High-spin structure of odd $^{71-81}$Ga isotopes with shell model

P.C. Srivastava

Physical Research Laboratory, Ahmedabad 380 009, India

Abstract.

The recently measured experimental data of Argonne National Laboratory for high-spin states in neutron-rich ^{71,73,75,77}Ga isotopes have been interpreted in the framework of large-scale shell model. Calculations have been performed in $f_{5/2}pg_{9/2}$ model space with two recent effective shell model interactions, JUN45 and jj44b. We also predict high-spin states for ^{79,81}Ga, where very little is known experimentally. The calculated results show that existence of band structure built on top of the $3/2^-$, $5/2^-$ and $9/2^+$ levels in $^{71-77}$Ga. The collective structure reflected in experimental data is not well reproduced in calculated values. The calculated positive parity states in ^{71,73,75}Ga are higher in energy in comparison to experimental finding, while for ^{77,79}Ga, the positive parity states are in better agreement. Both the interactions predict, leading configuration of $\pi(f^3_{5/2})$ and $\pi(p_{3/2}f^2_{5/2})$ for ^{79,81}Ga. The $B(E2)$ values for ^{71,73}Ga which is recently measured at REX-ISOLDE, have been also compared, the agreement for ^{73}Ga is quite good with jj44b interaction. Further, $B(E2)$ values for ^{75,77,79,81}Ga for future experiment are also predicted. These results show that more theoretical developments and new experimental measurements are needed.

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1. Introduction

Neutron-rich nuclei in the vicinity of ^{78}Ni attracted much experimental and theoretically attention due to importance of the $\nu g_{9/2}$ orbital. In the pioneering work of Franchoo *et al.*, that sudden change of the lowering of the $\pi 1f_{5/2}$ state from ^{73}Cu onwards, with the increasing occupancy of the $\nu 1g_{9/2}$ was pointed out [1, 2]. The competition of single-particle and collective modes and monopole migration in copper isotopes have been studied in great detail in [3, 4, 5, 6, 7, 8, 9, 10]. Finally, Flanagan *et al.*, experimentally established inversion of $5/2^-$ and $3/2^-$ levels in ^{75}Cu, while measuring nuclear spins and magnetic moments of ^{71,73,75}Cu [4]. K. Sieja and F. Nowacki [11], have recently shown the results for spectra and magnetic moments for odd copper isotopes using hybrid interaction in $f_{7/2}pg_{9/2}$ space but it remains to test proposed interaction is universal or not for this region. Zn isotopes, have attracted experimental attention for measuring g factor and $B(E2)$ values. Using Coulomb excitation of neutron-rich Zn isotopes, observation of the 2^+ state for the first time in ^{80}Zn has been reported in [12]. Theoretically, importance of the intruder $1g_{9/2}$ orbital for lower fp shell nuclei, namely neutron-rich Cr, Mn, Fe and Co isotopes [13, 14, 15, 16, 17, 18, 19, 20] and further inclusion of $2d_{5/2}$ orbital on demand of growing experimental evidence for collective behavior of Cr and Fe isotopes with $N \sim 40$ have been reported in [21]. Recently for even-even Ge isotopes, comparison of shell model results with JUN45 and jj44b interactions by Zamick group are reported in [22], they have called attention to include $B(E2)$ and Q values while fitting the residual effective interaction parameters. In the present paper we consider neutron-rich Ga isotopes. Earlier shell model calculation using pairing plus quadrupole-quadrupole interaction for ^{75,77,79}Ga isotopes have been reported by Yoshinaga *et. al.,* [23]. They consider only few low lying in the analysis.

The structural changes between $N = 40$ and $N = 50$ of odd-mass gallium isotopes recently attracted much experimental attention. Vergnes *et. al.,* observed levels of ^{71,73}Ga in the (t, p) reactions, and they found abrupt structural changes beyond $N = 40$ [24]. At Argonne National Laboratory, Stefanescu *et. al.,* have populated odd-A $^{71-73}$Ga isotopes in deep-inelastic reactions of a ^{76}Ge beam at 530 MeV with a thick ^{238}U target [25]. More recently, in the Coulomb excitation experiment at REX-ISOLDE, the existence of a $1/2^-$, $3/2^-$ ground-state doublet has been proposed in ^{73}Ga [26]. Verney *et. al.,* have recently studies low-energy states of ^{81}Ga by β decay of the neutron-rich ^{81}Zn at the PARRNe mass separator at the IPN Orsay [27]. For Ga isotopes nuclear spins and moments has been reported in [28]. The evolution of the $1/2^-$ and $5/2^-$ levels in odd-A gallium isotopes is shown in Fig. 1. Except ^{73}Ga and ^{81}Ga all have ground state $3/2^-$. The first $1/2^-$ reaches minimum in ^{73}Ga where it become ground state and the first $5/2^-$ start decreasing with $N = 40$ onwards and it becomes ground state in ^{81}Ga. This figure also demonstrate abrupt changes of structure from $N = 40$ to $N = 42$.

Following our recent shell-model (SM) studies for neutron-rich odd and even isotopes of Fe [16, 17], odd-odd Mn isotopes [18], odd-mass ^{61,63,65}Co isotopes [20], and even-even Ni and Zn and odd-A Cu isotopes [29], in this paper we report large

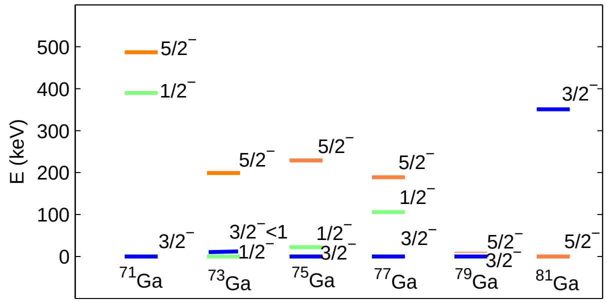

Figure 1. Experimental low-energy systematics of odd-A gallium isotopes [25, 28].

scale shell model calculations for odd-mass $^{71-81}$Ga isotopes in $f_{5/2}pg_{9/2}$ model space. The aim of present study is to analyze the more recent accumulated experimental data which includes high-spain states on neutron-rich Ga isotopes. Further, this work will add more information in the earlier work by Cheal *et al.* [28], where only few exited states are studied. Now we will give a preview.

