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AN INVESTIGATION OF THE GAMOW-TELLER 1^+ STATES IN ^{90}Nb ISOTOPES

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Abstract- In this study, based on Pyatov-Salamov method, the properties of the Gamow-Teller(GT) 1^+ states in ^{90} Nb have been investigated and the agreement of our results calculated by this method for the energy of Gamow-Teller Resonance (GTR) and the corresponding strengths of the 1^+ excitations in ^{90}Nb with the experimental values has been tested. As a result of the calculations, it was seen that the calculated values for the energy and strength of the GTR are sufficiently in agreement with the experimental ones.
Keywords- Gamow-Teller Resonance, Gamow-Teller strength.

1. INTRODUCTION

When the historical background of the GTR studies is reviewed, it is necessary to go back to 40 years ago. The theoretical predictions toward the existence of these resonances in 1963 and 1965 [1,2] played a pioneer role on the initiation of the studies on this matter. Although the detailed experimental investigation of the GTR have already started in the early of 1970`s [3-5], approximately 10 years later after theoretical predictions, the first experimental observation for the GTR was done in 1975 in the ^{90}Zr(p,n)^{90}Nb reaction at the incident proton energy of 35 MeV [6]. In 1980, the giant GTR was actually found to be preferentially excited in the (p,n) reactions at high bombarding energies [7]. The (p,n) reaction has become a powerful tool in the study of the GTR at intermediate energies and it has been widely used. Therefore, there has also been many attempts to measure the strength of the GT excitation in the ^{90}Nb isotope via the (p.n) reaction at different energies [6-15]. The second alternative to measure this strength experimentally is to use the (^{3}He,t) reaction. Using this reaction, the GT strength in ^{90}Nb has been investigated at various energies [16-20]. Although most charge exchange studies have used the (p,n) and the (^{3}He, t) reaction, the (^{6}Li,^{6}He) reaction was found to be a suitable and alternative probe for the investigation of spin-isospin modes and for the determination of the GT strength with high accuracy [21-27].

As a theoretical framework in the present paper, Pyatov-Salamov method is used. In this method, the effective interaction strength was determined self consistently by relating it to the average field. This method was applied different kind of studies [28-

37]. As a recent application, the Gamow-Teller 1^+ States in ^{208}Bi has been investigated [38].

In this study, the properties of the GT 1^+ states in ^{90}Nb are investigated by using Pyatov-Salamov method. For this purpose, the GTR energy, the contribution of the GT strength to the Ikeda Sum Rule and the differential cross sections for the ^{90}Zr(p,n)^{90}Nb and ^{90}Zr(^{3}He,t)^{90}Nb reactions at energies of 120 and 450 MeV are calculated. The results of the calculations have been compared with the corresponding experimental data.

2. FORMALISM

Our formalism is based on Pyatov-Salamov method in which the effective interaction strength has been determined self-consistently by relating it to average field. Let us now briefly mention about the details of this method. As it is known, the central term in the nuclear part of the shell model single particle Hamiltonian operator is not commutative with the GT operator. In other words,

$$\left[H_{sp}-(V_c+V_{ls}),G_\mu^{(\pm)}\right]\neq 0\,, \qquad (1)$$

where H_{sp} is the single particle Hamiltonian operator and it is defined as:

$$H_{sp}=\sum_{jm}\varepsilon_j(\tau)a_{jm}^{+}a_{jm} \qquad (2)$$

V_c is the Coulomb potential given by the following expression:

$$V_c=\sum_{i=1}^{A}v_c(r_i)(\frac{1}{2}-t_z^i),\quad t_z^i=\begin{Bmatrix}1/2 & \text{for neutrons;}\\ \text{-}1/2 & \text{for protons,}\end{Bmatrix} \qquad (3)$$

with the radial part of the Coulomb potential:

$$v_c(r)=\frac{e^2(Z-1)}{Z}\int\frac{\rho_p(r')}{|\vec{r}-\vec{r}'|}\,d\vec{r}' \qquad (4)$$

Here $\rho_p(r)$ is the proton density distribution in the ground state.
The term V_{ls} is the spin-orbit part of the average field potential and it is defined as:

$$V_{ls}=-\xi_{ls}\sum_{i=1}^{A}\frac{1}{r_i}\frac{dV(r_i)}{dr_i}(\vec{l}_i.\vec{s}_i)\,. \qquad (5)$$

