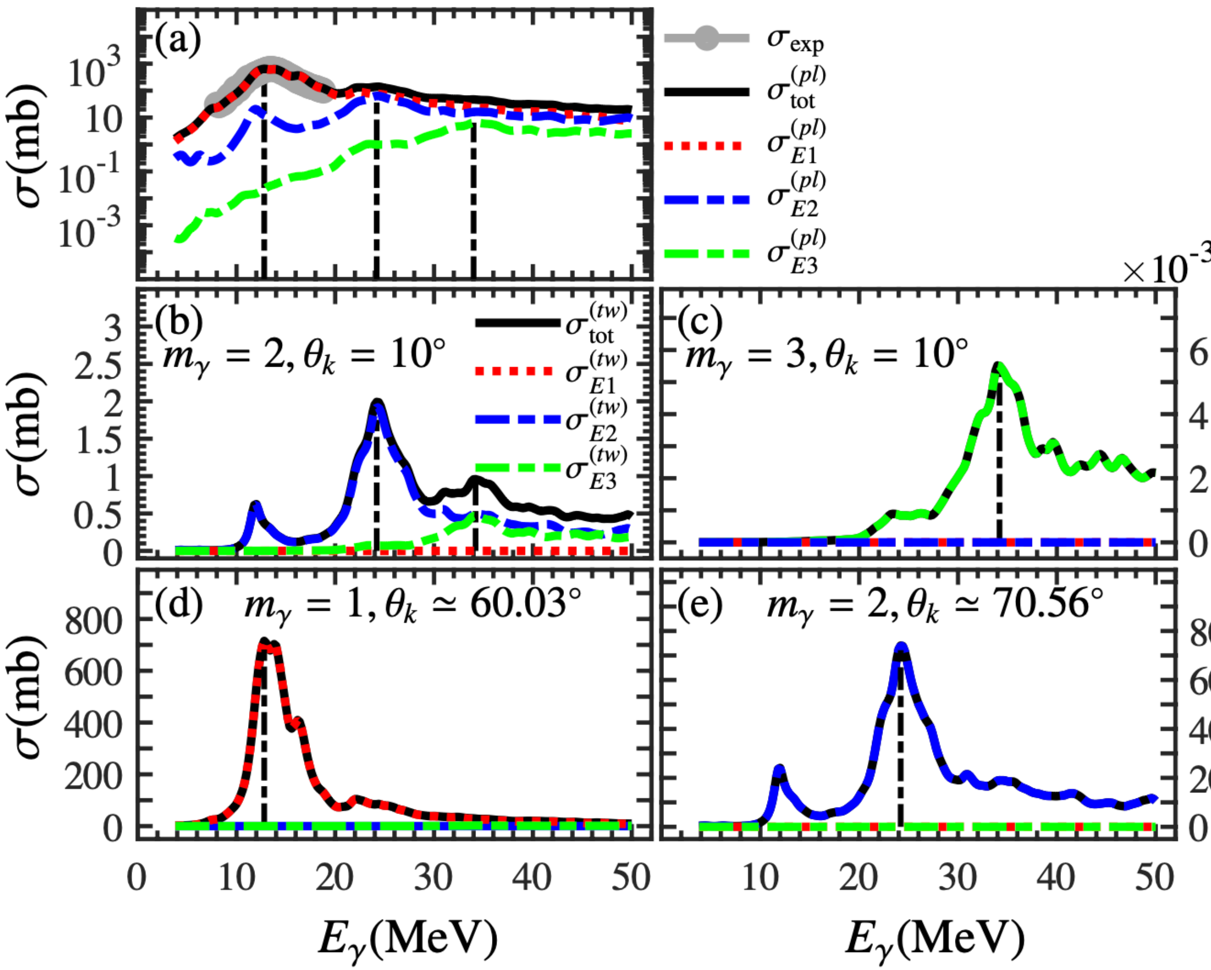
$$M_f - M_i = \Lambda$$

Λ: helicity

Photo-absorption cross section: plane wave vs. vortex

$\Lambda = 1, \quad b = 0$

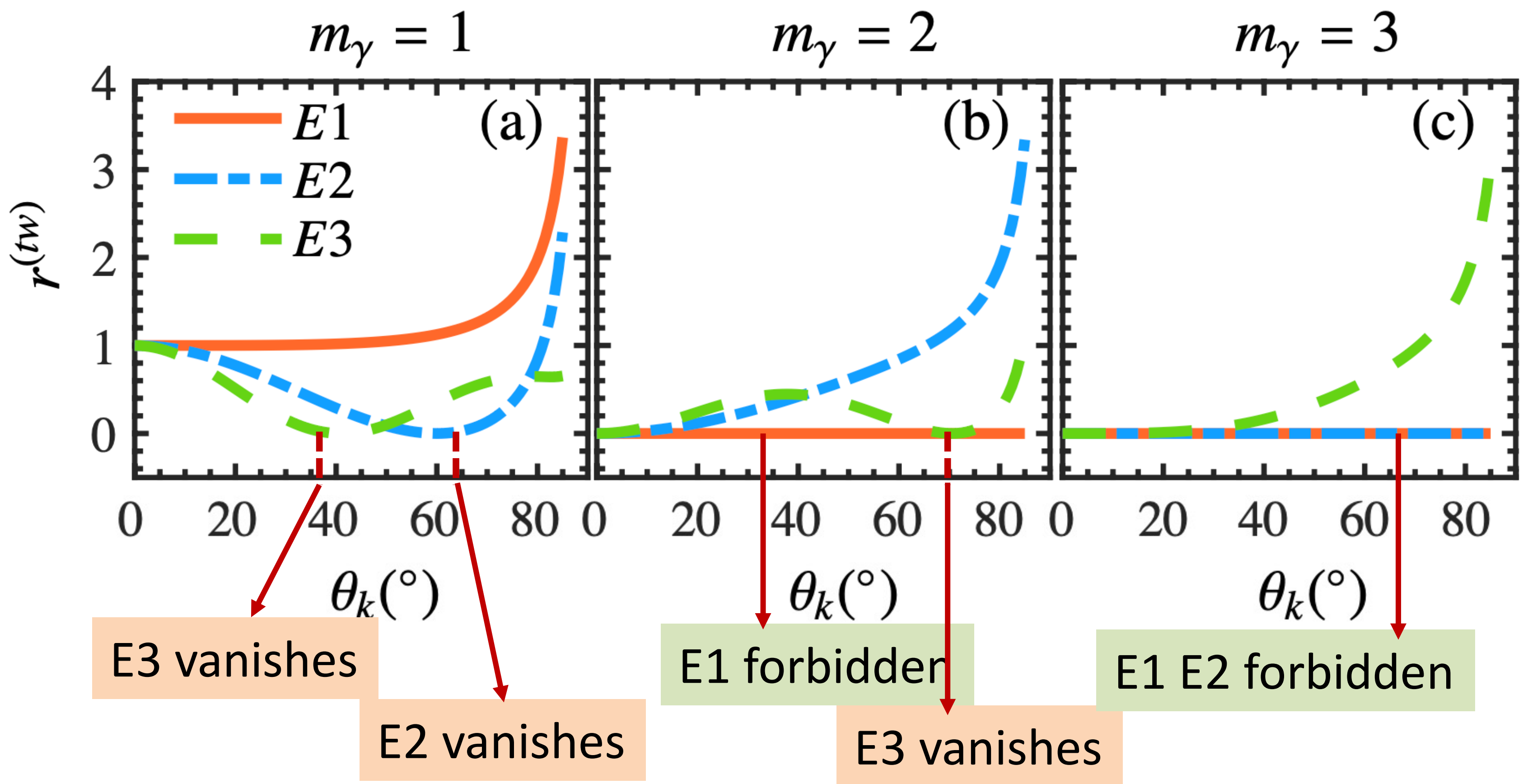
RPA+PVC calculation SAMi-T



- Plane-wave photon case
- Vortex photon case
  - Forbidden of $J < |m_\gamma|$ due to selection rule: $M_f - M_i = m_\gamma$
  - Forbidden of $J = |m_\gamma| + 1$ due to properties of Wigner d-function $d^{J_f}_{m_\gamma \Lambda}(\theta_k)$ which vanishes at specific angle

