Araştırma Makalesi / Research Article

Comparission of E1 Response of ^{154}Sm and ^{155}Sm in the Pygmy Dipole Resonance (PDR) Region

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Abstract
The dipole response associated with the pygmy dipole resonance (PDR) in ^{154}Sm and ^{155}Sm has been studied. In the ^{154}Sm nucleus 1^- phonons with *K*=0 and *K*=1 branches have been calculated using the Translation and Galilean Invariant Quasiparticle Random Phase Approximation (TGI-QRPA). The structure of the more pronounced electric dipole (*E*1) peaks in PDR region in ^{154}Sm is composed of predominantly two-quasiproton or two-quasineutron states. The calculations in ^{155}Sm has been performed in the framework of the Translation and Galilean Invariant Quasiparticle Phonon Nuclear Model (TGI-QPNM) based on the TGI-QRPA 1^- phonons calculated for ^{154}Sm. When going from ^{154}Sm to neighbouring ^{155}Sm, the fragmentation of the *E*1 strength is dramatically enhanced. The results emphasize the role of the quasiparticle⊗phonon interactions in enhancing the fragmentation of the strength in the PDR region in ^{155}Sm. Even though the strong fragmentation of the *E*1 strength obtained for ^{155}Sm, in 5-8 MeV energy region the summed *E*1 strength is comparable to that in ^{154}Sm. The results indicate that one quasiparticle behaves solely as a spectator in ^{155}Sm.

Keywords: TGI-QRPA, TGI-QPNM, PDR, ^{154}Sm,^{155}Sm, *E*1.

Pygmy Dipol Rezonans (PDR) Bölgesinde ^{154}Sm ve ^{155}Sm'nin E1 Uyarılmalarının Karşılaştırılması

Öz
^{154}Sm ve ^{155}Sm izotoplarının pygmy dipol rezonansla (PDR) ilişkisi incelenmiştir. ^{154}Sm çekirdeğinde 1^- fononlarının K=0 ve K=1 dalları Öteleme ve Galileo Değişmez Kuaziparçacık Rastgele Faz Yaklaşımı (TGI-QRPA) modeli kapsamında hesaplanmıştır. ^{154}Sm için PDR bölgesinde daha belirgin olan elektrik dipolün (El) pik yapıları, ağırlıklı olarak iki-kuaziproton veya iki-kuazinötron durumlarından meydana gelmektedir. ^{155}Sm çekirdeği üzerine yapılan hesaplamalar, ^{154}Sm için kullanılan 1^- fononlarının hesaplandığı TGI-QRPA modeli baz alınarak, Öteleme ve Galileo Değişmez Kuasiparçacık Fonon Nükleer Model (TGI-QPNM) çerçevesinde yapılmıştır. ^{154}Sm'den komşu ^{155}Sm'ye giderken, E1 kuvvetinin çarpıcı bir biçimde parçalanmaktadır. Sonuçlar, kuaziparçacık⊗fonon etkileşimlerinin ^{155}Sm' de PDR bölgesi için kuvvetin parçalanmasındaki rolünü vurgulamaktadır. ^{155}Sm için elde edilen E1 gücünün güçlü parçalanmasına rağmen, 5-8 MeV enerji bölgesinde toplanan E1 gücü, ^{154}Sm'deki ile benzelrlik göstermektedir. Sonuçlar, bir kuasiparçacığın ^{155}Sm'de yalnızca bir izleyici olarak davrandığını göstermektedir.

Anahtar kelimeler: TGI-QRPA, TGI-QPNM, PDR, ^{154}Sm,^{155}Sm, *E*1.

1. Introduction

Collective excitations (magnetic and electric dipole excitations) play an important role in the study of the nuclear structure. GDR mode defined as the vibration of the proton system against the neutron system is the first collective mode [1]. In the early 1960s, thermal neutron capture experiments showed that there were E1 excitations around the neutron threshold energy [2]. These excitations are called PDR mode because the strength of this mode are smaller than GDR [3]. PDR mode in even-even spherical,

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semi-magic and double magic nuclei were theoretically and experimentally studied. Recently, interest in PDR mode studies in deformed nuclei has increased. In this context, only theoretical studies for even-even deformed Sm and Nd nuclei are available in the literature [4]. In odd-mass nuclei only experimental study was performed for ^{139}La [5]. Therefore, the structure of PDR mode in odd mass nuclei are a open question.

