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Level Excitation and Transition Probabilities of Some Nuclei in the Lower *fp*-Shell

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Abstract

Unrestricted shell model calculations in the lower *fp*-shell region for the nuclei ^{46}Ti, ^{46}Cr and ^{46}V have been performed for the isovector T=1 positive parity states using the shell model code OXBASH for Windows by employing the effective interactions GXPF1, FPD6 and KB3G. The level schemes and transition strengths $B(E2;\downarrow)$ are compared with the recently available experimental data. Better agreement was obtained in comparison with the experimental data and the previous theoretical work for all nuclei under study.

Keywords: Energy levels, Transition probabilities, Large-scale shell model

الخلاصة:

أجريت حسابات نموذج القشرة غير المقيدّه في منطقة الجزء الأسفل من القشرة (*fp*-shell) للنويات ^{46}Ti، ^{46}Cr و^{46}V ذوات المتجه الأحادي النظيري (T=1) ولمستويات الطاقة موجبة التماثل بأستخدام برنامج نموذج القشرة (OXBASH) والمخصص لنظام التشغيل وندوز عن طريق توظيف التفاعلات الفعّاله GXPF1، FPD6 و KB3G. قورنت مخططات مستويات الطاقة والأنتقالات النووية $B(E2;\downarrow)$ مع البياناتات التجريبية الحديثة المتوفرة. تم الحصول على نتائج أفضل بالمقارنة مع النتائج العملية والدراسات النظرية السابقة لكل النويات قيد الدراسة.

1. Introduction

The nuclear shell model has been very successful in our understanding of nuclear structure: once a suitable effective interaction is found, the shell model can predict various observables accurately and systematically. For light nuclei, there are several “standard” effective interactions such as the Cohen-Kurath [1] and the USD [2] interactions for the *p* and *sd*-shells, respectively. On the other hand, in the next major shell, *i.e.*, in the *fp*-shell, there were also “standard” interactions such as FPD6 [3] and GXPF1 [4].

The spectroscopy of nuclei, in the *fp*-shell region, has been well described within the shell model framework. Extensive shell model calculations have been performed in this mass region, using several model spaces and two-body interactions, the most remarkable work of Brown and co-workers [5, 6, 7, 8, 9, 10, and 11]. Four years ago, we made calculations in the *fp*-shell for the even-even $^{48-56}$Ti isotopes in this mass region [12]. Because of the quite importance of the *fp*-shell for variety of problems in nuclear structure, such as electron capture in supernova explosions. In the present study we report the shell model calculations in the lower *fp*-shell region for the nuclei ^{46}Ti, ^{46}Cr and ^{46}V, to test the ability of the present effective interactions in reproducing the experiment in this mass region.

2. Theory and calculations

The structure of the nuclei ^{46}Ti, ^{46}Cr and ^{46}V, has been studied in the framework of the shell model using the OXBASH code [13].
For the calculations, the shell model Hamiltonian can be written as [14]

$$H = \sum_i \varepsilon_i a_i^\dagger + \sum_{ijkl} V_{ijkl}\, a_i^\dagger a_j^\dagger a_i a_j$$

where ε_i: is the single-particle energies (SPE) that can be obtained from neighbors of closed shell nuclei having mass A=closed core+1.

V_{ijkl}: is the Two-Body Matrix Element (TBME) coupled to good spin and isospin.

$a_i^\dagger a_j^\dagger$: Creation operators (create pair of fermions).

$a_i a_j$: Annihilation operators (annihilate pair of fermions).

The TBME where calculated by using three effective interaction codenamed FPD6 [3], GXPF1 [4] and KB3G [15].

