γ DECAY OF GIANT RESONANCES WITHIN THE SKYRME FRAMEWORK

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OTRANTO 2011
NUCLEAR PHYSICS SCHOOL
"RAIMONDO ANNI"

Outline

- Introduction
- Formalism for the calculation of the γ decay width
  - Decay to the ground state
  - Decay to the low-lying states
- Results

Giant Resonances

- Nuclear collective modes, in which almost all the nucleons are involved
- Parameters of the Equation of State of nuclear matter

Monopole	⇨	Compressibility
Dipole	⇨	Simmetry Energy

- Over than 60 year of studies (since 1947)
- More exclusive experiments feasible ⇨ γ decay (LNL – INFN, June 2010)
    - Resonances in exotic nuclei (n – rich)
- Microscopically: coherent superposition of particle – hole excitation
    - RPA (linear response) ➡ Fully self – consistent calculations with microscopic interactions (Skyrme, Gogny, RMF)

Giant Resonances

Main Properties

- Energy: 10 – 30 MeV
- Width: 2 – 5 MeV
- High percentage of EWSR

Decay

- Particle emission (neutron)
- Coupling with doorway states $\longrightarrow$ compound nucleus
- γ decay

Giant Resonances

Decay

- Particle emission (neutron)
- Coupling with doorway states $\longrightarrow$ compound nucleus
- γ decay

- Suppressed with respect to particle emission (~10^{-3})
- Sensitive to resonace multipolarity
- Direct decay: complementary to inelastic scattering data (based on not completely under control ingredients – reaction model, optical potential…)
- Confront with experiment: γ decay from compound nucleus

Decay width

DECAY WIDTH

$$\Gamma_\gamma(E\lambda; i \to f) \propto E^{2\lambda+1} B(E\lambda; i \to f)$$

REDUCED TRANSITION PROBABILITY

$$B(E\lambda; i \to f) = \frac{1}{2J_i + 1} |\langle J_f \| Q_\lambda^{(E)} \| J_i \rangle|^2$$

ELECTROMAGNETIC OPERATOR (LONG-WAVELENGTH LIMIT)

$$Q_{\lambda\mu}^{(E)} = \sum_{i=1}^{A} e_i^\lambda i^\lambda r_i^\lambda Y_{\lambda\mu}^*(\hat{\mathbf{r}}_i)$$

EFFECTIVE CHARGE DUE TO NUCLEAR RECOIL IN $E\lambda$ TRANSITIONS:

$$e_p^\lambda = e\left[\left(1 - \frac{1}{A}\right)^\lambda + (-)^\lambda \frac{Z-1}{A^\lambda}\right] \qquad e_n^\lambda = eZ\left(-\frac{1}{A}\right)^\lambda$$

Nuclear Field Theory

Perturbative theory that describes the interweaving between single particle (fermionic) and phonon (bosonic) degrees of freedom
P. F. Bortignon et al., Phys. Rep.**30**(1977)*305*