The aim of the present work is to study the properties of PDR of in ^{154,155}Sm. The theoratical tool used in this paper based on selection of the suitable separable effective forces to restore the broken translational and Galilean invariances of the QPNM and QRPA hamiltonians for the description of the E1 excitations in odd- and even-mass nuclei, respectively. In our previous study, this method has been quite successful in explaining of the PDR in N=82 nuclei [6], low lying electric dipole excitations up to 4 MeV [7] and GDR mode in ^{235}U [8].

2. Theory

The model Hamiltonian that produces the E1 states in deformed nuclei can be written as follows:

$$H = H_{sqp} + h_0 + h_\Delta + W_1 \tag{1}$$

where H_{sqp} is the Hamiltonian for the single-quasiparticle motion, W_1 is the isovector part of the dipole-dipole ($\lambda = 1$) interaction, h_0 and h_Δ are separable effective residual interactions restoring the broken Translational and Galilean symmetry of the Hamiltonian, respectively.

$$H_{sqp} = \sum_{qq'} \varepsilon_S(\tau) B_{qq'}(\tau) \tag{2}$$

$$W_{dip} = \frac{3}{2\pi}\chi_1\left(\frac{NZ}{A}\right)^2\left(\vec{R}_N - \vec{R}_Z\right)^2, \vec{R}_\tau = \frac{1}{N_\tau}\sum_{k=1}^{N_\tau} r_k \tag{3}$$

$$h_0 = -\frac{1}{2\gamma}\sum_\mu [H_{sqp}, P_\mu]^+[H_{sqp}, P_\mu] \tag{4}$$

$$h_\Delta = -\frac{1}{2\beta}\sum_\mu [U_{çift}, R_\mu]^+[U_{çift}, R_\mu] \tag{5}$$

The coupling parameters $\gamma = \langle 0|[P_\mu^+,[H_{sqp},P_\mu]|0\rangle$ and $\beta = \langle 0|[P_\mu^+,[U_\Delta,R_\mu]|0\rangle$ are determined by the mean field and pairing potentials, respectively, where $R_\mu = \sum_{k=1}^{A} r_k Y_{lm}(\Theta_k,\Phi_k)$ is proportional to the c.m. coordinate of the nucleus.

The wave function of the odd mass deformed nuclei consists of a sum of single-quasiparticle and quasiparticle phonon terms

$$\psi_K^j(\tau) = \left\{ N_K^j(\tau)\alpha_K^+(\tau) + \sum_{i\mu}\sum_\nu G_j^{i\mu\nu}\alpha_\nu^+(\tau)Q_{i\mu}^+ \right\}|\psi_0\rangle \qquad \mu = 0, \pm 1 \tag{6}$$

To obtain the η_K excitation energies of *electric dipole resonance* for odd-mass nuclei, one has to solve the secular equation following secular equation.

$$P(\eta_K) \equiv \varepsilon_\varsigma - \eta_K - \sum_{i\mu}\sum_\nu \frac{\left(\kappa_1 \frac{2}{N_\tau} r_{\varsigma_q\nu}^\tau V_{\varsigma_q\nu}\overline{L_i} - \varepsilon_{\varsigma_q\nu}^{(-)} p_{\varsigma_q\nu}^\tau M_{\varsigma_q\nu} + \Delta_\tau r_{\varsigma_q\nu} L_{\varsigma_q\nu} L_i\right)^2}{4\omega_i Y(\omega_i)\left(w_i + \varepsilon_\nu - \eta_K\right)} = 0 \tag{7}$$

Where

$$L_i = \frac{\gamma}{\beta} \frac{\sum_{\tau} \Delta_{\tau} \sum_{qq'} r_{qq'} M_{qq'} w^i_{qq'}}{\sum_{\tau} \sum_{qq'} \varepsilon_{qq'} p_{qq'} L_{qq'} g^i_{qq'}} \qquad \overline{L_i} = \gamma \frac{\sum_{\tau} \frac{1}{N_{\tau}} \sum_{qq'} r_{qq'} u_{qq'} g^i_{qq'}}{\sum_{\tau} \sum_{qq'} \varepsilon_{qq'} p_{qq'} L_{qq'} g^i_{qq'}} \tag{8}$$