The reduced transition probability for electric multipole radiation is given by [16]

$$B(El, J_i \to J_f) = \frac{2J_f+1}{2J_i+1}\left|\int d^3r \left\langle f \left\| \hat{\rho}(r) r^l Y_l(\Omega) \right\| f \right\rangle\right|^2$$

Where $\hat{\rho}(r)$: is the charge density operator

$Y_l(\Omega)$: is the spherical harmonics

2.1 Excitation energies

As mentioned in the earlier section, the main motivations for studying these nuclei lies in the lower *fp*-shell due to the importance of these in the recent applications in astrophysics and because of the spin-orbit splitting that gives rise to a sizable energy gap in the *pf*-shell between $f_{7/2}$ orbit and the other orbits $p_{3/2}$, $p_{1/2}$ and $f_{5/2}$, producing the N or Z=28 magic number.

The calculations have been carried out using the code OXBASH for windows [13] in the FP model space which comprised of the $1p_{3/2}$, $1p_{1/2}$, $0f_{7/2}$ and $0f_{5/2}$ valence orbits outside the ^{40}Ca. Three effective interactions were employed with FP model space for the calculations of level spectra and transition probabilities, these effective in iterations are FPD6 [3], GXPF1 [4] and KB3G [15]. We should mention here that ^{46}Ti and ^{46}Cr have only isovector part T=1, while ^{46}V have isovector part T=1 and isoscalar T=0, in our study we considered only the isovector T=1.

Figure 1, presents the comparison of the experimental excitation energies of ^{46}Ti taken from ref. [16] with calculated values from FPD6, GXPF1 and KB3G effective interactions. The three effective interactions gives very good results in comparison with the experimental values for the 2^+ and 4^+ states while for higher $J^\pi > 6+$ up to $J^\pi = 12$ are in poor agreement with the experiment which is in consistent with the previous theoretical work due to the fact that the shell model calculations can reproduce experiment for the lower energy states and fail to reproduce the experiment for higher J^π values .

From Fig.1, we can notice that FPD6 are in good agreement with the experiment better than GXPF1 and KB3G for 2^+ and 4^+ states.

In figure 2 and figure 3, same comparisons were made using the three effective interactions for ^{46}Cr and ^{46}V respectively. From these figures same conclusion were drawn that FPD6 is the best for describing these nuclei lies in the lower part of the *fp*-shell.

2.2 Transition probabilities

Since the transition rates represent a sensitive test for the most modern effective interactions that have been developed to describe *fp*-shell nuclei. The transition strengths calculated in this work performed using the harmonic oscillator potential (HO) for each in-band transition by assuming pure *E*2 transition. Core polarization effect were included by choosing the effective charges for proton e_π=0.7*e* and for neutron e_ν=0.5*e*. Our results and the previous theoretical results using different models are listed in Table 1 for ^{46}Ti.

In Th.1 and Th.2 [20], the effective charges for proton and neutron were taken as 1.38*e* and 0.83*e* respectively. The effective charges for protons and neutrons taken to be equal in value as 0.7*e* in Th.3 which is MONSTER [21] and $e_\pi = e_\nu$=0.9*e* adopted in Th.4 "the $(f_{7/2})^6$ shell model [21]". As seen from Table 1, the $B(E2;\downarrow)$ values calculated in this work are in better agreement for the transitions $B(E2; 2_1^+ \rightarrow 0_1^+)$ and $B(E2; 4_1^+ \rightarrow 2_1^+)$ than the previous theoretical work, while the rest transitions, Th1., Th.2, Th.3, Th.4 and Th.6 are in better agreement with the experimental data, except Th.5 "the rotational model [22]" do not follow the trend of experimental data.

Although FPD6 effective interaction is more successful in description of energy level spectra, but the calculation of the transition strengths prove that it not the standard effective interaction for this region and the results obtained by GXPF1 are in better agreement with experiment in comparison with KB3G and FPD6 effective interactions, also the result of KB3G are not so far from the experimental values. For ^{46}Cr the same comparison were made in Table 2, but the experimental data are not available, therefore we can not judge which effective interaction reproduce the experimental data better.