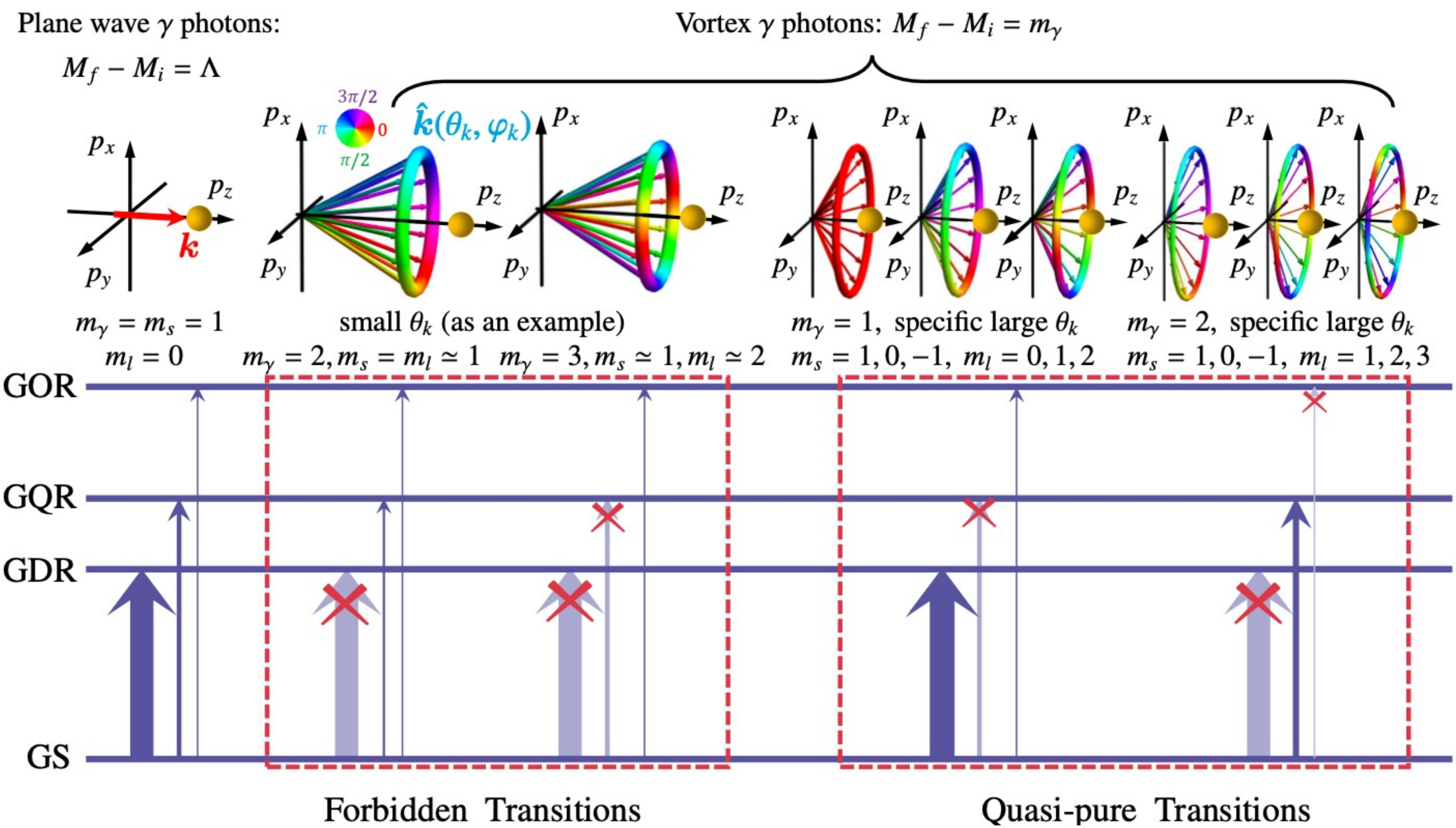
Ratio of the vortex and plane-wave cross section

$\Lambda = 1, \quad b = 0$ polar angle $\theta_k = \arctan(\varkappa/k_z)$



- $m_\gamma = 1, \theta_k = 0$: back to the plane-wave case $r^{(tw)}$=1
- dependence on θ_k comes from Wigner d-function $d^{J_f}_{m_\gamma \Lambda}(\theta_k)$

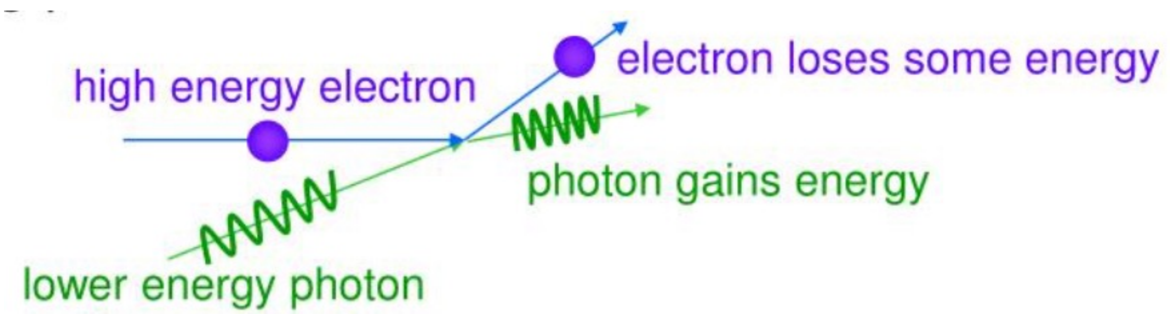
Manipulation of giant resonances via vortex photon



Z. W. Lu, L. Guo, Z. Z. Li, M. Ababekri, F. Q. Chen, C. B. Fu, C. Lv, R. R. Xu, X. J. Kong, Y. F. Niu, and J. X. Li, PRL 131, 202502 (2023)

