

Collective multipole excitations of exotic nuclei in relativistic continuum random phase approximation *

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Abstract: The isoscalar and isovector collective multipole excitations in exotic nuclei are studied in the framework of a fully self-consistent relativistic continuum random phase approximation (RCRPA). In this method the contribution of the continuum spectrum to nuclear excitations is treated exactly by the single particle Green's function. Different from the cases in stable nuclei, there are strong low-energy excitations in neutron-rich nuclei and proton-rich nuclei. The neutron or proton excess pushes the centroid of the strength function to lower energies and increases the fragmentation of the strength distribution. The effect of treating the contribution of continuum exactly is also discussed.

Key words: RPA, multipole collective excitations, continuum, neutron-rich nucleus, proton-rich nucleus

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1 Introduction

The structure of nuclei far from β -stable line is an exciting research field since a number of new phenomena are expected or have been observed in neutron-rich nuclei and proton-rich nuclei. Currently, physicists are interested in the study of the effect of neutron or proton excess on various collective excitations. As a result, the multipole response of exotic nuclei, such as neutron-rich nuclei and proton-rich nuclei, becomes a rapidly growing research field [1]. Collective excitations can be studied by the self-consistent relativistic random phase approximation (RRPA) built on the relativistic mean field (RMF) ground state [2–5]. However, in most previously random phase approximation calculations the contribution of the continuum might not be treated properly since the nucleon states in the continuum are discretized by a basis expansion or by setting a box approximation. The coupling between the bound states and the continuum becomes important since the Fermi surface is close to the particle continuum in exotic nuclei [6]. As a result, when one works on the properties of nuclei far from the β -stable line, it is required to consider the contribution of the continuum rigorously.

The fully self-consistent relativistic continuum random phase approximation (RCRPA) has been con-

structed in the momentum representation [7–10]. In this method the contribution of the continuum spectrum to nuclear excitations is treated exactly by the single particle Green's function. In this work, in order to clarify the effect of neutron or proton excess on collective excitations, the RCRPA method is used to study the isoscalar and isovector multipole collective excitations in neutron-rich, proton-rich and β -stable nuclei. Here we want to explore the effect of neutron (proton) excess on the strength distribution of multipole collective excitations; for simplicity, we choose some sub-closed shell nuclei and magic nuclei for our motivation, such as ^{34}Ca , ^{40}Ca , ^{48}Ca , ^{60}Ca , ^{16}O , ^{28}O , ^{100}Sn and ^{132}Sn , the pairing in sub-closed shell nuclei is not included in the present study.

The outline of this paper is as follows. The fully self-consistent RCRPA is introduced in Section 2. In Section 3 we discuss collective multipole excitations of exotic nuclei in RCRPA. Finally we give a brief summary in Section 4.

2 Fully consistent relativistic continuum random phase approximation

We start from the single particle Green's function

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which is defined by:

$$G(\mathbf{r}, \mathbf{r}'; E) = \sum_{b=h, A, \bar{\alpha}} \frac{f_b(\mathbf{r}) \bar{f}_b(\mathbf{r}')}{E_b - E \mp i\eta}. \quad (1)$$

The Green's function can be decomposed into radial functions $g_{ij}(r, r')$ and spin-spherical harmonics, then we can get the radial equation:

$$\begin{pmatrix} -M^* - V + E & d/dr - \kappa/r \\ d/dr + \kappa/r & -M^* + V - E \end{pmatrix} \begin{pmatrix} g_{11}^\kappa(r, r') & g_{12}^\kappa(r, r') \\ g_{21}^\kappa(r, r') & g_{22}^\kappa(r, r') \end{pmatrix} = \delta(r - r') \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}. \quad (2)$$

The regular and irregular solutions of the radial equation are

$$u^\kappa(r) = \begin{pmatrix} u_1^\kappa(r) \\ u_2^\kappa(r) \end{pmatrix}, \quad v^\kappa(r) = \begin{pmatrix} v_1^\kappa(r) \\ v_2^\kappa(r) \end{pmatrix}. \quad (3)$$

In terms of u^κ and v^κ , the radial Green's functions are given by

$$g_{ij}^\kappa(r, r') = \frac{1}{\Delta^\kappa} \begin{cases} u_i^\kappa(r) v_j^\kappa(r'), & r \leq r' \\ v_i^\kappa(r) u_j^\kappa(r'), & r > r' \end{cases} \quad i, j = 1, 2. \quad (4)$$

where $\Delta^\kappa = v_1^\kappa u_2^\kappa - u_1^\kappa v_2^\kappa$ is the Wronskian determinant.

