Calculation of Energy Levels and B (E2) for $^{46\text{-}45}$Ca, $^{46\text{-}45}$Sc and $^{46\text{-}45}$Ti by Using Nuclear Shell Model Code OXBASH

Ali Khalaf Hasan and Rasool Mohammed Kareem

Department of physics, Faculty of Education for Girls, University of Kufa, Najaf, Iraq.
www.rmk19861113@yahoo.com

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Abstract: In this paper, the energy levels for $^{46\text{-}45}$Ca,$^{46\text{-}45}$Ti and $^{46\text{-}45}$Sc isotopes have been calculated. Calculations were carried out in the f7-shell region by employing the effective interactions, f748pn and using the shell model code OXBASH for windows by applying spin-parity of valance nucleons. It is found that there is good convergence of energy levels values with the standard practical value.

Key words: Energy levels, OXBASH Code and gamma transitions.

1. Introduction

The aim of this paper is study of the energy levels of $^{46\text{-}45}$Ca,$^{46\text{-}45}$Ti and $^{46\text{-}45}$Sc isotopes by using OXBASH code for windows. This program is a set of codes carrying out shell-model calculations with dimensions up to about 50,000 in the J-T scheme and about 2,000,000 in the M-scheme. Oxbash comes with a library of model spaces and interactions [1, 2].

Applied the shell model and use a Modified Brown and Shirr (f748pn) interaction for neutron and proton orbits in $^{46\text{-}45}$Ca,$^{46\text{-}45}$Ti and $^{46\text{-}45}$Sc to calculate the energy levels values. Various observables can be predicted accurately and systematically in terms of the nuclear shell model. For light nuclei, there are several "standard" effective interactions such as the Cohen-Kurath [3] and the USD [4] interactions for the *p* and *sd* shells, respectively. On the other hand, in the next major shell, *i.e.*, in the f7-shell, there are also "standard" interaction such as f748pn [5].The spectroscopy of nuclei, in the f7-shell region, has been well described within the shell model framework. The best example for using several model spaces and two-body interactions is that of Brown et al, which is the most remarkable work in this field [6,7]. The starting point in all such shell-model calculations is the derivation of an effective interaction owing to the fact that the f7-shell is the most important for a variety of problems in nuclear structure such as electron capture in supernova explosions. In this work, the shell model calculations are carried out in the f7-shell region for the isotopes $^{46\text{-}45}$Ca,$^{46\text{-}45}$Ti and $^{46\text{-}45}$Sc, to test the ability of the present effective interactions in reproducing the experiment in this mass region.

2. Shell Model Calculations

The calculations have been carried out in the nuclear shell model f7 using the code OXBASH for windows [6]. The code uses an m-scheme Slater determinant basis. With a projection technique, there are been constructed wave functions with good angular momentum J and isospin T. The f7pn model space is comprised of (1f7/2) below the closed N = Z=20 shell [8]. One can find the calculated results of states of the odd A and even A nuclei, number of protons, i.e., 20 to the $^{46\text{-}45}$Ca, with neutron numbers (25 , 26) , number of protons, 21 to the $^{46\text{-}45}$Sc, with neutron numbers (24 , 25) and number of protons, 22 to the $^{46\text{-}45}$Ti, with neutron numbers (23 , 24) energy levels value.

2.1. Energy Levels Calculations

The calculations have been carried out using the code OXBASH for windows [9]. In the f7 model space comprised of the 0f7/2 valence orbits outside the ^{40}Ca. Two effective interactions have been employed with f7 model space for the calculations of level spectra, these effective interaction is f748pn [5]. It is worth mentioning that ^{45}Ca and ^{46}Ca have Isospin part (T = 2.5 and 3) respectively, ^{45}Sc and ^{46}Sc have Isospin part (T = 1.5 and 2) respectively, while ^{45}Ti and ^{46}Ti have Isospin part (T = 0.5 and 1) respectively.

