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Application of Shell Model Calculations with Modified Surface Delta Interaction For the Two Nuclei $^{134}_{52}Te$ and $^{134}_{50}Sn$

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Abstract- By applying Shell model with Modified Surface Delta Interaction on Tellurium nucleus $^{134}_{52}Te$ and Tin nucleus $^{134}_{50}Sn$, that have two valence nucleons outside the closed core $^{132}_{50}Sn_{82}$, we obtained the values of the energy levels and excitation energies of the two nuclei, after determining the value of the two constants A_T and B_T for Modified Surface Delta Interaction by least square fitting method.

When we comparing the value of standard deviation of our calculated excitation energies with some previous studies calculated in different ways, we found that nucleus $^{134}_{52}Te$ shows good agreement with experimental values compared to these studies, while nucleus $^{134}_{50}Sn$ does not show a good agreement. Therefore the application of the Shell model with Modified Surface Delta Interaction, in its present form, on nuclei whose valence nucleons are located after the magic number N = 82, needs to be modified, such as taking into account the excitation closed core and configuration mixing.

Keywords - Shell Model, Modified Surface Delta Interaction, closed core, Valance Space.

I. INTRODUCTION

The model in nuclear physics is a hypothesis that describes the position of nucleons inside the nucleus as well as the forces acting between them, so that their properties can be easily calculated. Some successful models provide a more or less acceptable description of some nuclear properties with a less in-depth understanding of others[1]. Among the models that imposed themselves on the nuclear physical area, is the shell model, which succeeded in determining the angular moments of the majority of atomic nuclei, in addition to its success in reaching the magic numbers[2]. This model, developed by Mayer and Jensen in 1948[2], is based on the assumption that every nucleon in any nucleus is moving in two potentials: the first is an average potential resulting from the rest of the nucleons, called the standard potential, which expresses a central field, and the second resulting from the interactions between each two nucleons of nucleons is called the residual potential. Among the remaining potentials, we mention the Modified Surface Delta Interaction (MSDI), which is one of the separable potentials, which allows obtaining an analytical solution to the Schrödinger equation[3].

According to this model, nucleons are located on separate energy levels called single-particle levels, which are determined by solving the Schrödinger equation, and the way of placing them on these levels determines the so-called nucleon configurations. When the number of nucleons is large, the process of taking the mutual effect between all nucleons becomes a very complex process, so we resort to approximating the Valence Space[4], Which assumes the existence of a closed core is the closest magical double nucleus to the studied nucleus, therefore the study is limited to valence nucleons (the nucleons that lie outside or within the closed core) instead of all nucleons, where these valence nucleons exchange influence via residual interaction. The shell model calculations were expanded applied to nuclei with valence nucleons located in fpg shell, using a MSDI potential[8-5]. However, nuclei with valence nucleons located in higher shells have not been sufficiently studied. Therefore, in this study, we will verify the validity of applying the shell model with the MSDI potential to the nuclei that fall within this region.

We chose in this study the Tellurium nucleus which has two protons locate in $1h_{9/2}$ level outside closed core $^{132}_{50}Sn_{82}$, while the Tin nucleus $^{134}_{50}Sn$ has two neutrons locate in $1g_{7/2}$ level outside same closed core. We calculate energy levels and excitation energies, and determining the value of the two strength interaction of MSDI by least square fitting method, this is due to the absence of nuclear data regarding the strength interaction of this potential within the studied range.

II. NUCLEAR SHELL MODEL

The basic assumption of the nuclear shell model is that to a first approximation each nucleon moves independently in a potential that represents the average interaction with the other nucleons in a nucleus. This independent motion can be understood qualitatively from a combination of the weakness of the long-range nuclear attraction and the Pauli exclusion principle. In a non-relativistic approximation, nuclear properties are described by the Schrodinger equation for A nucleons[9], i.e.

$$\hat{H}\left|\Psi\right\rangle = E\left|\Psi\right\rangle \tag{1}$$

where Ψ is an A-body wave function, and $\hat{H}$ contains nucleon kinetic energy operators and interactions between nucleons of a two-body, and a three-body character, in the present study we will consider only the two-body interaction, i.e

$$\hat{H} = \sum_{i=1}^{A}(-\frac{\hbar^2}{2m}\Delta_i) + \sum_{i<j=1}^{A} W(i,j) \tag{2}$$