The paper is organized as follows: sect. 2 gives details of the calculation. Results and discussion are given in sect. 3. Finally in sect. 4 a summary is given.

2. Details of Calculation

The present shell model calculations have been carried out with two recent effective shell model interactions, JUN45 and jj44b, that have been proposed for $1p_{3/2}$, $0f_{5/2}$, $1p_{1/2}$ and $0g_{9/2}$ single-particle orbits. For JUN45 interaction the single-particle energies are taken to be -9.8280, -8.7087, -7.8388, and -6.2617 MeV for the $p_{3/2}$, $f_{5/2}$, $p_{1/2}$ and $g_{9/2}$ orbit, respectively. Similarly for jj44b interaction the single-particle energies are taken to be -9.6566, -9.2859, -8.2695, and -5.8944 MeV for the $p_{3/2}$, $f_{5/2}$, $p_{1/2}$ and $g_{9/2}$ orbit, respectively. JUN45 which is recently develop by Honma *et al.* [30], this realistic interaction based on the Bonn-C potential with fitting 400 experimental binding and excitation energy data with mass numbers A=63$\sim$96. Since the present model space is not sufficient to describe collectivity in these region thus data have been not used while fitting in the middle of the shell along $N = Z$ line. For JUN45, the data mostly fitted to develop this interaction closure to $N = 50$, thus this interaction is very suitable for shell-model study of neutron rich Ga isotopes as $N \sim 50$. Although this interaction is not successful to explain data for Ni and Cu isotopes possibly due to missing $0f_{7/2}$ orbit in the present model space. The jj44b interaction due to Brown *et al.* [31] was developed by fitting 600 binding energies and excitation energies with $Z = 28 - 30$ and $N = 48 - 50$. Instead of 45 as in JUN45, here 30 linear combinations of good $J - T$ two-body matrix elements varied, with the rms deviation of about 250 keV from experiment.

In Fig. 2, we compared the effective single-particle energy of the proton orbit for

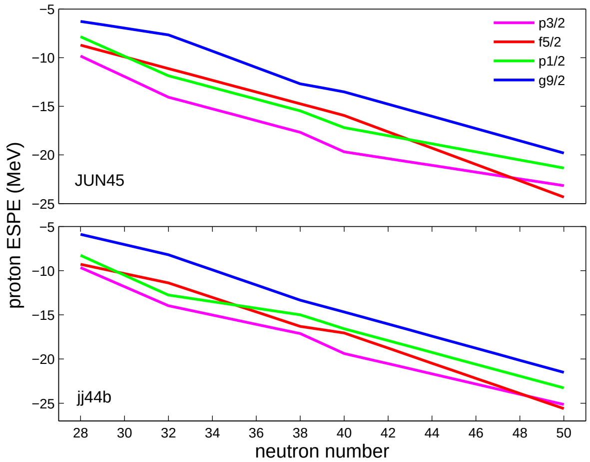

Figure 2. Effective single-aparticle energies of proton orbits for Cu isotopes for JUN45 and jj44b interaction.

Cu isotopes in JUN45 and jj44b interaction. Both the interactions show a rapid decrease in $f_{5/2}$ proton single-particle energy relative to $p_{3/2}$ as neutrons start filling in $g_{9/2}$ orbit and it becomes lower than $p_{3/2}$ for $N > 48$.

All the SM calculations have been carried out using the code `ANTOINE` [32, 33, 34] and in this code the problem of giant matrices is solved by splitting the valence space into two parts, one for the protons and the other for the neutrons. All calculations are performed on the 20-node cluster computer at PRL. The dimension of matrices involved in the calculations are shown in Table 1.

Table 1. Dimensions of the shell model matrices for $^{71-81}$Ga in the m-scheme for $f_{5/2}pg_{9/2}$ space.

J^π	^{71}Ga	^{73}Ga	^{75}Ga	^{77}Ga	^{79}Ga	^{81}Ga
1^-	30582379	15478857	3797229	405940	14899	87
3^-	29887514	15109936	3696696	392899	14202	79
5^-	28542771	14397362	3503487	368174	12935	64
7^-	26633293	13388628	3232166	334156	11293	48
9^-	24275964	12148523	2902165	293850	9493	36
11^-	21607432	10751971	2535184	250276	7687	25
13^-	18772491	9277496	2153377	206306	5994	18
15^-	15910869	7799757	1776963	164287	4465	12
17^-	13147625	6384632	1423218	126141	3157	7
19^-	10584007	5084152	1105045	93139	2091	3
21^-	8293523	3934906	830859	66025	1291	1

3. Results and Discussion

Gallium isotopes are experimentally studied by four different approaches, β decay, single- and multiparticle transfer reactions, deep inelastic reactions, and more recently by Coulomb excitations. In more recent experiment Cheal *et al.*, [28] investigated systematics of low-lying $1/2^-$, $3/2^-$, and $5/2^-$ levels and assigned the ground state spins and structure up to $N = 50$ shell closure.

