

Deformation Projected RMF Calculation for Cr and Fe nuclei in Hybrid Derivative Coupling Model

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The ground state properties of even mass Cr and Fe isotopes are studied using the generalized hybrid derivative coupling model. The energy surface of each isotope is plotted as a function of the mass quadrupole moment. The neutron numbers $N=20$ and $N=40$ are seen to remain magic numbers but $N=28$ and 50 are predicted to be non-magic. The neutron number $N=70$ turns out to be a magic number according to the present calculation. In all the isotopes studied the calculated binding energy values are less than those obtained from experiment while the deformation is in better agreement.

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1. Introduction

Recent advances in producing light nuclei close to the drip line using radioactive ion beams has produced a renewed interest in the study of these nuclei. These nuclei, with extreme values of isospin, provide a testing ground of different theoretical models.

Relativistic mean field (RMF) calculations achieved considerable success in the description of various ground state properties of nuclei including the binding energy, deformation and charge radius throughout the periodic table.¹ In a related approach, Zimanyi and Moszkowsky used derivative coupling between the scalar meson and the nucleon.² One important problem of their model is that it predicts a high value of the effective nucleon mass and consequently a lower spin orbit splitting. A better description of various properties of nuclear matter at zero and finite temperature as well as finite nuclei can be obtained using the generalized hybrid derivative coupling model^{3,4} where both Yukawa point coupling and derivative coupling between the baryons and the scalar meson were used with a strength ratio $\alpha/(1-\alpha)$ where $\alpha = 0.25$. In a previous work⁵ we employed the generalized hybrid derivative coupling model to study the ground state of even-even Ne, Mg, Si and S isotopes. The deformation values obtained were close to the experimental measurements in most of the nuclei studied. In contrast, the conventional RMF models using the NL3 or NL-SH sets of parameters often fails to accurately predict the deformation in lighter nuclei. The success of the model in describing the shape of lighter nuclei prompted us to extend our study to Cr and Fe isotopes. The principal aim of this work is to study the deformation in these nuclei.

2. Calculation and Results

The details of the method of calculation have been presented in elsewhere^{4,5} and are not described here. The starting point is a scaled Lagrangian with both scalar and derivative $\sigma - N$ couplings. Under the usual approximations, *eg.* classical meson fields, time-reversal symmetry, point-like nucleons, no sea approximation, the surviving components for the the time independent equations, for the meson fields and the nuclear wave function are given in our earlier publications⁴ and are

not repeated here.

We have employed the BCS formalism in a constant gap approach. The gap parameters are either taken from the odd-even mass difference or calculated using the formula $\Delta_{n(p)} = 11.2/\sqrt{N(Z)}$. In the present work we have assumed axial symmetry and plotted the energy surface as a function of the mass quadrupole moment. The energy surface provides a better understanding of the deformed system. It indicates the possibility of shape co-existence and also, considering the shallowness of the minima, the possibility for nuclear shape to be triaxial. We have taken the numbers of oscillator shells for both Fermions and Bosons to be 12. Increasing the number of shells has very little effect on the total binding energy or the quadrupole deformation, even for very neutron rich nuclei. For example, in ^{82}Cr , if the number of each type of shell is taken to be 14, the total binding energy increases by only 0.3 MeV while there is no change in the shape of the energy surface.

In most of the nuclei we have studied, we have obtained more than one minimum, generally corresponding to prolate and oblate shapes. If one of the minima is much deeper than the other, we have assumed it to be the ground state. If the energies of the two are very close to each other and both of them are deep, one of them is possibly the true minimum. However, if both the minima are very shallow, the nucleus is more likely to be triaxial and the minima obtained are actually saddle points.