The energy levels values for ^{45}Ca nucleus, the energy levels values are shown in table 1. these values are agreement with the experimental values, and new energy levels have been reached.

Table 1 shows a comparison of the energy levels values with respect to the ground state were calculated from f748pn effective interactions with experimental excitation energies of ^{45}Ca

Exp .Res[10]		**F748pn**	J^{π}
J^{π}	Energy elevels		
$7/2^-$	0.000	0.000	$7/2_1^-$
$5/2^-$	0.174	0.151	$5/2_1^-$
$3/2^-$	1.434	1.221	$3/2_1^-$
----------	1.584	1.616	$11/2_1^-$
----------	1.94	1.927	$9/2_1^-$
----------	2.953	2.936	$15/2_1^-$

The energy levels values for ^{46}Ca nucleus from f748pn effective interaction is shown in table 2 and these effective interactions give good results in comparison with the experimental values.

Table 2 shows a comparison of the energy levels values with respect to the ground state were calculated from f748pn effective interactions with experimental excitation energies of ^{46}Ca

Exp .Res[11]		**F748pn**	J^{π}
J^{π}	Energy elevels		
0^+	0.000	0.000	0_1^+
2^+	1.346	1.346	2_1^+
4^+	2.574	2.575	4_1^+
6^+	2.973	2.974	6_1^+

The energy levels values for ^{45}Sc nucleus from f748pn effective interaction is shown in table 3 and these effective interaction results reasonably consistent with experimental data. The total angular momentum and parity are ($7/2_1^-$, $11/2_1^-$, $9/2_1^-$, $15/2_1^-$, $7/2_3^+$, $5/2_2^-$, $9/2_3^-$, $19/2_1^-$, $23/2_1^-$, $7/2_7^-$) respectively, confirmation of which is ($7/2^-$, $15/2^-$, $21/2^-$, $5/2^-$) as well as confirmation of momentum only, which is ($1/2$, $3/2$, $9/2$, $5/2$, $3/2$) respectively, and new energy levels have been reached.

Table 3 shows a comparison of the energy levels values with respect to the ground state were calculated from f748pn effective interactions with experimental excitation energies of ^{45}Sc

Exp .Res[10]		**F748pn**	J^{π}
J^{π}	Energy elevels		
$7/2^-$	0.000	0.000	$7/2_1^-$
$11/2^-$	1.236	1.268	$11/2_1^-$

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$9/2^-$	1.662	1.436	$9/2^-_1$
----------	1.716	1.707	$3/2^-_1$
----------	1.900	1.883	$5/2^-_1$
$15/2^-$	2.090	1.969	$15/2^-_1$
(1/2,3/2,5/2)	2.151	2.298	$1/2^-_1$
----------	2.152	2.416	$13/2^-_1$
$(7/2^-)$	2.341	2.461	$7/2^-_2$
$(1/2^+,3/2,5/2)$	2.531	2.490	$3/2^-_2$
----------	2.700	2.730	$11/2^-_2$
$(9/2^+,11/2^-)$	2.960	2.838	$9/2^-_2$
$5/2^-,7/2^-$	2.747	2.920	$7/2^-_3$
$1/2^+,3/2,5/2$	3.092	2.958	$5/2^-_2$
$5/2^-,7/2^-,9/2^-$	3.136	3.171	$9/2^-_3$
----------	3.198	3.181	$17/2^-_1$
----------	3.224	3.280	$13/2^-_2$
$(15/2^-)$	3.363	3.307	$15/2^-_2$
+	3.443	3.424	$11/2^-_3$
$19/2^-$	3.692	3.556	$19/2^-_1$
----------	3.722	3.691	$15/2^-_3$
----------	4.129	4.131	$9/2^-_4$
----------	4.178	4.190	$7/2^-_4$
----------	4.244	4.220	$5/2^-_3$
----------	4.307	4.260	$11/2^-_4$
----------	4.424	4.343	$13/2^-_3$
----------	4.464	4.448	$5/2^-_4$
----------	4.546	4.526	$17/2^-_2$
$(1/2,3/2)$	4.662	4.565	$3/2^-_3$
----------	4.713	4.631	$11/2^-_5$
----------	4.713	4.667	$7/2^-_5$
----------	4.774	4.759	$13/2^-_4$
----------	4.801	4.792	$1/2^-_2$
----------	5.219	5.206	$15/2^-_4$
----------	5.261	5.272	$3/2^-_4$
----------	5.374	5.313	$9/2^-_5$
----------	5.374	5.402	$5/2^-_5$
$23/2^-$	5.418	5.563	$23/2^-_1$
$(21/2^-)$	5.710	5.672	$21/2^-_1$
----------	5.774	5.674	$7/2^-_6$
----------	5.834	5.843	$19/2^-_2$
----------	6.244	6.239	$11/2^-_6$
----------	6.332	6.347	$9/2^-_6$
$5/2^-,7/2^-,9/2^-$	6.551	6.419	$7/2^-_7$
----------	6.609	6.510	$17/2^-_3$
$(5/2^-,7/2^-,9/2^-)$	6.667	6.653	$5/2^-_6$
----------	----------	6.757	$13/2^-_5$
----------	7.696	7.618	$3/2^-_5$

