Calculations of the Energy Levels and the Electric Quadrupole Transition Probabilities of the ^{148,150,152,154,156,158}Sm Isotopes Using IBA-1and IBA-2 Model

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Abstract:

The level scheme of the ^{148,150,152,154,156,158}Sm isotopes have been investigated using both IBA-1 and IBA-2 versions of Interacting Boson Model (IBM). IBA-1 and IBA-2 Hamiltonian parameters are obtained as well as the extraction of the energy levels. Also, the electric quadrupole transition probabilities B(E2; $J_i \rightarrow J_f$) of the Sm isotopes were calculated. In calculations, the theoretical energy levels and the electric quadrupole transition probabilities have been obtained by using PHINT code. Very good agreement was found from comparison between the calculated energy levels and the electric quadrupole transition probabilities B(E2) of the Sm isotopes with the experimental data.

الخلاصة:

مخطط مستويات الطاقة لنظائر السماريوم ^{148,150,152,154,156,158}Sm قدتحقق باستخدام كلا من الاصدارالاول والثاني (IBA-1 and IBA-2)لنموذج البوزونات المتفاعلة. تم الحصول على متغيرات الهاملتونين لنموذج البوزونات المتفاعل الاول والثاني بالاضافة الى استنباط مستويات الطاقة. كذلك حسبت احتمالية الانتقال الكهربائية الرباعي B(E2; $J_i \rightarrow J_f$). في هذه الحسابات , مستويات الطاقة واحتمالية الانتقال الكهربائية الرباعي حصل عليها باستخدام البرنامج PHINT. وجد تقارب جيدجدا من المقارنة بين النتائج النظرية لمستويات الطاقة واحتمالية الانتقال الكهربائية الرباعي(B(E2 لنظائر السماريوم مع القيم العملية .

INTRODUCTION:

The interacting boson approximation represents a significant step towards our understanding of nuclear structure. It offers a simple Hamiltonian, capable of describing collective nuclear properties across a wide range of nuclei, and is founded on rather general algebraic group theoretical techniques which have also recently found application to problems in atomic, molecular, and high-energy physics [1,2]. The applications of this model for the deformed nuclei are currently a subject of considerable interest and controversy [3].

Interacting boson model calculations of even-even Sm isotopes using both IBM1 and IBM2 versions have been performed many times [4-8] and were used to account for energy levels and electromagnetic properties of the deformed nuclei for different region in the nuclear chart. Special attention was paid to the effect of the partial sub-shell closure for Z = 64 [9, 10] and its inclusion into the calculations using an effective number of bosons.

In the previous studies, the shape transition in the Sm isotopes was studied in the framework of the s-d IBA model using the most general Hamiltonian. It is found that only three terms are necessary to reproduce the transition and obtain an excellent fit [11]. Effective boson numbers were introduced in 1BA-1 calculations to simulate the partial sub-shell closure effects at Z=64. The energy levels, wave functions and B(E2) values of Sm isotopes were calculated and compared with the experimental data. It was found that the agreement with the experimental data can be improved by introducing effective boson numbers in the calculations [12]. The interacting boson model had been used to calculate the isotope shift in $^{146-154}$Sm isotopes [13]. The E2 transition rates in Sm isotopes with neutron number N= 86-90 were studied in the frame of the $(sd)^{N_B-1}f$ interacting boson model [14]. A truncation scheme of interaction boson model 2 with an F-spin value equal to F_{max} and F_{max}-1 was suggested [15]. Wave functions with definite F-spin values were constructed. The boson coefficients of fractional parentage with F spin were calculated by a group theoretical method. The model was applied to calculate the energy levels, B(E2) values, and B(M1) values of the Sm isotopes. It was found that the energy levels including the lowest 1^+ state can be reproduced quite well. The B(E2) and B(M1) values can be produced reasonably well. The low-lying decay scheme of ^{150}Sm was studied through the (n, γ) reaction. Precise energy level as well as lifetimes measured with the gamma-ray induced Doppler technique provides important structural information of this nucleus. A comparison with the predictions of interacting boson model calculations confirm that this nucleus in near to the phase transitions between spherical and quadrupole axial symmetry shapes, lying just before the critical point on the spherical side of the shape transitions [16].

