Soft Dipole Modes in Neutron-rich Ni-isotopes in QRRPA

Li-Gang Cao\textsuperscript{1} and Zhong-Yu Ma\textsuperscript{2,3}\textsuperscript{*}

\textsuperscript{1}Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100039, P.R. of China
\textsuperscript{2}China Center of Advanced Science and Technology (World Laboratory), P.O.Box 8730, Beijing 100080, P.R. of China and
\textsuperscript{3}China Institute of Atomic Energy, Beijing 102413, P.R. of China

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The soft dipole modes in neutron rich even-even Ni-isotopes are investigated in the quasiparticle relativistic random phase approximation. We study the evolution of strengths distribution, centroid energies of dipole excitation in low-lying and normal GDR regions with the increase of the neutron excess. It is found in the present study that the centroid energies of the soft dipole strengths strongly depend on the thickness of neutron skin along with the neutron rich even-even Ni-isotopes.

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\textbf{I. INTRODUCTION}

Currently there is, in nuclear physics community, a strong interest in the study of weakly bound nuclei both experimentally and theoretically. The experiments with the radioactive ion beam provide the possibility to study the properties of weakly bound nuclei with a large neutron or proton deficient. One of the most hot issues on the weakly bound nuclei, presently, is focused on the study of multipole response of nuclei far from $\beta$-stability line, especially in the isovector dipole mode. A genuine feature of weakly bound nuclei is the appearance of soft electric dipole modes, so-called Pygmy Dipole Resonances. The appearances of low-lying dipole modes in weakly bound nuclei are of particular interest because they are expected to reflect the motion of neutron skin against the core formed with equal number of neutrons and protons as well as to provide important information on the isospin and density-dependent parts of the effective interactions. Over the last decade, much effort has

\textsuperscript{*}also Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator of Lanzhou, Lanzhou 730000 and Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100080
been dedicated to the investigation of the properties of soft dipole modes in light neutron rich nuclei [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11]. In order to obtain more valuable information for such a peculiar mode, detail studies of the low-lying dipole excitation over sufficiently long isotopic chains are required.

In neutron rich nuclei, the weakly bound outermost neutrons form neutron skin at the nuclear surface. The investigation of neutron skin has been paid more attentions due to the fact that the thickness of neutron skin are related to the equation of state (EoS) of asymmetric nuclear matter near saturation density, which is an essential ingredient in the calculation of the properties of neutron stars [12, 13, 14, 15]. Various experiments have been performed or proposed to measure the neutron density distribution and therefore, the differences between radii of the neutron and proton distribution [16, 17, 18, 19, 20, 21, 22, 23]. Although the neutron density distribution is difficult to be measured, the experiments on the giant dipole resonance (GDR) or spin-dipole resonance (SDR) excitation may provide some information of the difference between neutron and proton radii [22, 23].

In order to describe the collective excitations in exotic nuclei, a number of theoretical works have been devoted to study the properties of multipole responses in open shell nuclei by taking into account the effect of pairing correlations in the framework of quasiparticle random phase approximation (QRPA) [24, 25, 26, 27, 28]. In this paper, we aim at the investigation of the evolution of low-lying dipole modes of neutron rich even-even Ni-isotopes. The method we used is the quasiparticle relativistic random phase approximation (QRRPA), which has been formulated in the response function method [29]. We first investigate the ground state properties of neutron rich Ni-isotopes in the extended RMF+BCS approximation [30], where the contribution of the resonant continuum to the pairing correlations is treated properly. Based on the ground states in RMF+BCS calculations, we construct the configurations of quasiparticle excitations, solve the Bethe-Salpeter equation and then study the nuclear dipole modes in Ni-isotopes. The evolution of dipole strengths in both low-lying region and normal GDR region in neutron rich Ni-isotopes is discussed. In addition, the relationship of the neutron skin and low-lying dipole resonance is investigated.