Here, $p^{\mu}_{qq'} = \langle q | p_{\mu} | q' \rangle$ and $r^{\mu}_{qq'} = \langle q | r_{\mu} | q' \rangle$ are the single particle matrix elements of the linear momentum and core mass center position operator, respectively. The Bogolyubov canonical transformation parameters (u_q and v_q) are also expressed in $V_{qq'} = u_q u_{q'} - v_q v_{q'}$, $U_{qq'} = u_q v_{q'} + u_{q'} v_q$, $L_{qq'} = u_q v_{q'} - u_{q'} v_q$ and $M_{qq'} = u_q u_{q'} - v_{q'} v_q$,respectively. $\psi^i_{qq'}$ and $\varphi^i_{qq'}$ terms are two quasiparticle amplitudes of the even-even core and given in the $g^i_{qq'} = \psi^i_{qq'} + \varphi^i_{qq'}$ and $w^i_{qq'} = \psi^i_{qq'} - \varphi^i_{qq'}$. Finally, the $Y(\omega_i)$ term is obtained from the normalization condition of the wave function of the core nucleus. $\varepsilon_{qq',\tau} = \varepsilon_q + \varepsilon_{q'}$ and $\varepsilon^{-}_{qq',\tau} = \varepsilon_q - \varepsilon_{q'}$ are terms are two quasiparticle energies.

$$\left(N^j_K\right)^{-2} = 1 + \sum_{i\mu} \sum_{\nu} \left(\frac{-4\kappa_1 \frac{1}{Z} r^p_{\varsigma_q \nu} V_{\varsigma_q \nu} \overline{L_i} - 2\varepsilon^{(-)}_{\varsigma_q \nu} p^p_{\varsigma_q \nu} M_{\varsigma_q \nu} + 2\Delta_n r^p_{\varsigma_q \nu} L_{\varsigma_q \nu} L_i}{4\omega_i Y(\omega_i)(\omega_i + \varepsilon_{\nu} - \eta_K)} \right)^2 \tag{9}$$

$$G^{i\mu\nu}_j = -N^j_{\varsigma} \left\{ \frac{-4\kappa_1 \frac{1}{N} r^p_{\varsigma_q \nu} V_{\varsigma_q \nu} \overline{L_i} - 2\varepsilon^{(-)}_{\varsigma_q \nu} p^p_{\varsigma_q \nu} M_{\varsigma_q \nu} + 2\Delta_n r^p_{\varsigma_q \nu} L_{\varsigma_q \nu} L_i}{\sqrt{4\omega_i Y(\omega_i)}(\omega_i + \varepsilon_{\nu} - \eta_K)} \right\} \tag{10}$$

Probabilities of $E1$ transitions from the ground-states to the excited-states in odd-mass and even-even deformed nuclei, respectively can be written as follows:

$$B(E1, I_i K_i \to I_f K_f) = \sum_{\mu} \langle I_i 1 K_i \mu | I_f K_f \rangle^2 \left| -\frac{1}{2} e^n_{eff.} \sum_{q} N^j_{\varsigma_q} N^j_{\varsigma_0} r^{\tau}_{\varsigma_q \varsigma_0} V_{\varsigma_q \varsigma_0} + N^j_{\varsigma_0} \sum_{i\mu} G^{i\mu\varsigma_0}_j \frac{\kappa_1 (1 - L_i)}{\sqrt{\omega_i Y(\omega_i)}} \left(e^n_{eff.} \frac{F_n}{N} - e^n_{eff.} \frac{F_p}{Z} \right) \right|^2 \tag{11}$$

where $e^p_{eff} = N/A$ and $e^n_{eff} = -Z/A$ are neutron and proton effective charges, respectively.

The QRPA theory for even-even nuceus was in ref [7].