The response function of a quantum system to an external field is given by the imaginary part of the retarded polarization operator,

$$R(P, P; E) = \frac{1}{\pi} \text{Im} \Pi^R(P, P; \mathbf{k}, \mathbf{k}'; E) |_{\mathbf{k}=\mathbf{k}'=0}, \quad (5)$$

where $P = \gamma_0 r^J Y_{JM}(\hat{r})$ for the isoscalar electric multipole excitation and is multiplied by τ_3 for isovector excitation. The RCRPA polarization operator is obtained by solving the Bethe-Salpeter equation,

$$\begin{aligned} \Pi(P, P; \mathbf{k}, \mathbf{k}', E) &= \Pi_0(P, P; \mathbf{k}, \mathbf{k}', E) \\ &\quad - \sum_i g_i^2 \int d^3 k_1 d^3 k_2 \Pi_0(P, \Gamma^i; \mathbf{k}, \mathbf{k}_1, E) \\ &\quad \times D_i(\mathbf{k}_1, \mathbf{k}_2, E) \Pi(\Gamma_i, P; \mathbf{k}_2, \mathbf{k}', E). \end{aligned} \quad (6)$$

We can obtain the unperturbed retarded polarization operator Π_0 in the RMF ground state:

$$\begin{aligned} \Pi_0^{\text{RMF}}(P, Q; \mathbf{r}, \mathbf{r}'; E) &= \sum_h [\bar{f}_h(\mathbf{r}) P^\dagger G(\mathbf{r}, \mathbf{r}'; \omega^+) Q f_h(\mathbf{r}') \\ &\quad + \bar{f}_h(\mathbf{r}') Q G(\mathbf{r}', \mathbf{r}; \omega^-) P^\dagger f_h(\mathbf{r})], \end{aligned} \quad (7)$$

where $\omega^\pm = E_h \pm E \pm i\eta$.

3 Collective multipole excitations of exotic nuclei

The response functions of isoscalar and isovector giant resonances of multiplicities $L=0-2$ for ^{34}Ca , ^{40}Ca , ^{48}Ca and ^{60}Ca calculated in RCRPA are plotted in Fig. 1. The dashed-dotted, dashed, solid and dotted curves represent the results of ^{34}Ca , ^{40}Ca , ^{48}Ca and ^{60}Ca , respectively. As we know, ^{60}Ca is a neutron-rich nucleus and ^{34}Ca is a proton-rich nucleus. In neutron-rich and proton-rich nuclei, the neutron or proton density has different profile. From Fig.1, we find that the neutron or proton excess has large effects on the energy distribution of the strength, it leads to strong low-energy excitations and pushes the centroid of the strength function to lower energies. In the isovector resonances, one observes some fragmentation in neutron-rich nucleus ^{60}Ca , namely, the neutron excess increases the fragmentation of the strength distribution. In contrast to the response function of stable nucleus ^{48}Ca , in neutron-rich nucleus ^{60}Ca and proton-rich nucleus ^{34}Ca , strong low-energy excitations are found, especially in the case of ^{60}Ca . In the case of the isoscalar giant quadrupole resonance (ISGQR), it is clearly found that the response functions of the normal nuclei ^{40}Ca and ^{48}Ca are similar, in contrast, the response function of neutron-rich nucleus ^{60}Ca is shifted to lower-energy region remarkably, the response function of proton-rich nucleus ^{34}Ca is separated into higher-energy region and low-energy excitations. In the compressional isoscalar giant monopole resonance (ISGMR) and isoscalar giant dipole resonance (ISGDR), a strong strength at lower energy is found in neutron-rich nucleus ^{60}Ca . Lower-energy excitation can also be found in proton-rich nucleus ^{34}Ca , but it is smaller than that of ^{60}Ca . On the other hand, the higher-energy part of the strength in ^{60}Ca goes up, while the higher-energy part in ^{34}Ca drops down.

