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The Dependence of Gamow-Teller and Isobaric Analogue Resonances on The Mean Field Parameters

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Abstract. The variation of Gamow-Teller and isobaric analogue resonances by the mean field parameters for double magic nuclei such as ^{90}Zr and ^{48}Ca has been searched within the framework of quasi random phase approximation (QRPA). The nucleon-nucleon effective interaction potential has been defined by considering the commutativity of the Gamow-Teller operator with the central term in the nuclear part of the total Hamiltonian. The effective interaction constant has been found from this commutativity and taken out to be a free parameter.

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1. INTRODUCTION

It is well known that charge exchange Fermi and Gamow-Teller transitions are very important to understand the basic astrophysical and nuclear processes such as the initial step of the hydrogen fusion reaction leading to nucleosynthesis, the electron capture reactions leading to stellar collapse and supernova formation [1]. The establishment of the new proton-rich nuclei with the development of heavy mass ion technology allows us to study the isospin mixing effects in the ground state of these nuclei which are very important in the estimates of the vector coupling constants based on Fermi transitions, and in the description of the energies and the widths of the analogue states and the isospin multiplets [2-5]. The study of the 0^+ and 1^+ excitations in odd-odd nuclei has also great importance in understanding the double beta decay process [6].

The first experimental analysis of the Gamow-Teller resonance was done for $^{90}Zr\ (p,n)$ reaction at 35 MeV [7]. The (p,n) charge exchange reaction is one of the most efficient ways in the experimental identification of Gamow-Teller resonance in heavy nuclei at intermediate energies [8-12]. The experimental position of the isobaric analogue resonance for ^{48}Ca was also shown in [12].

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Furthermore, it was also shown that the $(^{3}He,t)$ reaction is another efficient way in the experimental investigation of the Gamow-Teller excitations for the bombarding energies exceeding 100 MeV/nucleon [13,14]. These excitations were extracted by using the $^{208}Pb(^{3}He,t)^{208}Bi$ reaction at different energies [15-17]. $(^{6}Li,{}^{6}He)$ reaction is also important to study the collective spin-isospin excitations [18]. The Gamow-Teller excitations were searched for $^{48}Ca \rightarrow {}^{48}Sc$, $^{90}Zr \rightarrow {}^{90}Nb$ and $^{208}Pb \rightarrow {}^{208}Bi$ transitions by using $(^{6}Li,{}^{6}He)$ reaction at different energies [19-22]. The energy difference between Gamow-Teller and isobaric analogue resonances for ^{90}Zr was calculated by using an empirical formula $(\omega_{GTR} - \omega_{IAR} = -30.00\ (N-Z)/A + 6.7)$ [23]. The total transition strength of the Gamow-Teller excitations is given by a model-independent sum rule $S_{\beta-} - S_{\beta+} = 3(N-Z)$, which should be nearly exhausted by the β^{-} transition strength summed over all Gamow-Teller states in the daughter nucleus (Z+1, N-1) formed after the (p,n) reactions. Surprisingly, only a half of the GT sum rule value was identified from (p,n) measurements in the 1980's on targets throughout the periodic table [24]. This difficulty is known as the quenching problem of the GT strength. Wakasa et al. accurately measured the $^{90}Zr(p,n)$ spectra at 295 MeV [25]. They successfully identified the GT strength in the continuum region through multipole decomposition (MD) analysis which extracted the $\Delta L = 0$ component from the cross sections. They obtained a GT quenching factor, defined as $Q = (S_{\beta-} - S_{\beta+})/3(N-Z)$, of 0.90 ± 0.05, where the error is due to the uncertainty of the MD analysis. To reduce the systematic uncertainties, K.Yako et al. performed consistent analyses on both the (p,n) and (n,p) data. They measured $^{90}Zr(n,p)$ reaction at 293 MeV and obtained a reliable GT quenching factor $(Q = 0.88 \pm 0.06)$ [26].