In this work, the energy levels of the Sm isotopes were calculated. Sm isotopes have proton boson number N_π =6 (Z=62) and neutron boson numbers N_υ = 2, 3,4,5,6 and 7, (N=86-96). In addition, the electromagnetic transition probabilities have been also calculated (B(E2)).

THEORITICAL

The IBA [17, 18] provides a unified description of collective nuclear states in terms of a system of interacting bosons.

1-The Interacting boson Approximation Model-1 (IBA-1)

The IBA-1 Hamiltonian which used to describe the ^{148,150,152,154,156,158} Sm nuclei in this study has the standard form as given in Ref.[17]. The calculations were done using the computer codes PHINT for energy levels and BEFM for B(E2) values [19]. To obtain the values of the parameters which provides the best fit, it is necessary to calculate for each energy level the difference between the experimental and calculated values. It is taking in the account the sum over the squares of all these differences to find the local minimum for this summation. The least square fit procedure was used to find the best fit to the three lowest bands (ground state and γ-state bands) of the Sm isotopes under consideration. In terms of s- and d-boson operators the most general IBA Hamiltonian can be expressed as [20]

$$\begin{aligned} H_B = & \mathrm{EPS} n_d + \frac{1}{2}\mathrm{ELL}(\mathbf{L}\cdot\mathbf{L}) + \frac{1}{2}\mathrm{QQ}(\mathbf{Q}\cdot\mathbf{Q}) \\ & -5\sqrt{7}\mathrm{OCT}[(d^+\tilde{d})^{(3)}x(d^+\tilde{d})^{(3)}]_0^{(0)} \\ & +15\mathrm{HEX}[(d^+\tilde{d})^{(4)}x(d^+\tilde{d})^{(4)}]_0^{(0)}, \end{aligned} \quad (1)$$

where

$$\mathbf{L}\cdot\mathbf{L} = -10\sqrt{3}[(d^+\tilde{d})^{(1)}x(d^+\tilde{d})^{(1)}]_0^{(0)} \quad (2)$$

and

$$\begin{aligned} \mathbf{Q}\cdot\mathbf{Q} = \sqrt{5}\Bigg[& \left\{(s^+\tilde{d}+d^+s)^{(2)} + \frac{\mathrm{CHQ}}{\sqrt{5}}(d^+\tilde{d})^{(2)}\right\} x \\ & \times \left\{(s^+\tilde{d}+d^+s)^{(2)} + \frac{\mathrm{CHQ}}{\sqrt{5}}(d^+\tilde{d})^{(2)}\right\}\Bigg]_0^{(0)}. \end{aligned} \quad (3)$$

Values of the interaction parameters in the IBA-1 Hamiltonian (in terms of code PHINT notation EPS, ELL, QQ, OCT and HEX) which provides the best fit to the experimental data are in MeV and are given in Table 1.

A successful nuclear model must yield a good description not only of the energy spectrum of the nucleus but also of its electromagnetic properties. The most important electromagnetic features are the E2 transitions. The B(E2*)* values were calculated using the E2 operator. The E2 transition operator must be a Hermitian tensor of rank two and therefore the number of bosons must be conserved. With these constraints the general E2 operator can be written as:

$$B(E2;\ J_i \rightarrow J_f) = \frac{1}{2J_i+1}|(J_f||T(E2)||J_i)|^2. \tag{4}$$

2-The Interacting Boson Approximation Model-2 (IBA-2)

In the first version of the interacting boson model (IBA-1) [21], no distinction is made between proton and neutron variables while describing triaxiality explicitly. This can be done by introducing the cubic terms in the boson operators [24, 25]. In contrast to the recent work of [26, 27] that showed that triaxiality also occurs in particular dynamic symmetries of the IBA-2 which is distinguish between protons and neutrons.