All the notations in Eq.(5) have been taken from Ref.[39]:

$$V(r)=-f(r)V_0[1-2\eta\frac{N-Z}{A}t_z] \qquad (6)$$

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

where V_0, R_0, ζ_{ls}, η and a are the parameters of the average field potential.
The GT beta transition operators $G_\mu^{\pm}$ are defined as:

$$G_{\mu}^{(+)} = \sum_{i=1}^{A} \sigma_{\mu}(i) t_{+}(i)\,, G_{\mu}^{(-)} = \sum_{i=1}^{A} (-1)^{\mu} \sigma_{-\mu}(i) t_{-}(i)\,, \qquad G_{\mu}^{(-)} = (G_{\mu}^{(+)})^{+}\,. \tag{7}$$

$\sigma_\mu(i)$ is the Pauli operator in the spherical basis (μ=0,±1). $t_-(i)$ ($t_+(i)$) is the spin lowering(raising) operator.

In Pyatov-Salamov method, the commutativity of the central term in the Hamiltonian operator with the GT operators is provided by adding the effective interaction (h) to the commutation relation in Eq. (1), i.e.

$$\left[H_{sp} - (V_c + V_{ls}) + h, G_{\mu}^{(\pm)}\right] = 0\,, \tag{8}$$

where h is defined as: [37,40]

$$h = \frac{1}{2\gamma} \sum_{\substack{\mu=0,\pm1 \\ \rho=\pm}} \left[H_{sp} - (V_c + V_{ls}), G_{\mu}^{(\rho)}\right]^{+} \left[H_{sp} - (V_c + V_{ls}), G_{\mu}^{(\rho)}\right] \tag{9}$$

Using Eq. (8), the effective interaction parameter γ can be obtained:

$$\gamma = \langle 0 | [[H_{sp} - (V_c + V_{ls}), G_{\mu}^{(+)}], G_{\mu}^{(-)}] | 0 \rangle\,. \tag{10}$$

The average is taken over the ground state of the parent nucleus. Then, the total Hamiltonian operator can be written in the form of

$$H = H_{sp} + h\,. \tag{11}$$

The basic set of the particle-hole operators for the GT 1^+ states generated by spin dependent charge exchange forces (h) is given by

$$A_{j_n j_p}(\mu) = \sqrt{\frac{3}{2j_n + 1}} \sum_{m_n m_p} \left(j_n m_p 1\mu | j_n m_n\right) a^{+}_{j_n m_n} a_{j_p m_p}\,, \tag{12}$$

where $a^{+}_{j_\tau m_\tau}$ ($a_{j_\tau m_\tau}$) is the nucleon creation(annihilation) operators in a state with the momentum j_τ and its projection m_τ $(\tau = n, p)$. The average value of the commutator of these operators is determined by the equation:

$$[A_{j_n j_p}(\mu), A^{+}_{j_n j_p}(\mu')] \approx \delta_{\mu\mu'}, [A_{j_n j_p}(\mu), A_{j_n j_p}(\mu')] = 0\,. \tag{13}$$

The effective interaction h defined in Eq. (8) can be written in terms of the boson operators as follows:

$$h=\frac{1}{2\gamma}\sum_{j_n,j_p}K_{j_nj_p}K_{j_n^{'}j_p^{'}}\left[A^{+}_{j_nj_p}(\mu)A_{j_n^{'}j_p^{'}}(\mu^{'})+A_{j_n^{'}j_p^{'}}(\mu^{'})A^{+}_{j_nj_p}(\mu)\right]$$
$$\gamma=-\sum_{\substack{j_n,j_p\\ j_n^{'},j_p^{'}}}K_{j_nj_p}b_{j_nj_p}(n_{j_n}-n_{j_p}), \tag{14}$$

with

$$K_{j_nj_p}\equiv b_{j_nj_p}(\varepsilon_{j_n}-\varepsilon_{j_p})-d_{j_nj_p}-f_{j_nj_p}+g_{j_nj_p},$$
$$b_{j_nj_p}=\frac{1}{\sqrt{3}}\left\langle j_n\|\sigma\|j_p\right\rangle,$$
$$d_{j_nj_p}=\frac{1}{\sqrt{3}}\left\langle j_n\|v_c(r)\sigma\|j_p\right\rangle,$$
$$f_{j_nj_p}=\frac{1}{2\sqrt{3}}[j_p(j_p+1)-l_p(l_p+1)-\frac{3}{4}]\left\langle j_n\|U_1^{ls}(r)\sigma\|j_p\right\rangle,$$
$$g_{j_nj_p}=\frac{1}{\sqrt{3}}\left\langle j_n\left\|(U_0^{ls}(r)-\frac{1}{2}U_1^{ls}(r))(-i[\vec{l}\times\vec{\sigma}]\right\|j_p\right\rangle,$$
$$U_0^{ls}(r)=\xi_{ls}V_0\frac{1}{r}\frac{df(r)}{dr},$$
$$U_1^{ls}(r)=1.26\frac{N-Z}{A}U_0^{ls}(r),$$

