MICROSCOPIC DESCRIPTION OF PYGMY DIPOLE RESONANCE IN NEUTRON-RICH NUCLEI

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Outline

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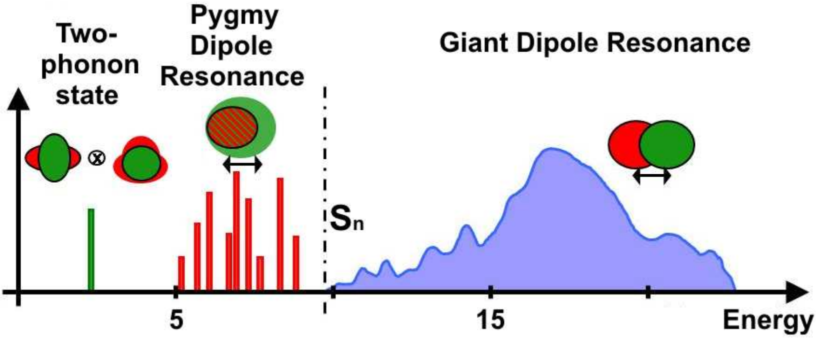
Introduction

$E1$ strength in (spherical) atomic nuclei



Courtesy: N. Pietralla

Relevance of the PDR

1. The PDR might play an important role in nuclear astrophysics. For example, the occurrence of the PDR could have a pronounced effect on neutron-capture rates in the r-process nucleosynthesis, and consequently on the calculated elemental abundance distribution.

S. Goriely, **Phys. Lett.** B436, **10 (1998)**.

2. The study of the pygmy $E1$ strength is expected to provide information on the symmetry energy term of the nuclear equation of state. This information is very relevant for the modeling of neutron stars.

C. J. Horowitz and J. Piekarewicz, **Phys. Rev. Lett.** 86, **5647 (2001)**.

3. New type of nuclear excitation: these resonances are the low-energy tail of the GDR, or if they represent a different type of excitation, or if they are generated by single-particle excitations related to the specific shell structure of nuclei with neutron excess.

N. Paar, D. Vretenar, E. Khan, G. Colò, **Rep. Prog. Phys.** 70, **691 (2007)**.

MAIN INGREDIENTS OF THE MODEL

Realization of QRPA

We employ the effective Skyrme interaction with the tensor terms in the particle-hole channel

$$V(\vec{r}_1,\vec{r}_2)^C = t_0\left(1+x_0\hat{P}_\sigma\right)\delta(\vec{r}_1-\vec{r}_2) + \frac{t_1}{2}\left(1+x_1\hat{P}_\sigma\right)\left[\delta(\vec{r}_1-\vec{r}_2)\vec{k}^2 + \vec{k}'^2\delta(\vec{r}_1-\vec{r}_2)\right]$$
$$+\, t_2\left(1+x_2\hat{P}_\sigma\right)\vec{k}'\cdot\delta(\vec{r}_1-\vec{r}_2)\vec{k} + \frac{t_3}{6}\left(1+x_3\hat{P}_\sigma\right)\delta(\vec{r}_1-\vec{r}_2)\rho^\alpha\left(\frac{\vec{r}_1+\vec{r}_2}{2}\right)$$
$$+\, iW_0\,(\vec{\sigma}_1+\vec{\sigma}_2)\cdot\left[\vec{k}'\times\delta(\vec{r}_1-\vec{r}_2)\right]$$

and

$$V(\vec{r}_1,\vec{r}_2)^T = \frac{T}{2}\left\{[(\sigma_1\cdot\vec{k}')(\sigma_2\cdot\vec{k}') - \frac{1}{3}(\sigma_1\cdot\sigma_2)\vec{k}'^2]\delta(\vec{r}_1-\vec{r}_2)\right.$$
$$\left.+\, \delta(\vec{r}_1-\vec{r}_2)[(\sigma_1\cdot\vec{k})(\sigma_2\cdot\vec{k}) - \frac{1}{3}(\sigma_1\cdot\sigma_2)\vec{k}^2]\right\}$$
$$+\, U\left\{(\sigma_1\cdot\vec{k}')\delta(\vec{r}_1-\vec{r}_2)(\sigma_1\cdot\vec{k}) - \frac{1}{3}(\sigma_1\cdot\sigma_2)[\vec{k}'\delta(\vec{r}_1-\vec{r}_2)\vec{k}]\right\}$$