We can re-write the Hamiltonian (2), adding and subtracting a one-body potential of the form $\sum_{i=1}^{A} U(i)$ as

$$\hat{H} = \sum_{i=1}^{A}[-\frac{\hbar^2}{2m}\Delta_i + U(i)] + \sum_{i<j=1}^{A} W(i,j) - \sum_{i=1}^{A} U(i) = \hat{H}^{(0)} + \hat{H}^{(1)} \tag{3}$$

Where $\hat{H}^{(0)}$ is the zero Hamiltonian and it is a sum of single-particle Hamiltonians, and expresses the average potential of all nucleons, i.e.

$$\hat{H}^{(0)} = \sum_{i=1}^{A}[-\frac{\hbar^2}{2m}\Delta_i + U(i)] \equiv \sum_{i=1}^{A}\hat{h}(i) \tag{4}$$

$\hat{H}^{(1)}$ called a residual interaction, and it writes as

$$\hat{H}^{(1)} = \sum_{i<j=1}^{A} W(i,j) - \sum_{i=1}^{A} U(i) \equiv \hat{V} \tag{5}$$

We can expand Ψ in any complete orthonormal basis $\Phi_1, \Phi_2, \Phi_3 \ldots$ as

$$\left|\Psi\right\rangle = \sum_{k=1}^{N} a_k \left|\Phi_k\right\rangle \tag{6}$$

where $\left|\Phi\right\rangle = \left|\bar{n}_1 \ell_{1j_1}\, \bar{n}_2 \ell_{2j_2}\, \bar{n}_3 \ell_{3j_3} \ldots, J\right\rangle$, a_k is amplitude of wave functions $\left|\Phi_k\right\rangle$, N is the number of nucleon configurations, so the Schrodinger equation became as

$$\hat{H}\sum_{k=1}^{N} a_k \left|\Phi_k\right\rangle = E\sum_{k=1}^{N} a_k \left|\Phi_k\right\rangle \tag{7}$$

We can write the projection of the eigenvalue in the last equation onto the basis state $\left\langle\Phi_L\right|$ i.e.

$$\sum_{k=1}^{N} a_k \left\langle\Phi_L\right|\hat{H}\left|\Phi_k\right\rangle = E\sum_{k=1}^{N} a_k \left\langle\Phi_L\right|\left.\Phi_k\right\rangle \tag{8}$$

$$\sum_{k=1}^{N} H_{Lk} a_{\Gamma k} = E\, a_L \tag{9}$$

$$H_{Lk} \equiv \left\langle\Phi_L\right|\hat{H}\left|\Phi_k\right\rangle = E_k^{(0)}\delta_{Lk} + H_{Lk}^{(1)} \tag{10}$$

$$; H_{Lk}^{(1)} = \left\langle\Phi_L\right|\hat{H}^{(1)}\left|\Phi_k\right\rangle \tag{11}$$

H_{Lk} is matrix element and $\hat{H}^{(1)}$ residual matrix element.

It is clear that when the number of nucleons is large, the Hamiltonian matrix becomes very large, so we use an approximating Valence Space or Model Space, which consists of all single-particle orbitals actively involved in the generation of configurations of the many-nucleon system considered, and assumes the existence of a closed core is the closest doubly magic nucleus to the studied nucleus, and therefore the study is limited to valence nucleons (the nucleons that lie outside the closed core) instead of being between all nucleon. When the nucleus has two valance nucleons outside closed core, the equation(10) take the form[9]

$$E(Cab) = E(C) + \varepsilon_a + \varepsilon_b + \left\langle ab\right|V\left|ab\right\rangle \tag{12}$$

Where $E(C)$ is closed core energy, we can obtain from last eq. the energy of two valance nucleons as

$$E_\Gamma = E(Cab) - E(C) = \varepsilon_a + \varepsilon_b + \left\langle ab\right|V\left|ab\right\rangle \tag{13}$$

