# Renormalizing random-phase approximation by using exact pairing†

L. Tan Phuc,*1 N. Quang Hung,*1 and N. Dinh Dang*2

The random-phase approximation (RPA) is a popular theoretical method to study the low-lying excitations and high-lying giant resonances in nuclei. The excited states of RPA are built on the particle-hole ($ph$) components, which are represented by the $ph$ pairs operators: $B_{ph}$ and $B^{\dagger}_{ph}$. Because of the unknown of the RPA ground state $|RPA\rangle$, the quasi-boson approximation (QBA), which assumes a $ph$ pair as a boson and $|RPA\rangle \sim |HF\rangle$, is used to derive the RPA expectation value, namely $\langle RPA|[B_{ph}, B^{\dagger}_{p'h'}]|RPA\rangle \sim \langle HF|[B_{ph}, B^{\dagger}_{p'h'}]|HF\rangle = \delta_{pp'}\delta_{hh'}$.[1] Using QBA within RPA leads to a basic drawback that is the violation of Pauli principle because the nucleons are fermions instead of boson as the assumption of QBA.

To overcome this problem, the ground-state correlations (GSC) factor $D_{ph}$ are taken into account to renormalize the residual interaction of RPA (RRPA). The RPA expectation value becomes $\langle RPA|[B_{ph}, B^{\dagger}_{p'h'}]|RPA\rangle \simeq D_{ph} \equiv f_h - f_p$, where $f_p$ and $f_h$ are $p$ and $h$ occupation numbers.[2] Although the RRPA restored the Pauli principle, the energy-weighted sum rule (EWSR) was violated.[3] Therefore, another technique was developed to fix this drawback, namely the $pp$ and $hh$ correlations were added in the $ph$RRPA matrix to fulfill the EWSR.[3] However, this way doubled the matrix size of RPA equations and lead to time-consuming. On the other hand, the RRPA does not include superfluid pairing. Therefore, we propose a method to overcome all these shortcomings. In particular, by using the Hartree-Fock mean field plus exact pairing solution (HFEP),[4] we can supply a good set of initial inputs for RPA. The GSC factor $D_{ph}$, which is used to renormalize the residual interactions, is calculated directly from exact pairing (EP). These are expected to preserve both Pauli principle and EWSR without adding any $pp$ and $hh$ correlations that make time-consuming.

The proposed approach is applied for the dipole case in several light-, medium-, and heavy-mass nuclei, namely $^{22,24,28}$O, $^{60}$Ni, and $^{90}$Zr. The calculations are performed within the conventional RPA, HFEP+RPA (HFEPRPA) and self-consistent HFEPRPA (SC-HFEPRPA). The E1 EWSR will be compared with the model independent sum rule such as the Thomas-Reich-Kuhn (TRK) sum rule. Our approach shows that the drawback of the $ph$RRPA is removed, namely the EWSR are fulfilled without adding any $pp$ and $hh$ configurations, hence the extension of RPA matrices and time-consuming calculations are avoided. As compared to the RPA results, the effects of GSC and EP in the renormalization are significant in light nuclei and small in medium and heavy nuclei (see the shift of $S(E)$ in Fig. 1(a)–(c)). The antipairing effect is observed for the first time within the SC-HFEPRPA, which reduces the pairing energy from more than 10% up to around 30% in the neutron-rich $^{22}$O nucleus. This shows the contribution from the mutual effect of the short-range pairing and long-range $ph$ residual interaction to the mean field. The PDR is also found to be enhanced in neutron-rich nuclei because of the pairing effect.

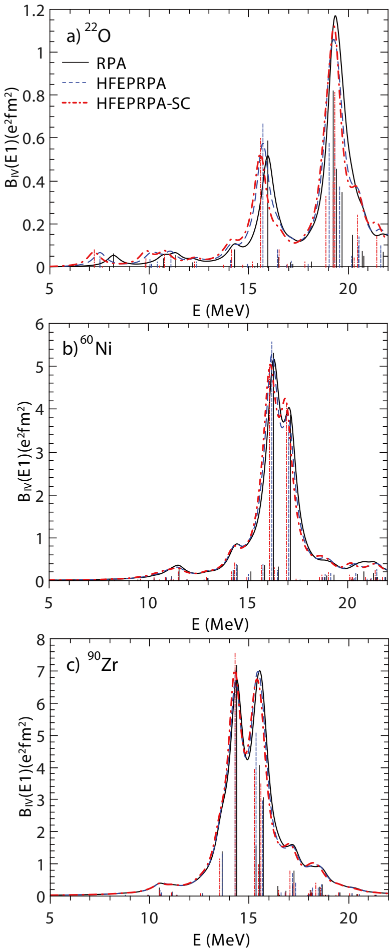


Fig. 1. The Isovector dipole transition probabilities of $^{22}$O (a), $^{60}$Ni (b) and $^{90}$Zr (c) obtained within different approaches. The sticks and lines represent to the probabilities $B(E1, 0 \to 1^-)$ and strength functions $S(E)$.

References

1) P. Ring, P. Schuck, *The Nuclear Many-Problem* (Springer, 2004).
2) F. Catara, N. D. Dang, M. Sambataro, Nucl. Phys. A **579**, 1 (1994).
3) N. Q. Hung, N. D. Dang, T. V. N. Hao, L. T. Phuc, Phys. Rev. C **94**, 064312 (2016).
4) L. T. Phuc, N. Q. Hung, N. D. Dang, Phys. Rev. C **97**, 024331 (2018).

† Condensed from the article in Phys. Rev. C **99**, 064322 (2019)
*1 Duy Tan University
*2 RIKEN Nishina Center