In addition, in order to show the above discussion is more general, we present the response functions of ^{16}O and ^{28}O for $L=0-3$ calculated in RCRPA in Fig. 2. The solid and dashed curves represent the results of ^{28}O and ^{16}O , respectively. We also show the response functions of ^{100}Sn and ^{132}Sn for $L=0-3$ calculated in RCRPA in Fig. 3. The solid and dashed curves represent the results of ^{132}Sn and ^{100}Sn , respectively. Here, ^{16}O is a normal nucleus, and ^{100}Sn is a proton-rich nucleus, while ^{28}O and ^{132}Sn are neutron-rich nuclei. From Fig. 2, 3, it is also found that the neutron excess leads to strong low-energy excitations and increases the fragmentation of the strength distribution. It can be seen easily that the above results are similar to those of Ca isotopes.

It is known that the continuum in the RCPA calculations is usually discretized by the box boundary conditions, while the continuum plays an important role in description of the properties of neutron-rich nuclei and

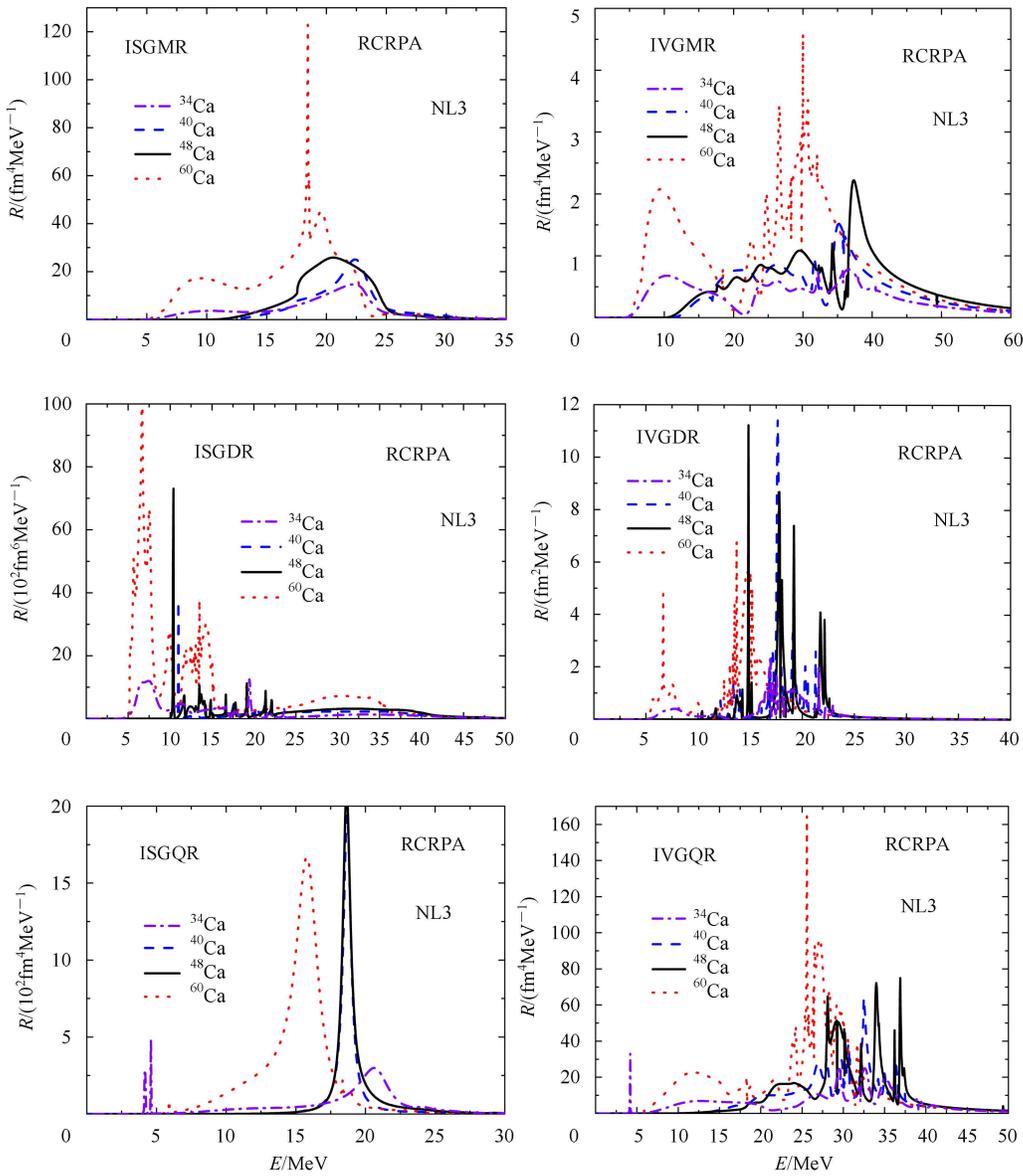


Fig. 1. (color online) The response functions of ^{34}Ca , ^{40}Ca , ^{48}Ca and ^{60}Ca in RCRPA. The dashed-dotted, dashed, solid and dotted curves represent the results of ^{34}Ca , ^{40}Ca , ^{48}Ca and ^{60}Ca , respectively.

