Microscopic theory of the γ-decay of nuclear giant resonances

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14-16 November 2011

http://arxiv.org/abs/1111.0619

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Outline

Giant Resonances
General features

- Signature of some many-body correlations inside the nucleus
- Nuclear interaction in a given channel
  - Gamow – Teller Resonance ⇛ Spin – Isospin interaction
- Parameters of the equation of state of nuclear matter
  - Monopole ⇛ Nuclear Compressibility
  - Dipole ⇛ Simmetry Energy
  - Quadrupole ⇛ Effective mass
- 60-year-studies on GRs (since 1947), two books
  - P.F. Bortignon, A. Bracco, R.A. Broglia, 1998
  - M.N. Harakeh, A. van der Woude, 2001
- Nowadays: more exclusive experiments ⇛ γ-decay (LNL-INFN, June 2010)
- Resonances in exotic nuclei (n – rich)

Giant Resonances
General features

- Energy: 10 – 30 MeV
- Width: 2 – 5 MeV
- High fraction of
  Energy Weighted Sum Rule (EWSR)

Decay of GRs

- Particle emission (neutrons)
- Compound nucleus
- γ-decay

γ-decay

- suppressed with respect to particle decay ($\sim 10^{-3}$)
- extremely sensitive to the resonance multipolarity
- decay to GS: strength of resonances
- decay to low-lying: sensitive to the wavefuctions
- direct decay complementary to inelastic scattering data
  (based on not well known assumption – reaction model, optical potential)
- compound γ-decay should be taken into account for a comparison with experimental data

Giant Resonances
Theoretical description

RPA...

Microscopically: coherent superposition of p – h excitations

⇓

RPA ⇒
- Linear response theory
- Fully self - consistent calculations with microscopic interactions (Skyrme, Gogny, RMF)

Giant Resonances

Theoretical description

RPA...

Microscopically: coherent superposition of p – h excitations

RPA ⇒

- Linear response theory
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...and Beyond

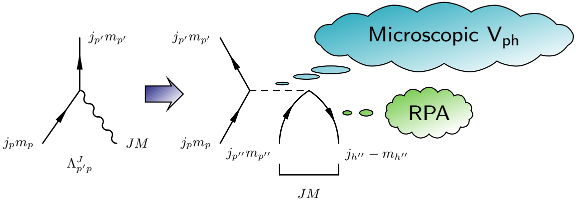
Some features (as decay to low-lying states) need non-linear term.

Nuclear Field Theory
Bortignon et al.
*Phys. Rep.***30**(1977)305 ⇒

- Perturbative theory
- Interweaving between single-particles and phonons

Particle-Vibration Coupling (PVC) vertex

- In the past: many phenomenological calculations with uncontrolled inputs
- Microscopic calculations are now feasible. From Hartree or Hartree-Fock with V_{eff} (assuming this includes short-range correlations), add PVC on top of it. All calculated using the same Hamiltonian or EDF consistently.



- Pioneering Skyrme calculation by V. Bernard and N. Van Giai in the 80s (neglect of the velocity-dependent part of V_{eff} in the PVC vertex). *Nucl. Phys.* **A348**(1980)75.
- RMF + PVC calculations have been done first by E. Litvinova and P. Ring. More results recently by E. Litvinova and A. Afanasjev.

Particle-Vibration Coupling (PVC) vertex

A consistent study

In the version of PVC implemented here the treatment of the coupling is exact, namely we do not wish to make any approximation in the vertex.

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

The whole phonon wavefunction is considered, and all the terms of the Skyrme force enter the p-h matrix elements

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

Consistent treatment of the coupling vertex in the Skyrme framework:

HF single particle states, RPA phonons, microscopic interaction in PVC vertex (G. Colò, H. Sagawa, P. F. Bortignon, *Phis. Rev.* **C82**(2010)64307)

γ 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)

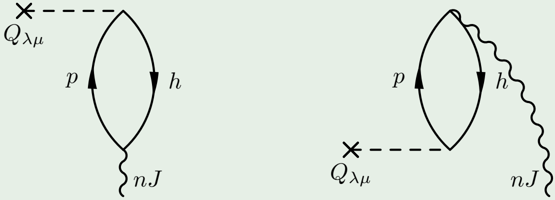
$$Q_{\lambda\mu}^{(E)} = \sum_{i=1}^{A} e_i^\lambda i^\lambda r_i^\lambda Y_{\lambda\mu}^*(\hat{\mathbf{r}}_i)$$

Effective charge due to nuclear recoil

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

γ decay to the ground state

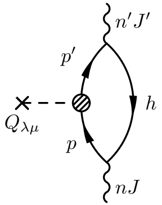
$\langle 0|Q_{\lambda\mu}|nJM\rangle$

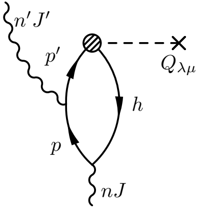


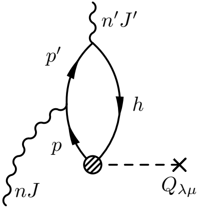
$$\langle 0\|Q_\lambda\|nJ\rangle = \sum_{ph}\langle p\|Q_\lambda\|h\rangle\left(\frac{\langle p\|V\|h,nJ\rangle}{E_J-\epsilon_{ph}+i\eta}-\frac{\langle h\|V\|p,nJ\rangle}{E_J+\epsilon_{ph}+i\eta'}\right)$$