According to [28], IBA Hamiltonian takes on different forms, depending on the regions (SU (5), SU (3) and O (6)) of the traditional IBA triangle. The consider Hamiltonian is in the form [24, 29]:

$$H \ = \ H_{sd} + \Sigma\theta_L[d^+d^+d^+]^{(L)}[d^{\sim}d^{\sim}d^{\sim}]^{(L)}, \tag{5}$$

where H_{sd} is the standard Hamiltonian of the IBA [30,31],

$$H_{sd} \ = \ \in_d\eta_d + \kappa\mathbf{Q}\cdot\mathbf{Q} + \kappa'\mathbf{L}\cdot\mathbf{L} + \kappa\mathbf{P}^+\cdot\mathbf{P} + q_3\mathbf{T}_3\cdot\mathbf{T}_3 + q_4\mathbf{T}_4\cdot\mathbf{T}_4. \tag{6}$$

In the Hamiltonian, $\in_d\eta_d$ and $\mathbf{P}^+\cdot\mathbf{P}$ terms produce the characteristics of U(5) and O(6) structures, respectively. Therefore, the Hamiltonian is a mixture of the U (5) and SO (6) chains, but not diagonal in any of the IBA chains. In the IBA–2 model the “neutrons” and “protons” degrees of freedom are taken into account explicitly. Thus the Hamiltonian [32] can be written as

$$H = \varepsilon_v n_{dv} + \varepsilon_\pi n_{d\pi} + \kappa\mathbf{Q}_\pi\cdot\mathbf{Q}_v + V_{\pi\pi} + V_{vv} + M_{\pi v}, \tag{7}$$

where $n_{d\nu(\pi)}$ is the neutron(proton) d-boson number operator.

$$n_{d\rho} = d^+d^{\sim},\ \rho = v,\ \pi$$
$$d^{\sim}_{\rho m} = (-1)^m d_{\rho-m} \tag{8}$$

The rest of the operators in equation (7) are defined as

$$Q_\rho \ = \left(s^+_\rho d^{\sim}_\rho + d^+_\rho s_\rho\right) + \chi_\rho\left(d^+_\rho d^{\sim}_\rho\right)$$
$$V_{\rho\rho} = \sum_{L=0,2,4} C_{L\rho}\left(\left(d^+_\rho d^+_\rho\right)^{(L)}\ \left(d^+_\rho d^{\sim}_\rho\right)^{(L)}\right)^{(0)} \ ;\rho = \nu,\ \pi \tag{9}$$

where $s^+_\rho,\ d^+_{\rho m}$ and $s_\rho,\ d_{\rho m}$ represent the s- and d-boson creation and annihilation operators.
and

$$M_{\pi\nu};\sum_{L=1,3}\xi_L\left(d_\nu^+ d_\pi^+\right)^{(L)}\left(d_\nu d_\pi\right)^{(L)}+\xi_2\left(s_\nu d_\pi^\sim - s_\pi d_\nu^\sim\right)^{(2)}\cdot\left(s_\nu^+ d_\pi^+ - s_\pi^+ d_\nu^+\right)^{(2)}. \quad (10)$$

In the present case, $M_{\pi\nu}$ affects only the position of the non-fully symmetric states relative to the symmetric states. For this reason $M_{\pi\nu}$ is often referred to as the Majorana force [32].
The selection rules of choice for the total angular momentum is given as

$$|J_i - J_f| \le L\gamma \le |J_i + J_f| \quad (11)$$

Values of the interaction parameters in the IBA-2 Hamiltonian which provides the best fit to the experimental data are given in Table 2.

RESULTS and CONCLUSIONS

The $^{148-158}$Sm isotopes have proton boson number=6 (relative to Z = 50) and neutron boson number varies from 2 to 7 (relative to N = 82), the parameters which used in IBA-1 and IBA-2 shows in Table 1 and 2, respectively. This parameter is extremely important because it is related to the nuclear shape (prolate or oblate). The behaviors of the corresponding IBA-2 parameters depending on the neutron number are shown in figure 1. The energy levels which are fitted by these parameters (IBA-1 and IBA-2) shown in figure 2. Table 3 shows the comparison of estimated and experimental energy levels for $^{148-158}$Sm. As can be seen, the agreement between experiment and theory is quite good and the general features are reproduced well. In the figure 3, comparison between the measured and the calculated energies of 5 levels of $_{62}$Sm are shown for even numbers of neutrons. This figure shows that the calculated energies (solid line) in agreement with experimental data (dot symbol) over all neutron number. Figure 4 shows comparison between $\boldsymbol{E_{J^\pi_1}/E_{2^+_1}}$($\boldsymbol{J^\pi}$**=4$^+$, 6$^+$** and **8$^+$**) measured (dot symbol) and calculated (solid lines) energies of $_{62}$Sm for even numbers of neutrons. The compression between the calculations and the experimental data at the low neutron number is in disagreement.