proton-rich nuclei since the Fermi surface of those nuclei is close to the particle continuum, one shall treat the contribution of the continuum properly. As a result, it is required to consider the contribution of the continuum rigorously in exotic nuclei both for the ground states and excited states calculations. Finally, in order to clarify the effect of treating the contribution of continuum exactly, the ISGMR response functions given by RCRPA are compared with those obtained by RRPA. The ISGMR response functions of ^{34}Ca , ^{40}Ca , ^{48}Ca and ^{60}Ca given by RCRPA and RRPA are plotted in Fig. 4. The solid and dashed curves represent the results of RCRPA

and RRPA, respectively. From the Fig. 4, it can be noted that the response functions calculated in RCRPA and RRPA are different from each other, in the case of RRPA results the width of strength functions is given artificially, in the present calculations we set it equal to 2 MeV, while it is given automatically by the RCRPA calculations, not only the Landau width but also the escaping width. For example, there is a sharp peak in the ISGMR strength of ^{60}Ca given by RCRPA calculation. This is mainly due to the contribution of the single-particle resonances states in the continuum, but it cannot be reproduced by the RRPA calculation.

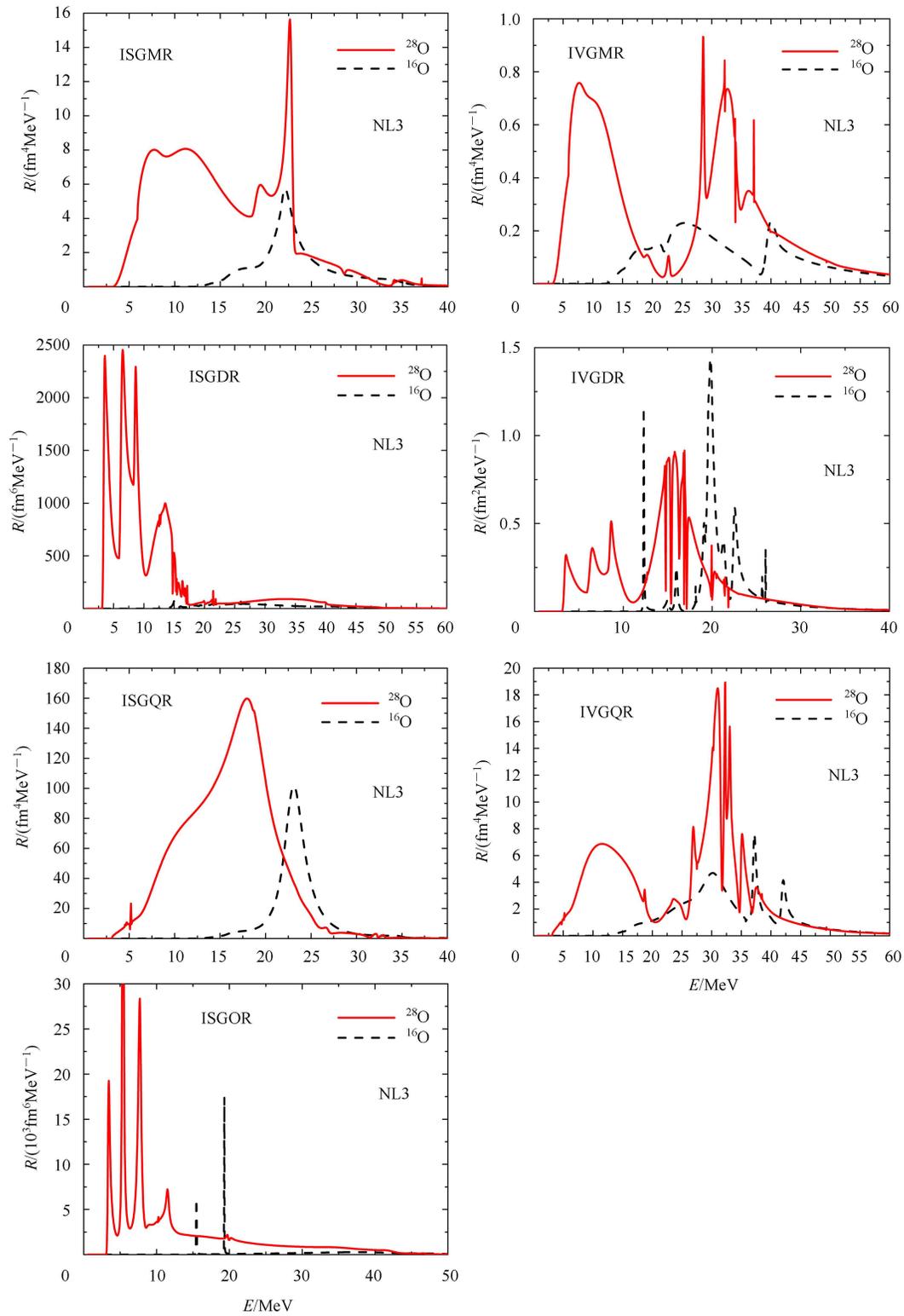


Fig. 2. (color online) The response functions of ^{16}O and ^{28}O in RCRPA. The solid and dashed curves represent the results of ^{28}O and ^{16}O , respectively.