----------	8.118	7.973	$11/2^-_7$
----------	8.305	8.250	$9/2^-_7$
----------	9.164	9.085	$15/2^-_5$

For ^{46}Sc nucleus the energy levels calculations from f748pn effective interaction is shown in table 4. The effective interactions give results reasonably consistent with experimental data. The total angular momentum and parity are ($3^+_1, 5^+_1, 2^+_1, 5^+_2, 4^+_1$, 7^+_1, 3^+_4, 1^+_2, 4^+_4, 0^+_1) respectively, confirmation of which is (2^+, 4^+) respectively, as well as confirmation of momentum only is (3, 3) respectively, and new energy levels have been reached.

Table 4 shows a comparison of the energy levels values with respect to the ground state were calculated from f748pn effective interactions with experimental excitation energies of ^{46}Sc

Exp .Res[11]		F748pn	J^π
J^π	Energy elevels		
6+	0.520	0.000	6^+_1
4+	0.000	0.122	4^+_1
3+	0.227	0.214	3^+_1
5+	0.280	0.238	5^+_1
2+	0.444	0.497	2^+_1
5+	0.774	0.814	5^+_2
4+	0.835	0.909	4^+_2
7+	0.978	0.979	7^+_1
----------	1.298	1.473	1^+_1
3+,4+,(2+)	1.427	1.556	2^+_2
----------	1.676	1.671	8^+_1
----------	1.825	1.894	6^+_2
(3)+	2.070	2.045	3^+_2
----------	2.084	2.109	5^+_3
----------	2.395	2.406	7^+_2
(4+,5+)	2.431	2.409	4^+_3
----------	2.486	2.472	9^+_1
----------	2.534	2.583	2^+_3
3+,4+	2.568	2.596	3^+_3
3+	2.705	2.748	3^+_4
1+	2.815	2.770	1^+_2
----------	2.890	2.888	5^+_4
----------	3.081	3.082	8^+_2
----------	3.081	3.102	6^+_3
4+	3.176	3.169	4^+_4
----------	3.338	3.351	7^+_3
----------	3.381	3.355	1^+_3
----------	3.813	3.813	9^+_2
----------	3.868	3.823	6^+_4
----------	3.937	3.915	10^+_1
----------	3.945	3.934	2^+_4
----------	3.961	3.967	8^+_3
----------	4.039	4.050	5^+_5
----------	4.200	4.197	11^+_1
----------	4.447	4.459	3^+_5

----------	4.846	4.840	7^+_4
----------	4.972	4.995	4^+_5
0+	5.022	5.004	0^+_1
----------	5.327	5.331	5^+_6
----------	6.362	6.354	2^+_5
----------	----------	7.470	4^+_6
----------	----------	7.808	6^+_5

