Projected band-mixed spectra of Fe and Ni isotopes

Jyoti K. Parikh
Department of Science and Technology, New Mehrauli Road, New Delhi-29, India
(Received 21 August 1974)

The nuclear spectra of ^{54,56,58}Fe and ^{58,60,62}Ni are obtained by mixing various bands. The bands for each nucleus are obtained by considering the prolate and oblate Hartree-Fock solutions. The third band is obtained by considering two-particle–two-hole excitations on whichever is the lower solution of the above two. The states with definite angular momenta are projected and the orthogonalization is carried out to obtain the nuclear spectra. The Yukawa-Rosenfeld interaction (YR) and the Kuo-Brown interaction modified by McGrory *et al.* (KM) are used as the two-body interactions. The single particle energies are varied for each nucleus to give a good fit. A comparison between the interactions shows that the KM interaction for the Fe isotopes and the YR interaction for the Ni isotopes give better results. In general, the agreement with the experimental spectra is very good. However, the second 2^+ state in ^{56,58}Fe and ^{60}Ni cannot be explained by this model which considers only $K = 0$ bands. The high spin states have also been obtained. The effects of the band mixing on the nuclear spectra are discussed in detail for each nucleus.

[NUCLEAR STRUCTURE ^{54,56,58}Fe, ^{58,60,62}Ni calculated energy levels. Projected Hartree-Fock method, band mixing.]

I. INTRODUCTION

The ferrous and nickel isotopes are of particular interest in the f-p shell region because of several reasons: (i) they are not $f_{7/2}$ shell nuclei—i.e., the admixtures of p and $f_{5/2}$ shells with the $f_{7/2}$ shell cannot be ignored,[1] (ii) the nuclei change their shapes from prolate to oblate[1] in this region of mass number, and (iii) the most common assumption in the earlier methods—such as the shell model[2] and quasiparticle methods[3]—is that for more than eight particles outside the ^{40}Ca core, the $f_{7/2}$ shell is assumed to be filled and only the $p_{3/2}$, $p_{1/2}$, and $f_{5/2}$ shells are considered. However, recently calculations for the Ni isotopes were carried out taking the full $f_{7/2}$ shell into account[1,4,5]; holes in the $f_{7/2}$ shell have been found implying that the $f_{7/2}$ shell is not filled up and there is considerable configuration mixing with the other states.

Earlier Hartree-Fock-Bogoliubov (HFB) calculations by us[1] show that the occupation numbers of the neutron states of the ^{58}Ni are 6.8, 1.0, and 2.1 in the $f_{7/2}$, $f_{5/2}$, and p shells, respectively, and the proton occupation numbers are 5.2, 0.6, and 2.1 for the same states. Corresponding experimental numbers from the $(\alpha, {}^3\mathrm{He})$ and (α, t) experiments by Roussel *et al.*[6] are 6.7, 0.9, and 2.5 for the neutrons and 4.1, 0.7, and 2.8 for the protons.

Thus, the often made assumption of ^{56}Ni forming a doubly closed core has been questioned very frequently in the literature recently[1,5] and therefore some fresh calculations taking the entire f-p shell into account are required for those nuclei which are neither $f_{7/2}$ shell nuclei nor p-$f_{5/2}$ shell nuclei. For the heavier nuclei such as the Zn and Ge isotopes, $g_{9/2}$ needs to be considered and for the lighter isotopes such as the Ti and Cr isotopes which are near ^{40}Ca core, the $f_{7/2}$ shell approximation is adequate. This leaves us with ^{56,58}Fe and ^{58,60,62}Ni isotopes. The calculations for ^{54}Fe have been also carried out for reasons which will be given later in Sec. III.

To treat these nuclei in the exact shell model is a tedious numerical task and does not give insight into the bandlike structure which is experimentally observed. However, some calculations have been done using the exact shell model[7] but again using the $f_{7/2}$ shell closure approximation.

The method used here is that of the band mixing where several bands are obtained from the Hartree Fock (HF) calculations. In the Fe-Ni region, prolate and oblate solutions are quite close energetically. Therefore, both the shapes are considered and one more $K = 0$ band is obtained either by considering 2p-2h excitations or by obtaining the constrained HF solutions on whichever is the lowest of the above two. Having obtained these bands, the method of projecting the states with good angular momentum is used to obtain band-mixed spectra. However, the bands are not orthogonal and care has been taken to consider this. Two well known interactions, the Yukawa-Rosenfeld (YR) and the Kuo-Brown interaction[8] modified by McGrory, Wildenthal, and Halbert[9] (KM), are considered with varying single particle energies.

It turns out that this study throws considerable light on these interactions and brings out their merits and inadequacies and gives a guideline on how to obtain a better interaction by synthesizing

the best of both.

The method is discussed in the Sec. II. Section III includes a discussion of the effects of both the interactions and the effects of the band mixing on nuclear spectra of the Fe and Ni isotopes. The conclusions are given in Sec. IV.