II. MODIFIED SURFACE DELTA INTERACTION (MSDI)

The effect of the residual interaction is only between valence nucleons, and its contribution to the total Hamiltonian is small compared to the standard field potential, so it is treated as a perturbation, and this interaction takes different forms. In this study, we chose the Surface Delta Interaction (SDI) because it is easy to deal with and it is a separable potential, which allows obtaining an analytical solution to the Schrödinger equation. This form of interaction was postulated in 1966 by Moszkowski et.al[3] , This is based on the Pauli principle, which forbidden the collisions occur at the full levels and allows collisions to occur mainly at the valance levels, this potential take the form as[9]

$$V_{ab}[\mathrm{SDI}] = -4\pi A_T\, \delta(\Omega_{ab})\delta(r_a - R)\delta(r_b - R) \tag{14}$$

Where A_T is strength interaction of MSDI, Ω_{ab} is the angular coordinate between interacting particles a and b, and R the nuclear radius. The matrix element of residual interaction for one of the interacting valence-nucleon pairs is as follows[3]

$$\left\langle j_a\, j_b, JT \left| V_{\text{SDI}} \right| j_c\, j_d, JT \right\rangle_{JT} = \frac{A_T}{2(2J+1)}\left[\frac{(2j_a+1)(2j_b+1)(2j_c+1)(2j_d+1)}{(1+\delta_{ab})(1+\delta_{cd})}\right]^{\frac{1}{2}}$$
$$\{(-1)^{\ell_a+\ell_c+j_b+j_d}\left\langle j_b -\frac{1}{2}\, j_a\, \frac{1}{2}|\, J\,0\right\rangle\left\langle j_d -\frac{1}{2}\, j_c\, \frac{1}{2}|\, J\,0\right\rangle[1-(-1)^{\ell_c+\ell_d+J+T}]-$$
$$-\left\langle j_b\, \frac{1}{2}\, j_a\, \frac{1}{2}|\, J1\right\rangle\left\langle j_d\, \frac{1}{2}\, j_c\, \frac{1}{2}|\, J1\right\rangle[1+(-1)^T]\} \quad (15)$$

The symbol $(j -\frac{1}{2}\, j\, \frac{1}{2}|\, J\,0)$ indicates to Clebsch-Gordan coefficients, and j is angular momentum of nucleon, and J is total angular momentum of two nucleon interaction, and the symbol T refers to total isospin produced by the isospin coupling of the two interacting nucleons.

This interaction was developed by Glaudesmans, and called Modified Surface Delta Interaction(MSDI). The matrix element of residual interaction for one of the interacting valence-nucleon pairs is as follows [3]

$$V_{ab}[\text{MSDI}] = -4\pi A_T\, \delta(\Omega_{ab})\delta(r_a - R)\delta(r_b - R) + B_T\, \tau_a \tau_b \quad (16)$$

Where A_T , B_T is two constants represents the strength interaction of MSDI, τ_a, τ_b is Pauli operators for two nucleons interaction, The matrix element of residual interaction for one of the interacting valence-nucleon pairs is as follows[3]

$$\left\langle j_a\, j_b, JT \left| V_{\text{MSDI}} \right| j_c\, j_d, JT \right\rangle_{JT} = \frac{A_T}{2(2J+1)}\left[\frac{(2j_a+1)(2j_b+1)(2j_c+1)(2j_d+1)}{(1+\delta_{ab})(1+\delta_{cd})}\right]^{\frac{1}{2}}$$
$$\{(-1)^{\ell_a+\ell_c+j_b+j_d}\left\langle j_b -\frac{1}{2}\, j_a\, \frac{1}{2}|\, J\,0\right\rangle\left\langle j_d -\frac{1}{2}\, j_c\, \frac{1}{2}|\, J\,0\right\rangle[1-(-1)^{\ell_c+\ell_d+J+T}]-$$
$$-\left\langle j_b\, \frac{1}{2}\, j_a\, \frac{1}{2}|\, J1\right\rangle\left\langle j_d\, \frac{1}{2}\, j_c\, \frac{1}{2}|\, J1\right\rangle[1+(-1)^T]\} + B_T\,[2T(T+1)-3]\delta_{ac}\delta_{bd} \quad (17)$$