The effective charges for proton and neutron are taken to be 0.5*e* and 0.4*e* respectively, for the calculations of the transition strengths of ^{46}V. Our theoretical results are in excellent agreement with the experimental values for the transitions $B(E2; 2_1^+ \rightarrow 0_1^+)$ and $B(E2; 4_1^+ \rightarrow 2_1^+)$, using GXPF1 effective interaction, also our theoretical predictions are in better agreement in comparison with the previous theoretical work, Th.2 [18] and Th.3 [27] as summarized in Table 3.

Table 1: The $B(E2)$ values in the ground-state band of ^{46}Ti. Their units are e^2 fm^4. Exp. is the experiment [20, 21, 22, 23]; Th.1 is PPNC; Th.2 is the projected of the pure HF ground-state configuration [18]; Th.3 is MONSTER [18]; Th.4 is the $(f_{7/2})^6$ shell model [19]; Th.5 is the rotational model [19]; Th.6 is ANTOINE [22]. This work is assumed pure $E2$ transition limit.

$J_i^\pi \to J_f^\pi$	Exp.	Th.1	Th.2	Th.3	Th.4	Th.5	Th.6	Present work		
								GXPF1	KB3G	FPD6
$2_1^+ \to 0_1^+$	180±8[a] 190±10[b] 215±20[c] 191±2[d]	132	134	138	116	215	116	183	195	233
$4_1^+ \to 2_1^+$	206±39[c] 231±27[d]	186	184	186	127	304	154	233	256	328
$6_1^+ \to 4_1^+$	147±29[c] 170±17[d]	196	188	189	110	342	154	213	241	309
$8_1^+ \to 6_1^+$	108±20[c] 154±25[d]	183	175	172	122	325	140	211	233	291
$10_1^+ \to 8_1^+$	117±29[c] 110±10[d]	143	157	119	69	362	101	160	174	222
$12_1^+ \to 10_1^+$	29±3[c] 42±5[d]	56	124	51	41	372	41	65	75	84

[a]Reference[21], [b]Reference[22], [c]Reference[20], [d]Reference[23]

Table 2: The $B(E2)$ values in the ground-state band of ^{46}Cr. Their units are e^2 fm^4. Exp. is the experiment [24]. This work is assumed pure $E2$ transition limit.

$J_i^\pi \to J_f^\pi$	Exp.	Present work		
		GXPF1	KB3G	FPD6
$2_1^+ \to 0_1^+$	186±40	183	195	233
$4_1^+ \to 2_1^+$		233	256	328
$6_1^+ \to 4_1^+$		213	241	309
$8_1^+ \to 6_1^+$		211	233	291
$10_1^+ \to 8_1^+$		160	174	222
$12_1^+ \to 10_1^+$		65	75	84

Table 3: The $B(E2)$ values in the ground-state band of ^{46}V. Their units are e^2 fm^4. Exp. is the experiment [18, 25]. This work is assumed pure $E2$ transition limit.

$J_i^\pi \to J_f^\pi$	Exp.	Th.1	Th.2	Th.3	Present work		
					GXPF1	KB3G	FPD6
$2_1^+ \to 0_1^+$	137±35[a] 138±35[b]	537	142	142	137	145	175
$4_1^+ \to 2_1^+$	≥ 169[a]	676	187	187	173	191	245
$6_1^+ \to 4_1^+$		658		175	159	180	231
$8_1^+ \to 6_1^+$		601		167	156	173	217
$10_1^+ \to 8_1^+$					119	130	165
$12_1^+ \to 10_1^+$				54	48	56	63

[a]Reference[25], [b]Reference[17]

3. Summary and conclusions

Full *fp*-space shell model calculations were performed using the code OXBASH for Windows. The FP model space were employed with the effective interactions GXPF1, FPD6 and KB3G to reproduce the level spectra and transition strengths $B(E2)$ for the nuclei ^{46}Ti, ^{46}Cr and ^{46}V.

Good agreement was obtained by comparing these calculations with the recently available experimental data for the level spectra using FPD6 effective interaction. Calculation of the transition strengths prove that GXPF1 is more consistent in reproducing the experiment than FPD6 for the lower *fp*-shell region.