The paper is arranged as the follows. In Sec.II we briefly introduce the formalism of the QRRPA in the response function method. The calculated ground state properties, such as the binding energy, the difference of neutron and proton rms radii as well as the neutron and proton density distributions, in neutron rich even-even Ni-isotopes are presented in Sec.III. In Sec.IV the evolution of isovector dipole resonances in the low-lying region as well as in the GDR region are shown and discussed. The relationship of neutron skin and low-lying
dipole resonance is also investigated. Finally we give a brief summary in Sec.V.

II. THE QUASIPARTICLE RELATIVISTIC RANDOM PHASE APPROXIMATION

It is important to take into account the pairing correlations in the study of multipole collective excitations for open shell nuclei. The QRRPA in the response function formalism is employed at the present study, which has provided a convenient and useful method to describe collective excited states of nuclear many-body systems. For the detailed description of QRRPA based on ground state of the RMF+BCS can be found in Ref.[29]. In this section we briefly summarize the essential points of Ref.[29].

In the QRRPA calculation we first solve the Dirac equation and the equations of meson fields in the coordinate space. For neutron rich nuclei the contribution of the particle continuum to the pairing correlations should be considered. In this work, a proper treatment of the resonant continuum to pairing correlations has been performed in the extended RMF+BCS approximation[30], where the resonant continuum is solved with an asymptotic scattering boundary condition. It has been shown that the simple BCS approximation with a proper treatment of the resonant continuum works well in the description of ground state properties even for neutron rich nuclei[30, 31]. Then the positive energy continuum states and negative energy states beyond the pairing active space are solved by expanding the nucleon spinors in a complete set of bases, such as eigenfunctions of a spherical harmonic oscillator potential.

When the pairing correlations are taken into account, the elementary excitation in the pairing active space is a two-quasiparticle excitation, rather than a particle-hole excitation. Beyond the pairing active space the RRPA configurations remain: a set of particle-hole pairs($(\alpha h)$) and negative energy particle-hole $(\bar{\alpha}h)$ pairs, where the particle $\bar{\alpha}$ is in the Dirac sea. The unperturbed polarization operator in the QRRPA in the response function formalism can be constructed in a similar way as done in Ref.[32]:

$$
\Pi^R_0(P, Q; k, k'; E) = \frac{(4\pi)^2}{2L+1} \left\{ \sum_{\alpha, \beta} (-1)^{j_{\alpha} + j_{\beta}} A_{\alpha \beta} \left[ \frac{\langle \phi_\alpha \| P_L \| \phi_\beta \rangle \langle \phi_\beta \| Q_L \| \phi_\alpha \rangle}{E - (E_\alpha + E_\beta) + i\eta} - \frac{\langle \phi_\beta \| P_L \| \phi_\alpha \rangle \langle \phi_\alpha \| Q_L \| \phi_\beta \rangle}{E + (E_\alpha + E_\beta) + i\eta} \right] 
+ \sum_{\alpha, \beta} (-1)^{j_{\alpha} + j_{\beta}} \nu_{\alpha}^2 \left[ \frac{\langle \phi_\alpha \| P_L \| \phi_\beta \rangle \langle \phi_\beta \| Q_L \| \phi_\alpha \rangle}{E - (E_\alpha + \lambda - \varepsilon_{\bar{\beta}}) + i\eta} - \frac{\langle \phi_\beta \| P_L \| \phi_\alpha \rangle \langle \phi_\alpha \| Q_L \| \phi_\beta \rangle}{E + (E_\alpha + \lambda - \varepsilon_{\bar{\beta}}) + i\eta} \right] \right\},
$$

(1)

with

$$
A_{\alpha \beta} = (u_\alpha u_\beta + (-1)^L \nu_\alpha u_\beta)^2 (1 + \delta_{\alpha \beta})^{-1},
$$

