Study of spectroscopic properties of some Ni, Cu and Zn isotopes in nuclear shell model

Priti Pandey[1], Vivekanand[1], K.Chaturvedi[1],* R.Gautam[2], R.Chandra[2]
[1]Department of Physics, Bundelkhand University, Jhansi – 284128 INDIA
[2]Department of Physics, Babasaheb Bhimrao Ambedkar University, Lucknow - 226025, INDIA
*email: kaushlendra_c@yahoo.co.in

Introduction

The nuclei around the *pf* shell region attract much attention and interest because of observed and expected phenomena, for instance, shape-coexistence, anomalously low-lying 0^+ excited states, various kinds of isomers, and double β decay. Among these, the evolution of the shell structure can be found in many nuclei. The measured mass systematic shows the narrowing of the N = 50 shell gap toward Z = 32 [1], while the persistence of the N = 50 shell closure is suggested in ^{80}Ge based on the $B(E2)$ data [2]. In Cu isotopes, the large energy gap above the $19/2^-$ state in ^{71}Cu [3] is interpreted as a support of the stability of the N = 40 shell gap. On the other hand, beyond N = 40, the low excitation energies of $1/2^-$ states and the measured large $B(E2)$ values among low-lying states in ^{71}Cu and ^{73}Cu indicate an onset of collective effects [3]. A unified shell-model approach has contributed critically to detailed understandings and quantitative predictions in lighter-mass regions. Fukui [4] and the USD interactions [5] have been shown to be quite successful for the *p* shell and the *sd* shell, respectively. The KB3 interaction and its descendants [6,5] have been frequently used also for the *pf* shell but such an approach has been missing for the nuclei in the upper part of *pf* shell.

The effective interaction

To study the nuclei in the upper *pf* shell, an effective interaction is used in the model space consisting of four spherical orbits, namely the single-particle orbits $p_{3/2}$, $f_{5/2}$, $p_{1/2}$, and $g_{9/2}$. The model space is called f_5pg_9 shell. The f_5pg_9 model space has been adopted in several investigations. Xi and Wildenthal [7] developed an empirical effective interaction for the N = 50 isotones. Lisetskiy *et al.* have proposed effective interactions [8] for Z = 28 isotopes and N = 50 isotones separately in the f_5pg_9 shell. For many nuclei in the middle of the present f_5pg_9 shell, very large $B(E2)$ values are observed experimentally for transitions among low-lying states, suggesting a significant deformation. The present model space is insufficient to describe such a large quadrupole collectivity because of the lack of the $f_{7/2}$ orbit in the $N_{\rm osc}$ = 3 shell and the $d_{5/2}$ orbit in the $N_{\rm osc}$ = 4 shell, both important orbits needed to account for the development of such a collectivity. Therefore, the data on nuclei with N <46 and Z > 33 is excluded. As a result, the target nuclei for which a reasonable description is expected within the f_5pg_9 shell are mainly the $Z \sim 32$ nuclei and the $N \sim 50$ nuclei. The present inert core ^{56}Ni is soft and single-particle energies are taken to be −9.8280, −8.7087, −7.8388, and −6.2617MeV for the $p_{3/2}$, $f_{5/2}$, $p_{1/2}$, and $g_{9/2}$ orbit, respectively.

Results and discussion

Using the above single particle energies and f_5pg_9 interaction, the spectroscopic properties namely the excitation energies of corresponding J^π states, electric quadrupole moments and magnetic dipole moments are calculated for ^{58,60,61,62,64}Ni, ^{63,65}Cu and ^{63,64,65,68,69,70}Zn isotopes. These results are compared with experimental data. The calculated excitation energies along with experimental data for some of the Ni and Zn isotopes stated above are shown in Table 1 while electric quadrupole moments are shown in Table 2. In Table 3, the magnetic dipole moments are presented. The calculation for all above stated isotopes along with Cu will be presented in the symposium.

Table 1- The experimentally observed and theoretically calculated values of excitation energies (E_x) of ^{58,60,61}Ni and ^{64,68,69}Zn isotopes

Nuclei	J^π	E_x (MeV)	
		Calcu.	**Exp.** [9]
^{58}Ni	2^+	1.298	1.454
^{60}Ni	2^+	1.634	1.333
^{61}Ni	$3/2^-$	0.080	0.000
^{64}Zn	2^+	0.943	0.992
^{68}Zn	2^+	1.104	1.077
^{69}Zn	$9/2^+$	0.000	0.439

Table 2- Comparison of quadrupole moments (Q) of ^{58,60,61}Ni and ^{64,68,69}Zn isotopes

Nuclei	J^π	Quadrupole moment (eb)		
		Q_1	Q_2	Q_{exp} [9]
^{58}Ni	2^+	-0.034	-0.074	-0.10(6)
^{60}Ni	2^+	-0.076	-0.167	0.03(5)
^{61}Ni	$3/2^-$	0.049	0.107	0.16(15)
^{64}Zn	2^+	-0.246	-0.343	-0.32(6)
^{68}Zn	2^+	-0.010	-0.034	-0.11(2)
^{69}Zn	$9/2^+$	-0.276	-0.432	-0.45(7)

Table 3- Comparison of magnetic moments (μ_N) of ^{58,60,61}Ni and ^{64,68,69}Zn isotopes

Nuclei	J^π	Magnetic moment (μ_N)		
		μ_{fth}	μ_{effth}	μ_{exp} [9]
^{58}Ni	2^+	-0.703	-0.492	0.076(18)
^{60}Ni	2^+	-0.271	-0.189	0.32(6)
^{61}Ni	$3/2^-$	-1.308	-0.916	-0.75(4)
^{64}Zn	2^+	0.842	0.804	0.89(6)
^{68}Zn	2^+	1.229	1.078	0.87(10)
^{69}Zn	$9/2^+$	-1.693	-1.157	1.157(2)

In Table 2, Q_1 and Q_2 correspond to two different choices of the effective charges: (e_p,e_n) = (1.5,0.5) and (1.5,1.1), respectively. It is seen that that the latter choice gives a better description for most of the data points and that the deviation between theory and experiment is large for those cases where the experimental error bar is large. The shell-model results for Ni exhibit a poor agreement with data, primarily due to the missing $f_{7/2}$ orbit. For Zn isotope, the results agree well with the experiment.In table 3, the magnetic moment operator used is

$$\boldsymbol{\mu} = g_s\,\boldsymbol{s} + g_l\,\boldsymbol{l}$$

where g_s and g_l are the spin and the orbital g factors, respectively. By using the free-nucleon factors g_s = 5.586, g_l = 1, for protons and g_s = −3.826, g_l = 0 for neutrons, the agreement between calculations ($\mu_{\rm fth}$) and experiment ($\mu_{\rm exp}$) appears to be reasonable. The small deviations present using free nucleon g factors disappear almost when we use effective spin g factors,

$$g(\text{eff.})s = 0.7g(\text{free})s .$$

Here, the "quenching" factor q_s = 0.7 is determined via a least squares fit to the experimental data [10]. In column 4, μ_{effth} are shown.

Conclusion

To summarize, we have calculated the spectroscopic properties of ^{58,60,61,62,64}Ni, ^{63,65}Cu and ^{63,64,65,68,69,70}Zn isotopes in f_5pg_9 model space. Complete results will be presented in the symposium.

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