The Gamow-Teller Resonance (GTR) for double magic nuclei has been searched within the framework of different theoretical models. Especially, there have been different attempts to study GTR distribution in ^{208}Bi [27-32]. The calculations in Ref [28,29,31] have been performed in a self-consistent way. The phonon damping model has been used to calculate the strength distribution of the Gamow-Teller resonance in ^{90}Nb and the results which are in reasonable agreement with the experimental data have been obtained [33]. The relativistic version of random phase approximation is an important way to study the Gamow-Teller transitions [34]. The GTR in ^{48}Sc, ^{90}Nb and ^{208}Bi has been searched within the framework of the relativistic random phase approximation [35, 36]. The main aim of the present work is to apply the method developed by Pyatov and Salamov [37-43] in which the strength parameter of the effective interaction is determined in a self-consistent way by relating it to the average field. The isobaric analogue resonance for $^{112-124}Sn$ was searched using this method [44]. The method has already been used to study the GT 1^{+} states in ^{208}Bi [45] and a good agreement with the corresponding experimental data has been obtained. Here, the method has been extended to the investigation of the GTR and IAR for ^{48}Sc and ^{90}Nb .

The aim of the present work is the investigation of the sensitivity of GTR and IAR to the mean field parameters. In this respect, the variation of GTR and IAR with the isovector, spin-orbit and Coulomb radius parameters for ^{48}Sc and ^{90}Nb has been calculated within the framework of RPA method with a self consistent residual interaction. Moreover, the GTR and IAR quantities have been computed by using a fixed set of these parameters which are obtained from the experimental single particle energies and a comparison of the calculated values with the corresponding experimental data is given in Section 3.

2. THEORETİCAL FORMALISM

The conserved quantities such as linear momentum, angular momentum, particle number are the consequence of the invariance of the total nuclear Hamiltonian under symmetry transformations, but the Hamiltonians with the broken symmetry are often handled in constructing the nuclear model or in approximate solution of the problem. For instance, the study of the 1^- states in even-even nuclei (electric dipole excitations) is related to the translational invariance of total Hamiltonian. The restoration of the rotational invariance in coordinate space is important in the investigation of the 1^+ states in even-even nuclei (magnetic dipole excitations). Unlike the rotational invariance in coordinate space, the rotational invariance in isospin space is not an exact symmetry of the total Hamiltonian. However, the rotational invariance in isospin space is an exact symmetry of the nuclear part of the total Hamiltonian. In other words, the nuclear part of the total Hamiltonian commutes with the isospin operator. This commutativity is violated in the mean field approximation and its restoration plays an important role in understanding the isobaric analogue excitations. Furthermore, the central term in the nuclear part of the total Hamiltonian commutes with the Gamow-Teller operator. The violation of this commutativity due to the mean field approximation is an important difficulty in the study of the Gamow-Teller excitations. Hence, this violation should be restored to perform a reliable investigation about these excitations.

In the present work, the mean field potential is described in the following form:

(1)

$$V_{mean} = V_{central}(r) + V_{ls}(r)(\vec{l}\vec{s}) + V_c(r)\left(\frac{1}{2} - t_z\right).$$

The central part of the mean field potential consists of the isoscalar and isovector terms:

$$V_{central}(r) = -V_0 f(r)\left(1 - 2\eta \frac{N-Z}{A} t_z\right),$$

The spin-orbit term is defined as

$$V_{ls}(r) = -\xi_{ls} \frac{1}{r}\frac{dV_{central}(r)}{dr},$$

and the Coulomb part is given as

$$V_c(r) = e^2 \frac{Z-1}{r}\frac{3r}{2R_c} - \frac{1}{2}\left(\frac{r}{R_c}\right)^3, (r \leq R_c),$$

$$V_c(r) = e^2 \frac{Z-1}{r}, (r > R_c),$$

$$f(r) = \frac{1}{1 + e^{\frac{r-R_0}{a}}},$$

$$t_z = 1/2, (neutrons), \qquad t_z = -1/2, (protons).$$

2.1. Gamow-Teller Excitations in Odd-Odd Nuclei

The spin-isospin transition (Gamow-Teller) operator is defined as:

$$G_\mu^+ = \sum_{i=1}^{A} \sigma_\mu(i) t + (i),$$

$$G_\mu^- = (-1)^\mu \sum_{i=1}^{A} \sigma_{-\mu}(i) t - (i), \tag{2}$$

$$G_\mu^- = (G_\mu^+)^\dagger.$$

Here, $\sigma_\mu(i)$ is the Pauli operator in the spherical basis $(\mu = 0, \pm 1)$. t-(i) and t+(i) are the isospin lowering and raising operators, respectively. The commutation condition between the total nuclear Hamiltonian and Gamow-Teller (GT) operator can be described as follows:

$$[H, G_\mu^\pm] = [V_c + V_{\vec{l}\vec{s}}, G_\mu^\pm], \tag{3}$$

where V_c , and $V_{\vec{l}\vec{s}}$ are Coulomb, and spin-orbit interaction potentials, respectively. Let us consider a system of nucleons in a spherical symmetric average field. In this case, the corresponding single particle Hamiltonian of the system is given by

$$H_{sp} = \sum_{jm} \varepsilon_j(\tau) a_{jm}^{\dagger}(\tau) a_{jm}(\tau), (\tau = n\ ,p) \tag{4}$$

where $\varepsilon_j(\tau)$ is the single particle (sp) energy of the nucleons with angular momentum $j(\tau)$, and the $a_{jm}^{+}(\tau)$ $(a_{jm}(\tau))$ is the particle creation (annihilation) operator. The commutation of the Hamiltonian in Eq.(4) with GT operator is different from the expression in Eq.(3):

$$[H_{sp}, G_{\mu}^{\pm}] \neq [V_c + V_{\vec{l}\vec{s}}, G_{\mu}^{\pm}],$$

or

$$[H_{sp} - (V_c + V_{\vec{l}\vec{s}}), G_{\mu}^{\pm}] \neq 0 \tag{5}$$

According to Pyatov-Salamov method, the nucleon-nucleon residual interaction giving the GT excitations in the neighbor odd-odd nuclei is chosen in the following form:

$$h_{GT} = \sum_{\rho=\pm} \frac{1}{2\gamma_{\rho}} \sum_{\mu=0,\pm1} [H_{sp} - V_c - V_{\vec{l}\vec{s}}, G_{\mu}^{\rho}]^{\dagger} [H_{sp} - V_c - V_{\vec{l}\vec{s}}, G_{\mu}^{\rho}] \tag{6}$$

This effective interaction is considered in such a way that the broken commutation relation between the total Hamiltonian operator and GT operator is restored. The strength parameter of the residual interaction is found from the following condition

$$[H_{sp} + h_{GT} - V_c - V_{\vec{l}\vec{s}}, G_{\mu}^{\rho}] = 0 \tag{7}$$

and taken out to be a free parameter.

$$\gamma_{\rho} = \frac{1}{2} \langle 0 | [[H_{sp} - (V_c + V_{ls}), G_{\mu}^{\rho}], G_{\mu}^{\rho}] | 0 \rangle. \tag{8}$$

Thus, the total Hamiltonian giving the GT 1^{+} states in intermediate nuclei can be defined as follows:

$$H = H_{sp} + h_{GT}. \tag{9}$$

In QRPA, the m^{th} excited 1^{+}states in odd-odd nuclei are considered as the phonon excitations and described by:

$$|m>= Q_m^{\dagger}(\mu)|0>=\sum_{np}[\psi_{np}^{m}A_{np}^{\dagger}(\mu)+(-1)^{\mu}\varphi_{np}^{m}A_{np}(\mu)]|0>, \qquad (10)$$

where $Q_m^{\dagger}(\mu)$ is the QRPA phonon creation operator, $|0>$ is the phonon vacuum which corresponds to the ground state of an even-even nucleus and fulfills $Q_m(\mu)|0>=0$ for all m. The ψ_{np}^{m} and φ_{np}^{m} are quasi boson amplitudes. Assuming that the phonon operators obey the commutation relations given below