The calculations of the electromagnetic transitions provide a good test of the nuclear structural model wave functions [33]. The proton and the neutron effective charges were determined by normalizing to the experimental values for B(E2; $2_1^+ \to 0_1^+$), B(E2; $0_2^+ \to 2_1^+$), B(E2; $4_1^+ \to 2_1^+$), B(E2; $2_2^+ \to 2_1^+$) and B(E2; $2_2^+ \to 0_1^+$). The effective charges e_π and e_υ are needed for the electric quadrupole transition operator. The E2 transition operator employed in this study is defined as [33, 34]

$$T(E2) = e_\pi Q_\pi + e_\nu Q_\nu \quad (12)$$

where Q_π and Q_υ are quadrupole operators. Boson effective charges have been fitted to determine the best computational B(E2) transition values. After determining the values of boson effective charges, values of B(E2; $2_1^+ \to 0_1^+$), B(E2; $0_2^+ \to 2_1^+$), B(E2; $4_1^+ \to 2_1^+$), B(E2; $2_2^+ \to 2_1^+$) and B(E2; $2_2^+ \to 0_1^+$) have been calculated using the code PCIBAEM. The calculated B(E2) values for ^{148,150,152,154}Sm isotopes are compared with experimental data as shown in Table 4.

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Table-1: IBA-1 parameters. All parameters are in MeV except N and CHQ.

Isotope	N	EPS	ELL	QQ	CHQ	OCT	HEX
^{148}Sm	8	0.8	-0.0008	-0.0364	0.3353	0.0044	0.0074
^{150}Sm	9	0.64	0.0004	-0.0420	-0.7267	0.0039	0.0065
^{152}Sm	10	0.35	0.0013	-0.0459	-0.6149	-0.0002	0.0003
^{154}Sm	11	0.3	0.0015	-0.0045	-0.6708	-0.0018	0.003
^{156}Sm	12	0.28	0.0015	-0.0436	-0.6708	-0.0021	0.0035
^{158}Sm	13	0.26	0.0015	-0.0431	-0.7267	-0.0018	0.003

Table-2: IBA-2 parameters. All parameters are in MeV except NN, CHN and CHP.

Isotope	NN	ED	RKAP	CHN	CHP	CLN	CLP
^{148}Sm	2	0.80	-0.085	-1.00	0.3	0.0	0.0
^{150}Sm	3	0.64	-0.084	-0.95	0.3	-0.8	-0.3
^{152}Sm	4	0.35	-0.083	-0.90	0.3	0.0	-0.05
^{154}Sm	5	0.30	-0.082	-0.90	0.3	0.3	0.0
^{156}Sm	6	0.28	-0.080	-0.90	0.3	0.3	0.0
^{158}Sm	7	0.26	-0.080	-0.95	0.3	0.2	0.0