New γ beam facilities

- **Inverse compton scattering**

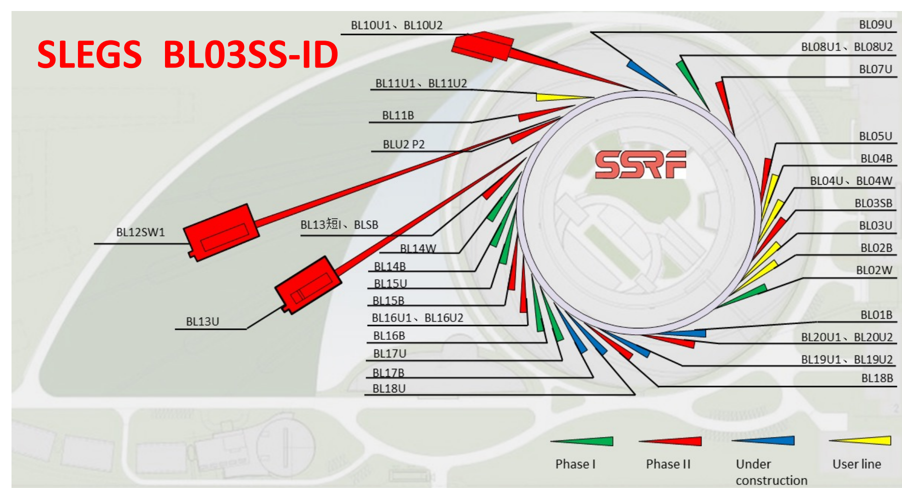


$$E_\gamma^{max} \approx 4\gamma^2 E_l$$

E_e=3.5GeV
E_L=0.116eV(CO_2)
γ = 6849
E_γ =$4\gamma^2 E_L$=21.7MeV

- **High Intensity γ-ray Source (HIγS)** *H. R. Weller et al., Prog. Part. Nucl. Phys. 62, 257 (2009)*
- **Extreme Light Infrastructure – Nuclear Physics (ELI-NP)** *K. A. Tanaka et al., Matter Radiat. Extremes 5, 024402 (2020)*
- **Shanghai Laser Electron Gamma Source (SLEGS)**

H. W. Wang et al., 原子核物理评论 37, 1 (2020); Nucl. Sci. Tech. 33:87 (2022)



Possibility to produce vortex gamma photon

PRL **106,** 013001 (2011) PHYSICAL REVIEW LETTERS week ending 7 JANUARY 2011

Generation of High-Energy Photons with Large Orbital Angular Momentum by Compton Backscattering

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[2]*Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany*
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(Received 22 July 2010; published 5 January 2011)

In this Letter, we show that it is possible to produce high-energy twisted photons by Compton backscattering of twisted laser photons off ultrarelativistic electrons.

Experiments at SLEGS?

Summary and Perspectives

Summary

- Fully self-consistent QRPA+QPVC based on Skyrme density functional for non-charge-exchange channel is developed
  - ✓ Succesfully applied to the study of giant multipole resonances
- New possibilites to study nuclear giant resonances with vortex gamma photons are explored
  - ✓ Forbidden transitions and quasi-pure transitions are found
  - ✓ Provide a clean probe for the study of IV giant quadrupole resonances

Perspectives

- Applications in astrophysics
- Vortex electrons interaction with nucleus
- Explore how to generate vortex gamma beam
- …

Acknowledgement

Collaborators:

LZU: Z. Z. Li   L. Guo   F. Q. Chen   PKU: J. Meng   Anhui Uni.: Z. M. Niu

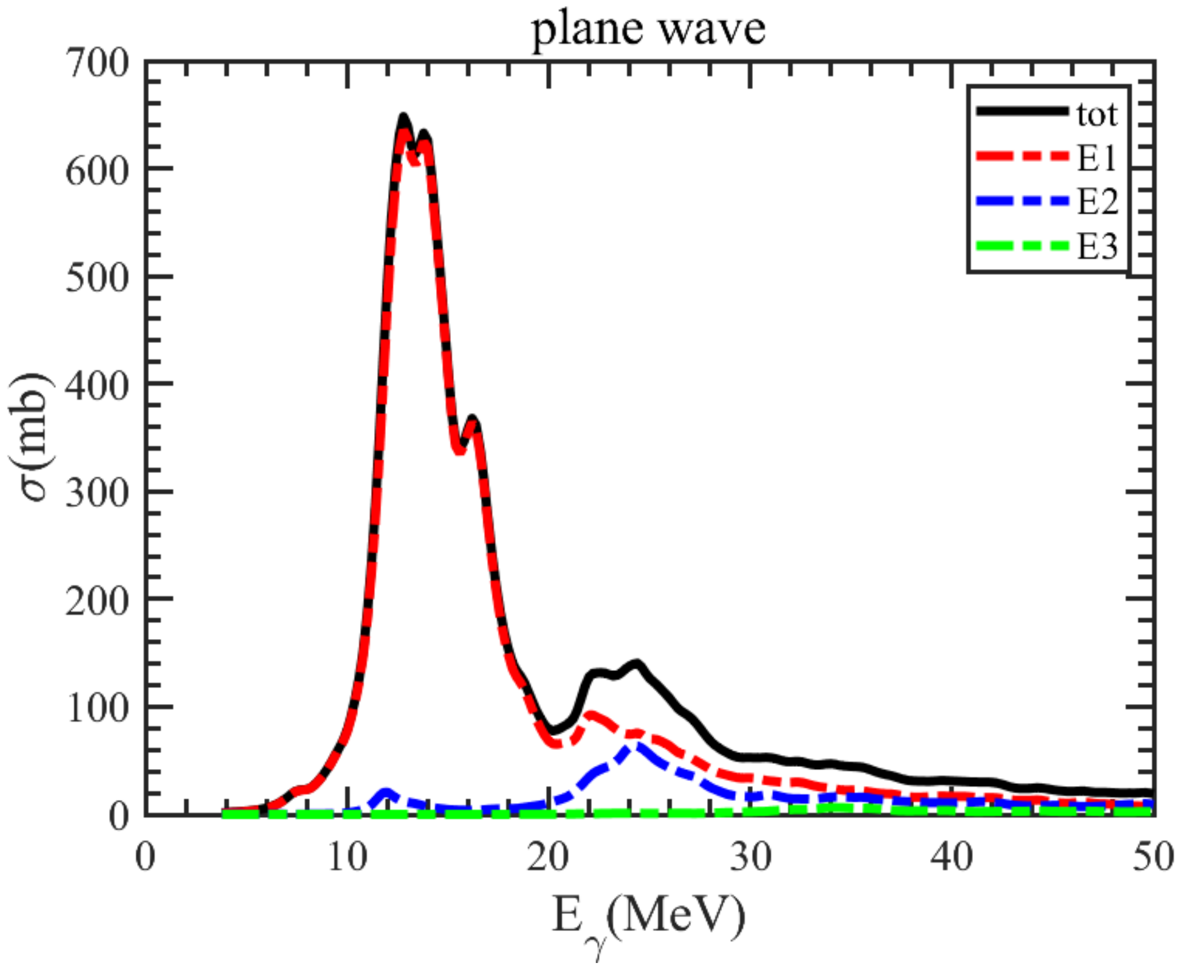
Aizu Univ. and RIKEN: H. Sagawa   Milan Univ. : G. Colo, E. Vigezzi

Xian Jiaotong Uni.: Z. W. Lu, M. Ababekri, J. X. Li

CIAE: R. R. Xu, C. Lv   Fudan Uni.: C. B. Fu, X. J. Kong

Thank you!

Chanllenges?