3. Results and Discussions

For calculation of the E1 dipole transitions in the ^{155}Sm the mean field deformation parameters δ_2 are calculated according to [9] using deformation parameters β_2 defined from experimental quadrupole moments [10]. The single-particle energies were obtained from the Warsaw deformed Woods–Saxon potential [11]. The pairing-interaction constants taken from Soloviev [12] are based on the single-particle levels corresponding to the nucleus studied. The calculation for the E1 excitation was performed using a strength parameter $\chi_1 = 350 / A^{5/3} MeV fm^{-2}$, values of the pairing parameters Δ and λ are given in Table 1.

Table 1. Pairing correlation parameters (in MeV) and δ_2 values

Nucleus	**[Nn$_z$Λ]Σ**	**Δ_n**	**Δ_p**	**λ_n**	**λ_p**	**δ_2**
^{155}Sm	[521] 3/2$^-$	1.11	1.22	-6.702	-8.569	0.234

The distribution of B(E1) strength calculated for ^{154}Sm and ^{155}Sm are shown in Fig.1. Theory predicts three strong E1 transitions at 6.348 MeV, 6.916 MeV and 7.779 MeV energies for K=0 branches and four strong E1 transitions at 6.645 MeV, 6.919 MeV, 7.167 MeV and 7.6 MeV energies for K=1 branches in ^{154}sm core nucleus. Similar situations are seen in the $K_f=K_0$ and $K_f=K_0\pm1$ branches of the ^{155}Sm nucleus.

The gross features of the E1 strength in 5-8 MeV energy range in ^{154,155}Sm are given in Table 2. For ^{154}Sm theory predicts nineteen negative-parity K=0 states with ΣB(E1)=0.387 e^{2}fm^2 and thirty K=1 states with ΣB(E1)=0.193 e^{2}fm^2. K=0 branch ^{154}Sm corresponds to $K_f=K_0$ in odd mass ^{155}Sm, K1 branch of core ^{154}Sm nucleus corresponds to $K_f=K_0$-1 and $K_f=K_0$+1 states of odd mass ^{155}Sm. In addition, because of the Clebsh-Gordon coefficients in the B(E1) transition expression, $K_f=K_0$ branch has two {(K_0-1,I_0-1),(K_0-1,I_0)} branches, $K_f=K_0$-1 branch has three {(K_0-1,I_0-1),(K_0-1,I_0), (K_0-1,I_0+1)} branches and $K_f=K_0$+1 branch has one {K_0+1,I_0+1} branch. For ^{155}Sm nucleus, thirty six $K_f=K_0$ (3/2$^+$) branch with ΣB(E1)=0.376 e^{2}fm^2, nine $K_f=K_0$-1 (1/2$^+$) branch with summed ΣB(E1)=0.017 e^{2}fm^2 and thirty five $K_f=K_0$+1 (5/2$^+$) branch with summed ΣB(E1)=0.017 e^{2}fm^2 were calculated. It is seen from Table 2 that K = 0 (or $K_f=K_0$ for odd mass nucleus) branch is the dominant branch in PDR region from the results of both core ^{154}Sm and odd mass ^{155}Sm nuclei.