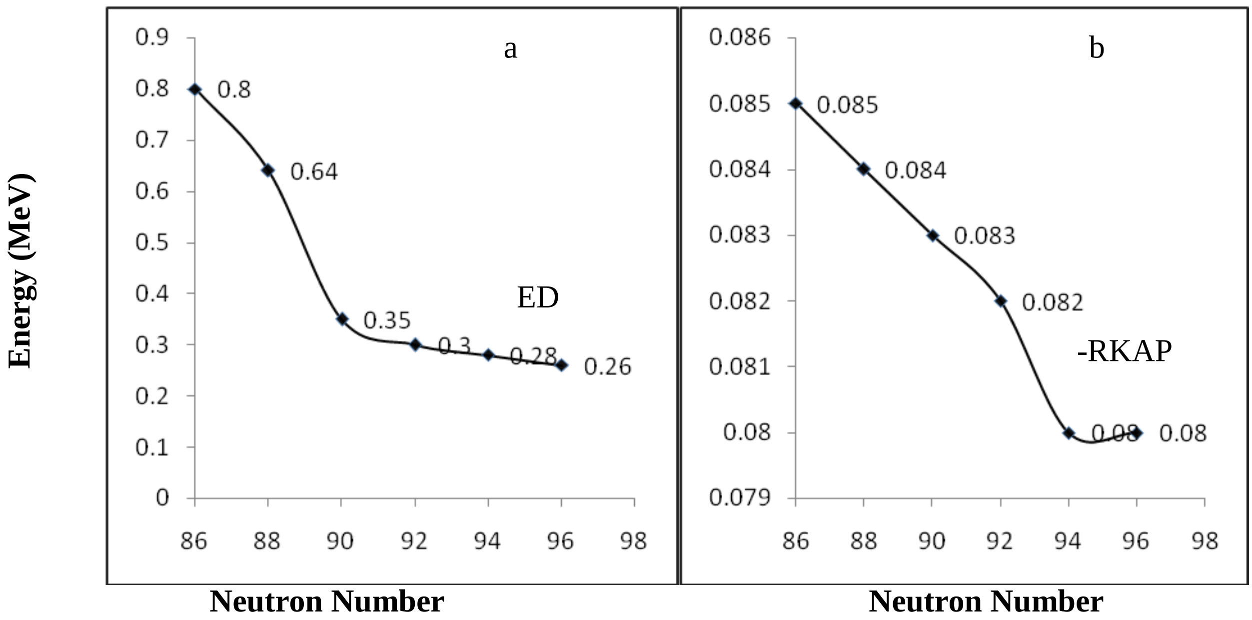

Figure 1: The behavior of the corresponding IBA-2 parameters depending on the neutron number.