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

D. Vautherin and D. M. Brink, **Phys. Rev. C5, 626 (1972).**

Realization of QRPA

The Hamiltonian includes the surface peaked density-dependent zero-range force in the particle-particle channel.

$$V_{pair}(\vec{r}_1, \vec{r}_2) = V_0 \left(1 - \frac{\rho(r_1)}{\rho_c}\right) \delta(\vec{r}_1 - \vec{r}_2),$$

where $\rho(r_1)$ is the particle density in coordinate space, ρ_c is equal to the nuclear saturation density. The strength V_0 is a parameter fixed to reproduce the odd-even mass difference of nuclei in the studied region.

A. P. Severyukhin, V. V. Voronov, N. V. Giai, **Phys. Rev. C77, 024322 (2008).**

The starting point of the method is the HF-BCS calculations of the ground state, where spherical symmetry is assumed for the ground states. The continuous part of the single-particle spectrum is discretized by diagonalizing the HF Hamiltonian on a harmonic oscillator basis.

J. P. Blaizot and D. Gogny, **Nucl. Phys. A284, 429 (1977).**

Realization of QRPA

The residual interaction in the particle-hole channel V_{res}^{ph} and in the particle-particle channel V_{res}^{pp} can be obtained as the second derivative of the energy density functional $\mathcal{H}$ with respect to the particle density ρ and the pair density $\tilde{\rho}$, respectively.

$$V_{res}^{\mathrm{ph}} \sim \frac{\delta^2 \mathcal{H}}{\delta\rho_1 \delta\rho_2} \quad V_{res}^{\mathrm{pp}} \sim \frac{\delta^2 \mathcal{H}}{\delta\tilde{\rho}_1 \delta\tilde{\rho}_2} \, .$$

G. T. Bertsch and S. F. Tsai, **Phys. Rep. 18, 125 (1975).**

We simplify V_{res} by approximating it by its Landau-Migdal form

$$V_{res}(\vec{k}_1, \vec{k}_2) = N_0^{-1} \sum_{l=0} \left[F_l + G_l \sigma_1 \cdot \sigma_2 + (F_l' + G_l' \sigma_1 \cdot \sigma_2) \tau_1 \cdot \tau_2 \right] P_l \left(\frac{\vec{k}_1, \vec{k}_2}{k_F^2} \right) ,$$

where $\tau_{\mathbf{i}}$ is the isospin operator, and $N_0 = 2k_F m^* / \pi^2 \hbar^2$ with k_F and m^* standing for the Fermi momentum and nucleon effective mass.

A. B. Migdal, **Theory of Finite Fermi Systems and Applications to Atomic Nuclei (Wiley, New York, 1967).**

Realization of QRPA

Moreover we keep only Landau parameters F_0 and F_0'. Thus, we can write the residual interaction in the following form:

$$V_{res}^{(\mathrm{a})}(\vec{r}_1,\vec{r}_2) = N_0^{-1}\left[F_0^{(\mathrm{a})}(r_1) + F_0'^{(\mathrm{a})}(r_1)(\tau_1\cdot\tau_2)\right]\delta(\vec{r}_1-\vec{r}_2)\,,$$

where $\mathrm{a}=\{\mathrm{ph},\mathrm{pp}\}$ is the channel index.
The expressions for F_0 and F_0' in terms of the Skyrme force parameters can write in the following form:

$$F_0^{\mathrm{ph}}=N_0\left\{\frac{3}{4}t_0+\frac{1}{16}t_3\rho^{\alpha}(\alpha+1)(\alpha+2)+\frac{1}{8}k_F{}^2[3t_1+(5+4x_2)t_2]\right\},$$