We have calculated the ground state binding energy and deformation values for $^{44-92}\text{Cr}$ and $^{48-96}\text{Fe}$, nuclei which are stable against nucleon drip according to the present model. Figures 1 and 2 represent the excitation energy surfaces as a function of the mass quadrupole deformation for Cr and Fe isotopes, respectively. The nature of the curves are similar to those obtained for lighter isotopes such as Ne, Mg, Si and S.⁵

Table 1 compares the calculated binding energy and deformation for Cr isotopes with experiment. In the case of Cr isotopes with neutron magic number $N=20$ and $N=40$, i.e. for ^{44}Cr and ^{64}Cr respectively, the ground state solutions are found to be spherical. In ^{46}Cr both the minima are very shallow indicating possible triaxiality. The ground state of the isotopes $^{48-58}\text{Cr}$ are prolate although the oblate

minima becomes progressively deeper with neutron number. The next two even Cr isotopes $^{60,62}\text{Cr}$ are found to be oblate though they actually may be triaxial. The ground state of ^{66}Cr turns out to be spherical. The earlier pattern of prolate minima being the ground state while the oblate minima getting deeper continues throughout $^{68-84}\text{Cr}$. The present work predicts the ground state of ^{86}Cr to be oblate. The isotopes $^{88,90}\text{Cr}$ are probably triaxial. The dripline nucleus ^{92}Cr is nearly spherical. In our calculation quadrupole deformation for $^{48-54}\text{Cr}$ isotopes are closer to the experimental values in comparison to the an earlier work. For example Lalazissis *et al*⁸ found ^{52}Cr to be spherical. In fact, all the available mean field calculations predict this nucleus to be spherical. In contrast our calculation predicts the deformation to be 0.345, closer to the experimentally measured value 0.224. The prediction of the ground state deformation of ^{52}Cr can be traced to the low spin-orbit splitting in the present model. In the conventional RMF calculation at zero deformation, using the parameter set NL3, the spin-orbit splitting between the neutron $1f_{7/2}$ and the $1f_{5/2}$ levels comes out to be nearly 8 MeV, a value double than that obtained in the present model, i.e. 4 MeV. Consequently, the shell gap is 4 MeV in the present approach, while conventional RMF calculations predict it to be nearly 8 MeV. The energy level spacing is very similar to that of the other N=28 nucleus studied in the present work, *viz.* ^{54}Fe , whose single particle energy levels at zero deformation are given later in Figure 3. The neutron number N=28 can no longer be considered as a magic number. The absence of the shell gap at N=28 signifies that the nucleus ^{52}Cr lies near neutron midshell and hence show a large deformation. All the other neighbouring Cr and Fe isotopes show this feature.

Table 2 compares the calculated and the experimental binding energy and deformation for Fe isotopes. In ^{48}Fe both the prolate and the oblate minima are very shallow. Hence the nucleus is likely to have a triaxial shape. In isotopes $^{50-60}\text{Fe}$ the prolate minimum is deeper than the oblate minimum. But the oblate minimum grows deeper as the neutron number increases and becomes the ground state at ^{62}Fe . The minima are comparatively shallow and the shape may actually be triaxial. The nucleus ^{64}Fe may also possibly be triaxial in its ground state. The neutron magic nucleus ^{66}Fe with N=40 is found to be spherical. The ground state

of ^{68}Fe is nearly spherical. Again from ^{70}Fe to ^{88}Fe the prolate minimum is deeper indicating it to be the ground state. In ^{90}Fe two minima are nearly equal. In ^{92}Fe the oblate minimum is slightly deeper but both the minima are very shallow indicating possible triaxiality. The nuclei $^{94,96}\text{Fe}$ are spherical. For ^{54}Fe and for ^{56}Fe , the deformation is slightly greater than experimental value. But for ^{58}Fe and ^{60}Fe deformations values are predicted with greater accuracy.