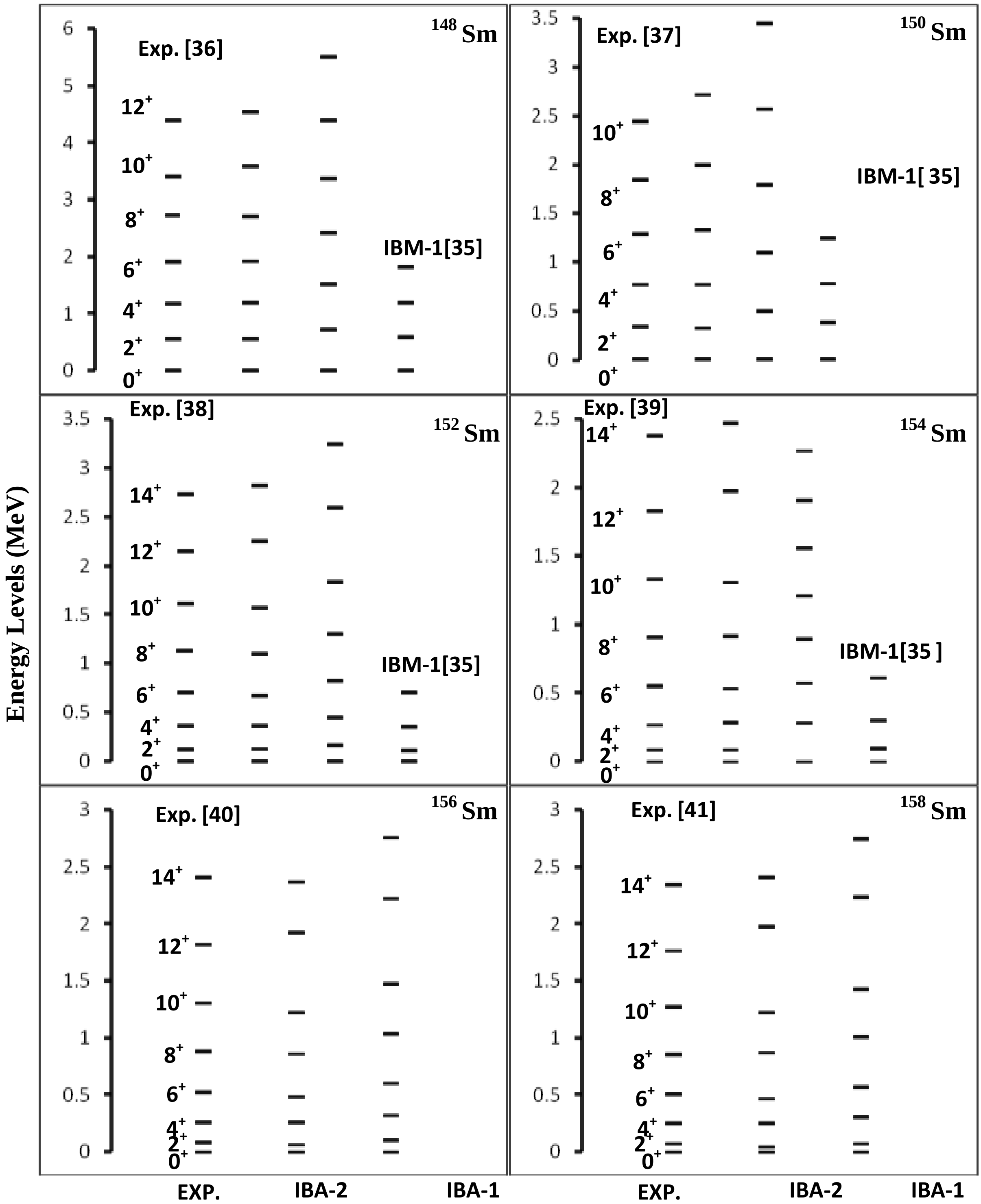

Figure-2: The calculated energy levels using both IBA-1 and IBA-2 (ground band) of the Sm isotopes as well as the experimental data[36-41].

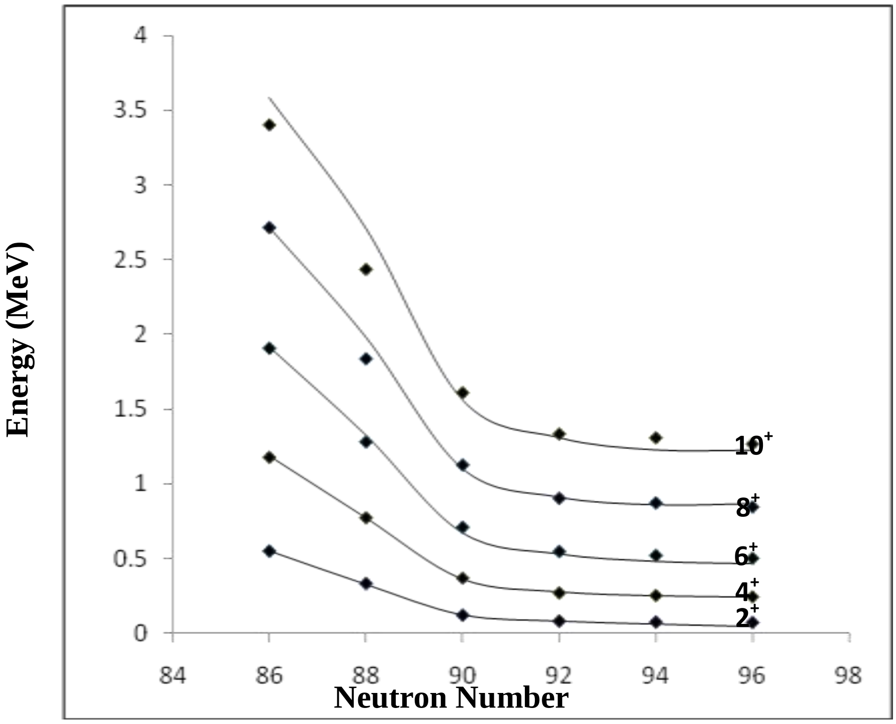

Figure-3: Comparison between measured [36-41] and calculated energies of 5 levels of $_{62}Sm$ with even number of neutrons.