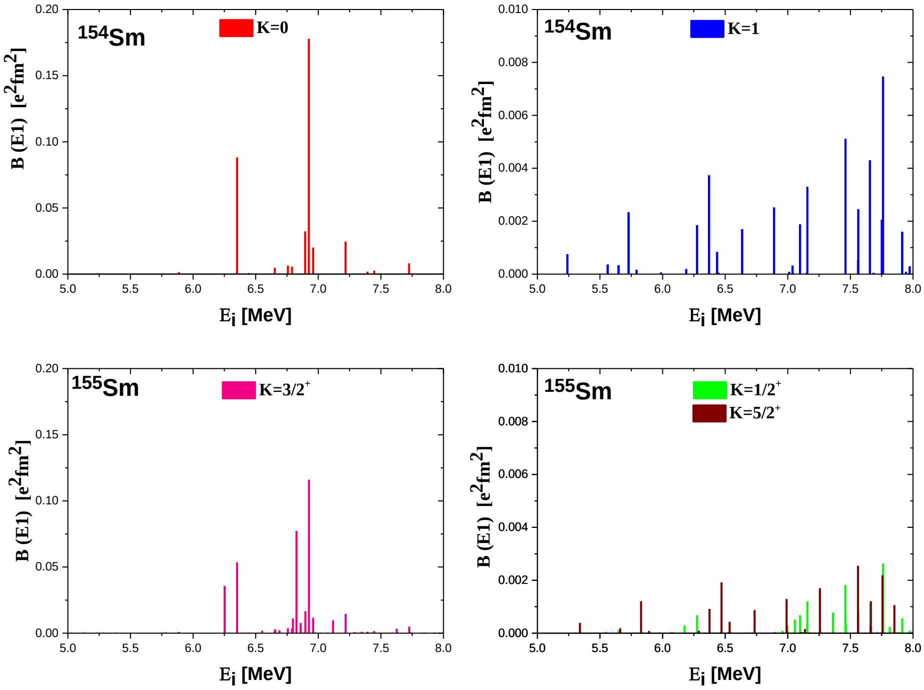

Figure 1. Comparison of the B(E1) values calculated for ^{154}Sm and ^{155}Sm nucleus.

Table 2. The comparison of theoretical values of summed *E*1 strength for ^{154,155}Sm nuclei in the energy range of 5-8 MeV.

^{154}Sm	ΣB(E1) (e^{2}fm^2)	^{155}Sm	ΣB(E1) (e^{2}fm^2)
K=1$^-$0	0.376	K=3/2$^+$	0.387
K=1$^-$1	0.046	K=1/2$^+$	0.017
		K=5/2$^+$	0.017
K=All	0.422	K=All	0.421

Excitations energies, B(E1) transitions, one-quasiparticle and Quasiparticle⊗Phonon amplitudes for odd mass ^{155}Sm nucleus have been shown in Table 3. The E1 states in the PDR region in^{155}Sm nucleus have approximately 99% Quasiparticle⊗Phonon character. In ^{155}Sm for instance, the strongest transitions are dominated by the [521] ↑⊗Q_j.

Table 3. Energies, B(E1↑)values, amplitudes, and the structure of PDR in odd-mass ^{155}Sm isotope.

E_i (MeV)	B(E1) (e^2fm^2)	K^π	N_K	$\sum_{i\mu}\sum_{\nu} G_j^{i\mu\nu}$	Sturcture
6.348	0.0078	$3/2^+$	0.0912	-0.9946	% 100 [521] ↑⊗Q_{13}
6.896	0.030	$3/2^+$	0.0295	-0.9948	% 99 [521] ↑⊗Q_{18}
6.917	0.153	$3/2^+$	0.104	-0.2919	% 8.5 [521] ↑⊗Q_{18}
				-0.9414	% 89 [521] ↑⊗Q_{19}
				0.1223	% 1.5 [521] ↑⊗Q_{20}
6.956	0.025	$3/2^+$	0.00943	0.9997	% 99 [521] ↑⊗Q_{20}
7.167	0.016	$1/2^+$	0.0278	0.9995	% 99 [521] ↑⊗Q_{38}
7.215	0.026	$3/2^+$	0.124	-0.9892	% 97.8 [521] ↑⊗Q_{21}
7.664	11.7713	$1/2^+$	0.00915	0.9995	% 99 [521] ↑⊗Q_{48}
7.780	69.5644	$3/2^+$	0.0565	0.9878	% 98 [521] ↑⊗Q_{28}
				-0.1225	% 2 [521] ↑⊗Q_{28}
7.786	21.4048	$3/2^+$	0.925	-0.1009	% 1 [521] ↑⊗Q_{27}
				0.7079	% 50 [521] ↑⊗Q_{28}
				0.6899	% 48 [521] ↑⊗Q_{29}

4. Conclusion

In this study, E1 transitions were theoretically calculated for ^{154,155}Sm isotopes in the frame of QRPA and QPNM, respectively.The calculations show existance of the resonance like structure between 6.2-8 MeV energy intervals, which can be identified as pygmy dipole resonance. When the total B(E1) transition values of the core and odd mass have been compared, it has been seen that the total transition is close to each other in PDR region. However, due to the coupling properties of the E1 operator, E1 spectra of ^{155}Sm are much more fragmented than the core's. The calculations show that the effect of the one quasiparicle component in the wave function on the structure of the E1 levels in ^{155}Sm is very weak, and the contribution of the Quasiparticle⊗Phonon components are dominant.

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