III. LEAST SQUARE FITTING METHOD

The Method of least square fitting is a procedure to determine the best fit line to data. This method is considered a standard method for finding the solution a set of equations with more than one variable. This allows using this method to determine values of the constants in theoretical formulas by fitting them to the empirical values. The fitting is best when the sum of the squares of the differences between experimental and theoretical values is minimal, as follows[10]

$$S = \sum_i (y_i - f(x_i))^2 \quad (18)$$

Where $f(x_i) = \sum_{k=0}^{k=j} a_k x_i^{\,k}$ is polynomial, and a_k are polynomial constants. Since the function S is dependent on several variables, it reaches a local maximum at the point where all its partial derivatives of the first order are zero, that is, when the following equations are fulfilled

$$\frac{\partial S}{\partial a_0} = 0, \frac{\partial S}{\partial a_1} = 0, \frac{\partial S}{\partial a_2} = 0, ..., \frac{\partial S}{\partial a_k} = 0 \quad (19)$$

This set of equations whose number of variables is equal to the number of equations is arranged in the following matrix form

$$\begin{bmatrix} n & \sum x_i & \sum x_i^2 & \cdots & \sum x_i^j \\ \sum x_i & \sum x_i^2 & \sum x_i^3 & \cdots & \sum x_i^{j+1} \\ \sum x_i^2 & \sum x_i^3 & \sum x_i^4 & \cdots & \sum x_i^{j+2} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \sum x_i^j & \sum x_i^{j+1} & \sum x_i^{j+2} & \cdots & \sum x_i^{2j} \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ \vdots \\ a_j \end{bmatrix} = \begin{bmatrix} \sum y_i \\ \sum (x_i y_i) \\ \sum (x_i^2 y_i) \\ \vdots \\ \sum (x_i^j y_i) \end{bmatrix} \quad (20)$$

By solving the system of these equations, we get the values of the constants $a_0, a_1, a_2, ..., a_j$

IV. CALCULATIONS AND RESULTS

A. Finding constants A_T and B_T for MSDI potential

To calculate the strength of the MSDI potential, we will use the least squares fitting method. In this method, the proportionality between theoretically values and experimental values is the best when the sum of the squares of the differences between the experimental and theoretical values is minimal, as follows[10]:

$$S = \sum_i \left(y_i - \left\langle j_a\, j_b, JT \left| V_{\text{MSDII}} \right| j_c\, j_d, JT \right\rangle_{JT} \right)^2$$

Where y_i is the experimental values for residual interaction between two valance nucleons, which we get it from eq. (12), where we take the value for single neutron in $1h_{9/2}$ level is $\varepsilon_{\nu 1g_{7/2}} = -3.6293(Mev)$ and single proton in $1g_{7/2}$ level is $\varepsilon_{\pi 1h_{9/2}} = -1.0902(Mev)$ and the closed core $^{132}_{50}Sn_{50}$ experimental energy is $E(C) = -1102.841(MeV)$, and expermental energy for two nucleus $^{134}_{52}Te$, $^{134}_{50}Sn$ is $E(Cab) = -1123.411(MeV)$ respectively[11].

Since the function S is dependent on two variables, it reaches a local maximum at the point where all its partial derivatives of the first order are zero, that is, when the following equations are fulfilled

$$\frac{\partial S}{\partial A_T} = -2\sum_i A_T \left(y_i - \left\langle j_a\, j_b, JT \left| V_{\text{MSDII}} \right| j_c\, j_d, JT \right\rangle_{JT} \right)^2 = 0$$
$$\frac{\partial S}{\partial B_T} = -2\sum_i B_T \left(y_i - \left\langle j_a\, j_b, JT \left| V_{\text{MSDII}} \right| j_c\, j_d, JT \right\rangle_{JT} \right)^2 = 0$$

This set of equations whose number of variables is equal to the number of equations is arranged in the following matrix form

$$\begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} \cdot \begin{bmatrix} A_T \\ B_T \end{bmatrix} = \begin{bmatrix} D_1 \\ D_2 \end{bmatrix}$$