$$F_0'^{\mathrm{ph}}=-N_0\left\{\frac{1}{4}t_0(1+2x_0)+\frac{1}{24}t_3\rho^{\alpha}(1+2x_3)+\frac{1}{8}k_F{}^2[t_1(1+2x_1)-t_2(1+2x_2)]\right\},$$

$$F_0^{\mathrm{pp}}(r)=\frac{1}{4}N_0V_0\left(1-\frac{\rho(r)}{\rho_c}\right),$$

$$F_0'^{\mathrm{pp}}(r)=F_0^{\mathrm{pp}}(r).$$

N. V. Giai and H. Sagawa, **Phys. Lett. B106, 379 (1981).**

A. P. Severyukhin, V. V. Voronov, N. V. Giai, **Phys. Rev. C77, 024322 (2008).**

Realization of QRPA

We introduce the phonon creation operators

$$Q^{+}_{\lambda\mu i} = \frac{1}{2} \sum_{jj'} \left(X^{\lambda i}_{jj'} \, A^{+}(jj'; \lambda\mu) - (-1)^{\lambda-\mu} \, Y^{\lambda i}_{jj'} \, A(jj'; \lambda - \mu) \right) ,$$

$$A^{+}(jj'; \lambda\mu) = \sum_{mm'} C^{\lambda\mu}_{jm\, j'm'} \alpha^{+}_{jm} \alpha^{+}_{j'm'} .$$

The index λ denotes total angular momentum and μ is its z-projection in the laboratory system. One assumes that the ground state is the QRPA phonon vacuum $|0\rangle$ and one-phonon excited states are $Q^{+}_{\lambda\mu i}|0\rangle$ with the normalization condition

$$\langle 0|[Q_{\lambda\mu i}, Q^{+}_{\lambda\mu i'}]|0\rangle = \delta_{ii'} .$$

Making use of the linearized equation-of-motion approach one can get **the QRPA equations**

$$\begin{pmatrix} \mathcal{A} & \mathcal{B} \\ -\mathcal{B} & -\mathcal{A} \end{pmatrix} \begin{pmatrix} X \\ Y \end{pmatrix} = \omega \begin{pmatrix} X \\ Y \end{pmatrix} .$$

Solutions of this set of linear equations yield the one-phonon energies ω and the amplitudes X, Y of the excited states.

P. Ring and P. Schuck, **The Nuclear Many Body Problem** (Springer, Berlin 1980).

Phonon-phonon coupling (**PPC**)

To take into account the effects of the phonon-phonon coupling (PPC) in the simplest case one can write the wave functions of excited states as

$$\Psi_\nu(JM) = \left[\sum_i R_i(J\nu) Q^+_{JMi} + \sum_{\lambda_1 i_1 \lambda_2 i_2} P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu) \left[Q^+_{\lambda_1 \mu_1 i_1} Q^+_{\lambda_2 \mu_2 i_2}\right]_{JM}\right] |0\rangle$$

with the normalization condition

$$\sum_i R_i^2(J\nu) + 2 \sum_{\lambda_1 i_1 \lambda_2 i_2} \left[P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu)\right]^2 = 1\,.$$

V. G. Soloviev, **Theory of Atomic Nuclei: Quasiparticles and Phonons (Inst. of Phys., Bristol 1992).**

Phonon-phonon coupling (PPC)

Using the variational principle in the form

$$\delta\Big(\langle\Psi_\nu(JM)|\mathcal{H}|\Psi_\nu(JM)\rangle - E_\nu[\langle\Psi_\nu(JM)|\Psi_\nu(JM)\rangle - 1]\Big) = 0\,,$$

one obtains a set of linear equations for the unknown amplitudes $R_i(J\nu)$ and $P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu)$:

$$(\omega_{Ji} - E_\nu)R_i(J\nu) + \sum_{\lambda_1 i_1 \lambda_2 i_2} U^{\lambda_1 i_1}_{\lambda_2 i_2}(Ji)P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu) = 0\,;$$

$$\sum_i U^{\lambda_1 i_1}_{\lambda_2 i_2}(Ji)R_i(J\nu) + 2(\omega_{\lambda_1 i_1} + \omega_{\lambda_2 i_2} - E_\nu)P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu) = 0\,.$$