The energy levels values for ^{45}Ti nucleus from f748pn effective interaction is shown in table 5 and these effective interaction results reasonably consistent with experimental data. The total angular momentum and parity are ($9/2^-_1$, $11/2^-_1, 7/2^-_2, 15/2^-_1, 17/2^+_1$, $5/2^-_2$, $23/2^-_1$, $27/2^-_1$) respectively, confirmation of which is ($3/2^-$) as well as confirmation of momentum only, which is ($3/2$, $11/2$, $13/2$, $7/2$, $17/2$) respectively, and new energy levels have been reached.

Table 5 shows a comparison of the energy levels values with respect to the ground state were calculated from f748pn effective interactions with experimental excitation energies of ^{45}Ti

Exp .Res[10]		**F748pn**	J^{π}
J^{π}	Energy elevels		
$5/2^-$	0.039	0.000	$5/2^-_1$
$7/2^-$	0.000	0.210	$7/2^-_1$
$9/2^-$	1.353	1.411	$9/2^-_1$
$11/2^-$	1.466	1.490	$11/2^-_1$
$(1/2^-\ TO\ 7/2^-)$	1.799	1.729	$3/2^-_1$
3/2 TO 11/2	2.432	2.477	$3/2^-_2$
$5/2^-, 7/2^-$	2.500	2.544	$7/2^-_2$
----------	----------	2.927	$5/2^-_2$
$15/2^-$	3.015	2.990	$15/2^-_1$
----------	3.200	3.299	$1/2^-_1$
-----------	3.200	3.310	$13/2^-_1$
----------	3.200	3.334	$7/2^-_3$
----------	3.200	3.341	$9/2^-_2$
$17/2^-$	3.601	3.383	$17/2^-_1$
----------	----------	3.765	$9/2^-_3$
(11/2 TO 15/2)	3.937	3.856	$11/2^-_2$
----------	----------	3.892	$19/2^-_1$
----------	----------	3.911	$5/2^-_3$
(11/2 TO 15/2)	3.937	4.000	$13/2^-_2$
----------	----------	4.045	$7/2^-_4$
(7/2)-	4.723	4.319	$7/2^-_5$
----------	-----------	4.351	$11/2^-_3$
----------	----------	4.650	$15/2^-_2$
----------	----------	4.818	$9/2^-_4$
----------	----------	4.844	$11/2^-_4$
(17/2+)	5.239	5.114	$17/2^-_2$
----------	5.540	5.120	$5/2^-_4$
----------	5.540	5.163	$15/2^-_3$
----------	5.540	5.167	$11/2^-_5$
----------	5.540	5.167	$9/2^-_5$
----------	5.540	5.190	$13/2^-_3$