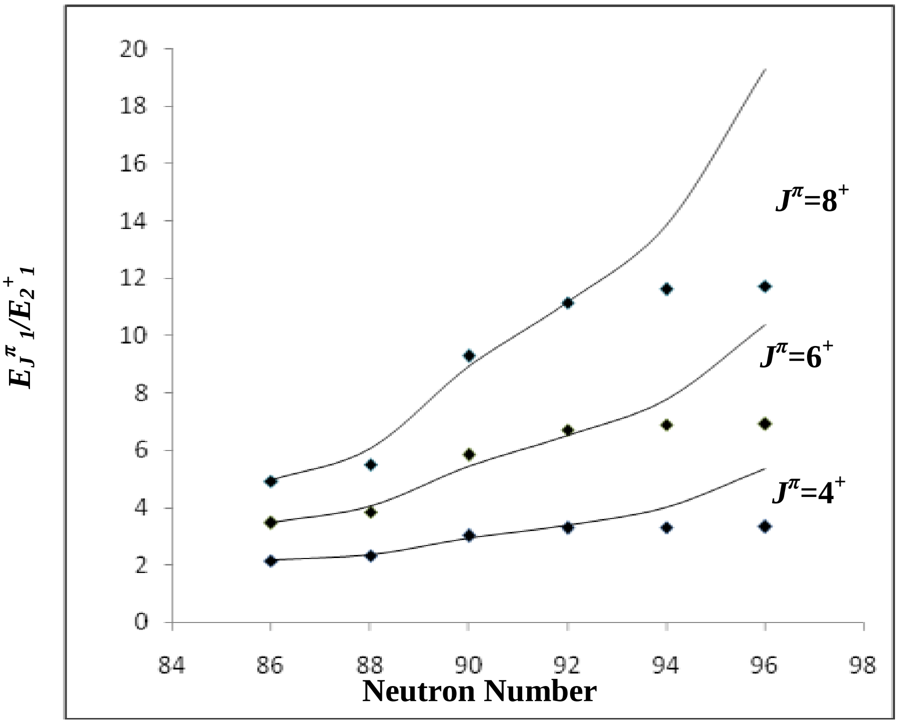

Figure-4: Comparison between $E_J^{\pi}{}_1/E_2^+{}_1$($J^{\pi}=4^+$, 6^+ and 8^+) measured (dot symbol) [36-41] and calculated (solid lines) energies of $_{62}Sm$ with even number of neutrons.

Table -3: The comparison of estimated and experimental energy levels for $^{148-158}$Sm.

Isotope	Spin Parity (I^{π})	IBA-2 (MeV)	Experiment (MeV)
^{148}Sm	0^+_1	0.000	0.0[36]
	2^+_1	0.549	0.550
	4^+_1	1.190	1.180
	6^+_1	1.914	1.905
	8^+_1	2.716	2.714
	10^+_1	3.587	3.398
	12^+_1	4.541	4.401
	0^+_2	1.093	
	2^+_2	1.194	
	4^+_2	1.918	
	6^+_2	2.719	
	8^+_2	3.590	
^{150}Sm	0^+_1	0.000	0.0[37]
	2^+_1	0.326	0.333
	4^+_1	0.774	0.773
	6^+_1	1.325	1.278
	8^+_1	1.984	1.836
	10^+_1	2.714	2.433
	0^+_2	0.831	
	2^+_2	0.821	
	4^+_2	1.371	
	6^+_2	2.021	
	8^+_2	2.740	
^{152}Sm	0^+_1	0.000	0.0[38]
	2^+_1	0.123	0.121
	4^+_1	0.362	0.366
	6^+_1	0.673	0.706
	8^+_1	1.104	1.125
	10^+_1	1.564	1.609
	12^+_1	2.250	2.148
	14^+_1	2.817	2.736
	0^+_2	0.728	0.684
	2^+_2	0.493	0.810
	4^+_2	0.790	1.022
	6^+_2	1.193	1.310
	8^+_2	1.633	1.666

Table -3: Continued.