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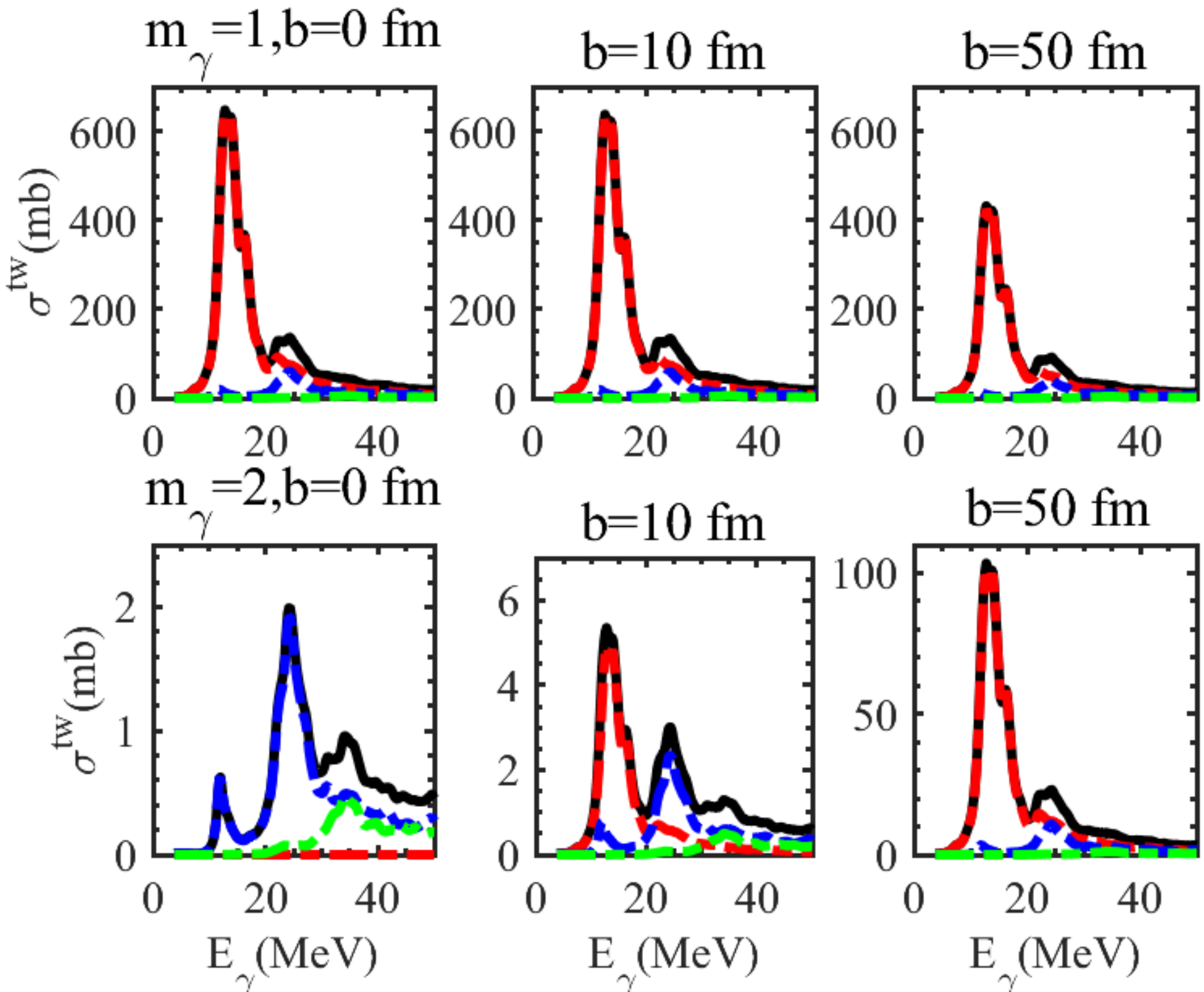
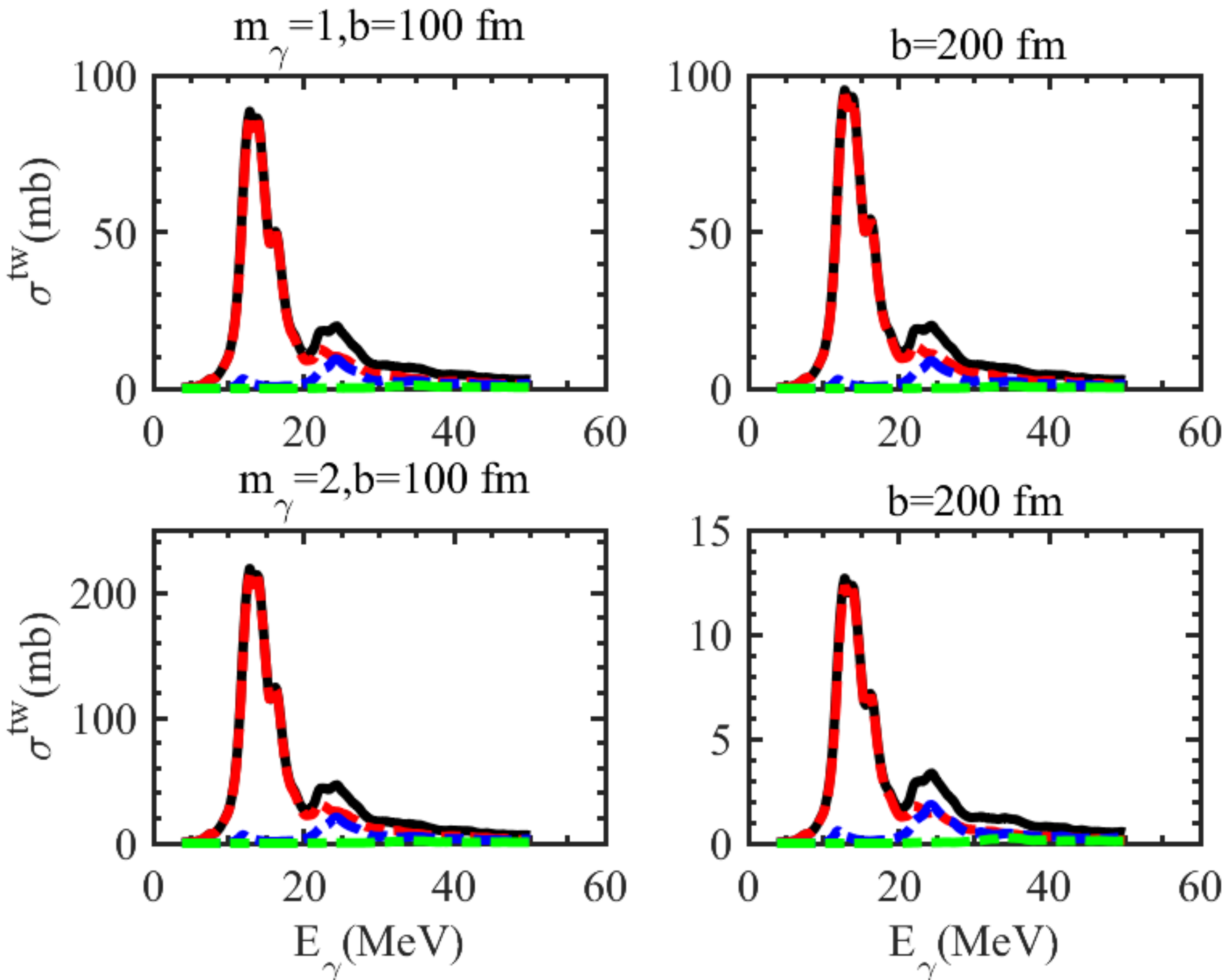