3.1. Excitation energies and comparison with the data

3.1.1. ^{71}**Ga :** Experimentally for ^{71}Ga, the spins and parities for the levels below the $9/2^+$ were assigned in [35, 36, 37]. Stefanescu *et al.* [25] using deep-inelastic reaction at Argonne National Laboratory, assigned positive parity states at 2082, 2941, and 4028 keV, for $9/2^+$, $17/2^+$, and $21/2^+$ respectively. In the same experiment the negative states $9/2^-$, $13/2^-$, $17/2^-$, and ($19/2^-$, $21/2^-$) are proposed at 1498, 2684, 3696, and 4165 keV, respectively. In this paper they argue that these sequence of levels arise due to coupling of $\pi f_{5/2}$ and $\nu g_{9/2}$. The previous study of transfer reaction indicate that low-lying $3/2^-$, $1/2^-$, $5/2^-$ and $9/2^+$ states arise from dominant single- particle character from the proton $p_{3/2}$, $p_{1/2}$, $f_{5/2}$, and $g_{9/2}$ orbitals. In Fig. 3, experimental data for ^{71}Ga are compared with the calculated energy levels using JUN45 and jj44b interaction. Stefanescu *et al.* [25], predicted bands built on $3/2^-$, $5/2^-$ and $9/2^+$. The band built on $3/2^-$, is reproduced correctly by JUN45 interaction, while levels are compress with jj44b interaction. These results show that the yrast sequence of levels $3/2^-$–$5/2^-$–$7/2^-$–$11/2^-$ is connected with strong $E2$ transitions. The $B(E2)$ values for $5/2^- \rightarrow 3/2^-$,$7/2^- \rightarrow 5/2^-$, $11/2^- \rightarrow 7/2^-$, are 6, 222 and 223 e^{2}fm^4 respectively with JUN45 and corresponding value for jj44b are 5, 209 and 383 e^{2}fm^4. Similarly, a band built on $5/2^-$, with JUN45 interaction is slightly higher, while jj44b intraction predicted compress states. The band built on $9/2^+$, with the JUN45 interaction, predicted $9/2^+$, $13/2^+$, $17/2^+$, $21/2^+$ are at 2478, 2893, 3526 and 4979 keV, while its corresponding experimental values are 1493, 2082, 2941 and 4028 keV respectively. The calculated positive parity states around 1 MeV higher than experimental data. The predicted results show the inadequacy of this interaction to explain positive parity states. The jj44b interaction predicts $9/2^+$, $13/2^+$, $17/2^+$, $21/2^+$ at 1922, 2855, 3689 and 4866 keV respectively, which is better than JUN45 interaction. The calculated $B(E2)$ values are shown in Table 2. Both the interaction predicts, leading configuration of $\pi(f^3_{5/2})$ and $\pi(p^2_{3/2}f_{5/2})$ for this isotope. The calculated occupancy of g$_{9/2}$ orbital is 0.53, 0.83 by JUN45 and jj44b interaction respectively. The wave function contribution for the ground state and first excited states of ^{71}Ga are shown in Table 5.

3.1.2. ^{73}**Ga :** The level scheme of ^{73}Ga was proposed in earlier experiments [38, 24]. Runte *et al.*, [39] while studying beta decay of ^{73}Zn assigned ground state (g.s.) as $3/2^-$, and $3/2^-_2$, $5/2^-_1$, $3/2^-_3$, $3/2^-_4$ are proposed at 218, 496, 911 , 2108 keV respectively. The $3/2^-_2$ is assigned at 218, (earlier it was 214 keV in Ref. [38]). Stefanescu et al.

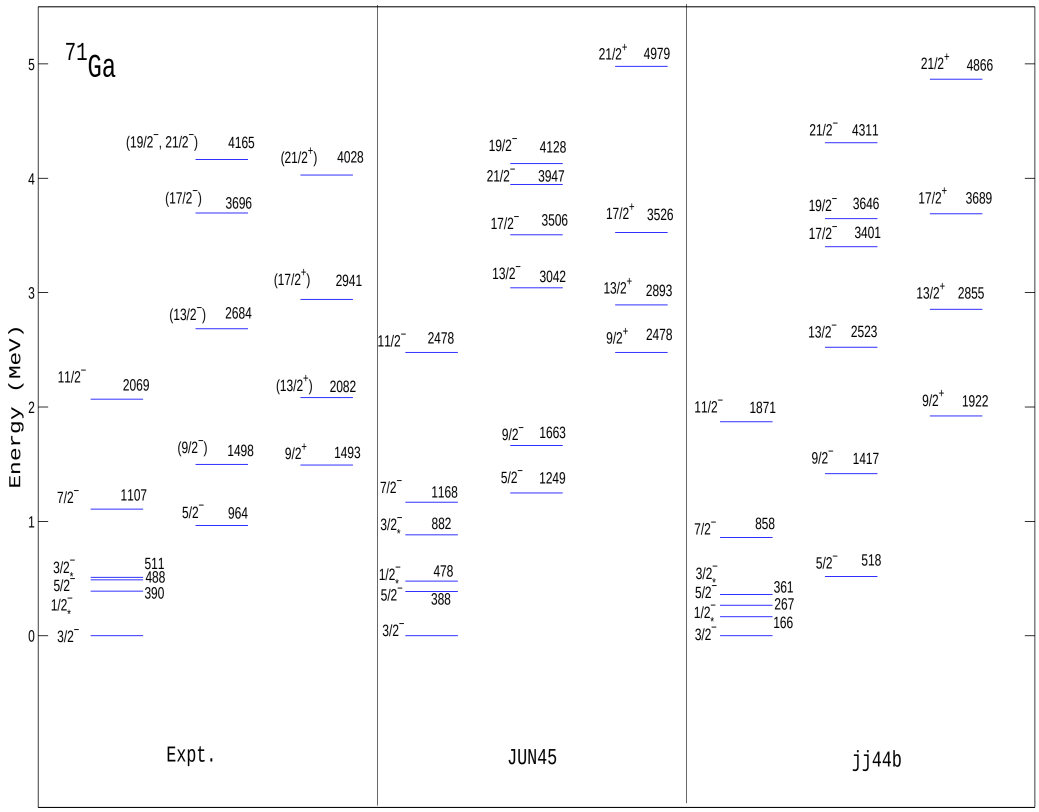

Figure 3. Experimental data for ^{71}Ga compared with shell-model results. The levels marked with an asterisk (*) have been also experimentally found, but not form a band.

[25], first time assigned positive parity states, in this paper both positive and negative parity high-spin states are also reported. Dirikin *et al.* [26], using Coulomb excitation at REX-ISOLDE, predict a $1/2^-$ for the ground state, they have also shown an evidence for a $1/2^-$, $3/2^-$ doublet near the ground state, with the excitation energy of the ~ 0.8 keV for $3/2^-$. In Fig. 4, experimental data for ^{73}Ga are compared with the calculated energy levels using JUN45 and jj44b interaction. In contrast to ground state doublet predicted in recent experiment [28], the JUN45 and jj44b interaction predicts $1/2^-$ state at 219 and 91 keV respectively. Stefanescu *et al.* [25], predicted bands builts on $3/2^-$, $5/2^-$, $7/2^-$ and $9/2^+$.