----------	5.540	5.234	$3/2^-_3$
----------	5.540	5.365	$19/2^-_2$
----------	5.540	5.465	$7/2^-_6$
----------	5.540	5.494	$5/2^-_5$
----------	5.540	5.503	$13/2^-_4$
----------	5.540	5.580	$11/2^-_6$
----------	5.540	5.626	$9/2^-_6$
----------	5.540	5.708	$1/2^-_2$
----------	5.540	5.766	$21/2^-_1$
----------	5.540	5.770	$3/2^-_4$
----------	5.540	5.784	$7/2^-_7$
$23/2^-$	6.163	5.814	$23/2^-_1$
----------	----------	5.974	$5/2^-_6$
----------	----------	6.064	$1/2^-_3$
----------	----------	6.071	$15/2^-_4$
----------	----------	6.141	$3/2^-_5$
----------	----------	6.143	$13/2^-_5$
----------	----------	6.160	$17/2^-_3$
----------	----------	6.179	$9/2^-_7$
----------	----------	6.195	$11/2^-_7$
----------	----------	6.211	$15/2^-_5$
----------	----------	6.216	$7/2^-_8$
----------	----------	6.295	$17/2^-_4$
----------	----------	6.344	$13/2^-_6$
----------	----------	6.371	$9/2^-_8$
----------	----------	6.405	$5/2^-_7$
----------	----------	6.457	$3/2^-_6$
----------	----------	6.536	$13/2^-_7$
----------	----------	6.657	$11/2^-_8$
----------	----------	6.668	$15/2^-_6$
----------	----------	6.677	$7/2^-_9$
----------	----------	6.689	$13/2^-_8$
----------	----------	6.725	$9/2^-_8$
----------	----------	6.789	$19/2^-_3$
----------	----------	6.843	$7/2^-_{10}$
----------	----------	6.857	$15/2^-_7$
----------	----------	6.937	$11/2^-_9$
$27/2^-$	7.143	6.881	$27/2^-_1$
----------	----------	6.956	$5/2^-_8$
----------	----------	6.977	$21/2^-_2$
----------	----------	7.047	$11/2^-_{10}$
----------	----------	7.126	$17/2^-_5$
----------	----------	7.187	$9/2^-_9$
----------	----------	7.403	$17/2^-_6$
----------	----------	7.404	$19/2^-_4$
----------	----------	7.432	$15/2^-_8$
----------	----------	7.441	$13/2^-_9$

----------	----------	7.505	$13/2^-_{10}$
----------	7.830	7.543	$23/2^-_2$
----------	7.830	7.588	$15/2^-_9$
----------	7.830	7.703	$3/2^-_7$
----------	7.830	7.709	$1/2^-_4$
----------	7.830	7.714	$25/2^-_1$
----------	7.830	7.732	$17/2^-_7$
----------	7.830	7.841	$5/2^-_9$
----------	7.830	7.879	$19/2^-_5$
----------	7.830	7.908	$15/2^-_{10}$
----------	7.830	7.939	$3/2^-_8$
----------	----------	8.354	$5/2^-_{10}$
----------	----------	8.574	$21/2^-_3$
----------	----------	8.840	$17/2^-_8$
----------	----------	9.009	$19/2^-_6$
----------	----------	9.013	$1/2^-_5$
----------	----------	9.069	$3/2^-_9$
----------	9.643	9.650	$19/2^-_7$
----------	9.643	9.693	$21/2^-_4$
----------	9.643	9.706	$23/2^-_3$
----------	9.643	9.764	$3/2^-_{10}$
-----------	----------	10.657	$17/2^-_9$

For ^{46}Ti nucleus the energy levels calculations from f748pn effective interaction is shown in table 6. The effective interactions give results reasonably consistent with experimental data. The total angular momentum and parity are ($0^+_1, 2^+_1, 4^+_1, 2^+_2, 6^+_1$, 1^+_1, 2^+_5, 4^+_6, 8^+_3, $4^+_9, 11^+_2$, 1^+_5 , 12^+_3 , 1^+_7) respectively, confirmation of which is (4^+)

Table 6 shows a comparison of the energy levels values with respect to the ground state were calculated from f748pn effective interactions with experimental excitation energies of ^{46}Ti

Exp .Res[11]		**F748pn**	J^{π}
J^{π}	Energy elevels		
0^+	0.000	0.000	0^+_1
2^+	0.889	0.945	2^+_1
4^+	2.009	1.890	4^+_1
2^+	2.961	2.541	2^+_2
----------	3.213	2.815	4^+_2
6^+	3.298	2.855	6^+_1
----------	3.338	3.306	2^+_3
----------	3.553	3.453	3^+_1
----------	3.553	3.458	4^+_3
----------	3.579	3.540	5^+_1
1^+	3.731	3.662	1^+_1
+	3.771	3.703	6^+_2
----------	4.322	4.249	6^+_3
----------	4.322	4.276	8^+_1