II. METHOD

In this section we give the formalism for obtaining the band-mixed spectra from the two HF intrinsic states ϕ_K and $\phi_{K'}$ having the band quantum numbers K and K', respectively, which is such that it can be generalized for more than two bands as well. These intrinsic states may not be orthogonal. A method for solving such a problem has been described by Gunye[10] for two bands in a form which cannot be easily generalized for more than two bands. The present method is only different in its orthogonalizing procedure and only the outline is given.

First, one has to use the usual[1,11] projection method to obtain the states with good angular momenta and also to consider the off-diagonal terms such as $\langle\phi_K|HP^J|\phi_{K'}\rangle$ and $\langle\phi_K|P^J|\phi_{K'}\rangle$. Here H is the usual Hamiltonian

$$H=\sum_{\alpha}\epsilon_{\alpha}a_{\alpha}^{+}a_{\alpha}+\tfrac{1}{4}\sum_{\alpha\beta\gamma\delta}V_{\alpha\beta\gamma\delta}a_{\alpha}^{\dagger}a_{\beta}^{\dagger}a_{\delta}a_{\gamma}\ . \tag{1}$$

Here ϵ_α are the single particle energies and V is the two-body interaction. P^J is the projection operator.[1]

$$H^J_{KK'}=\langle\phi_K|HP^J|\phi_{K'}\rangle \tag{2}$$

and

$$N^J_{KK'}=\langle\phi_K|P^J|\phi_{K'}\rangle\ . \tag{3}$$

Here each $|\phi_K\rangle$ is normalized by the factor $(N^J_{KK'})^{-1/2}$. We want to solve the Schrödinger equation

$$(H^J-\mathcal{E}^JN^J)|\psi^J\rangle=0\ , \tag{4}$$

where

$$|\psi^J\rangle=\sum_{K'}C^J_{KK'}|\phi_{K'}\rangle\ . \tag{5}$$

Let U be the transformation which diagonalizes the matrix $N^J_{KK'}$

$$UN^J_{KK'}U^{-1}=\eta^J$$

or

$$\frac{1}{\sqrt{\eta^J}}UN^J_{KK'}U^{-1}\frac{1}{\sqrt{\eta^J}}=\delta_{KK'}\ , \tag{6}$$

where $\delta_{KK'}$ is the Kronecker δ symbol. Having obtained the orthogonal and orthonormal basis, one can get the solution of the Eq. (4) by applying similar transformation on

$$\mathcal{H}^J=\frac{1}{\sqrt{\eta^J}}UHU^{-1}\frac{1}{\sqrt{\eta^J}}\ . \tag{7}$$

The Eq. (4) is then rewritten as

$$(\mathcal{H}^J-\mathcal{E}^J)|\psi^J\rangle=0\ . \tag{8}$$

III. NUMERICAL RESULTS

A. Parameters

The parameters are essentially the two-body matrix elements (interaction) and the single particle energies (SPE). We have used two interactions: Yukawa-Rosenfeld with $V=51$ MeV [a phenomenological interaction (YR) to maintain continuity with our earlier calculations[1,4,12]] and Kuo-Brown[8] interaction modified by McGrory *et al.*[9] (KM) (to use the interaction which is obtained from the nucleon-nucleon scattering data).

The single particle energies were varied from nucleus to nucleus because in the density dependent HF method, if one uses the same density independent interaction, too much deformation is produced as the number of the nucleons gets larger. For example, the same YR interaction with the same SPE which gives remarkably good agreement for the Ti isotopes[12] by the projected HFB method gives very compressed spectra (i.e., large moment of inertia and too much deformation) for the Cr and Fe isotopes.[13] As a corrective measure, single particle energies are increased so as to reduce the configuration mixing, and thereby reducing the deformation to get "noncompressed" spectra.

TABLE I. The single particle energies (SPE) for various interactions and isotopes with respect to the $f_{7/2}$ shell. The proton and neutron SPE are the same. The mass quadrupole moments for the prolate and oblate shapes are given.

Nucleus	Interactions	SPE $p_{3/2}$	$p_{1/2}$	$f_{5/2}$	Q_P	Q_O
^{54}Fe	KM	2.5	4.5	6.5	10.68	−7.15
^{56}Fe	KM	3	5	7.5	24.01	−14.37
	YR	3	5	7.5	25.07	−14.47
^{58}Fe	KM	3.5	5.2	8.0	26.18	−18.65
	YR	3.5	5.2	8.0	26.66	−20.01
^{58}Ni	KM	2.5	4.3	6.5	14.95	−10.93
	YR	2.5	4.3	6.5	16.28	−18.29
^{60}Ni	YR	3.5	5.5	8.0	11.90	−20.77
^{62}Ni	YR	3.5	5.5	8.0	18.91	−15.26

These single particle energies are given in Table I for both the interactions. The mass quadrupole moments of these nuclei are also given in this Table. Note that in ^{54,56,58}Fe as the number of extracore nucleons gets larger, the SPE are adjusted to decrease the deformation. However, for ^{58}Ni, they are again roughly the same as in ^{54}Fe due to the fact that the $f_{7/2}$ shell is closed and the configuration mixing is automatically less and one does not have to adjust the SPE artificially to reduce the deformation as in the case of ^{56}Fe and ^{58}Fe. For ^{60}Ni again they are adjusted to compensate for too much deformation. For ^{62}Ni, however they are kept the same as in ^{60}Ni, because for this nucleus $p_{3/2}$ and $p_{1/2}$ states are "filled" and further deformation is not produced.