The band built on $3/2^-$, reproduced correctly by JUN45 and jj44b interaction. The band built on $5/2^-$, is more correctly reproduced by jj44b interaction. These results show that the yrast sequence of levels $5/2^-$–$9/2^-$–$13/2^-$–$17/2^-$ is connected with strong $E2$ transitions. The $B(E2)$ values for $9/2^-\to5/2^-$,$13/2^-\to9/2^-$, $17/2^-\to13/2^-$, are 42, 194 and 4 e^{2}fm^4 respectively with JUN45 and corresponding value for jj44b are 81, 270

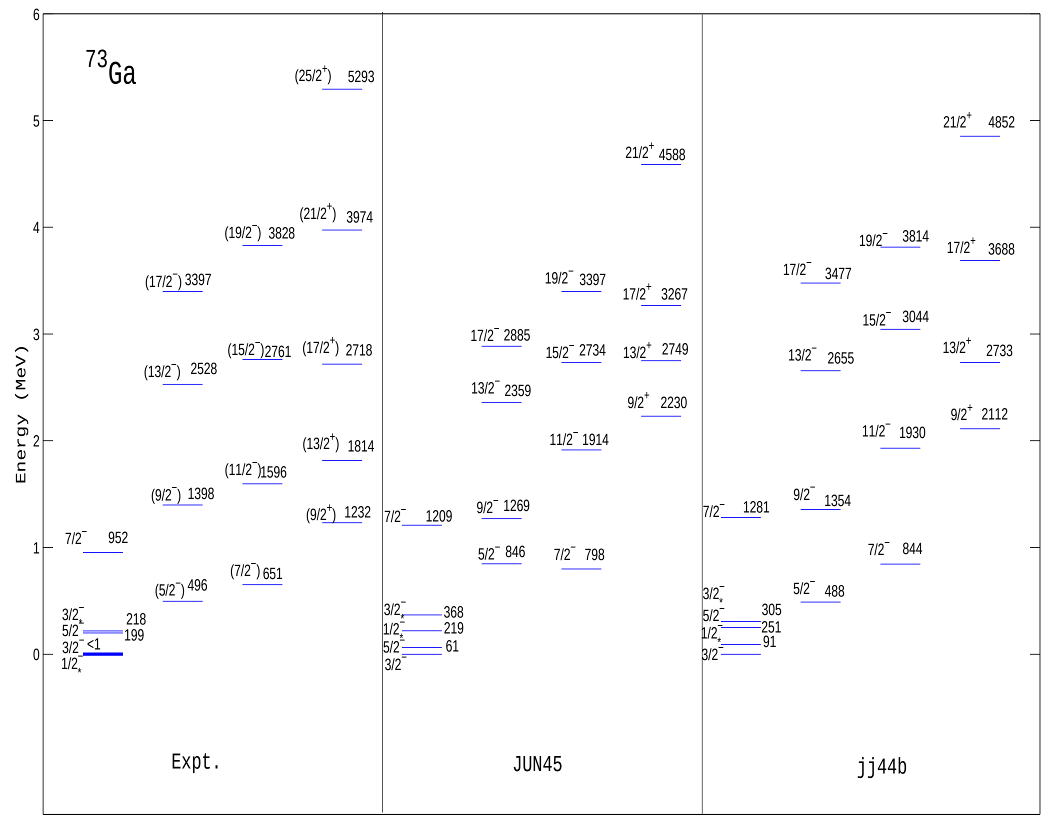

Figure 4. Same as figure 3 for ^{73}Ga.

and 161 e^{2}fm^4. The results of band built on $7/2^-$, is better for jj44b in comparison to JUN45. The band built on $9/2^+$, with the JUN45 interaction, predicted $9/2^+$, $13/2^+$, $17/2^+$, $21/2^+$ are at 2230, 2749, 3267 and 4588 keV, while its corresponding experimental values are 1232, 1814, 2718 and 3974 keV respectively. The jj44b interaction predict first $9/2^+$ at 2112 keV. The occupancy of first $g_{9/2}$ orbital is predicted by JUN45 and jj44b interaction as 0.92 and 0.83 respectively. The wave function contribution for the ground state and first excited states of ^{73}Ga are shown in Table 5.

3.1.3. **^{75}Ga :** In the earlier β decay experiment, Aleklett *et al.*, predicted three lowest levels in ^{75}Ga are at 228, 432 and 606 keV [40]. Latter on in [38], it is shown that this 228 keV level corresponds to second exited level of ^{75}Ga using (d,^{3}He) reaction. However spin value is not determined for any level in this study also. In [41] the sequence of negative-parity levels and positive-parity states above $9/2^+$ have been shown. In Fig. 5, experimental data for ^{75}Ga are compared with the calculated energy levels using JUN45 and jj44b interaction. Stefanescu *et al.* [25], predicted bands built on $3/2^-$,