where l_p is the orbital angular momentum of the proton; ε_{j_n} and ε_{j_p} are the single particle energies of the neutron and proton states; n_{j_n} and n_{j_p} are the occupation numbers of the neutron and proton states.

A set of Hermitian operators can be constructed in terms of the boson operators:

$$P_k(\mu)=\frac{i}{\sqrt{2}}\sum_{j_nj_p}\psi^k_{j_nj_p}[A^{+}_{j_nj_p}(\mu)-A_{j_nj_p}(\mu)],$$

$$L_k(\mu)=\frac{1}{\sqrt{2}}\sum_{j_nj_p}\varphi^k_{j_nj_p}[A^{+}_{j_nj_p}(\mu)+A_{j_nj_p}(\mu)], \tag{15}$$

where $\psi^k_{j_nj_p}$ and $\varphi^k_{j_nj_p}$ are the real amplitudes. Following the equations of motion in RPA,

$$[H_{sp}+h,P_k(\mu)]=i\omega_k^2L_k(\mu),$$
$$[H_{sp}+h,L_k(\mu)]=-iP_k(\mu), \tag{16}$$

we obtain the system of equations for the eigenenergies ω_k of the Gamow-Teller 1^+ states in the neighborhood odd-odd nucleus and the real amplitudes $\psi^k_{j_n j_p}$ and $\varphi^k_{j_n j_p}$ as follows:

$$\begin{aligned}(\varepsilon_{j_p} - \varepsilon_{j_n})\psi^k_{j_n j_p} - \frac{1}{2\gamma} K_{j_n j_p} X^k &= \omega_k^2 \varphi^k_{j_n j_p}, \\ (\varepsilon_{j_p} - \varepsilon_{j_n})\varphi^k_{j_n j_p} - \frac{1}{2\gamma} K_{j_n j_p} Y^k &= \omega_k^2 \psi^k_{j_n j_p},\end{aligned} \tag{17}$$

with

$$\begin{aligned}X^k &= \sum_{j_n j_p} K_{j_n j_p} \psi^k_{j_n j_p} (n_{j_n} - n_{j_p}), \\ Y^k &= \sum_{j_n j_p} K_{j_n j_p} \varphi^k_{j_n j_p} (n_{j_n} - n_{j_p}).\end{aligned} \tag{18}$$

Without showing the details for the solution of Eq. (18), the resulting equation for the energies ω_k is in the form of

$$F(\omega_k)\phi(\omega_k) = 0, \tag{19}$$

where

$$\begin{aligned}F(\omega_k) &= \sum_{j_n j_p} [\omega_k b_{j_n j_p} - d_{j_n j_p} - f_{j_n j_p} + g_{j_n j_p}] \frac{K_{j_n j_p}(n_{j_n} - n_{j_p})}{\varepsilon_{j_p} - \varepsilon_{j_n} - \omega_k}, \\ \phi(\omega_k) &= F(-\omega_k).\end{aligned} \tag{20}$$

From Eq. (19), we have two different solutions:

$$F(\omega_k) = 0 \tag{21a}$$

$$\phi(\omega_k) = 0 \tag{21b}$$

The analytical expressions for the real amplitudes are:

$$\begin{aligned}\psi^k_{j_n j_p} &= \frac{X^k}{2\gamma} \frac{K_{j_n j_p}}{\varepsilon_{j_p} - \varepsilon_{j_p} \pm \omega_k}, \\ -\varphi^k_{j_n j_p} &= \mp \frac{1}{\omega_k} \psi^k_{j_n j_p},\end{aligned} \tag{22}$$

where plus and minus signs correspond to the solutions of Eq. (21a) and (21b), respectively. The eigenstates of the total Hamiltonian in Eq. (11) with the energies ω_k are the one-phonon excitations of the correlated phonon vacuum $|0\rangle$ of the parent nucleus $(Q_k|0\rangle = 0)$. Thus,