Where the terms of matrix $C \equiv \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix}$ gives as

$$C_{11} = \sum \left(\frac{1}{2(2J+1)} \left[\frac{(2j_a+1)(2j_b+1)(2j_c+1)(2j_d+1)}{(1+\delta_{ab})(1+\delta_{cd})} \right]^{\frac{1}{2}} \right.$$

$$\times \{(-1)^{\ell_a+\ell_c+j_b+j_d} \left\langle j_b -\frac{1}{2} j_a \frac{1}{2} | J 0 \right\rangle \left\langle j_d -\frac{1}{2} j_c \frac{1}{2} | J 0 \right\rangle$$

$$[1-(-1)^{\ell_c+\ell_d+J+T}] - \left\langle j_b \frac{1}{2} j_a \frac{1}{2} | J 1 \right\rangle \left\langle j_d \frac{1}{2} j_c \frac{1}{2} | J 1 \right\rangle [1+(-1)^T]\} \Big)^2$$

$$C_{22} = \sum \left([2T(T+1)-3] \delta_{ac} \delta_{bd} \right)^2$$

$$C_{12} = C_{21} = \sum \left(\frac{1}{2(2J+1)} \left[\frac{(2j_a+1)(2j_b+1)(2j_c+1)(2j_d+1)}{(1+\delta_{ab})(1+\delta_{cd})} \right]^{\frac{1}{2}} \right.$$

$$\{(-1)^{\ell_a+\ell_c+j_b+j_d} \left\langle j_b -\frac{1}{2} j_a \frac{1}{2} | J 0 \right\rangle \left\langle j_d -\frac{1}{2} j_c \frac{1}{2} | J 0 \right\rangle$$

$$[1-(-1)^{\ell_c+\ell_d+J+T}] - \left\langle j_b \frac{1}{2} j_a \frac{1}{2} | J 1 \right\rangle \left\langle j_d \frac{1}{2} j_c \frac{1}{2} | J 1 \right\rangle [1+(-1)^T]\} \Big) \times$$

$$\left([2T(T+1)-3] \delta_{ac} \delta_{bd} \right)$$

And terms of matrix $D \equiv \begin{bmatrix} D_1 \\ D_2 \end{bmatrix}$ gives as

$$D_1 = \sum \left(\frac{1}{2(2J+1)} \left[\frac{(2j_a+1)(2j_b+1)(2j_c+1)(2j_d+1)}{(1+\delta_{ab})(1+\delta_{cd})} \right]^{\frac{1}{2}} \times \right.$$

$$\{(-1)^{\ell_a+\ell_c+j_b+j_d} \left\langle j_b -\frac{1}{2} j_a \frac{1}{2} | J 0 \right\rangle \left\langle j_d -\frac{1}{2} j_c \frac{1}{2} | J 0 \right\rangle$$

$$[1-(-1)^{\ell_c+\ell_d+J+T}] - \left\langle j_b \frac{1}{2} j_a \frac{1}{2} | J 1 \right\rangle \left\langle j_d \frac{1}{2} j_c \frac{1}{2} | J 1 \right\rangle [1+(-1)^T]\} \Big) \times y_i$$

$$D_2 = \sum \left([2T(T+1)-3] \delta_{ac} \delta_{bd} \right) \times y_i$$

So, we can get the constant matrix $M = \begin{bmatrix} A_T \\ B_T \end{bmatrix}$ by invert matrix C as $M = C^{-1}.D$. We find from calculating the matrix M, the values of constant MSDI potential for two study nuclei as $A_T = 0.4435$, $B_T = 0.4934$ for $^{134}_{52}Te$ and $A_T = 0.3068$, $B_T = 0.2762$ for $^{134}_{50}Sn$

B. Calculating Excitation Energies for Two Nuclei $^{134}_{52}Te$ and $^{134}_{50}Sn$

The total angular momentum J of atomic nuclei which have two valence nucleons where angular momentum of each of them j_1, j_2 are determined, according to the shell model, by the following inequality[9]