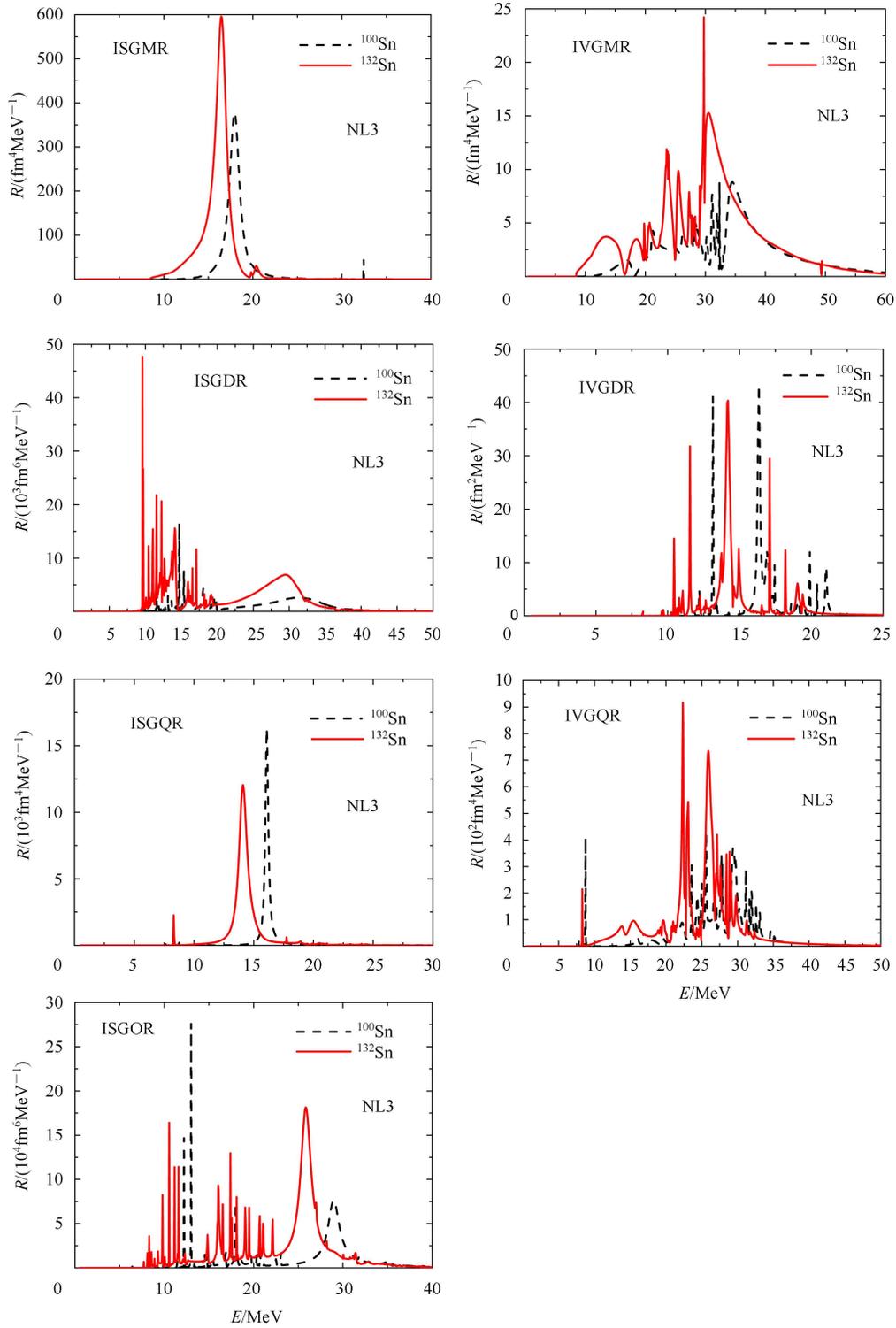


Fig. 3. (color online) The response functions of ^{100}Sn and ^{132}Sn in RCRPA. The solid and dashed curves represent the results of ^{132}Sn and ^{100}Sn , respectively.

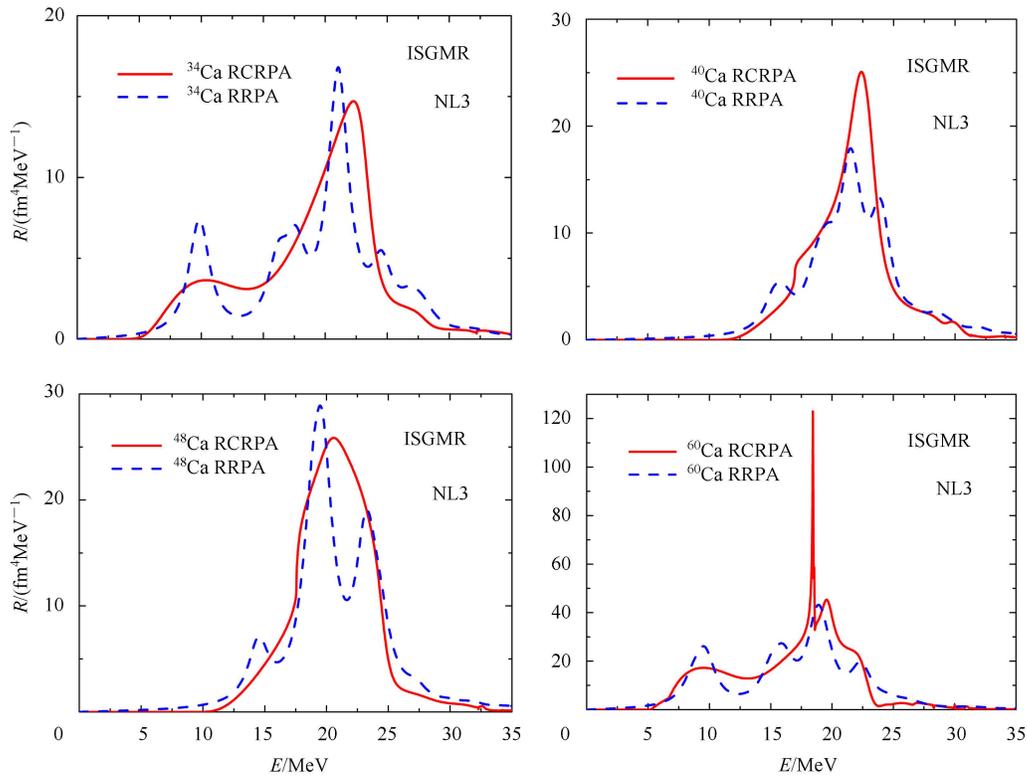


Fig. 4. (color online) The ISGMR response functions of ^{34}Ca , ^{40}Ca , ^{48}Ca and ^{60}Ca in RCRPA and RRP. The solid and dashed curves represent the results of RCRPA and RRP, respectively.

4 Summary

In conclusion, we have studied the isoscalar and isovector collective multipole excitations in exotic nuclei in the RCRPA framework. The method is based on the Green's function technique and the contribution of the

continuum spectrum is treated exactly. We have found strong low-energy excitations in neutron-rich nuclei and proton-rich nuclei which is different from the case in β -stable nuclei. Namely, the neutron or proton excess leads to strong low-energy excitations and increases the fragmentation of the strength distribution. The effects of treating the contribution of continuum exactly are also discussed.

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