$$<0|[Q_m(\mu),Q_{m'}^{\dagger}(\mu')]|0>=\delta_{mm'}\delta_{\mu\mu'},$$

we obtain the following ortho-normalization condition for amplitudes ψ_{np}^{m} and φ_{np}^{m} :

$$\sum_{np}[\psi_{np}^{m}\psi_{np}^{m'}-\varphi_{np}^{m}\varphi_{np}^{m'}]=\delta_{mm'}. \qquad (11)$$

The energies and wave functions of the GT 1^{+} states have been obtained from the QRPA equation of motion:

$$[H,Q_m^{\dagger}(\mu)]|0\geq \omega_m Q_m^{\dagger}(\mu)|0>, \qquad (12)$$

where ω_m is the energy of the GT 1^{+} states occurring in neighboring odd-odd nuclei. For Gamow-Teller beta strength function, we have

$$B_{GT}^{(\pm)}(\omega_m)=\sum_{\mu}|\langle 1_m^{+},\mu|G_{\mu}^{\pm}|0_{g.s.}^{+}\rangle|^{2}, \qquad (13)$$

These strength functions are related to each other by the Ikeda sum rule:

$$\sum_{m}B_{GT}^{(-)}(\omega_m)-\sum_{m}B_{GT}^{(+)}(\omega_m)=3(N-Z). \qquad (14)$$

2.2. Isobaric Analogue Excitations in Intermediate Nuclei

The QRPA Hamiltonian for the investigation of the isobaric analogue states has been described as follows:

(15)

$$H = H_{sp} + h_F$$

where the h_F is the effective interaction potential which ensures the restoration of the broken isospin invariance and defined as:

$$h_F = \sum_{\rho=\pm} \frac{1}{2\gamma_\rho} [H_{sp} - V_c, T^\rho]^\dagger [H_{sp} - V_c, T^\rho] \tag{16}$$

where the β decay operator for Fermi type transitions is defined as follows:

$$T^+ = \sum_{i=1}^{A} t_+(i),$$

$$T^- = [T^+]^\dagger.$$

The strength parameter of the effective interaction potential is found from the commutativity of the nuclear Hamiltonian with the isospin lowering or raising operator:

$$[H_{sp} - V_c + h_F, T^\rho] = 0 \tag{17}$$

$$\gamma_\rho = \langle 0 | [[H_{sp} - V_c, T^\rho], T^\rho] | 0 \rangle. \tag{18}$$

The phonon creation operator for the isobaric analogue states is described as:

$$|k >= Q_k^\dagger |0 >= \sum_{np} [\psi_{np}^k A_{np}^\dagger + \varphi_{np}^k A_{np}] |0 >, \tag{19}$$

The following equation has been solved to obtain the energies and wave functions of the isobaric analogue excitations,