$$j_1 - j_2 | \leq J \leq j_1 + j_2$$

So, the two study nuclei $^{134}_{52}Te$ and $^{134}_{50}Sn$ have two valance nucleon located outside the closed core $^{132}_{50}Sn_{82}$, where the $^{134}_{52}Te$ has two proton located in the $1g_{7/2}$ level outside the closed core $^{132}_{50}Sn_{82}$, so the angular momentum and Parity for this nucleus is $J^{\pi} = 0^+, 2^+, 4^+, 6^+$. Where the $^{134}_{50}Sn$ has two neutron located in $1h_{9/2}$ level outside the same closed core, so the angular momentum and Parity for this nucleus is $J^{\pi} = 0^+, 2^+, 4^+, 6^+, 8^+$. For finding energy levels for two study nuclei, first we calculate the matrix elements for residual interaction from eq. (17), then substitution of this values in the eq.(13) to get the energy levels for every permissible angular momentum. By taking the energy levels for the every level subtracted from the ground level we get the values of the excitation energies for each nucleus, the value of energy levels and excitation energies for $^{134}_{52}Te$ illustrated in table(1), and for $^{134}_{50}Sn$ illustrated in table(2).

Table 1. Energy levels and excitation energies for $^{134}_{52}Te$ calculated using the MSDI potential according to the total angular momentum and Parity

J^{π}	E_{th}	E_x	$E_{exp.}$
0^+	-8.5164	0	0
2^+	-7.3543	1.1621	0.7256
4^+	-7.1755	1.3409	1.0734
6^+	-7.0969	1.4195	1.2474
8^+	-7.0443	1.4721	2.589

Table 2. Energy levels and excitation energies for $^{134}_{50}Sn$ calculated using the MSDI potential according to the total angular momentum and Parity

J^{π}	E_{th}	E_x	$E_{exp.}$
0^+	-20.5806	0	0
2^+	-19.2290	1.3516	1.2791
4^+	-19.0140	1.5666	1.5761
6^+	-18.9100	1.6706	1.6913

By calculating standard deviation between theoretically and experimental values of excitation energies from the relation[12] $\Delta \bar{E} = \frac{\sum_i | E_{x_i} - E_{\exp_i .} |}{n}$

Where n is the number of excitation levels, we found the deviation between theoretically and experimental values for

$^{134}_{52}Te$ is $\Delta\bar{E} = 0.0257(MeV)$, and $\Delta\bar{E} = 0.3986(MeV)$ for $^{134}_{50}Sn$. When we comparing the value of standard deviation of our calculated excitation energies with the values of some previous studies calculated in different ways, we found that nucleus $^{134}_{52}Te$ shows good agreement with experimental values compared to these studies as shown in the table(3), while nucleus $^{134}_{50}Sn$ show good agreement with experimental values compared to ref.[15] but does not show good agreement compared to ref.[13] while it take the shell model configuration mixing in to calculation, this comparisons are shown in the table(4)

Table 3. Comparison of our standard deviation for $^{134}_{52}Te$ with values in previous studies

References	[14]	[13]	Present Work
$\Delta\bar{E}$	0.1334	0.1881	0.0257

Table 4. Comparison of our standard deviation for $^{134}_{50}Sn$ with values in previous studies

References	[15]	[15]	[13]	Present Work
$\Delta\bar{E}$	0.1613	0.1503	0.2751	0.3986

V. CONCLUSION

Shell model calculations were performed using the Modified Surface Delta Interaction with Matlab 2015 program for the Tellurium nucleus $^{134}_{52}Te$ and the Tin nucleus $^{134}_{50}Sn$, which have two valence nucleons located outside the closed core $^{132}_{50}Sn_{82}$ ‘ we were able to obtain the values of the Parity and total angular moments, which were agreement with the experimental values, and we also obtained the values of the energy levels and excitation energies for these two nuclei, after determining the value of the two constants potential by using the least square fitting method. When comparing the value of the standard deviation of our calculated excitation energies with some previous studies computed in different ways, we found that the value computed by us for a nucleus $^{134}_{52}Te$ is better than of these studies, but the value for a nucleus $^{134}_{50}Sn$ which computed in previous studies by different methods is better than our computed value. Therefore, we can say the calculated excitation energies begin to diverge from the experimental values after the magic number N = 82, due to increasing deformation of the closed core, which affects the values of the energy levels. So, it needs to be corrected, such as taking into account the excitation closed core and configuration mixing. This investigation increases the theoretical knowledge of all isotopes with respect to energy levels. Also, the shell model configuration mixing in this region by the MSDI interaction is very important.

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