In all the isotopes studied the calculated values for binding energy are less than the experimental ones. This has been observed in our earlier work also.⁵ From the figures it is seen that both the Fe and Cr isotopes with neutron magic number $N=28$ and 50 are not spherical. Thus one feature that stands out is that $N=28$ and 50 are not magic numbers in our calculation. This is due to the fact that the splitting between the neutron $1f_{7/2}$ and $1f_{5/2}$ levels in the former and between the neutron $1g_{9/2}$ and the $1g_{7/2}$ levels in the latter are small. This is shown in figure 3 for ^{54}Fe and ^{76}Fe . Hence although $N=40$ is magic, $N=28$ and 50 are not. The $N=70$ nucleus, ^{96}Fe is spherical in its ground state. An examination of the single particle energy levels given in figure 3 reveal that the splitting between the neutron $1i_{11/2}$ and $1i_{9/2}$ is small. Thus the intruder orbital $1i_{11/2}$ lies higher up in energy and hence $N=70$ turns out to be magic.

3. Summary

To summarize we study ground state properties of Cr and Fe isotopes using the generalized hybrid derivative coupling model. The energy surface for each isotope is plotted as a function of the mass quadrupole moment. The neutron numbers $N=20$ and $N=40$ are magic numbers but $N=50$ turns out to be non-magic. The nucleus ^{96}Fe is predicted to be spherical in its ground state and $N=70$ turns out to be a magic number according to our calculation. In all the isotopes studied the calculated binding energy values are less than those obtained from experiment. However, the deformation is better in comparison to those in other works.

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Table 1: The calculated binding energy and deformation values for Cr isotopes. The results of the present calculation are compared with experimental values. The experimental binding energy and deformation values are from Ref. 6 and Ref. 7, respectively.

A	B.E. (MeV)		β		A	B.E. (MeV)		β
	Theo.	Expt.	Theo.	Expt.		Theo.	Theo.	
44	7.92	7.95	0.005		70	7.90	0.259	
46	8.17	8.30	0.258		72	7.75	0.341	
48	8.43	8.57	0.308	0.336	74	7.59	0.300	
50	8.50	8.70	0.355	0.293	76	7.42	0.286	
52	8.56	8.78	0.345	0.224	78	7.25	0.319	
54	8.57	8.78	0.296	0.250	80	7.09	0.265	
56	8.55	8.72	0.253		82	6.92	0.240	
58	8.52	8.64	0.214		84	6.76	0.217	
60	8.47	8.54	-0.132		86	6.62	-0.158	
62	8.43	8.43	-0.086		88	6.48	-0.150	
64	8.36		0.004		90	6.34	-0.099	
66	8.21		0.005		92	6.22	0.003	
68	8.05		0.223					

Table 2: The binding energy and deformation values for Fe isotopes. See caption of table 1 for details.

A	B.E. (MeV)		β		A	B.E. (MeV)	β
	Theo.	Expt.	Theo.	Expt.			
48	7.87	8.03	0.245		74	8.04	0.334
50	8.16	8.35	0.357		76	7.90	0.342
52	8.41	8.61	0.408		78	7.76	0.350
54	8.55	8.74	0.411	0.195	80	7.61	0.336
56	8.55	8.79	0.349	0.240	82	7.46	0.326
58	8.59	8.79	0.305	0.25	84	7.30	0.285
60	8.60	8.76	0.265	0.222	86	7.15	0.255
62	8.57	8.69	-0.153		88	7.01	0.213
64	8.54	8.61	-0.107		90	6.86	0.178
66	8.51	8.53	0.004		92	6.74	-0.105
68	8.39		0.004		94	6.61	0.001
70	8.27		0.218		96	6.50	0.000
72	8.16		0.277				