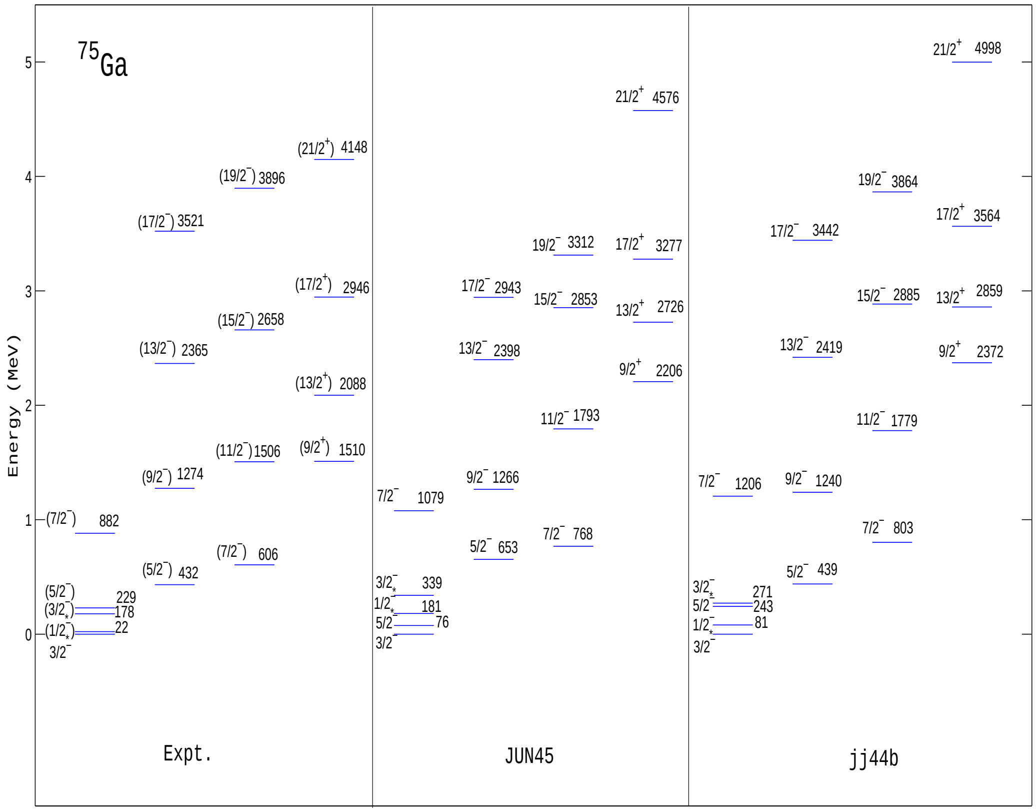

Figure 5. Same as figure 3 for ^{75}Ga.

$5/2^-$, $7/2^-$ and $9/2^+$.

The band built on $3/2^-$, reproduced correctly by JUN45 and jj44b interaction. The band built on $5/2^-$, is more correctly reproduced by jj44b interaction. The results of band built on $7/2^-$ is more better for jj44b. These results show that the yrast sequence of levels $7/2^-$–$11/2^-$–$15/2^-$–$19/2^-$ is connected with strong $E2$ transitions. The $B(E2)$ values for $11/2^-\rightarrow7/2^-$,$15/2^-\rightarrow11/2^-$, $19/2^-\rightarrow15/2^-$, are 278, 109 and 92 e^2fm^4 respectively with JUN45 and corresponding values for jj44b are 388, 368 and 281 e^2fm^4. The band built on $9/2^+$, with the JUN45 interaction, predicted $9/2^+$, $13/2^+$, $17/2^+$, $21/2^+$ are at 2206, 2726, 3277 and 4576 keV, while its corresponding experimental values are 1510, 2088, 2946 and 4148 keV respectively. The jj44b interaction predict first $9/2^+$ at 2372 keV. The occupancy of $g_{9/2}$ orbital is 0.96 and 0.49 predicted by JUN45 and jj44b interaction respectively for first $9/2^+$. The ground state having configuration $\pi(p_{3/2}f_{5/2}^2)$ with partition 14.9 and 22.4% for JUN45 and jj44b interaction. The wave function contribution for the ground state and first excited states of ^{75}Ga are shown in Table 5.

3.1.4. ^{77}**Ga :** With the β decay scheme of the $7/2^+$ ground state in ^{77}Zn the levels scheme of ^{77}Ga is reported in [41]. In this paper [41], based on experimental findings and shell model systematics, a spin and parity values of $9/2^+$ for the 2028.7 keV level is assigned.

Stefanescu *et al.* [25], predicted band built on $3/2^-$, $5/2^-$ and $9/2^+$. The band built on $3/2^-$, is reproduced correctly by JUN45 interaction, while levels are slightly higher with jj44b interaction. These results show that the yrast sequence of levels $3/2^-$–$7/2^-$–$11/2^-$ is connected with strong $E2$ transitions. The $B(E2)$ values for $7/2^-\rightarrow3/2^-$,$11/2^-\rightarrow7/2^-$, are 45 and 265 e^{2}fm^4 with JUN45 and corresponding value for jj44b is 38 and 310 e^{2}fm^4. The band built on $5/2^-$, is more correctly reproduced by jj44b interaction. The $B(E2)$ values for $9/2^-\rightarrow5/2^-$,$13/2^-\rightarrow9/2^-$, $17/2^-\rightarrow13/2^-$, are 135, 33 and 105 e^{2}fm^4 respectively with JUN45 and corresponding value for jj44b are 167, 78 and 101 e^{2}fm^4. The band built on $9/2^+$ is correctly reproduce by JUN45 interaction. The $13/2^+$ is predicted at 2724 keV by JUN45, while at 2345 keV by jj44b, which is slightly compressed. The wave function contribution for the ground state and first excited states of ^{77}Ga are shown in Table 5. The ground state as $3/2^-$ is predicted by both the interaction having configuration $\pi(p_{3/2}f^2_{5/2})$ with partition 35.7 and 24.5% for JUN45 and jj44b interaction respectively. The occupancy of $g_{9/2}$ orbital for first $9/2^+$ state is 0.96 for JUN45, while it is only 0.053 for jj44b interaction.

3.1.5. ^{79}**Ga :** For ^{79}Ga in [41], the g.s. $3/2^-$ is assigned in the β decay experiment of ^{79}Zn. A very low $5/2^-$ state at 5.3 keV is reported. Cheal *et al.* [28] also confirmed this findings and further proposed $7/2^-_1$, $7/2^-_2$ at 279 and 708 keV respectively. For this nucleus the experimentally first excited state i.e. $5/2^-$ is only 5 keV above. In Fig. 7, experimental data for ^{79}Ga are compared with the calculated energy levels using JUN45 and jj44b interaction. The jj44b interaction predict correctly $3/2^-$ as a ground state, while for JUN45 the inversion between $3/2^-$ and $5/2^-$ occur for this isotope. Experimentally the first $7/2^-$ is predicted at 279 keV, while calculated value for JUN45 and jj44b interaction is 1124 and 1026 keV. The calculated $9/2^-$ is slightly compress with jj44b in comparison to JUN45. Experimentally no positive parity states are known. But both the interaction predict $13/2^+$ lower in comparison to $9/2^+$. More experimental data is need to cheak the theoretical results. However recently B. Cheal *et al,* [28], reported that discrepancy between the experimentally observed moments and theoretically calculated value for ^{79}Ga is higher in comparison to other isotopes. The wave function contribution for the ground state and first excited states of ^{79}Ga are shown in Table 5. The JUN45 interaction predict $\pi(f^3_{5/2})$ configuration with 44% partition and jj44b predict $\pi(p_{3/2}f^2_{5/2})$ configuration with 39% . The occupancy of $g_{9/2}$ orbital for first $9/2^+$ state is 0.196 and 0.056 for JUN45 and jj44b interaction respectively.