(2)
where $v_\alpha^2$ is the BCS occupation probability and $u_\alpha^2 = 1 - v_\alpha^2$. $E_\alpha = \sqrt{(\varepsilon_\alpha - \lambda_n)^2 + \Delta_n^2}$ is the quasiparticle energy, where $\lambda_n$ and $\Delta_n$ are the neutron Fermi energy and pairing correlation gap, respectively. In the BCS approximation, the $\phi_\alpha$ is the eigenfunction of the single particle Hamiltonian with an eigenvalue $\varepsilon_\alpha$. In Eq.(1), the terms in the first square bracket represent the excitation with one quasiparticle in fully or partial occupied states and one quasiparticle in the partial occupied or unoccupied states. The terms in the second square bracket describe the excitation between positive energy fully or partial occupied states and negative energy states in the Dirac sea. For unoccupied positive energy states outside the pairing active space, their energies are $E_\beta = \varepsilon_\beta - \lambda_n$, occupation probabilities $v_\beta^2 = 0$ and $u_\beta^2 = 1$. For fully occupied positive energy states, the quasiparticle energies and occupation probabilities are set as $E_\alpha = \lambda_n - \varepsilon_\alpha$ and $v_\alpha^2 = 1$ in Eq.(1). The states in the Dirac sea are not involved in the pairing correlations, therefore the quantities $v_\beta^2$ and $u_\beta^2$ are set to be 0 and 1. Once the unperturbed polarization operator in the quasiparticle scheme is built, the QRRPA response function can be obtained by solving the Bethe-Salpeter equation as done in the RRPA.[32]

III. GROUND STATE PROPERTIES OF NEUTRON RICH NI-ISOTOPES

A reliable description on single particle energies and wave functions and self-consistent calculation in the QRRPA is very important. In this section we investigate the ground state properties of neutron rich even-even Ni-isotopes in the extended RMF+BCS approximation[30], where the continuum is treated by imposing a scattering boundary condition. Only those single particle resonant states in the continuum are considered in the pairing correlation, where the width of the resonant state is not included. The calculations are performed with parameter set NL3[33].

Ni isotopes have the proton number $Z = 28$, which is a closed shell. Therefore, the proton pairing gap is taken to be zero. For the neutron case, we use a state-independent pairing strength $G = C/A$, where the constant $C = 20.5$ MeV is adopted from Ref.[34]. It could also provide a best fit to reproduce experimental binding energies of known Ni-isotopes. In practical calculations, we restrict the pairing space to about one harmonic oscillator shell above and below the Fermi surface in the extended RMF+BCS model. The levels include $1f_{5/2}$, $2p_{3/2}$, $2p_{1/2}$, $1g_{9/2}$, $2d_{5/2}$, $3s_{1/2}$, $2d_{3/2}$, $1g_{7/2}$, $1h_{11/2}$ and $2f_{7/2}$. Some of them, such as $2d_{5/2}$, $2d_{3/2}$, $1g_{7/2}$, $2f_{7/2}$, and $1h_{11/2}$ are single particle resonant states depending on the isotopes.

In Fig.1 we show the binding energy per nucleon for neutron rich Ni-isotopes with mass
FIG. 1: The binding energy per nucleon of neutron rich Ni-isotopes with mass from 68 to 96. The open squares represent the results obtained by extended RMF+BCS approach with effective interaction NL3. The experimental data are taken from Ref. [35] denoted by solid circles.

FIG. 2: The differences of neutron and proton rms radii of neutron rich Ni-isotopes with mass from 68 to 96.
FIG. 3: The density distribution of neutron and proton of neutron rich Ni-isotopes with mass from 68 to 96.

One can find that the theoretical results obtained in the extended RMF+BCS approach reproduce the experimental data of binding energy perfectly. It has been understood that the RMF plus simple BCS approximation can give a good description on the ground state properties even for nuclei far from the $\beta$-stability line when the coupling of bound states and particle continuum is treated properly[30, 31]. The isotope shift, i.e. the difference of the neutron and proton rms radius in neutron rich Ni-isotopes is plotted as a function of the nuclear mass number in Fig.2. It can been seen that the difference of the neutron and proton rms radius becomes larger when the nucleus closes to the neutron drip line. The kink appeared around $A = 78$ is due to the effect of shell structure where the neutron number equals to 50.