$$Q_k^+(\mu)\left|0\right\rangle = \left\{-\frac{i}{\sqrt{2\omega_k}}P_k(\mu) + \sqrt{\frac{\omega_k}{2}}L_k(\mu)\right\}\left|0\right\rangle$$
$$= \left\{\begin{array}{l} \frac{1}{\sqrt{\omega_k}}\sum_{j_nj_p} A^+_{j_nj_p}(\mu), \omega_k \in F(\omega_k) = 0; \\ \frac{-1}{\sqrt{\omega_k}}\sum_{j_nj_p} A_{j_nj_p}(\mu), \omega_k \in \phi(\omega_k) = 0. \end{array}\right\} \quad (23)$$

The $\beta^{\pm}$ transition matrix elements from the 0^+ initial even-even nuclear state to the one phonon 1^+ states in odd-odd final nucleus are expressed by:

a) For the β^- transitions (N,Z)⇒(N-1,Z+1),

$$M_{\beta-}(\mu,\omega_{k_F};0^+ \to 1^+) = \left\langle 0\right|[Q_{k_f}, G_\mu^{(-)}]\left|0\right\rangle = \frac{1}{\sqrt{2\omega_{k_F}}}\sum_{j_nj_p} b_{j_nj_p}\psi^{k_F}_{j_nj_p}(n_{j_n} - n_{j_p}). \quad (24)$$

b) For the β^+ transitions (N,Z)⇒(N+1,Z-1),

$$M_{\beta+}(\mu,\omega_{k_\phi};0^+ \to 1^+) = \left\langle 0\right|[Q_{k_f}, G_\mu^{(+)}]\left|0\right\rangle = \frac{1}{\sqrt{2\omega_{k_\phi}}}\sum_{j_nj_p} b_{j_nj_p}\psi^{k_\phi}_{j_nj_p}(n_{j_n} - n_{j_p}). \quad (25)$$

For the GT beta strength function, we have

$$B^-_{GT}(\omega_{k_F}) = \sum_\mu \left|M_{\beta^-}(\mu,\omega_{k_F};0^+ \to 1^+)\right|^2,$$
$$B^+_{GT}(\omega_{k_\phi}) = \sum_\mu \left|M_{\beta^-}(\mu,\omega_{k_\phi};0^+ \to 1^+)\right|^2. \quad (26)$$

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

$$\sum_{k_F} B^{(-)}_{GT}(\omega_{k_F}) - \sum_{k_F} B^{(+)}_{GT}(\omega_{k\phi}) = 3(N-Z). \quad (27)$$

The differential cross section of zero degrees for the excitation of the GT 1^+ states can be written as [8,9,16]:

$$(\frac{d\sigma}{d\Omega})_{GTR}(q \approx 0, \theta = 0) = (\frac{\mu}{\pi\hbar^2})^2(\frac{k_f}{k_i})N_{\sigma\tau}J^2_{\sigma\tau}B^{(-)}_{GT}(\omega_{k_F}), \quad (28)$$

where $J_{\sigma\tau}$ is the volume integral of the central part of the effective spin dependent nucleon nucleon interaction; μ and k denote the reduced mass and the wave number in the center of mass system, respectively. $N_{\sigma\tau}$ is the distortion factor which may be approximated by the function $\exp(-xA^{1/3})$[9] and the value of x is taken from Ref. [16].

3.RESULTS AND DISCUSSIONS

In this section, we have calculated the GTR energy, the contribution of the GT beta transition strength to the Ikeda sum rule, and the differential cross sections for the

$^{90}Zr(^3He,t)^{90}Nb$ and $^{90}Zr(p,n)^{90}Nb$ reactions at energies of 450 MeV and 120 MeV, respectively. In calculations, the Wood-Saxon potential with Chepurnov parametrization [39] was used (V_0=53.3 MeV, η=0.63, a=0.63 fm, ξ_{ls}=0.263 fm^2).The basis used in our calculation contains all neutron-proton transitions which change the radial quantum number n by Δn=0,1,2,3. The single particle Ikeda sum rule is fulfilled with the approximately ≈%1 accuracy.

The calculation results have been given in Table I. In the first column of Table I, the excitation energies of the GT 1^+ states in ^{90}Nb have been presented. The second column gives the GT strengths corresponding to the excitation energies. In the last two columns, the calculated values of the differential cross sections for the $^{90}Zr(^3He,t)^{90}Nb$ and $^{90}Zr(p,n)^{90}Nb$ reactions at energies of 450 MeV and 120 MeV has been shown, respectively.