B. Solutions

In the Fe and Ni isotopes region the prolate and oblate solutions are very much near each other for both the interactions (see Table II). The nuclei ^{54,56,58}Fe and ^{58,62}Ni have prolate solutions lower than the oblate solutions. However, for ^{60}Ni, the reverse is the case. The third $K=0$ solution for a given nucleus is obtained by considering two-particle–two-hole excitations on whichever solution happens to be the lower of the two. Thus, the third band is constructed by considering the next unoccupied state as the occupied state thereby considering 2p-2h excitations.

Having obtained the solutions, we use the projection method to calculate the diagonal and off-diagonal matrix elements of the type $\langle\phi_K|HP^J|\phi_{K'}\rangle$ and $\langle\phi_K|P^J|\phi_{K'}\rangle$ and get the nuclear spectra after orthonormalization. The results of these calculations are discussed separately for each nucleus.

1. Nucleus ^{56}Fe

In this nucleus the prolate oblate solutions give the first two bands. Thie third band was obtained by the constrained HF method, where the HF solution is constrained to occupy the next unoccupied proton state while carrying out the HF iterations (rather than considering the next occupied state) after obtaining the solution with the minimum energy and then considering 2p-2h excitations as is done for the other nuclei. The SPE are roughly similar for both the interactions. Table II shows that the energies are lowered by 1 to 2 MeV after the projection. The band mixing brings down further the lowest 0^+ and pushes up the next two 0^+ states. The nuclear spectra are given in Fig. 1.

KM interaction. This interaction is very good in describing the lowest band. The lowest 2^+, 4^+, and 6^+ are obtained correctly. However, the second band has shifted upwards by 0.5 MeV. $K=2$ bands will have to be taken into account to explain the second 2^+ and 4^+ states. In the second band the 4^+ state comes below the 2^+ state and in the third band the 2^+ state comes below the 0^+ state due to the band mixing ("unmixed" states do not show this behavior). The third band starts at 5 MeV which is not yet observed experimentally.

YR interaction. The YR interaction gives the lowest band somewhat compressed and the 2^+, 4^+, and the 6^+ states are lower than the corresponding experimental states. The second band begins at 2.75 MeV which is roughly at the correct position. The third band starts at 4.5 MeV which is not observed experimentally. Band mixing puts the 4^+ of the second band below the 0^+ state—which

TABLE II. The intrinsic energies of the HF solutions for various nuclei and interactions are given in I. The letter P(O) indicates the prolate (oblate) nuclear shape. The projected energies ("unmixed") and the band-mixed energies of the 0^+ states are given in II and III, respectively.

		I HF energies			II Projected energies of the 0^+ states			III Band mixed energies of the 0^+ states		
Nucleus	Interaction	1	2	3	1	2	3	1	2	3
^{54}Fe	KM	−45.53(P)	−44.90(O)	−44.12(P)	−46.66	−46.50	−45.97	−46.72	−38.72	−34.78
^{56}Fe	KM	−45.18(P)	−42.38(O)	−41.86(P)	−46.78	−44.34	−43.80	−46.96	−43.14	−41.51
	YR	−46.40(P)	−45.60(P)	−44.18(O)	−47.56	−47.19	−45.57	−48.10	−45.73	−43.33
^{58}Fe	KM	−40.72(P)	−39.34(P)	−38.48(O)	−42.33	−41.06	−40.25	−42.65	−40.88	−39.23
	YR	−44.83(P)	−44.38(P)	−43.39(O)	−45.89	−45.63	−44.63	−46.52	−45.17	−43.42
^{58}Ni	YR	−61.75(P)	−60.35(O)	···	−63.51	−62.22	···	−63.57	−60.28	···
	KM	−59.06(P)	−58.71(O)	···	−60.54	−59.72	···	−60.66	−57.96	···
^{60}Ni	YR	−60.70(O)	−59.75(P)	−58.49(O)	−62.51	−61.16	−60.43	−62.63	−60.31	−59.07
^{62}Ni	YR	−61.56(P)	−60.87(O)	−58.99(P)	−62.90	−62.31	−60.92	−63.07	−60.96	−59.84

makes it disagree with the experiment by 0.7 MeV—and the 2^+ below the 0^+ state in the third band.

Apart from the above comments, there are some similar features of both the interactions. For both the interactions in the first band only the high spin states (we shall use this term to refer to the spins greater than 6) are affected by the band mixing except the lowest 0^+ states in that they come down in energy. In the second and third band however, the 0^+ states are pushed up by as much as 1.2 MeV. The 2^+ states are also pushed up roughly by 0.5 MeV. The 4^+ states of the second and third band do not deviate from their "unmixed" positions. The 6^+ states of both the bands are pushed up by roughly 0.5 MeV. The high spin states of both the bands are also pushed up.