3.1.6. ^{81}**Ga :** Experimentally ^{81}Ga reported in [28, 27]. The change in ground state from $3/2^-$ to $5/2^-$ occur, from ^{79}Ga to ^{81}Ga. In Fig. 8, experimental data for ^{81}Ga are compared with the calculated energy levels using JUN45 and jj44b interaction. The g.s.

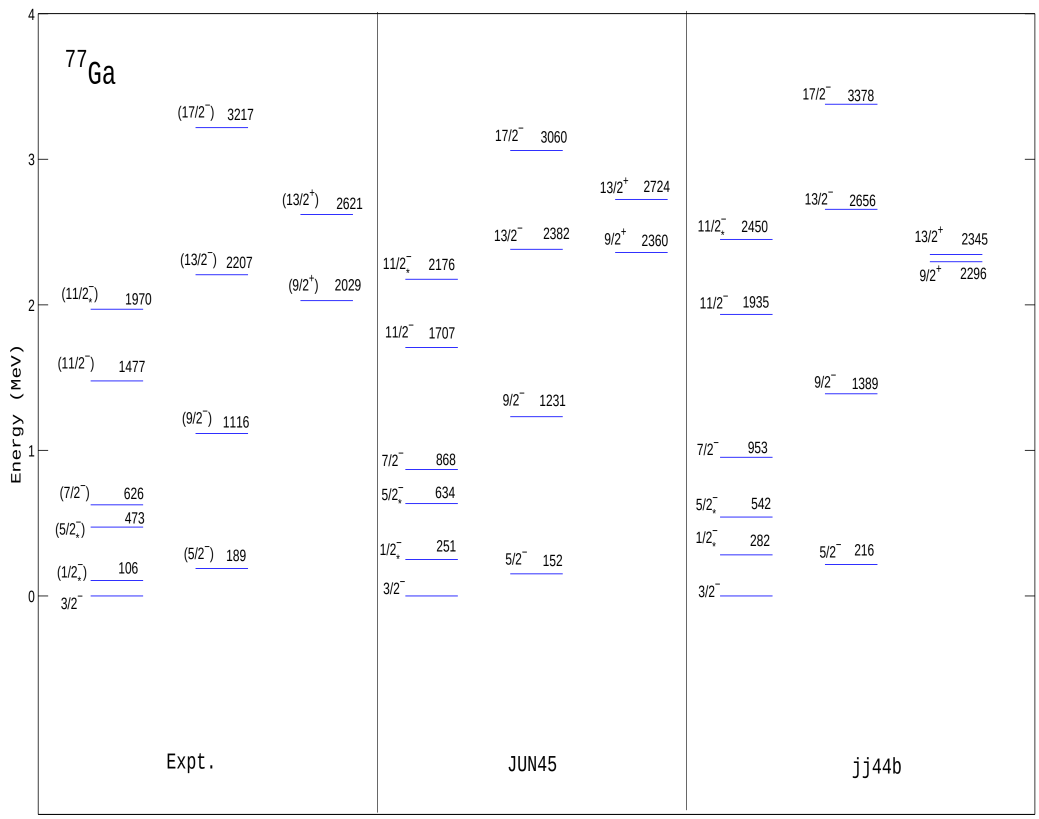

Figure 6. Same as figure 3 for ^{77}Ga.

is correctly predicted by both the interaction. The first $3/2^-$ experimentally observed at 351 keV, while JUN45 and jj44b interaction predicted it at 450 and 239 keV respectively. The wave function contribution for the ground state and first excited state of ^{81}Ga are shown in Table 5. The JUN45 and jj44b interaction predict $\pi(f^3_{5/2})$ configuration for g.s. with partition 79 and 75% respectively. The first excited $3/2^-$ have configuration $\pi(p_{3/2}f^2_{5/2})$ with partition 51 and 78% for JUN45 and jj44b interaction respectively. Thus it simply reflects that the three protons placed in the $f_{5/2}$ and $p_{3/2}$ orbits. For this isotope it is interesting to see the $Z = 28$ proton core polarization effect by including $f_{7/2}$ orbit in the model space.

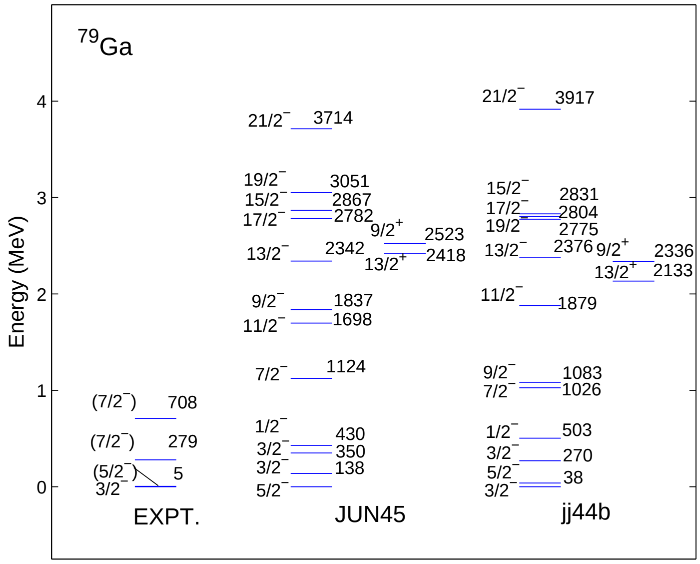

Figure 7. Same as figure 3 for ^{79}Ga.