Table I: Calculation results for the GT strengths of the 1^+ states in ^{90} Nb and the differential cross sections for the $^{90}Zr(^3He,t)^{90}Nb$ and $^{90}Zr(p,n)^{90}Nb$ reactions at energies of 450 MeV and 120 MeV, respectively.

ω_{GT} MeV	$B_{GT}/3(N-Z)$ %	$\left.\frac{d\sigma}{d\Omega}\right\|_{E(^3He)=450\,MeV}$	$\left.\frac{d\sigma}{d\Omega}\right\|_{E(p)=120\,MeV}$
2.02	16.59	33.27	3.67
7.61	82.26	163.96	17.78
14.36	0.16	0.33	0.04
15.91	0.07	0.14	0.02
16.10	0.14	0.28	0.03
16.80	0.18	0.35	0.04
19.32	0.17	0.33	0.03
20.52	0.13	0.26	0.03
21.00	0.10	0.20	0.02
21.69	0.07	0.13	0.01
21.82	0.15	0.30	0.03
25.86	0.52	1.01	0.10

The excitation energies of the GT 1^+ states in ^{90}Nb can be categorized into three energy regions: low energy region ($0<\omega_{GT}<5$ MeV), the GTR region ($5<\omega_{GT}<12$ MeV), high energy region (($12<\omega_{GT}<26$ MeV). In the low energy region, there exists only one state at ω_{GT}=2.02 MeV that exhausts 16.59% of the Ikeda sum rule. However, A. Krasznahorkay et al. [20] have found eight levels in the low energy region in ^{90}Nb. The reason for this difference can be attributed to the fact that the pairing correlations between nucleons has not been taken into account in our study.

In Table II, the experimental values for the GTR energy and the GT strengths have been presented. As seen from this table, the experimental values of the GTR energy range from 8.5 MeV to 8.9 MeV [7,20-24,27]. On the other hand, our calculation for this quantity gives a value of 7.61 MeV (See Table I). Then, it can be said that our calculated value for the GTR energy is not so far from the experimental value, i.e ~ 0.9-1.3 MeV lower than the experimental one. Moreover, the GTR state amounts to 82.26% of the the Ikeda sum rule(See Table I). As compared to the values obtained for the GT strengths in different experimental studies [3,23,24,27] given in Table II, our value is within the range of the upper limits given in Ref. 23,24. We hope that all these differences between the calculated and experimental value for the GTR energy and the GT strengths will be partly removed by the consideration of the pairing correlations between nucleons. Finally, we have calculated the differential cross sections for the $^{90}Zr(^{3}He,t)^{90}Nb$ and $^{90}Zr(p,n)^{90}Nb$ reactions at the excitation energies of 450 MeV and 120 MeV. They have the values of 163.96 mb/sr and 17.78 mb/sr, respectively.

Table II: The experimental values for the GTR energy and the GT strengths

ω_{GT} in MeV(Experimental)	**B(GT)/3(N-Z) % (Experimental)**
8.7±0.3 [7]	61±10[3]
8.7 [21]	75±10[23]
8.5 [22]	$66\pm^{20}_{10}$[24]
8.7 [23]	39±4[27]
8.9±1 [24]	
8.8±0.2 [20]	
8.84±0.1 [27]	

4. CONCLUSION

We have applied Pyatov-Salamov method to the investigation of the GT 1^+ states in ^{90}Nb and tested the agreement of the calculated quantities in the present study by this method with the experimental values. For this purpose, the excitation energies, the GT strengths of the 1^+ states in ^{90}Nb and the differential cross sections for the $^{90}Zr(^{3}He,t)^{90}Nb$ and $^{90}Zr(p,n)^{90}Nb$ reactions at energies of 450 MeV and 120 MeV have been calculated. As a result of our calculations, it has been seen that our calculated value for the GTR energy is sufficiently close to the experimental value, i.e ~ 0.9-1.3 MeV lower than the experimental one, and our value for the contribution of the GTR to the Ikeda sum rule is within the range of the upper limits given in Ref. 23,24. We hope that all these differences between the calculated and experimental value for the GTR energy and the GT strengths will be partly removed by the consideration of the pairing correlations between nucleons. In the next step, the pairing correlations between nucleons will be included in the investigation of the GT 1^+ states in ^{90}Nb and this will be done in our next study.

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