Unfortunately, high spin states are not experimentally observed which can clearly distinguish between the two interactions in that the YR interaction gives many high spin states from 5 to 8 MeV which is not the case with the KM interaction. Inclusion of $K=2$ bands could explain some of the states between 2.5 to 4 MeV.

2. *Nucleus* ^{58}Fe

As indicated in Table II, two prolate and one oblate $K=0$ solutions are considered for both the interactions. The band-mixed spectra are given in Fig. 2.

KM interaction. In this interaction the second prolate solution is lower than the oblate solution. It gives reasonably good agreement in that the 0^+ and 2^+ states of all the three bands are roughly correct except that the second band has come down by 0.5 MeV and the 0^+ state of the third band is pushed up a little. The 4^+ state of the

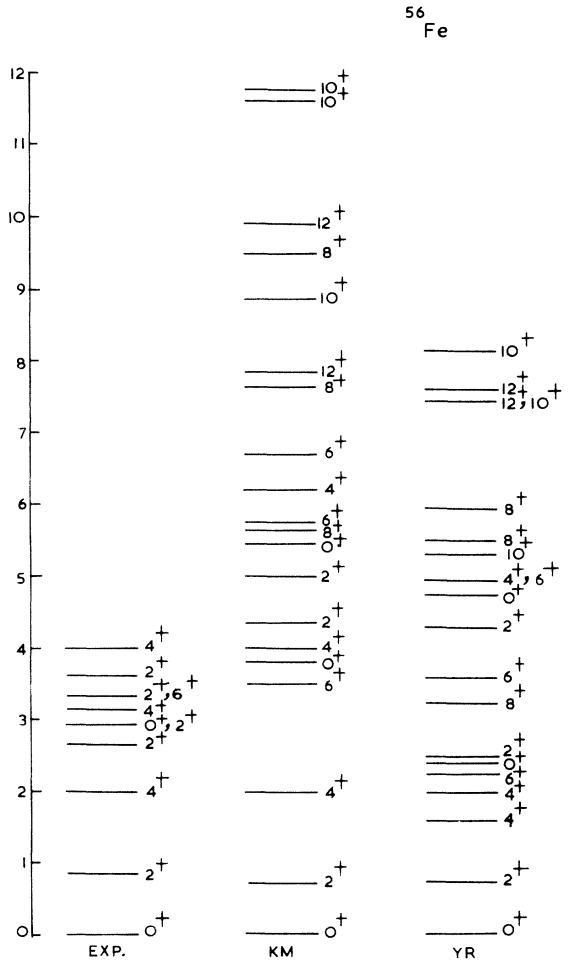

FIG. 1. The experimental (Ref. 14) and calculated nuclear spectra using the YR and KM interactions for three $K=0$ bands are given for the nucleus ^{56}Fe.

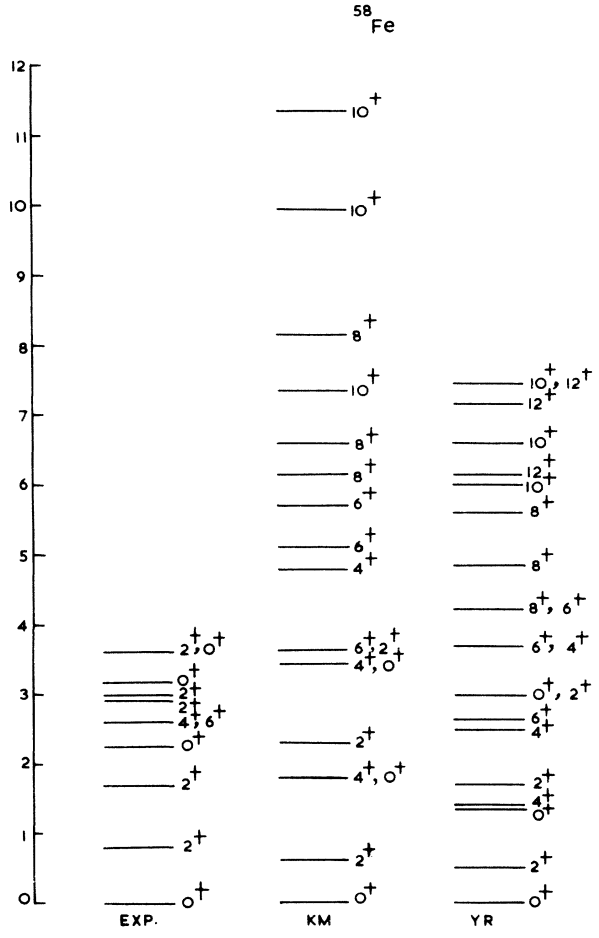

FIG. 2. The experimental (Ref. 15) and calculated nuclear spectra using the YR and KM interactions for three $K=0$ bands are given for the nucleus ^{58}Fe.

lowest band is lower and the 6^+ state is somewhat higher than the experimental positions. The high spin states occur after 6 MeV.