$$[H_{sp} + h_F, Q_k^\dagger] |0 >= \omega_k Q_k^\dagger |0 >. \tag{20}$$

3. RESULTS and DISCUSSION

The calculated results related to the GT and Fermi excitations in ^{48}Sc and ^{90}Nb are given in this section. The Woods-Saxon potential has been used to obtain basis wave functions. The basis used here contains all neutron-proton transitions which change the radial quantum number n by $\Delta n = 0,1,2,3,\ldots$. The calculated single particle energies and the corresponding experimental values are presented in Tables 1 and 2. The experimental energies have been taken from [46]. While the single particle energies for ^{48}Ca have been calculated according to Chepurnov parametrization [47] ($V_0 = 53.30\ MeV,\ a = 0.63\ fm,\ \eta = 0.63\ and\ \xi = 0.263\ fm^2$), the corresponding energies for ^{90}Zr have been obtained by using the same parameter set except for ξ. The spin-orbit parameter (ξ) for ^{90}Zr has been taken as $0.350\ fm^2$. The dependence of the GTR and IAR on Coulomb radius is given in Figure 1. The centroid energies for both GTR and IAR decrease with the increase of Coulomb radius. This is an expected result because the proton and neutron levels which are far away from each other due to Coulomb interaction now come closer. Hence, the percentage contribution of the GTR to the total strength increases as Coulomb radius increases. Thus, this increase can be seen in the variation of the percentage contribution of the GTR to the total strength. The dependence of the same quantities on the isovector parameter is shown in Figure 2. As seen, the variation of the isovector interaction has no important influence on the centroid energies. However, a slight decrease of the B(GTR) can be observed as the isovector parameter increases. The reason for this decrease can be attributed to the fact that the total strength shifts from the GTR region to the low energy and isovector spin monopole resonance regions with the increase of the isovector parameter. The dependence of the GTR and IAR quantities on the spin-orbit parameter is presented in Figures 3 and 4. It is important to study the dependence on the spin-orbit interaction because the difference between the GTR and IAR quantities largely stems from the spin-orbit interaction. The reason for this difference is attributed to the difference between the effective interaction potentials in Eqs.(6) and (16). While the spin-orbit interaction has an important influence on the GTR, it has a negligible influence on the IAR. Thus, the variation of the GTR and IAR by the spin orbit parameter given in Figures 3 and 4 shows that the centroid energy and the contribution to the total strength for GT states are sensitive to the spin-orbit parameter, but the centroid energy for Fermi states almost remains the same. The centroid energy for the GT states increases with the spin-orbit potential. This is an expected result due to the repulsive character of the spin-orbit interaction. For ^{48}Ca, the centroid of the GT excitations for the small values of the spin-orbit parameter is observed in the low energies. The centroid shifts to the GT energy region as the spin-orbit parameter increases. Therefore, the contribution of the GTR to the total strength increases up to a certain value of the spin-orbit parameter. The contribution to the total strength decreases after that value of the spin-orbit parameter, because the total strength shifts to the isovector spin monopole resonance region. The GTR and IAR quantities are computed according to the mean field parameters fixed to reproduce the experimental single particle levels in Tables 1 and 2 are shown in Table 3. As is seen, the calculated GTR and IAR energies are in good agreement with the corresponding experimental energies. Also, it can be said that the calculated B_{GTR} contribution for ^{90}Zr shows a good agreement with the experimental contribution. However, the calculated B_{GTR} for ^{48}Ca shows no agreement with the corresponding experimental data. This disagreement completely originates from the quenching problem of the total strength which arises in the experimental studies. Let us note that the experimental data have been taken from [12,20,48,49].

4. CONCLUSION

The dependence of the Gamow-Teller and isobaric analogue resonance on the mean field parameters for two double closed shell nuclei has been investigated within RPA. The effective interaction term for the GT excitations in the neighbor odd-odd nuclei has been considered in such a way that the central term in the nuclear part of the total Hamiltonian commutes with the GT operator. The effective interaction potential for the isobaric analogue states has been included by considering the isospin invariance of the nuclear part in the total Hamiltonian. The strength parameters of the effective interaction for both GT and Fermi states have been determined in a self-consistent way. Thus, our formalism has been provided to be free of the effective interaction parameter. In traditional calculations, the experimental position of the GTR and IAR is usually reproduced by an effective interaction containing at least one free parameter. The GTR and IAR quantities also show a sensitive behavior against the variation of the adjustable parameters in the mean field potential. Hence, the experimental data related to the GTR and IAR can be reproduced by adjusting the mean field parameters. However, the reliability of the mean field parameters which reproduce the experimental GTR and IAR quantities has to be confirmed by the single particle levels. Therefore, the mean field parameters have been firstly determined by checking the single particle energies. Then, the influences of Coulomb, isovector and spin-orbit variables on the GTR and IAR have been calculated separately and, finally a comparison of the calculated GTR and IAR quantities with the corresponding experimental data has been given. Thus, the GTR and IAR have been searched without using any adjustable effective interaction parameter.

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