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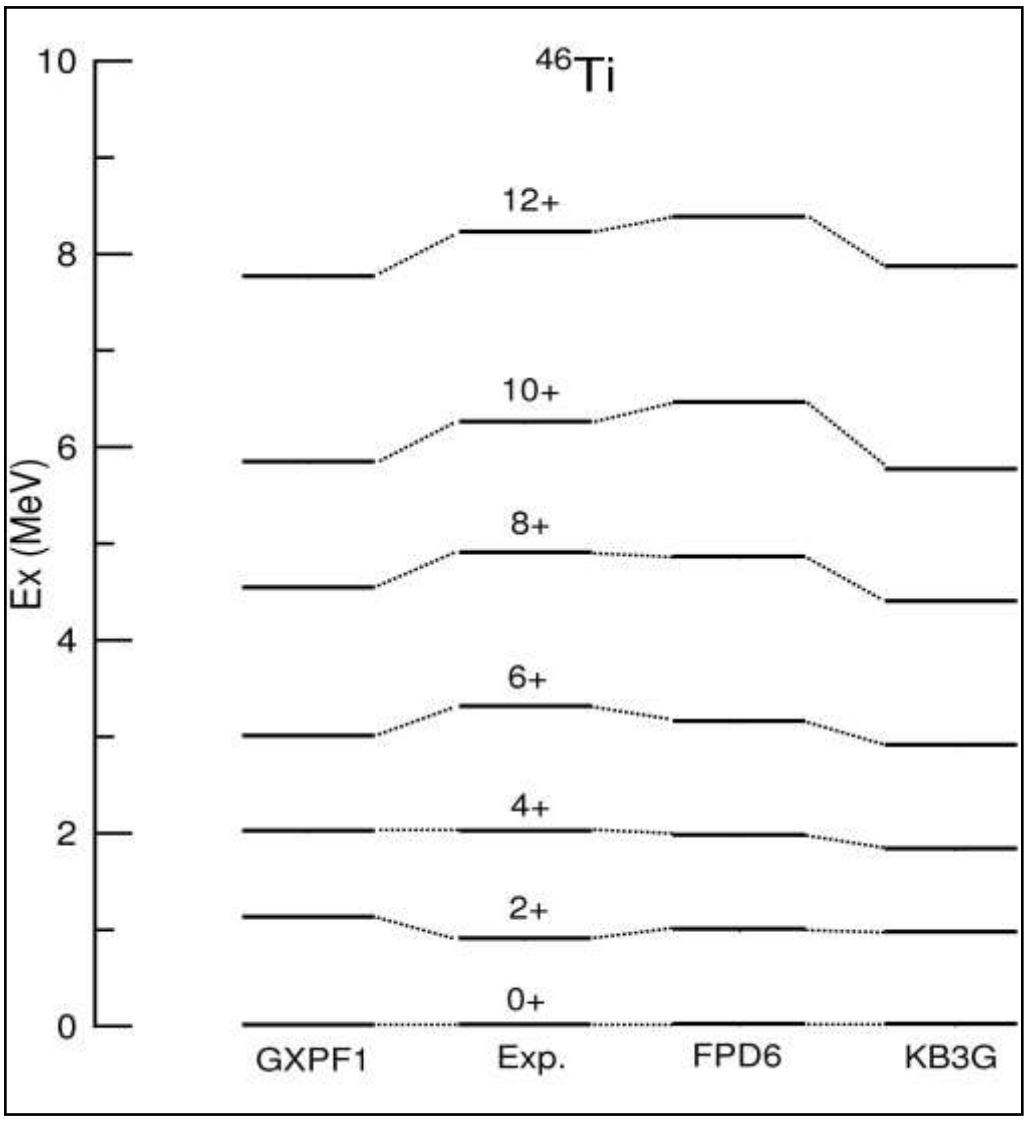


Figure 1: Comparison of the experimental excitation energies taken from Ref. [16] with the present theoretical work using FPD6, GXPF1 and KB3G effective interactions.