YR interaction. Here again, as in ^{56}Fe, the lowest band is quite compressed. The second and the third band start at 1.35 and 3.0 MeV instead of 2.5 and 3.5 MeV, respectively. The second band falls below the experimental value. However, the third band falls at the proper place. The high spin states start at 4.5 MeV which seems to be a bit too low. The experimental results show only one 4^+ state up to 4.5 MeV whereas our results show three of them. In the third band, due to the band mixing, the 0^+ and 2^+ states are degenerate states.

The common features for both the interactions are that neither of the interactions can explain the 2^+ state occuring at 1.67 MeV. However, the exact shell model calculations of McGrory[7] can explain this state. It seems this state can be explained in this model if one considers $K=2$ band. Except the 0^+ state which comes down by 0.25 MeV, none of the states of the lowest band deviate from their "unmixed" positions. In fact there is not very appreciable difference between the band-mixed and unmixed spectra obtained with the KM interaction. The YR interaction, also has very little band mixing and only the states in the third band are pushed up due to the band mixing. In short, for this nucleus also, KM interaction appears to be better than the YR interaction.

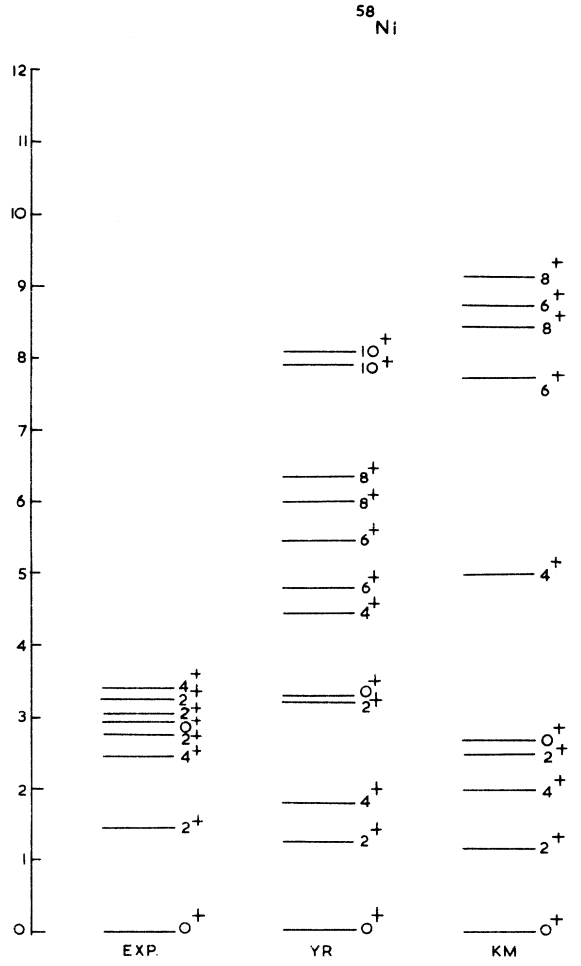

FIG. 3. The experimental (Ref. 16) and calculated nuclear spectra using YR and KM interactions for two $K=0$ bands are given for the nucleus ^{58}Ni.

3. *Nucleus* ^{58}*Ni*

In this nucleus only the prolate and oblate $K=0$ solutions are considered because the solutions obtained by neutron 2p-2h excitations on the prolate solutions (both the interactions give prolate shape) introduce numerical inaccuracies. This may be because of the fact that ^{58}Ni is quite close to ^{56}Ni and in this region, which is not too much deformed, only two solutions are possible.

Figure 3 shows that in this nucleus both the interactions give similar results. The first 2^+ state is well reproduced and the 4^+ is below the experimental 4^+ state. Due to the band mixing, the second 2^+ comes below the second 0^+ state for both the interactions. However, these two states are slightly above the experimental state in the YR interaction. In the YR interaction the 6^+ and the high spin states come lower than in the KM interaction.

The band-mixing affects only the second 0^+ and 2^+ state which are pushed up from their unmixed positions; other states do not change much. In the YR interaction, the first 0^+ state gains 1.7 MeV and the second 0^+ state gains 2 MeV energy (as compared to the intrinsic energies) due to the projection (see Table III), whereas in the KM interaction, gain due to projection is 1.4 and 1 MeV for the first and the second 0^+ states, respectively.

4. *Nucleus* ^{60}*Ni*

In this nucleus two oblate and one prolate $K=0$ solutions are considered since the oblate solution is lower than the prolate solution. Only the YR interaction is used because it was found that the KM interaction does not give reasonable separation between the prolate and oblate solutions for any choice of SPE, i.e., either they are too close or too far apart or too spherical to apply the deformed HF projection method.