γ decay to low-lying states

NFT necessary: 12 diagrams contribute to the matrix element







γ decay to low-lying states

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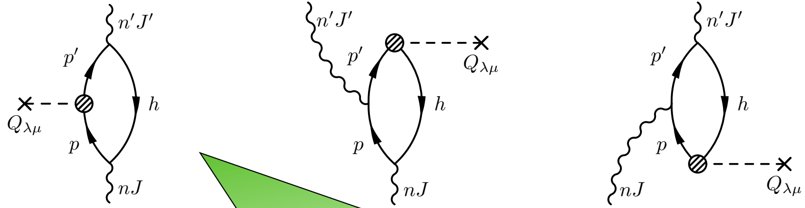
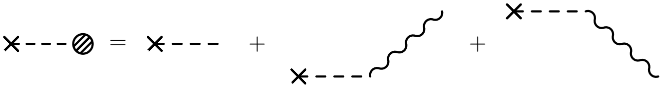


$$\sum_{pp'h}(-)^{J+\lambda+J'+1}\begin{Bmatrix} J & \lambda & J' \\ j_{p'} & j_h & j_p \end{Bmatrix}\frac{\langle p\|V\|h,nJ\rangle\langle h,mJ'\|V\|p'\rangle Q^{\lambda pol}_{pp'}}{(E_J-\epsilon_{ph}+i\eta)\left(E_{J'}-\epsilon_{p'h}\right)}$$

γ decay to low-lying states

The polarization contribution



Polarization

External field partially screened by the interaction with intermediate states

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

Results – ^{208}Pb

- Decay of Isoscalar Giant Quadrupole Resonance (ISGQR) in ^{208}Pb to the ground state and to the first $J^\pi = 3^-$ state
- Experiment at LNL in June 2010 (*Acta Phys. Pol. B***42**(2011)653)
- Consistent approach to the coupling vertex:
  - Single particle states: HF
  - Phonons: self-consistent RPA with Skyrme functional
  - PVC Vertex: microscopic Skyrme interaction
- 4 Skyrme interactions: SLy5, SGII, SkP, LNS
- Submitted to *PRC*, `http://arxiv.org/abs/1111.0619`

$$V(\mathbf{r}_1,\mathbf{r}_2) = t_0(1+x_0P_\sigma)\delta(\mathbf{r}) + \frac{1}{2}t_1(1+x_1P_\sigma)\left[\mathbf{P}'^2\delta(\mathbf{r}) + \delta(\mathbf{r})\mathbf{P}^2\right]$$
$$+ t_2(1+x_2P_\sigma)\mathbf{P}'\cdot\delta(\mathbf{r})\mathbf{P} + \frac{t_3}{6}(1+x_3P_\sigma)[\rho(\mathbf{R})]^\sigma\delta(\mathbf{r})$$
$$+ iW_0\boldsymbol{\sigma}\cdot[\mathbf{P}'\times\delta(\mathbf{r})\mathbf{P}]$$

Energy and collectivity of the states

J^π	ISGQR		3^-	
	E [MeV]	EWSR [%]	E [MeV]	$B(E3)\uparrow [10^5 e^2 \cdot \text{fm}^6]$
SLy5	12.28	70	3.62	6.54
SGII	11.72	72	3.14	6.58
SkP	10.28	82	3.29	5.11
LNS	12.10	67	3.19	5.67
Exp.	10.9 *3*	100	2.6145 *3*	6.11 *9*

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

Decay to the GS

Interaction	E_{GQR}[MeV]	Γ_γ [eV]	
		RPA	*RPA'*
SLy5	12.28	231.54	160
SGII	11.72	163.22	138
SkP	10.28	119.18	170
LNS	12.10	176.57	135
Speth et al.,*PRC***85**(1985)2310	10.60	112 – *theor.*	
Bortignon et al.,*PLB***148**(1984)20	11.20	142 – *theor.*	
Beene et al.,*PLB***164**(1985)19	11.20	175 – *theor.*	
Beene et al.,*PRC***39**(1989)1307	10.60	130±40 – *exp.*	

Consistent with experimental value through an energy scaling ($\Delta E = 1$ MeV $\Rightarrow$ increase Γ_γ by 50%)

Decay to the 3^- state

Interaction	E_{tran} [MeV]	Γ_γ [eV]
SLy5	8.66	3.39
SGII	8.58	29.18
SkP	6.99	8.34
LNS	8.90	39.87
Speth et al.,*PRC* **85**(1985)2310	7.99	4.00 – *theor.*
Bortignon et al.,*PLB* **148**(1984)20	8.59	3.50 – *theor.*
Beene et al.,*PRC* **39**(1989)1307	7.99	5.00±5.00 – *exp.*