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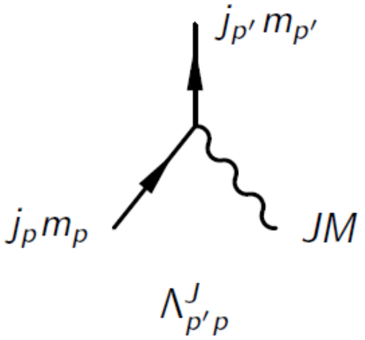
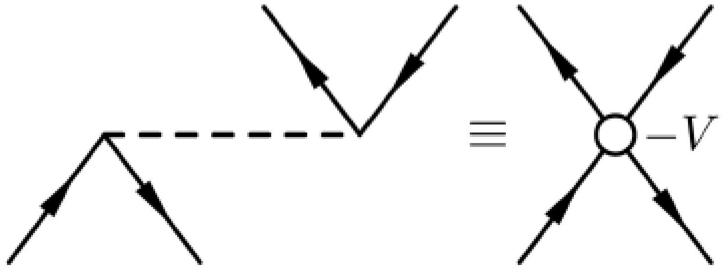
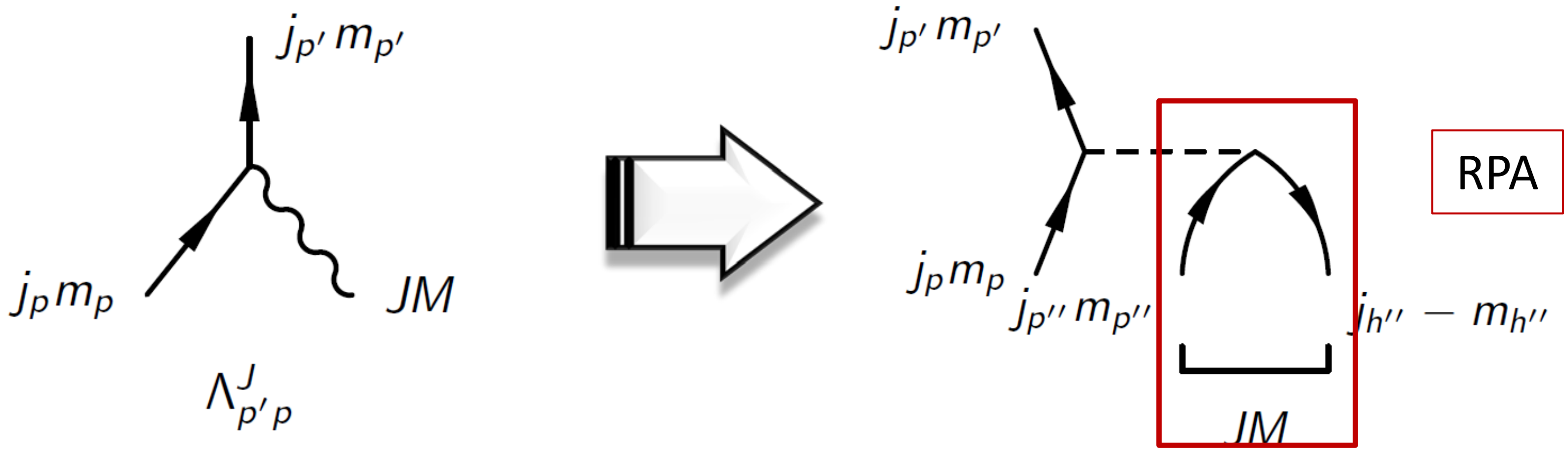




- Single particle moments
- Multiplets of even/odd nuclei
- Giant resonances width Γ
- Appropiate framework to describe the decay to low-lying states

Particle-Vibration Coupling vertex (PVC)



$$\langle i \| V \| j, nJ \rangle = \sqrt{2J+1} \sum_{ph} X^{nJ}_{ph} V_J(ihjp) + (-)^{j_h - j_p + J} Y^{nJ}_{ph} V_J(ipjh)$$

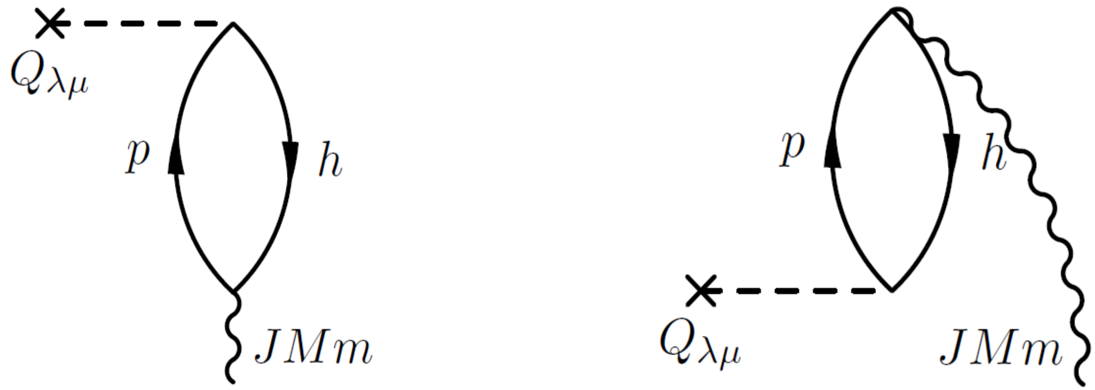
$$V_J(ihjp) = \sum_{\{m\}} (-)^{j_j - m_j + j_h - m_h} \langle j_i m_i j_j - m_j | JM \rangle \langle j_p m_p j_h - m_h | JM \rangle v_{ihjp}$$