Isotope	Spin Parity (I^{π})	This Work (MeV)	Experiment (MeV)
^{154}Sm	0^+_1	0.000	0.0[39]
	2^+_1	0.081	0.081
	4^+_1	0.277	0.266
	6^+_1	0.531	0.544
	8^+_1	0.912	0.902
	10^+_1	1.309	1.333
	12^+_1	1.969	1.825
	14^+_1	2.467	2.373
	0^+_2	0.679	1.099
	2^+_2	0.474	1.177
	4^+_2	0.712	1.337
	6^+_2	1.047	1.677
^{156}Sm	0^+_1	0.000	0.0[40]
	2^+_1	0.062	0.075
	4^+_1	0.250	0.249
	6^+_1	0.482	0.517
	8^+_1	0.860	0.871
	10^+_1	1.226	1.307
	12^+_1	1.915	1.819
	14^+_1	2.369	2.400
	0^+_2	0.681	
	2^+_2	0.482	
	4^+_2	0.696	
	6^+_2	1.010	
^{158}Sm	0^+_1	0.000	0.0[41]
	2^+_1	0.045	0.072
	4^+_1	0.241	0.240
	6^+_1	0.466	0.498
	8^+_1	0.867	0.844
	10^+_1	1.224	1.266
	12^+_1	1.971	1.765
	14^+_1	2.400	2.334
	0^+_2	0.749	
	2^+_2	0.540	
	4^+_2	0.744	
	6^+_2	1.045	

Table -4: The calculated and experimental B(E2) values for $^{148-154}Sm$. The experimental data are adopted from Ref. [15].

Isotope	Transition	B(E2) $(eb)^2$	
		Exp.	IBA
^{148}Sm	$2_1^+ \to 0_1^+$	$1.52x10^{-1}$	0.1495
	$4_1^+ \to 2_1^+$	$2.46x10^{-1}$	0.2633
	$2_2^+ \to 2_1^+$	$3.53x10^{-2}$	0.0222
	$2_2^+ \to 0_1^+$	$7.91x10^{-3}$	0.0067
^{150}Sm	$2_1^+ \to 0_1^+$	$2.64\ x10^{-1}$	0.2812
	$0_2^+ \to 2_1^+$	$2.58\ x10^{-1}$	0.3330
	$4_1^+ \to 2_1^+$	$5.31\ x10^{-1}$	0.6003
	$2_2^+ \to 4_1^+$	$5.23\ x10^{-1}$	0.3751
	$2_2^+ \to 0_1^+$	$3.88\ x10^{-3}$	0.0003
	$2_2^+ \to 0_2^+$	$5.23\ x10^{-1}$	0.4855
	$2_3^+ \to 4_1^+$	$4.40\ x10^{-2}$	0.00298
^{152}Sm	$2_1^+ \to 0_1^+$	$6.89\ x10^{-1}$	0.8067
	$4_1^+ \to 2_1^+$	1.00	1.2059
	$0_2^+ \to 2_1^+$	$1.57\ x10^{-1}$	0.0473
	$2_2^+ \to 4_1^+$	$9.60\ x10^{-2}$	0.0921
	$2_2^+ \to 0_1^+$	$4.81\ x10^{-3}$	0.0009
	$4_2^+ \to 2_2^+$	1.46	1.3500
	$4_2^+ \to 2_1^+$	$4.82\ x10^{-3}$	0.0244
	$2_3^+ \to 4_1^+$	$3.78\ x10^{-3}$	0.0065
^{154}Sm	$2_1^+ \to 0_1^+$	$8.56\ x10^{-1}$	0.8996
	$4_1^+ \to 2_1^+$	1.20	1.2500
	$2_2^+ \to 4_1^+$	$2.11\ x10^{-2}$	0.0600
	$2_2^+ \to 0_1^+$	$4.67\ x10^{-3}$	0.0007
	$2_3^+ \to 4_1^+$	$7.35\ x10^{-3}$	0.0013
	$2_3^+ \to 0_1^+$	$1.42\ x10^{-2}$	0.0086