$U^{\lambda_1 i_1}_{\lambda_2 i_2}(Ji)$ is the matrix element coupling one- and two-phonon configurations:

$$U^{\lambda_1 i_1}_{\lambda_2 i_2}(Ji) = \langle 0|Q_{Ji}\mathcal{H}\left[Q^+_{\lambda_1 i_1} Q^+_{\lambda_2 i_2}\right]_J|0\rangle\,.$$

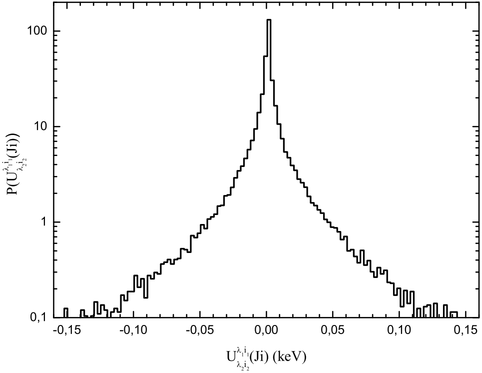
These equations have the same form as the QPM equations, but the single-particle spectrum and the parameters of the residual interaction are calculated with the Skyrme forces.

A. P. Severyukhin, V. V. Voronov, N. V. Giai, Eur. Phys. J. A22, 397 (2004).

A. P. Severyukhin, N. N. Arsenyev, N. Pietralla, V. Werner, Phys. Rev. C90, 011306(R) (2014).

Phonon-phonon coupling (**PPC**)

Distribution of coupling matrix elements $U^{\lambda_1 i_1}_{\lambda_2 i_2}(Ji)$ between the one- and two-phonon configurations in the PPC calculation of the GDR strength function for ^{132}Sn



***A. P. Severyukhin, S. Åberg, N. N. Arsenyev R. G. Nazmitdinov*, in preparation.**

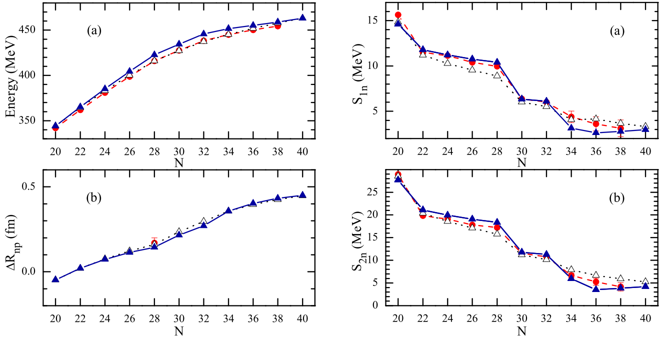
RESULTS AND DISCUSSION

Details of calculations SLy5 vs SLy5+T

We use the Skyrme interactions SLy5 and SLy5+T. The SLy5+T involve the tensor terms added without refitting the parameters of the central interaction (the tensor interaction parameters are α_T=-170 MeV·fm^5 and β_T=100 MeV·fm^5). The pairing strength V_0=-270 MeV·fm^3 is fitted to reproduce the experimental neutron pairing energies near ^{48}Ca.