When one takes into account the effect of pairing correlations, the nucleon density can be written as:

$$\rho(r) = \sum_\alpha \frac{(2j + 1)}{4\pi} v_\alpha^2 \phi_\alpha^\dagger(r)\phi_\alpha(r),$$

which runs over all states weighted by the factor $v_\alpha^2$. In Fig.3 we show the calculated particle density distribution in neutron rich Ni-isotopes with the mass number from 68 to 96. The neutron densities in those nuclei are much larger than the proton densities. The neutron
IV. EVOLUTION OF DIPOLE MODES IN NEUTRON RICH NI-ISOTOPES

We now apply the QRRPA to investigate the evolution of isovector giant dipole resonance (IVGDR) in neutron rich Ni-isotopes. The isovector dipole excitation is an $L = 1$ type electric (spin-non-flip) $\Delta T = 1$ and $\Delta S = 0$ giant resonance with spin and parity $J^\pi = 1^-$. The electric isovector dipole operator we used in present calculations is:

$$Q_{1m} = \frac{1}{2} e \sum_{i=1}^{A} (\tau_i^0 - \langle \tau^0 \rangle) r_i Y_{1m}(\hat{r}_i),$$  

where the average $\langle \tau^0 \rangle$ is $(N-Z)/A$.

In the QRRPA calculation the particle-hole residual interactions are taken from the same effective interaction NL3 as that in the description of the ground states of neutron rich Ni-isotopes. The fully occupied states and states in the pairing active space are calculated self-consistently in the RMF+BCS approach in the coordinate space. The unoccupied states outside of the pairing active space are obtained by solving the Dirac equation in the expansion on a set of harmonic oscillation basis. The response functions of the nuclear system to the external operator are calculated at the limit of zero momentum transfer. In order to guarantee the conservation of the vector current, the space-like parts of vector mesons in the QRRPA calculations are taken into account.

In Fig.4 we plot the response functions of isovector giant dipole resonance in neutron rich Ni-isotopes calculated in the QRRPA approach. It is found that the IVGDR strengths in those nuclei are very fragmented, especially in nuclei near the neutron drip line. In addition to the normal GDR strength around the energy at 16 MeV, the low-lying dipole strength appears at the excitation energy below 10 MeV. The low-lying dipole strengths increase as the neutron number increases. It is found that one pronounced peak appears in the low energy region in nuclei with the mass number less than 80. For those nuclei with the mass number larger than 80, one could observe more than one peak in the energy below 10 MeV. Moreover the strengths of those dipole excitations become more and more stronger when the nucleus is approaching to the neutron drip line.

In order to give clearer description on the evolution of those dipole states in neutron rich Ni-isotopes, we calculate the various moments of the IVGDR strengths in the QRRPA approach at a given energy interval:

$$m_k = \int_{E_1}^{E_2} R^k(E') dE',$$  

(5)
FIG. 4: The isovector dipole response functions in neutron rich Ni-isotopes with the mass number from 70 to 96 in the QRRPA approach.

The RPA equation is solved till $E = 60$ MeV in the present calculations. The centroid energy of the response function is defined as,

$$
\bar{E} = \frac{m_1}{m_0},
$$

we separate the energy interval to two regions: $0$ MeV $< E_x < 10$ MeV and $10$ MeV $< E_x < 60$ MeV. In the upper panel of Fig.5 the calculated centroid energies of the normal
FIG. 5: The centroid energies of the IVGDR in the normal GDR region (upper panel) and the low-lying region below 10 MeV (lower panel) as a function of the mass number in the Ni-isotopes. The empirical expression of $E = 31.2A^{-1/3} + 20.6A^{-1/6}$ for the normal GDR is plotted in the upper panel, which is compared with the theoretical results. The GDR are plotted, which are denoted by solid squares. It is compared with the empirical expression of the GDR energy $E = 31.2A^{-1/3} + 20.6A^{-1/6}$, which are displayed by a solid curve. One can see that the calculated centroid energies are in good agreement with the empirical values when the nuclei are not very far away from the $\beta$ stability line. With the
increase of the neutron excess, the calculated centroid energies become smaller and deviate from the empirical values. The calculated centroid energy of the IVGDR is 15.4 MeV for $^{90}\text{Ni}$, which is about 1 MeV smaller than the corresponding empirical value. The centroid energies of low-lying dipole strengths are plotted by solid circles in the lower panel of Fig. 5. The centroid energies predicted in the QRRPA approach decrease with the increase of the neutron excess.