Consistent treatment of the coupling vertex in the Skyrme framework: single particle states, RPA phonons, microscopic interaction

G. Colò, H. Sagawa, P. F. Bortignon, PRC**82**(2010)*064307*

Decay to the ground state

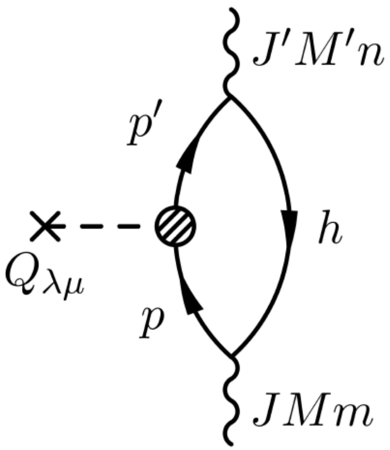
$$\langle 0|Q_{\lambda\mu}|GR, JM\rangle$$

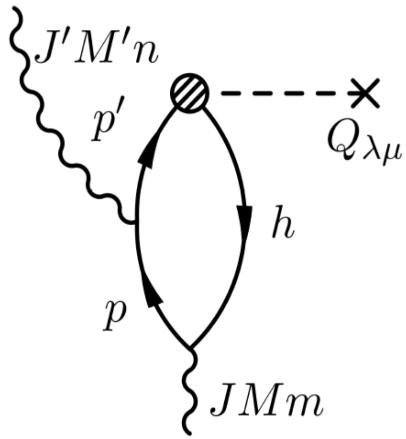


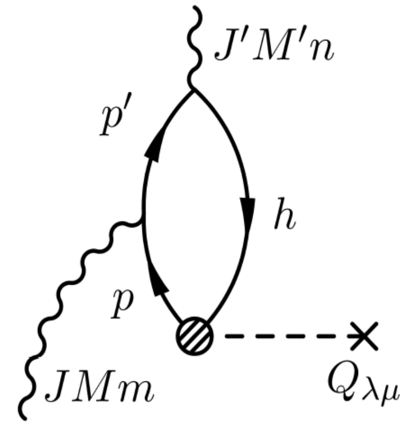
$$\langle 0||Q_\lambda||GR, J\rangle = \sum_{ph} \langle p||Q_\lambda||h\rangle \left(\frac{\Lambda^J_{ph}}{E_J - \epsilon_{ph} + i\eta} - \frac{\Lambda^J_{ph}}{E_J + \epsilon_{ph} + i\eta'} \right)$$