Chanllenges?



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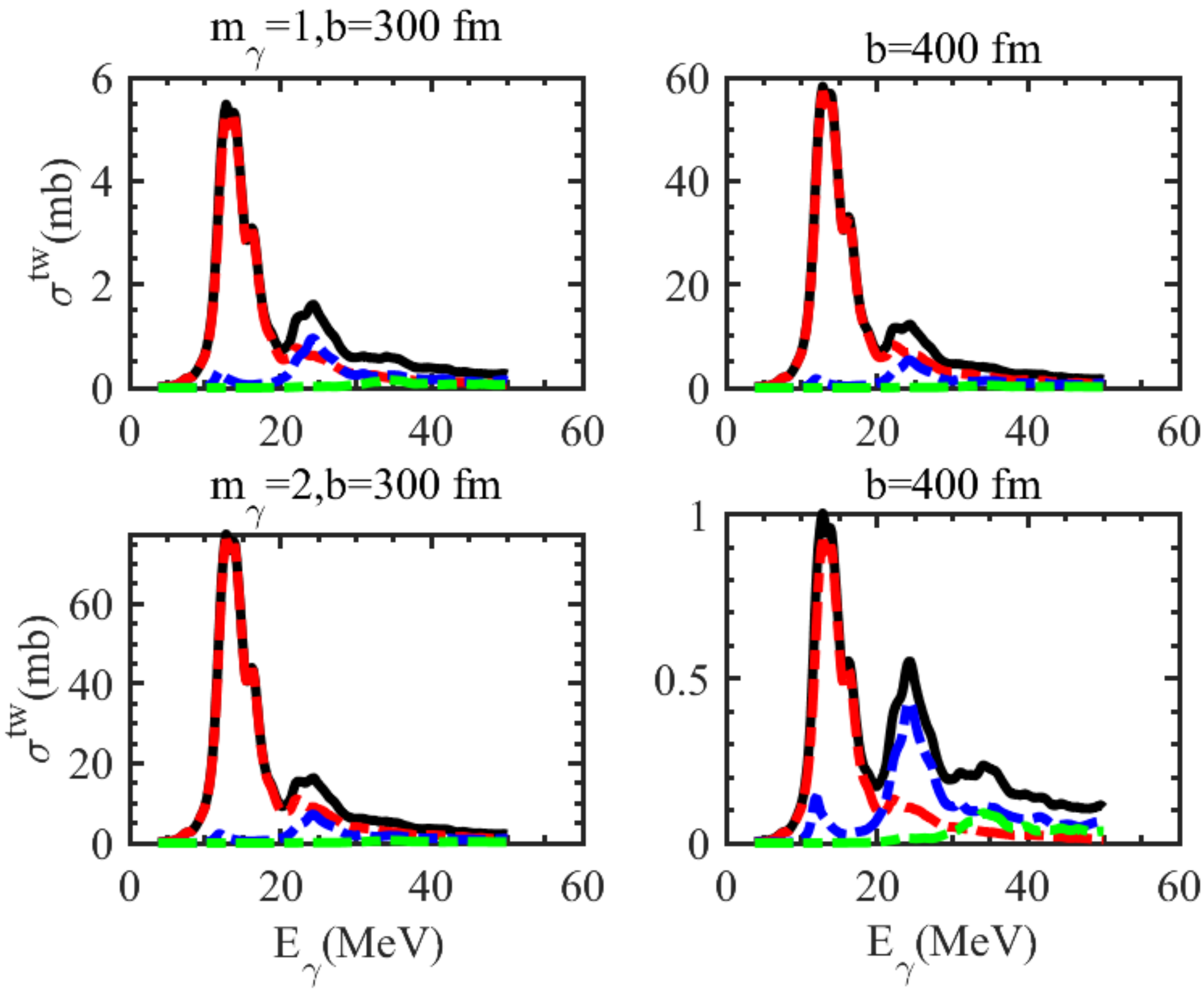