Figure 4 shows the nuclear spectra. The first 2^+ and the second 0^+ state are well reproduced. Inclusion of at least two $K=2$ bands seems to be necessary to obtain the 2^+ states at 2.15 and at 3.39

MeV. The first 4^+ state is 0.5 MeV below the experimental value. The third 0^+ and 2^+ are well reproduced. However, the 6^+ state is not observed experimentally. It seems the 4^+ state at 3.12 MeV could be explained by considering $K=2$ band. The 4^+ state at 5 MeV might be from the second $K=0$ band.

The band mixing does not change the states of the first and the second band but the states belonging the third band are pushed up by 0.5 to 1.8 MeV. The three 0^+ states deviate from the intrinsic energies by 1.9, 1.4, and 0.5 MeV, respectively. The high spin states occur after 6 MeV and they are not yet observed.

5. *Nucleus* ^{62}Ni

In this nucleus which has 28 protons and 34 neutrons, the $f_{7/2}$ shell for protons and the $f_{7/2}$, $p_{3/2}$, and $p_{1/2}$ shells for neutrons are filled up (in the single particle shell model). However, in the deformed HF model in the f-p shell space, this nucleus is somewhat deformed. Two prolate and one oblate $K=0$ solutions are considered using the YR interaction. The agreement shown in the Fig. 5 is excellent and all the states are reproduced quite well by this model. However, the third 0^+ and 4^+ states are somewhat higher than the experimental states.

The 6^+ state at 4.24 MeV is not yet observed. The rest of the 6^+ and 8^+ states are above 6 MeV. Due to the somewhat spherical nature of the intrinsic states, the higher states are not reliable. Due to the projection, the 0^+ states differ from the intrinsic states by 1.3, 1.4, and 2 MeV, respectively.

The band mixing lowers the states of the lowest band by a small amount. The 2^+ state and the 8^+ state of the second band are lowered by 2.3 and

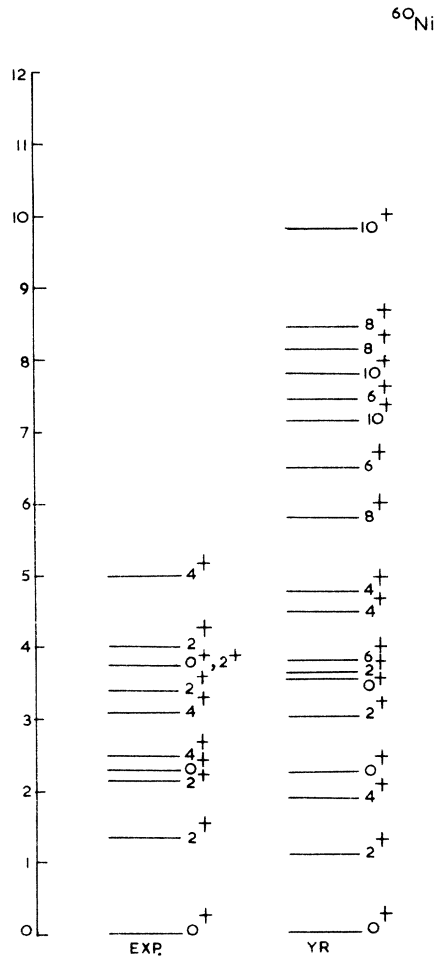

FIG. 4. The experimental (Ref. 17) and calculated nuclear spectra using the YR interaction for three $K=0$ bands are given for the nucleus ^{60}Ni.

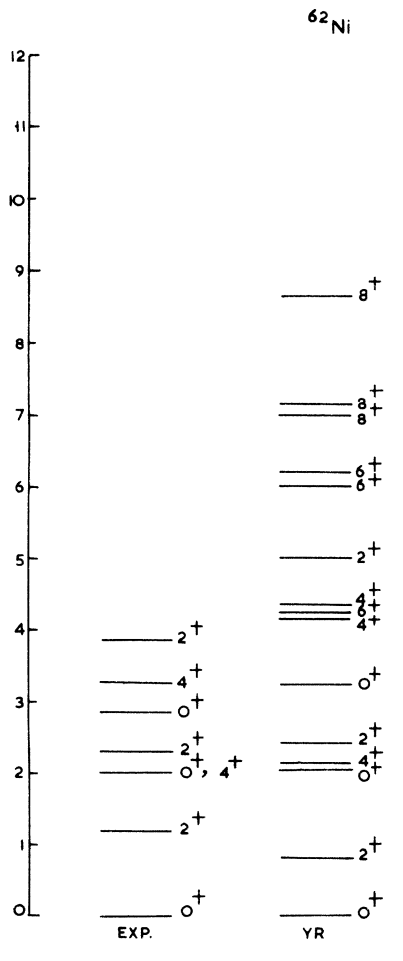

FIG. 5. The experimental (Ref. 17) and calculated nuclear spectra using the YR interaction for three $K=0$ bands are given for the nucleus ^{62}Ni.

0.9 MeV, respectively. The other states are not affected much. However, the 0^+ and 2^+ state of the third band are pushed up by as much as 3 MeV due to the band mixing. Due to this the 4^+ state of the third band is lower than the 2^+ state. Thus, the YR interaction with our choice of SPE seems very suitable for this nucleus.