Decay to the 3^- state

The SLy5 case

Γ_γ for a typical ph at 8.5 MeV [eV]	$\approx 10^3$

Γ_γ [eV]	3.39

Decay to the 3^- state

The SLy5 case

Γ_γ for a typical ph at 8.5 MeV [eV]	$\approx 10^3$
Recoupling	3
Quenching factors	
Γ_γ [eV]	3.39

Decay to the 3^- state

The SLy5 case

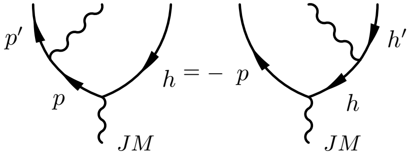
Γ_γ **for a typical ph at 8.5 MeV [eV]**		$\approx 10^3$
Quenching factors	**Recoupling**	3
	$\pi - \nu$ **cancellation**	3
	Γ_γ **[eV]**	3.39

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

Decay to the 3^- state

The SLy5 case

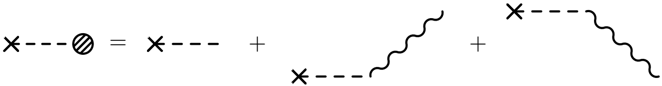
Γ_γ **for a typical ph at 8.5 MeV [eV]**		$\approx 10^3$
Quenching factors	**Recoupling**	3
	$\pi - \nu$ **cancellation**	3
	p − h cancellation	3 − 4
	Γ_γ **[eV]**	3.39



Decay to the 3^- state

The SLy5 case

Γ_γ for a typical ph at 8.5 MeV [eV]		$\approx 10^3$
Quenching factors	**Recoupling**	3
	$\pi - \nu$ cancellation	3
	p − h cancellation	3 − 4
	Polarization factor	6
	Γ_γ [eV]	3.39



Dipole modes (in part. IVGDR), as intermediate states, renormalize the dipole moment of the particle
(polarization of the nuclear medium)

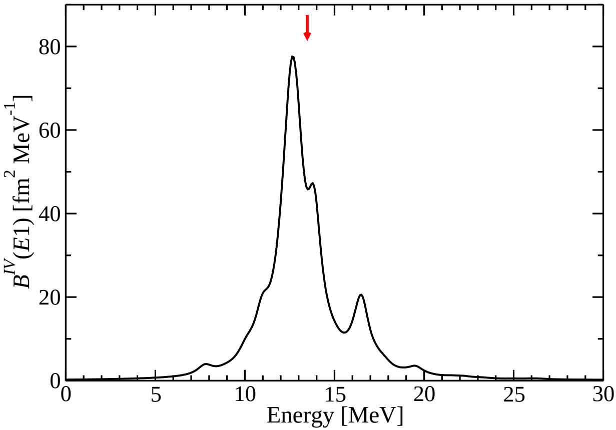
Conclusions

- Microscopic and consistent treatment of the γ decay
- γ decay width to the GS not so able to discriminate between models
- γ decay width to the 3^- very sensitive to the interaction used
  - Dipole states
- Comparison with the experiment at LNL – INFN (June 2010)
- Other closed shell nuclei: ^{90}Zr (LNL - 2010),...
- PDR?

Backup Slides

The dipole isovector strength

Back to Conclusions

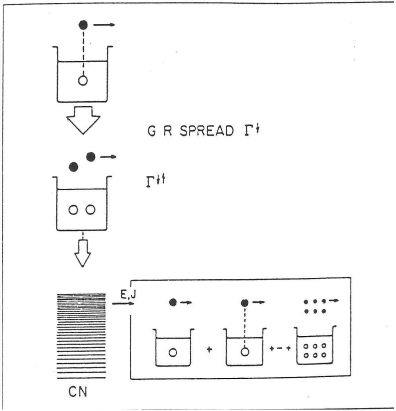


The decay of the compound nucleus

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

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

- $\rho_I(E)$ density of compound states with spin I at energy E
- $b_{E\lambda}(E)$ reduced transition probability per unit energy



Bohr – Mottelson model

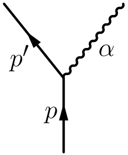
Back to PVC

In the original Bohr-Mottelson model, the phonons are treated as fluctuations δU of the mean field U and their properties are taken from experiment.

$$R = R_0 \left(1 + \sum_{\lambda\mu} \alpha_{\lambda\mu}(t) Y^*_{\lambda\mu}(\hat{r})\right) \Rightarrow U(\mathbf{r} - \mathbf{R}) = U(\mathbf{r} - \mathbf{R_0}) + \delta U$$

$$\delta U = -R_0 \frac{\partial U}{\partial r} \sum_{\lambda\mu} \alpha_{\lambda\mu} Y^*_{\lambda\mu}$$

$$\langle n_\alpha = 1, p' | \delta U | p \rangle \Leftrightarrow$$



γ decay width

$$\Gamma_\gamma(Ej; i \to f) = \frac{8\pi(2j+1)}{j[(2j+1)!!]^2}\left(\frac{E}{\hbar c}\right)^{2j+1} B(Ej; i \to f)$$