![Graph showing percentage of calculated energy weighted moments $m_1$](image)

**FIG. 6**: The percentage of the calculated energy weighted moments $m_1$ in the low-lying region ($E \leq 10$ MeV) with respect to the corresponding Thomas-Reiche-Kuhn dipole sum rule value as a function of the mass number of Ni-isotopes.

Recently the experimental results show that the low-lying dipole strength exhausts about 5% of the Thomas-Reiche-Kuhn (TRK) dipole sum rule for light neutron rich nuclei $^{18}\text{O}$, $^{20}\text{O}$ and $^{22}\text{O}$ [9]. In the future experiments the low-lying dipole excitation in more neutron rich medium-heavy nuclei will be performed. Therefore we calculate the energy weighted moments $m_1$ of the low-lying dipole strengths in the energy region $0 \text{ MeV} < E_x < 10$ MeV and the percentages to exhaust the corresponding classical TRK dipole sum rule value. The values to exhaust the TRK sum rule in various Ni-isotopes are shown in Fig. 6. It is found that the ratios of the energy weighted moments $m_1$ at the low energy region increase on the whole as the increase of the neutron excess. In present calculations, the contribution of low-lying dipole strength in $^{70}\text{Ni}$ exhausts 10.2% of the classical TRK dipole sum rule. Whereas
for $^{96}$Ni which is close to the neutron drip line, the low-lying dipole strength exhausts about 32.3% of the TRK dipole sum rule. A similar result for isovector dipole excitation in neutron rich nuclei has been obtained by D. Vretenar [10].

Differing from the normal GDR response, the low-lying resonance can be interpreted as the vibration of the excess neutrons against the core formed with equal number of protons and neutrons out of phase [10]. The recent experimental results show that one can extract the neutron skin by measuring the dipole excitation of nuclei [22, 23]. The calculated centroid energies of low-lying dipole strengths as a function of the differences of the neutron and proton rms radii in Ni-isotopes is plotted in Fig. 7. We notice that the evolution of centroid energies in the low energy region has a strong dependence on the thickness of neutron skin. This relationships was also noted and discussed in Ref. [17], where the low-lying dipole strength distribution in neutron rich nuclei was calculated in a quasiparticle phonon model. They found that the transition strengths and energy locations of low-lying dipole resonances are closely correlated with the neutron skin. Therefore, the experimental measurements on the low-lying dipole excitation in neutron-rich nuclei would provide information on the neutron skin.

FIG. 7: The centroid energies of the isovector dipole strengths in the low-lying region below 10 MeV versus the differences of the neutron and proton rms radii in Ni-isotopes.
V. SUMMARY

In the present work we have studied the evolution of the low-lying dipole resonances in neutron rich even-even Ni-isotopes in the framework of the QRRPA with an effective Lagrangian parameter set NL3. The pairing correlations are taken into account within the BCS approximation with a constant pairing gap. The distributions of dipole excitation in neutron rich nuclei are more fragmented and the soft mode of the dipole response is found at the low-energy region. The energy weighted moments $m_1$ at the low-lying region calculated in the QRRPA approach increase as the increase of the neutron excess. A considerably large percentage of the low-lying $m_1$ to exhaust the TRK sum rule, is found when the nuclei approach to the neutron drip line. The calculated centroid energies of normal GDR strengths is in good agreement with the empirical values when the nucleus is not very far away from the $\beta$ stability line. Whereas a deviation from the empirical value can be observed in nuclei close to the drip line. The centroid energies of low-lying dipole strengths decrease with the increase of the neutron excess. An interesting phenomenon is that the evolution of centroid energies at the low energy region has a strong dependence on the thickness of the neutron skin in neutron rich even-even Ni-isotopes. Therefore, the experimental measurement of the nuclear low-lying dipole strength distributions in neutron-rich nuclei is suggested, which will provide the information of neutron skin.

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