6. *Nucleus* ^{54}Fe

This nucleus is considered by this method—although perhaps it could be treated by the "$f_{7/2}$ shell model" considering only the six protons in the $f_{7/2}$ shell—because the conclusion seems to emerge that the KM interaction is good for the Fe isotopes and the YR interaction is good for the Ni isotopes. The YR interaction gave either too much or too little deformation for ^{54}Fe for most of the choices of SPE and the calculations are not carried out for want of satisfactory deformed HF solutions. Here also, the prolate solution is the lowest as in the case of ^{56}Fe and ^{58}Fe. Oblate and the second prolate $K=0$ solutions were considered but the prolate and oblate solutions are too degenerate and numerical inaccuracies are introduced in such a case if both the bands are considered. Hence, only the prolate band is considered as we are only interested in verifying if the interaction is correct; besides, the experimental spectrum indicates that the $K=2$ band is more important than the $K=0$ band. Figure 6 shows that the agreement for the lowest band is excellent.

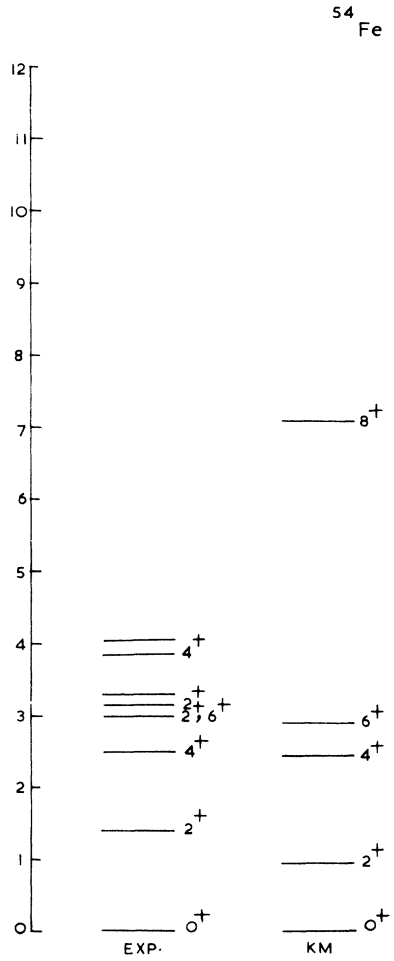

FIG. 6. The experimental (Ref. 18) and calculated nuclear spectra using the KM interaction for one $K=0$ band is given for the nucleus ^{54}Fe.

7. *Study of the two-body interactions*

In order to probe deeper into the reason why one interaction works better than the other for the Fe and Ni isotopes, we study the two-body matrix elements of both the interactions. Table III gives only these matrix elements for which either the difference between YR and KM interaction is greater than 0.5 MeV, or they play a significant role in the calculations. The rest of the matrix elements might average out to be the same statistically. (This is only an assumption and may

TABLE III. Some two-body matrix elements of the YR and KM interactions—where the differences between the two are significant—are given. The first four columns indicate $2j$ values for the indices j_1, j_2, j_3, and j_4. The difference is given in the last column. The asterisk (*) indicates that the sign of the matrix element depends upon the order of the indices.

Two-body state						YR matrix elements (MeV)	KM matrix elements (MeV)	(YR − KM) (MeV)
j_1	j_2	j_3	j_4	J	T			
7	7	7	7	0	1	−1.5470	−2.1100	0.5630
7	7	5	5	0	1	−1.9992	−2.7880	0.7888
7	7	7	7	1	0	0.4624	−0.5250	0.9874
7	7	5	5	1	0	3.5377	1.0710	2.4667
5	3	5	3	1	0	−2.7931	−2.1640	−0.6291*
3	3	3	1	1	0	2.4191	1.5540	0.8651*
3	3	1	1	1	0	1.8411	0.7090	1.1321
7	5	7	5	1	1	0.7616	−0.0370	0.7986
5	3	5	3	1	1	0.5559	−0.0320	0.5879
7	3	5	3	2	0	−1.6711	−1.1230	−0.5481*
7	3	5	1	2	0	2.2304	0.8380	1.3924*
7	3	3	7	2	0	−0.6171	0.2930	−0.9101*
7	7	7	7	2	1	−0.3689	−1.1100	0.7411
7	7	7	5	3	0	1.5963	1.0050	0.5913*
7	7	5	5	3	0	1.5521	0.5170	1.0351
7	5	7	5	6	0	−2.5160	−2.2170	−0.2990
7	5	7	5	6	1	−1.2478	−0.6440	−0.6038*
7	7	7	7	7	0	−2.516	−2.199	−0.315

not quite be true.)