----------	4.617	4.642	5_2^+
----------	4.617	4.695	4_4^+
+	4.845	4.851	0_2^+
----------	5.000	4.907	3_2^+
(4^+)	5.079	4.957	4_5^+
+	5.094	4.961	3_3^+
+	5.094	5.028	7_1^+
+	5.094	5.068	2_4^+
----------	5.154	5.161	7_2^+
+	5.180	5.272	8_2^+
2^+	5.363	5.364	2_5^+
----------	----------	5.420	5_3^+
----------	----------	5.424	6_4^+
----------	----------	5.504	10_1^+
4^+	5,794	5.513	4_6^+
+	5.811	5.696	7_3^+
+	5.840	5.839	6_5^+
+	5.903	5.896	5_4^+
----------	6.025	6.033	9_1^+
----------	6.025	6.064	6_6^+
----------	6.025	6.086	0_3^+
----------	----------	6.097	1_2^+
8^+	6.200	6.109	8_3^+
----------	6.251	6.225	3_4^+
----------	6.305	6.302	2_6^+
----------	6.305	6.354	10_2^+
+	6.424	6.378	5_5^+
----------	6.513	6.493	6_7^+
----------	6.513	6.519	4_7^+
+	6.550	6.562	8_4^+
----------	6.574	6.648	4_8^+
+	6.616	6.653	11_1^+
4^+	6.685	6.696	4_9^+
----------	---------	6.700	3_5^+
----------	---------	6.716	7_4^+
----------	6.794	6.761	9_2^+
----------	6.794	6.795	2_7^+
+	6.851	6.805	8_5^+
+	6.851	6.850	6_8^+
+	6.974	6.890	9_3^+
+	6.974	6.893	5_6^+
+	7.041	7.035	3_6^+
+	7.041	7.048	12_1^+
+	7.101	7.097	7_5^+
+	7.147	7.156	6_9^+
----------	7.172	7.191	10_3^+
----------	7.238	7.259	5_7^+

+	7.288	7.268	4^+_{10}
+	7.288	7.299	2^+_8
+	7.350	7.377	3^+_7
+	7.350	7.379	8^+_6
+	7.558	7.561	5^+_8
+	7.558	7.562	8^+_7
----------	7.660	7.688	6^+_{10}
+	7.710	7.708	7^+_6
+	7.788	7.798	2^+_9
+	7.849	7.801	10^+_4
+	7.849	7.839	5^+_9
----------	7.874	7.884	3^+_8
----------	7.937	7.953	5^+_{10}
----------	8.013	8.007	8^+_8
----------	8.013	8.011	9^+_3
----------	8.134	8.118	7^+_7
+	8.182	8.191	3^+_9
+	8.182	8.204	0^+_4
+	8.230	8.213	1^+_3
+	8.230	8.245	2^+_{10}
10,11,12+	8.283	8.383	11^+_2
+	8.384	8.400	9^+_4
+	8.467	8.467	8^+_9
+	8.574	8.557	7^+_8
+	8.621	8.609	3^+_{10}
+	8.701	8.744	1^+_4
+	8.761	8.759	7^+_9
+	8.808	8.776	10^+_4
+	8.860	8.865	7^+_{10}
+	8.860	8.879	8^+_{10}
+	8.984	8.984	10^+_5
+	9.070	9.085	12^+_2
+	9.253	9.202	14^+_1
+	9.253	9.246	9^+_5
+	9.345	9.332	13^+_1
1^+	9.420	9.441	1^+_5
+	9.474	9.467	0^+_5
+	9.572	9.536	11^+_2
$12^+, 14^+$	10.041	9.927	12^+_3
----------	10.212	10.141	9^+_6
----------	10.256	10.271	1^+_6
----------	10.321	10.300	10^+_6
+	10.523	10.525	9^+_7
----------	11.426	11.456	9^+_8
1^+	11.450	11.484	1^+_7
----------	----------	11.577	10^+_7
---------	---------	11.981	11^+_3

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