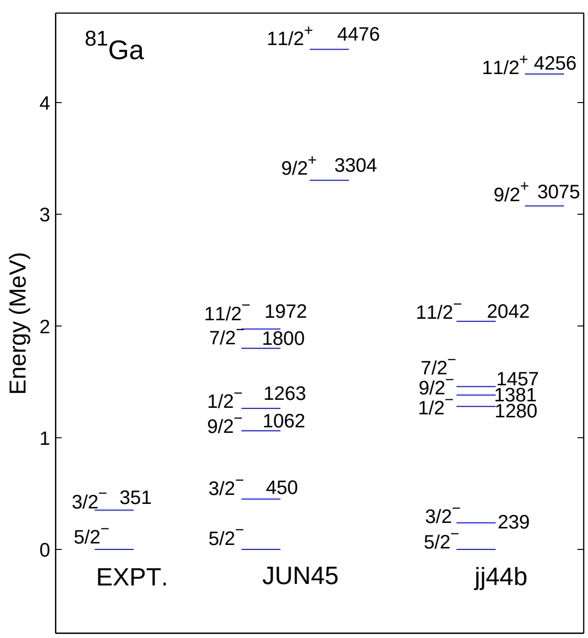

Figure 8. Same as figure 3 for ^{81}Ga.

Table 2. Calculated B(E2) values for some transition for $^{71-73}$Ga isotopes with standard effective charges: $e^{\pi}_{\rm eff}$=1.5e, $e^{\nu}_{\rm eff}$=0.5e (the experimental γ-ray energies corresponding to these transitions are also shown).

Nucleus	$I_i^\pi \rightarrow I_i^\pi$	E_γ (keV)	$B(E2)$ (W.u.)		
			Expt.	JUN45	jj44b
^{71}Ga	$5/2_2^- \rightarrow 3/2_1^-$	965	9.0(5)	4.43	16.82
	$7/2_1^- \rightarrow 3/2_1^-$	1107	0.8(1)	1.12	4.34
	$7/2_2^- \rightarrow 3/2_1^-$	1395	2.8(4)	1.77	8.38
^{73}Ga	$5/2_1^- \rightarrow 1/2_1^-$	199	11.0(2)	7.58	7.36
	$3/2_2^- \rightarrow 1/2_1^-$	218	7.5(10)	11.62	7.92
	$5/2_2^- \rightarrow 1/2_1^-$	496	6.5(10)	3.65	6.38
	$5/2_3^- \rightarrow 1/2_1^-$	1395	3.0(7)	0.265	2.60
^{75}Ga	$3/2_2^- \rightarrow 3/2_1^-$	178	-	9.44	4.47
	$5/2_2^- \rightarrow 3/2_1^-$	229	-	0.09	0.28
	$7/2_2^- \rightarrow 3/2_1^-$	606	-	0.34	5.09
^{77}Ga	$5/2_1^- \rightarrow 3/2_1^-$	189	-	0.75	7.62
	$3/2_2^- \rightarrow 3/2_1^-$	473	-	7.40	6.74
	$7/2_2^- \rightarrow 3/2_1^-$	626	-	2.30	1.94
^{79}Ga	$3/2_2^- \rightarrow 3/2_1^-$	-	-	0.07	0.85
	$7/2_2^- \rightarrow 3/2_1^-$	279	-	7.53	4.98
	$11/2_1^- \rightarrow 7/2_1^-$	-	-	6.32	2.23
	$13/2_1^- \rightarrow 9/2_1^-$	-	-	4.96	5.56
^{81}Ga	$9/2_1^- \rightarrow 5/2_1^-$	-	-	3.44	3.68
	$11/2_2^- \rightarrow 7/2_1^-$	-	-	3.71	4.42

3.2. Electromagnetic Properties

Recently Diriken *et al.* [26], experimentally measured the $B(E2)$ values for transitions in ^{71}Ga and ^{73}Ga at REX-ISOLDE. To investigate these experimental values theoretically, we have calculated $B(E2)$ values for the $^{71-81}$Ga isotopes with standard $e_p = 1.5e$ and $e_n = 0.5e$ which are shown in Table 2. For ^{71}Ga, JUN45 interaction predict better result in comparison to jj44b. For ^{73}Ga, the calculated results with jj44b interaction are closer to the experimental results than the JUN45 interaction.

The calculated magnetic moments for $^{71-81}$Ga, with three set of an effective $g_s = g_{free}$; $g_s = 0.7g_{free}$ and $g_s = 0.9g_{free}$ are shown in table 3. These results shows that for $g_s = 0.7g_{free}$ results are more reasonable in comparison to experimental data.

We have also calculated static quadrupole moments for the ground state for $^{71-81}$Ga with two set of effective charges, first with standard i.e. $e_p^{eff} = 1.5e, e_n^{eff} = 0.5e$ and also with $e_p^{eff} = 1.5e, e_n^{eff} = 1.1e$. For ^{71}Ga, JUN45 interaction predict correct sign of quadrupole moment; while the jj44b result is negative, suggesting prolate shape. Both

Table 3. The calculated magnetic moments and its corresponding experimental value. The results of $g_s = 0.7g_{free}$ are reported in [28].

Nucleus	I	$\mu_{expt}(\mu_N)$	$g_s = g_{free}$		$g_s = 0.7g_{free}$		$g_s = 0.9g_{free}$	
			$\mu_{JUN45}(\mu_N)$	$\mu_{jj44b}(\mu_N)$	$\mu_{JUN45}(\mu_N)$	$\mu_{jj44b}(\mu_N)$	$\mu_{JUN45}(\mu_N)$	$\mu_{jj44b}(\mu_N)$
^{71}Ga	3/2	+2.562	+2.645	+2.832	+2.188	+2.203	+2.492	+2.622
^{73}Ga	1/2	+0.209	-0.414	-0.456	-0.130	-0.176	-0.319	-0.362
^{75}Ga	3/2	+1.836	+3.133	+2.703	+2.441	+2.093	+2.902	+2.500
^{77}Ga	3/2	+2.020	+3.160	+2.685	+2.463	+2.146	+2.927	+2.505
^{79}Ga	3/2	+1.047	+3.262	+2.500	+2.543	+2.070	+3.022	+2.357
^{81}Ga	5/2	+1.747	+0.863	+0.888	+1.461	+1.477	+1.063	+1.084

Table 4. The calculated quadrupole moments with different set of effective charges and experimental value. The results of Set II are reported in [28].