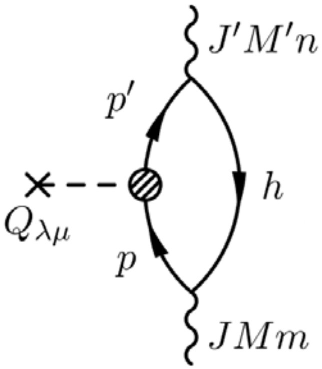
Decay to low-lying states

NFT: 12 diagrams contribute to the matrix element



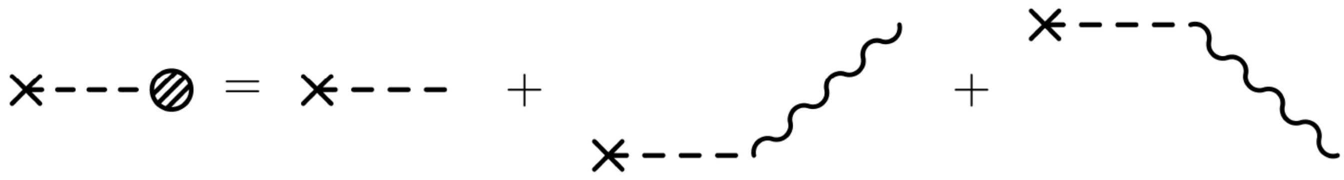






$$= \sum_{pp'h} (-)^{J+\lambda+J'+1} \begin{Bmatrix} J & \lambda & J' \\ j_{p'} & j_h & j_p \end{Bmatrix} \frac{\langle p\|V\|h, nJ\rangle\langle h, mJ'\|V\|p'\rangle Q^{\lambda pol}_{p'p}}{(E_J - \epsilon_{ph} + i\eta)\left(\hbar\omega_{J'} - \epsilon_{p'h}\right)}$$

Decay to low-lying states



Polarization charge:
External field partially screened through the interaction with intermediate states

$$Q_{ij}^{\lambda pol} = \langle i \| Q_\lambda \| j \rangle +$$

$$+ \sum_{n'} \frac{1}{\sqrt{2\lambda+1}} \left[\frac{\langle 0 \| Q_\lambda \| n'\lambda \rangle \langle i, n'\lambda \| V \| j \rangle}{(E_J - \hbar\omega_{J'}) - \hbar\omega_\lambda + i\eta} - \frac{\langle i \| V \| j, n'\lambda \rangle \langle n'\lambda \| Q_\lambda \| 0 \rangle}{(E_J - \hbar\omega_{J'}) + \hbar\omega_\lambda + i\eta} \right]$$

Results – ^{208}Pb

- Consistent approach to the couplling vertex:
  - single particle states – HF
  - phonons – self consistent RPA with Skyrme functional
  - microscopic Skyrme interaction
- No phenomenological ingredient
- 4 Skyrme parametrizzation: SLy5, SGII, SkP, LNS
- γ decay to the ground state and to first J^{π} = 3^{-} state of the Isoscalar Giant Quadrupole Resonance (ISGQR) in ^{208}Pb

Energy and collectivity of the states

J^π	2^+		3^-	
	E [MeV]	EWSR [%]	E [MeV]	$B(E3)\uparrow$ [$10^5 e^2\mathrm{fm}^6$]
Experimental	10.9 ± 0.3	100	2.6145 ± 0.0003	6.11 ± 0.09
SLy5	12.28	69.27	3.62	6.54
SGII	11.62	69.66	2.92	6.83
SkP	10.28	81.79	3.29	5.11
LNS	12.19	64.90	3.37	5.46

Experimental data from NDS**108**(2007)*1583*

Decay to the ground state

	E_{GQR}(MeV)	Γ_γ(eV)	
		RPA	RPA'
SLy5	12.28	231.54	160
SGII	11.62	170.09	154
SkP	10.28	119.18	169
LNS	12.19	176.19	135
Beene et al.,PRC**39**(1989)*1307*	10.60	146±36 – *exp.*	
Speth et al., PRC**85**(1985)*2310*	10.60	112 – *theor.*	
Beene et al., PLB**164**(1985)*19*	11.20	175 – *theor.*	

Consistent with the experimental value through
an energy and EWSR scaling of the GQR
(ΔE = 1 MeV ⇨ increase in Γ_γ of 40 %)

Decay to the 3^- state

	E_{tran}(MeV)	Γ_γ(eV)
SLy5	8.66	5.07
SGII	8.70	33.25
SkP	6.99	10.99
LNS	8.82	54.60
Beene et al.,PRC**39**(1989)*1307*	7.99	5±5 – *exp.*
Speth et al., PRC**85**(1985)*2310*	7.99	4.00 – *theor.*
Bortignon et al., PLB**148**(1984)*20*	8.60	3.50 – *theor.*