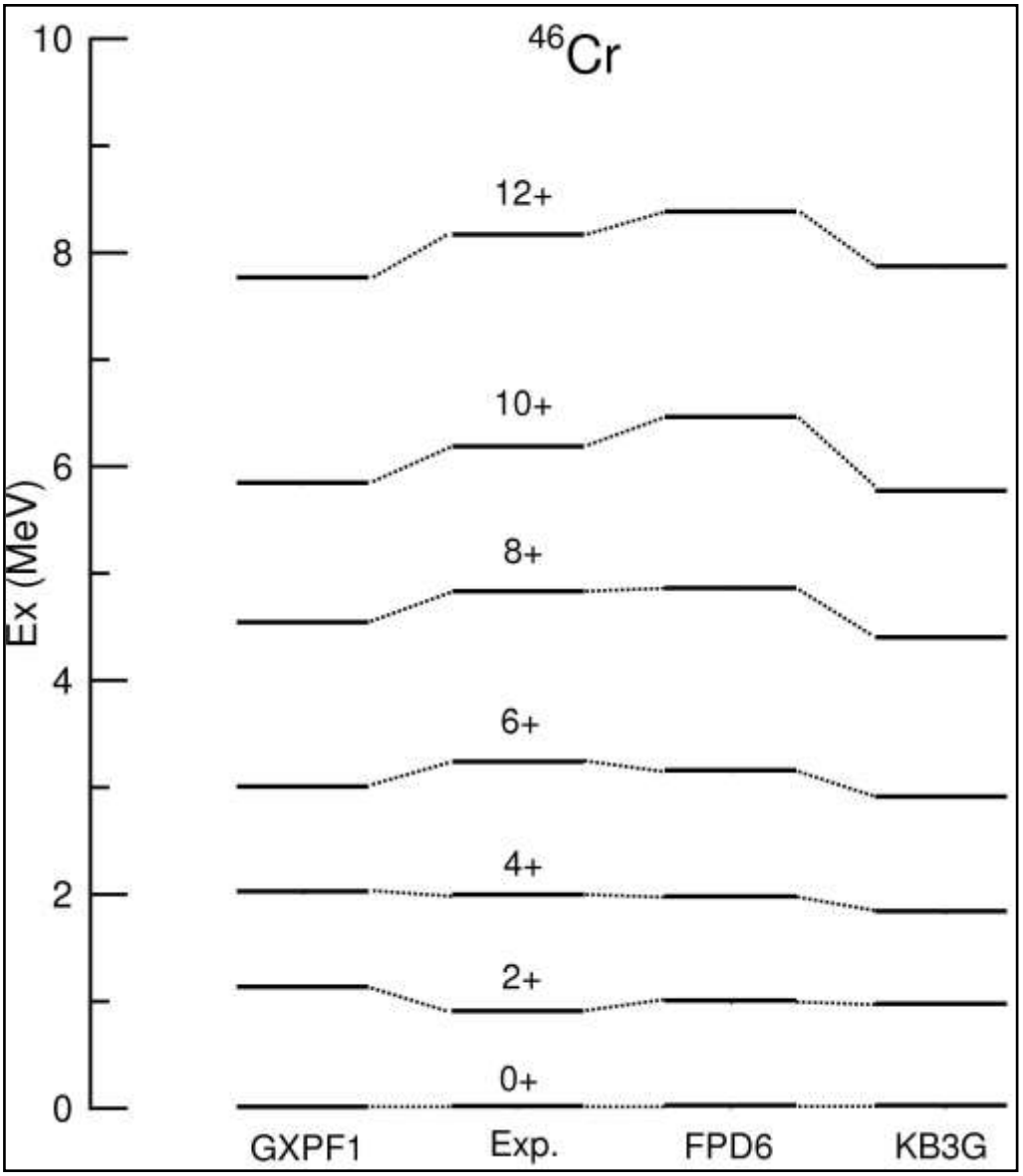
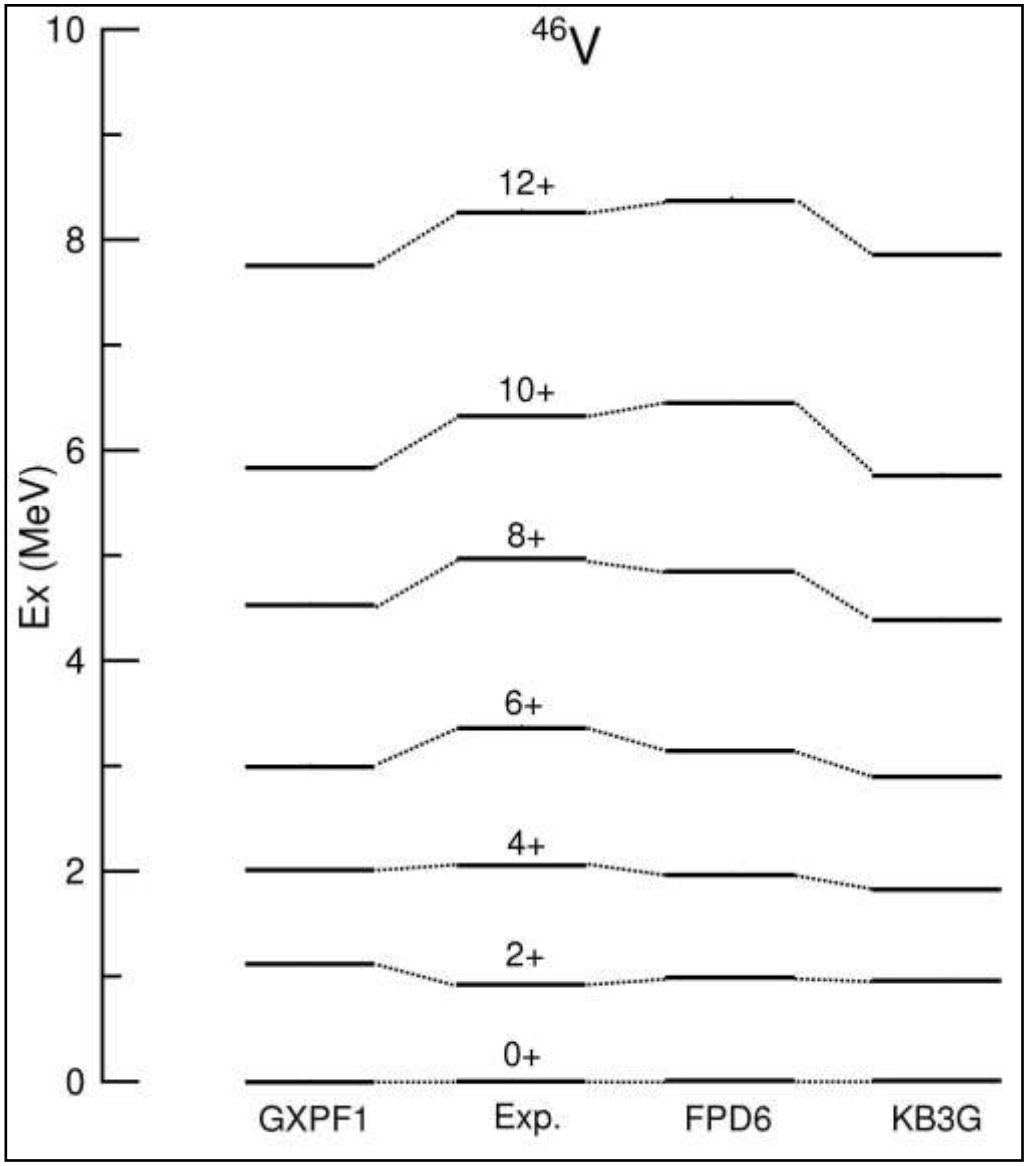


Figure 2: Comparison of the experimental excitation energies taken from Ref. [16] with the present theoretical work using FPD6, GXPF1 and KB3G effective interactions.



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