The study shows that the $J=0$ $T=1$ matrix elements are less bound in the YR interaction than in the KM interaction. The same is true for $J=1$ $T=0$, $J=1$ $T=1$, and $J=2$ $T=0$. In fact, in the YR interaction, some of the matrix elements are repulsive whereas KM interaction shows them to be attractive. However, the matrix elements of $J=6$ $T=0$, $J=6$ $T=1$, and $J=7$ $T=0$ are more bound in the YR interaction. These differences are small but significant. Thus, on the whole, the matrix elements with high J values are more bound in the YR interaction and vice versa. (Note that in some of the matrix elements the phase may change if one considers the V_{1243} instead of the V_{1234} matrix element.)

This is the reason why the states with high spins are lower in the YR interaction and the intrinsic binding energies are larger. The Fe isotopes where the importance of the matrix element with low values of J is greater, the KM interaction seems to do better and vice versa.

IV. CONCLUSIONS

The $K=0$ deformed HF bands are mixed using the projection method for the Fe and Ni isotopes. This work shows that this choice of basis—the deformed HF intrinsic states—is better than that of the usual shell model where the single particle spherical states are used as basis for several reasons:

(i) It is possible to carry out the calculations in a larger space (such as the f-p shell here) even for heavy nuclei such as the Fe and Ni isotopes, without using any closure approximations. This way much more configuration mixing is taken into account.

(ii) In this basis, the bandlike nature of the nuclear spectra is very transparent and one can label each state with proper K, hence retaining the rotational-model type interpretation for each state.

(iii) Moreover, a study of interactions is possible by this method as it is not numerically exhaustive.

The results of the individual nuclei are discussed in Sec. III. The spectra of ^{54,56,58}Fe and ^{58}Ni calculated with the KM interaction agree quite well with the experimental spectra. The spectra of ^{58,60,62}Ni calculated with the YR interaction also agree very well. The lowest bands are well reproduced in most of the cases. The low spin states of the higher bands also do not deviate by more than 0.5 MeV. The band mixing can significantly alter some of the states from their unmixed positions.

Some of the observations regarding the interactions are that the matrix elements of the YR interaction are less bound for the two-body states with low J values and more bound for high J values than the similar matrix elements of the KM interaction. On the whole, the KM interaction gives better results than the YR interaction except for the ^{60,62}Ni isotopes. It is nonetheless impressive that the YR interaction which is a simple phenomenological interaction comes quite close to the KM interaction which is obtained with great effort.

In most of the cases the low lying states can be explained by considering $K=0$ bands. However, the second 2^+ states in the case of ^{58}Fe and ^{60}Ni are not explained by this model and the inclusion of $K=2$ band seems to be necessary. It is also necessary for explaining some of the states above 3.5 MeV in the cases of the other nuclei. The measurements of the states with the high spins are most desired to analyze this model further.

ACKNOWLEDGMENTS

The author is very grateful for the encouragement and interest shown by Dr. G. R. Udas and Mr. N. S. Bhalla of the Atomic Minerals Division of the Department of Atomic Energy where most of the work was carried out. Thanks are due the staff of the computer center of the India Meteorological Division for their kind cooperation and help in the computational aspects of this paper.

[1] J. K. Parikh, Phys. Rev. C 5, 153 (1972).
[2] S. Cohen *et al.*, Phys. Rev. 160, 907 (1967); N. Auerbach, *ibid.* 163, 1203 (1967); J. McCullen, B. Bayman, and L. Zamick, Phys. Rev. 134, B515 (1964).
[3] R. Raj, Y. Gambhir, and M. Pal., Phys. Rev. 163, 1004 (1967).
[4] J. K. Parikh, Phys. Rev. C 6, 2177 (1972); C 7, 1466 (1973).
[5] S. K. Sharma and K. H. Bhatt, Phys. Rev. Lett. 30, 620 (1973).
[6] P. Roussel *et al.*, Nucl. Phys. A155, 306 (1970).
[7] J. B. McGrory, Phys. Lett. 26B, 604 (1968).
[8] T. T. S. Kuo and G. E. Brown, Nucl. Phys. A114, 241 (1968).
[9] J. B. McGrory, B. H. Wildenthal, and E. C. Halbert, Phys. Rev. C 2, 186 (1970).
[10] M. R. Gunye, Phys. Rev. C 7, 216 (1973).
[11] J. K. Parikh, Phys. Lett. 41B, 271 (1972).
[12] K. Sandhyadevi, S. Khadkikar, J. Parikh, and B. Banerjee, Phys. Lett. 32B, 179 (1970).
[13] K. Sandhyadevi, S. Khadkikar, and B. Banerjee, Phys. Rev. C 7, 1010 (1973).
[14] R. J. Petersen, Ann. Phys. (N.Y.) 53, 40 (1969).

[15]U. Fanger, W. Michaelis, H. Schmidt, and H. Ottmor, Nucl. Phys. A128, 641 (1969).
[16]D. Start *et al.*, Nucl. Phys. A162, 35 (1971).
[17]W. Darcey, R. Chapman, and S. Hinds, Nucl. Phys. A170, 253 (1971).
[18]G. S. Mani, Nucl. Phys. A157, 471 (1971); W. S. Gray, R. A. Kenefick, and J. J. Kraushaar, Nucl. Phys. 67, 330 (1964).