E. Chabanat et al., **Nucl. Phys. A635, 231 (1998).**

G. Colò et al., **Phys. Lett. B646, 227 (2007).**

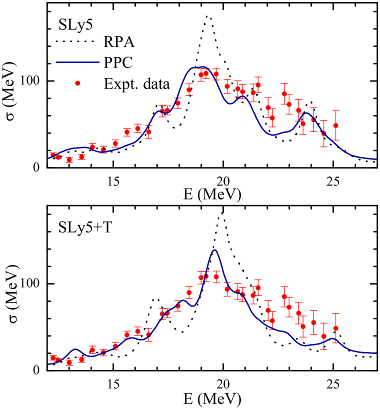


N. N. Arsenyev, A. P. Severyukhin, V. V. Voronov, N. V. Giai, **Phys. Rev. C95, 054312 (2017).**

M. Wang et al., **Chin. Phys. C36, 1603 (2012).**

J. Birkhan et al., **Phys. Rev. Lett. 118, 252501 (2017).**

The photonuclear cross section for ^{48}Ca SLy5 vs SLy5+T



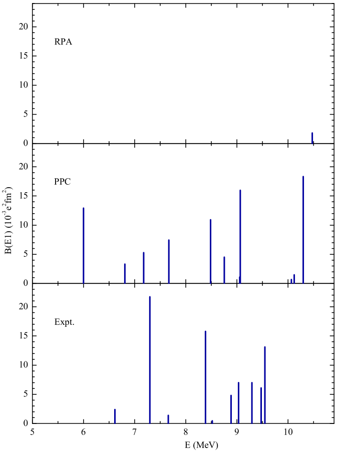
The general shape of the GDR obtained in the PPC are rather close to those observed in experiments.

	$\bar{E}$	Γ
SLy5:		
RPA	19.3	6.9
PPC	19.0	7.3
SLy5+T:		
RPA	19.4	6.3
PPC	19.1	6.7
Expt.:	19.5	7.0

***N. N. Arsenyev, A. P. Severyukhin, V. V. Voronov, N. V. Giai*, Phys. Rev. C95, 054312 (2017).**

***G. J. O'Keefe et al.*, Nucl. Phys. A469, 239 (1987).**

Low-energy 1^- distributions of ^{48}Ca SLy5



The dominant contribution in the wave function of the 1^- states comes from the two-phonon configurations ($>$ 60%). These states originate from the fragmentation of the RPA states above 10 MeV.

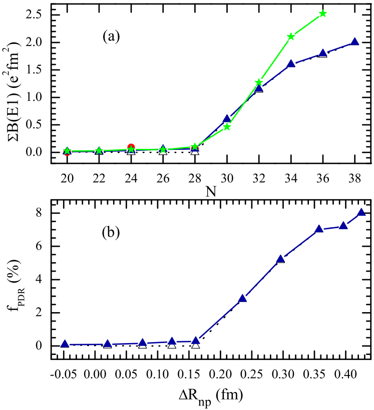
	$\sum B(E1;\uparrow)$	$\sum EB(E1;\uparrow)$
SLy5:		
RPA	0.00	0.00
PPC	0.06	0.50
Kamerdzhiev:	0.071	0.509
Egorova:	0.10	0.95
Expt.:	0.0687(75)	0.570(62)

N. N. Arsenyev, A. P. Severyukhin, V. V. Voronov, N. V. Giai, **Phys. Rev. C95, 054312 (2017).**

T. Hartmann et al. **Phys. Rev. Lett. 93, 192501 (2004).**

I. A. Egorova and E. Litvinova, **Phys. Rev. C94, 034322 (2016).**

The PDR fractions f_{PDR} and $\sum B(E1)$ values SLy5



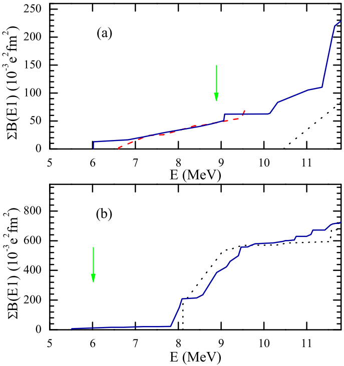
$$f_{PDR} = \frac{\sum_{k}^{\leq 10\ MeV} E_{1_k^-} B(E1; 0^+_{gs} \to 1^-_k)}{14.8NZ/A\ e^2\mathrm{fm}^2\mathrm{MeV}}$$

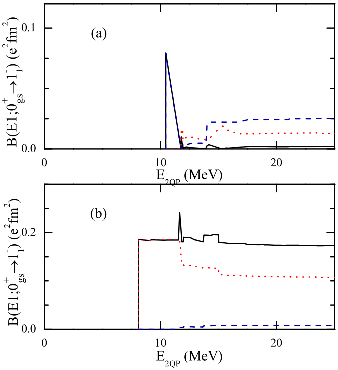
The strong increase of the summed $E1$ strength below 10 MeV $[\sum B(E1)]$, with increasing neutron number from ^{48}Ca till ^{58}Ca.