Nucleus	I	$Q_{s,expt}$(eb)	Set I ($e_p^{eff} = 1.5e; e_n^{eff} = 0.5e$)		Set II ($e_p^{eff} = 1.5e; e_n^{eff} = 1.1e$)	
			$Q_{s,JUN45}$(eb)	$Q_{s,jj44b}$(eb)	$Q_{s,JUN45}$(eb)	$Q_{s,jj44b}$(eb)
^{71}Ga	3/2	+0.106	+0.163	-0.168	+0.192	-0.244
^{73}Ga	1/2	0	0	0	0	0
^{75}Ga	3/2	-0.285	-0.113	-0.191	-0.149	-0.256
^{77}Ga	3/2	-0.208	-0.163	-0.116	-0.203	-0.147
^{79}Ga	3/2	+0.158	-0.172	-0.052	-0.207	-0.057
^{81}Ga	5/2	-0.048	+0.044	-0.034	+0.044	-0.035

the interactions, predicts correct sign in ^{75}Ga and ^{77}Ga, which have prolate shape. For ^{79}Ga, the experimental data suggest oblate shape while both the interaction predict prolate shape. The change in sign of quadrupole moments from ^{73}Ga, i.e. $N = 40$ onwards, demonstrate a changing shell structure. For ^{79}Ga and ^{81}Ga, the change in sign for the calculated and experimental value have been found. The discrepancy between the theoretical and experimental quadrupole moment is not known. If we take large value of effective charges, it increases magnitude of the quadrupole moments, but the signs is remained unchanged. The possibility of proton excitations across Z=28 may play important role, by including the proton $f_{7/2}$ orbital in the model space.

Table 5. Main configurations in the wave functions of the ground state (gs) and first exited states (1^{st} exc.) of $^{71-81}$Ga isotopes calculated with JUN45 and jj44b interaction.

Nuclei	Interaction	State	J^π	Main Configuration
^{71}Ga	JUN45	gs	$3/2^-$	29% $(\pi(p^3_{3/2}))$+...
		1^{st} exc.	$5/2^-$	16% $(\pi(p^2_{3/2}f_{5/2}))$+...
	jj44b	gs	$3/2^-$	12% $(\pi(p^1_{3/2}f^2_{5/2}))$ +...
		1^{st} exc.	$1/2^-$	8% $(\pi(p^1_{3/2}f^2_{5/2}))$+...
^{73}Ga	JUN45	gs	$3/2^-$	23% $(\pi(p^3_{3/2}))$+...
		1^{st} exc.	$5/2^-$	18% $(\pi(p^2_{3/2}f_{5/2}))$+...
	jj44b	gs	$3/2^-$	14% $(\pi(p^1_{3/2}f^2_{5/2}))$+...
		1^{st} exc.	$1/2^-$	7% $(\pi(p^1_{3/2}f^2_{5/2}))$+...
^{75}Ga	JUN45	gs	$3/2^-$	15% $(\pi(p^1_{3/2}f^2_{5/2}))$+...
		1^{st} exc.	$5/2^-$	22% $(\pi(p^2_{3/2}f^1_{5/2}))$+...
	jj44b	gs	$3/2^-$	22% $(\pi(p^1_{3/2}f^2_{5/2}))$+...
		1^{st} exc.	$1/2^-$	16% $(\pi(p^1_{3/2}f^2_{5/2}))$+...
^{77}Ga	JUN45	gs	$3/2^-$	36% $(\pi(p^1_{3/2}f^2_{5/2}))$+...
		1^{st} exc.	$5/2^-$	24% $(\pi(p^2_{3/2}f^1_{5/2}))$+...
	jj44b	gs	$3/2^-$	24% $(\pi(p^1_{3/2}f^2_{5/2}))$+...
		1^{st} exc.	$5/2^-$	13% $(\pi(f^3_{5/2}))$+...
^{79}Ga	JUN45	gs	$5/2^-$	44% $(\pi(f^3_{5/2}))$+...
		1^{st} exc.	$3/2^-$	60% $(\pi(p^1_{3/2}f^2_{5/2}))$+...
	jj44b	gs	$3/2^-$	39% $(\pi(p^1_{3/2}f^2_{5/2}))$+...
		1^{st} exc.	$1/2^-$	43% $(\pi(p^3_{3/2}))$+...
^{81}Ga	JUN45	gs	$5/2^-$	79% $(\pi(p^3_{3/2}))$+...
		1^{st} exc.	$3/2^-$	51% $(\pi(p^1_{3/2}f^2_{5/2}))$+...
	jj44b	gs	$5/2^-$	75% $(\pi(p^3_{3/2}))$+...
		1^{st} exc.	$3/2^-$	78% $(\pi(p^1_{3/2}f^2_{5/2}))$+...

4. Summary

In the present work, the results of large scale shell-model calculations for odd-mass $^{71-81}$Ga isotopes in $f_{5/2}pg_{9/2}$ model space using two recently derived effective interaction is reported. These results show that existence of band structure built on top of the $3/2^-$, $5/2^-$ and $9/2^+$ levels in $^{71-77}$Ga. The collective structure reflected in experimental data is not well reproduced in calculated values. For ^{71,73,75}Ga the calculated positive parity states are higher in energy and for ^{77,79}Ga the results are close to the experimental value. Our results, show that there is strong influence of the $\pi(f_{5/2})$ orbital in the ground state wave functions from ^{73}Ga ($N = 42$) onwards. The lowering of $f_{5/2}$ level probably due to attractive tensor interaction when neutrons start filling in $g_{9/2}$ orbital. The present interactions need more tuning and further inclusion of $\pi(f_{7/2})$ orbital in the model space. From experimental side to check the onset of collectivity measurement of $B(E2)$ and $B(M1)$ transition moments for these isotopes are needed.

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