Decay to the 3^- state

SLy5

Γ_γ **for a typical ph (eV) at 8.5 MeV**		$1.2 \cdot 10^3$
Quenching factors	**Recoupling**	3
	$\pi - \nu$ **cancellation**	5
	p – h cancellation	3 – 4
	Polarizzation factor	4
	Γ_γ**(eV)**	5.07

Decay to the 3⁻ state

SLy5

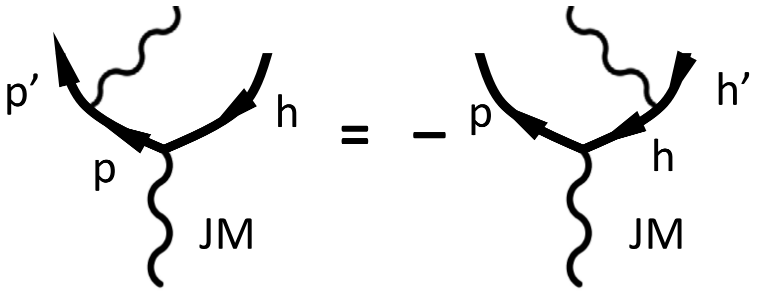
Γ_γ **for a typical ph (eV) at 8.5 MeV**		$1.2 \cdot 10^3$
Quenching factors	**Recoupling**	3
	$\pi - \nu$ **cancellation**	5
	p – h cancellation	3 – 4
	Polarizzation factor	4
	Γ_γ**(eV)**	5.07

$$Q_{ij} = \left(\tau_z - \frac{N-Z}{A}\right)_j \langle i \| r^\lambda Y_\lambda \| j \rangle$$

Decay to the 3$^-$ state

SLy5

Γ_γ **for a typical ph (eV) at 8.5 MeV**		$1.2 \cdot 10^3$
Quenching factors	**Recoupling**	3
	$\pi - \nu$ **cancellation**	5
	p – h cancellation	3 – 4
	Polarizzation factor	4
	Γ_γ**(eV)**	5.07



Decay to the 3^- state

SLy5

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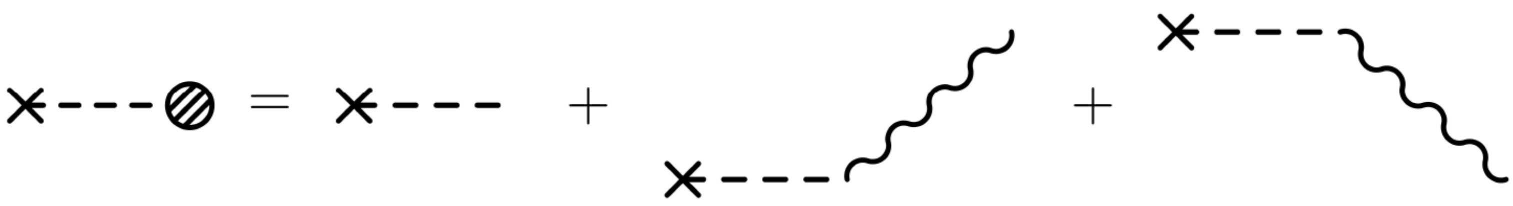

Conclusions

- Microscopic and consistent treatment γ decay
- γ decay to the GS: not able to discriminate between models
- γ decay to the 3^- state: sensitive to the interaction used
    - Dipole spectrum
- Comparison with the experiment at LNL – INFN (June2010)
- Other closed – shell nuclei: ^{90}Zr (LNL - 2010) …

Decay of the compound nucleus

$$\langle \Gamma_{\gamma 0}^{CN} \rangle = \frac{X(\lambda) b_{E\lambda}(E) \left(\frac{E}{\hbar c}\right)^{2\lambda+1}}{\rho_I(E)}$$

$$X(\lambda) = \frac{8\pi(\lambda+1)}{\lambda[(2\lambda+1)!!]^2}$$

- $\rho_I(E)$: density of state of the compound nucleus with spin I and energy E
- $b_{E\lambda}(E)$ reduced transition probability per unit of energy