N. N. Arsenyev, A. P. Severyukhin, V. V. Voronov, N. V. Giai, Phys. Rev. C95, 054312 (2017).

I. A. Egorova and E. Litvinova, Phys. Rev. C94, 034322 (2016).

^{48}Ca vs ^{50}Ca SLy5





***N. N. Arsenyev, A. P. Severyukhin, V. V. Voronov, N. V. Giai*, Phys. Rev. C95, 054312 (2017).**

N.Arsenyev

Conclusions

Starting from the Skyrme mean-field calculations, the properties of the electric dipole strength in neutron-rich Ca isotopes are studied by taking into account the coupling between one- and two-phonons terms in the wave functions of excited states.

We have found that the strong increase of the summed $E1$ strength below 10 MeV $[\sum B(E1)]$, with increasing neutron number from ^{48}Ca till ^{58}Ca. The dipole response for $^{52-58}$Ca is characterized by the fragmentation of the strength distribution and its spreading into the low-energy region.

In the general case, an investigation of the PDR requires to take into account complex configurations. Here the wave functions are considered up to two-phonon components. The model can be extended by enlarging the variational space for the 1^- states with the inclusion of the three-phonon configurations.

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THE END

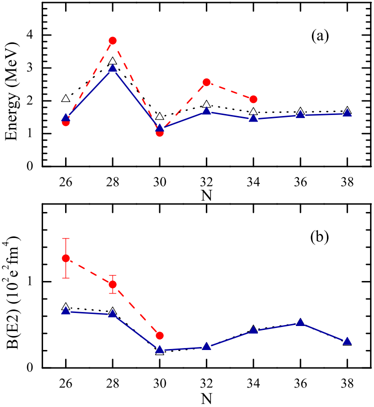
Properties of 2_1^+, 3_1^-, 4_1^+ and 5_1^- phonons SLy5

	λ_1^π	Energy, MeV		$B(E\lambda; 0_{gs}^+ \to \lambda_1^\pi)$, e^2b^λ	
		Expt.	Theory	Expt.	Theory
^{46}Ca	2_1^+	1.346	2.05	0.0127±0.0023	0.0070
	3_1^-	3.614	4.57	0.006±0.003	0.0049
	4_1^+	2.575	2.30		0.00035
	5_1^-	4.184	4.67		0.00027
^{48}Ca	2_1^+	3.832	3.19	0.00968±0.00105	0.0065
	3_1^-	4.507	4.47	0.0083±0.0020	0.0038
	4_1^+	4.503	3.51		0.00035
	5_1^-	5.729	4.52		0.00026
^{50}Ca	2_1^+	1.027	1.50	0.00375±0.00010	0.0018
	3_1^-	3.997	4.36		0.0045
	4_1^+	4.515	3.75		0.00051
	5_1^-	5.110	4.45		0.00029

N. N. Arsenyev, A. P. Severyukhin, V. V. Voronov, N. V. Giai, Phys. Rev. C95, 054312 (2017).

http://www.nndc.bnl.gov/ensdf/

Properties of 2_1^+ states in the Ca isotopes SLy5



- The $[2_1^+]_{QRPA}$ phonons of the even-even $^{46-58}$Ca isotopes exhibit pure neutron two-quasiparticle excitations ($> 72\%$).
- The crucial contribution in the wave function structure of the first 2^+ state comes from the $[2_1^+]_{QRPA}$ ($> 89\%$) configuration.

N. N. Arsenyev, A. P. Severyukhin, V. V. Voronov, N. V. Giai, **Phys. Rev. C95, 054312 (2017).**

B. Pritychenko et al. **At. Data Nucl. Data Tables 107, 1 (2016).**