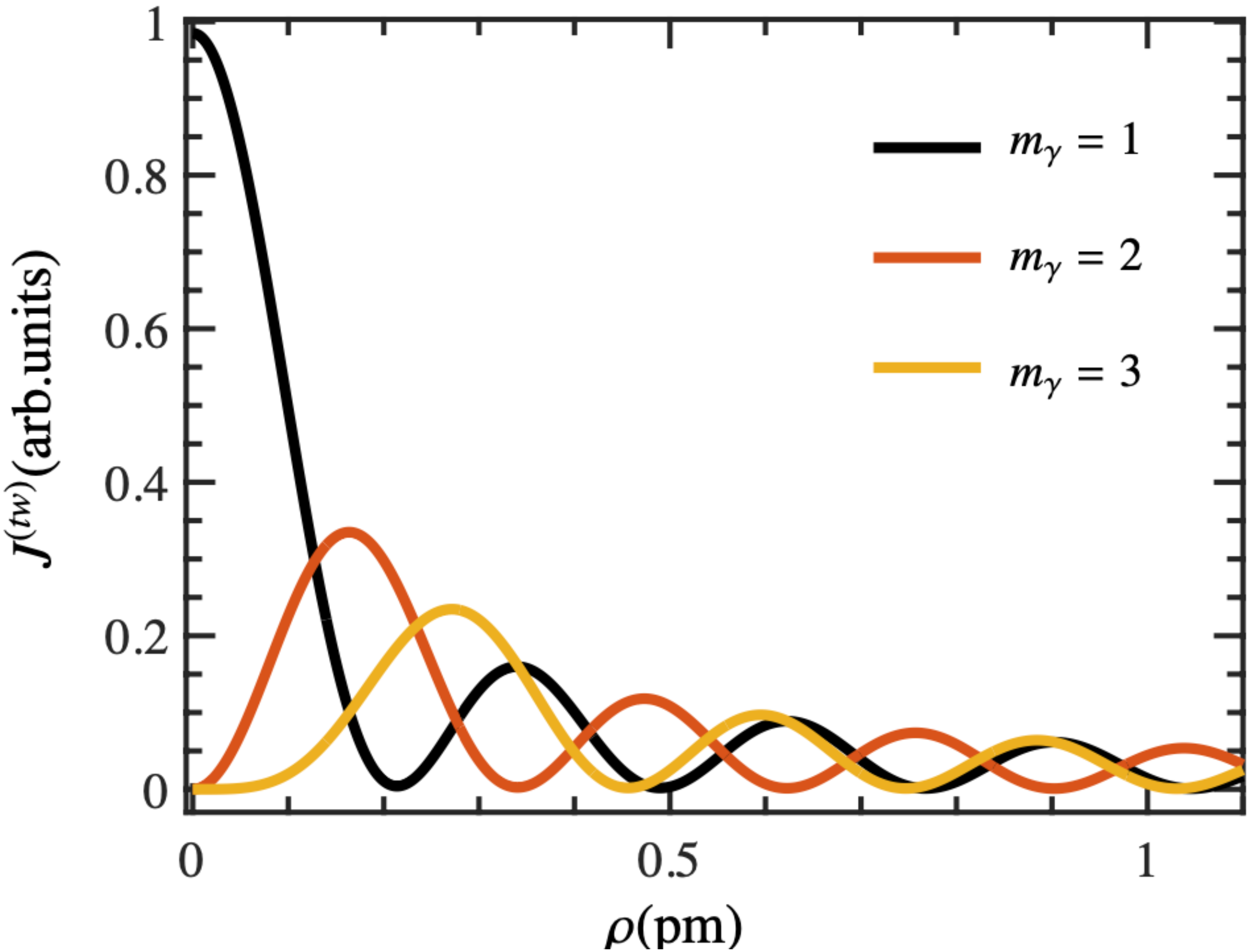

1
0.8
0.6
0.4
0.2
0
0
0.5
1
$J^{(tw)}$(arb.units)
ρ(pm)
$m_\gamma = 1$
$m_\gamma = 2$
$m_\gamma = 3$

Experimental probes

Table 2 Relative cross sections[a] of isoscalar and isovector excitations for various reactions

	Isoscalar	Isovector
(e, e')	1	1
(p, p')	1	$\approx 1/9$
$(^3\mathrm{He}, {}^3\mathrm{He}')$	1	$\approx 1/30$
(α, α') (d, d')	1	≈ 0
(n, p) $(t, {}^3\mathrm{He})$	0	1
(p, n) $(^3\mathrm{He}, t)$ $N = Z$ nuclei	0	1

[a] Relative cross section normalized to 1 for the stronger excitation.