List of figure captions

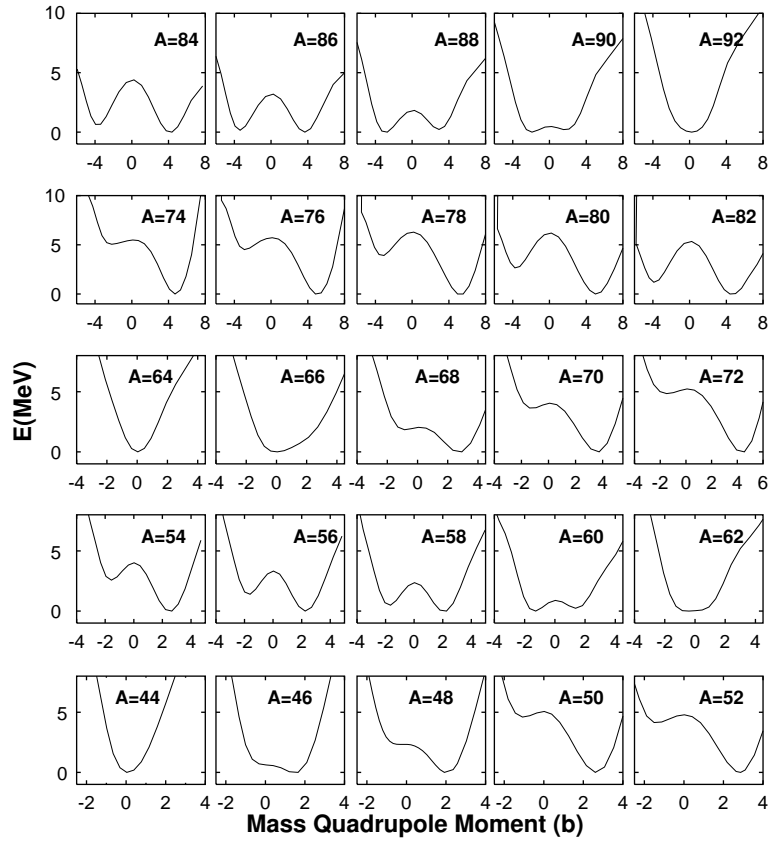


Figure 1: The excitation energy surfaces of different Cr isotope as a function of the mass quadrupole moment.

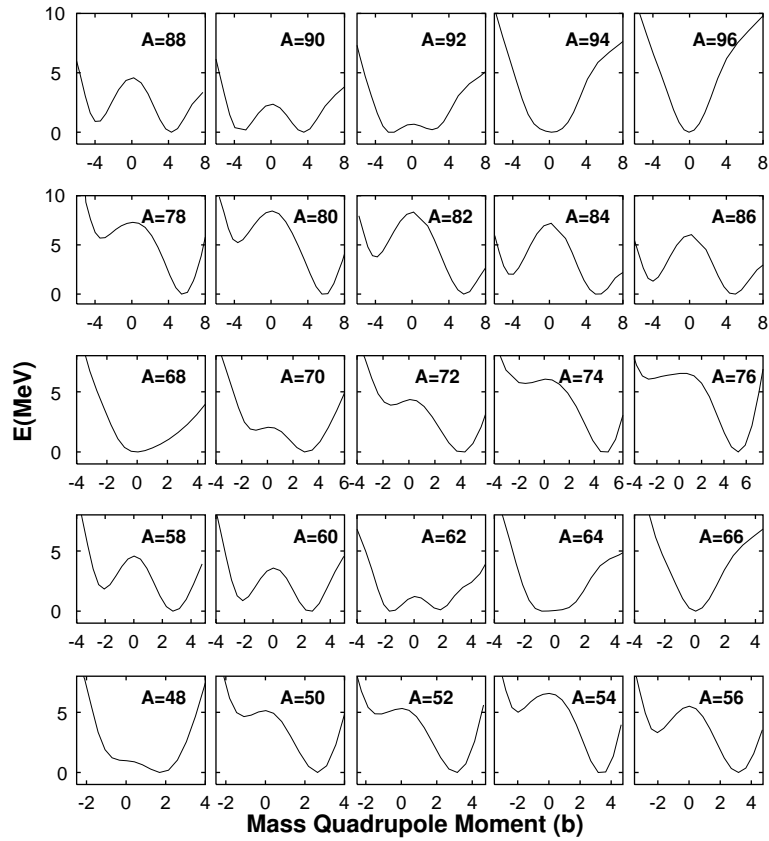


Figure 2: The excitation energy surfaces of different Fe isotope as a function of the mass quadrupole moment.

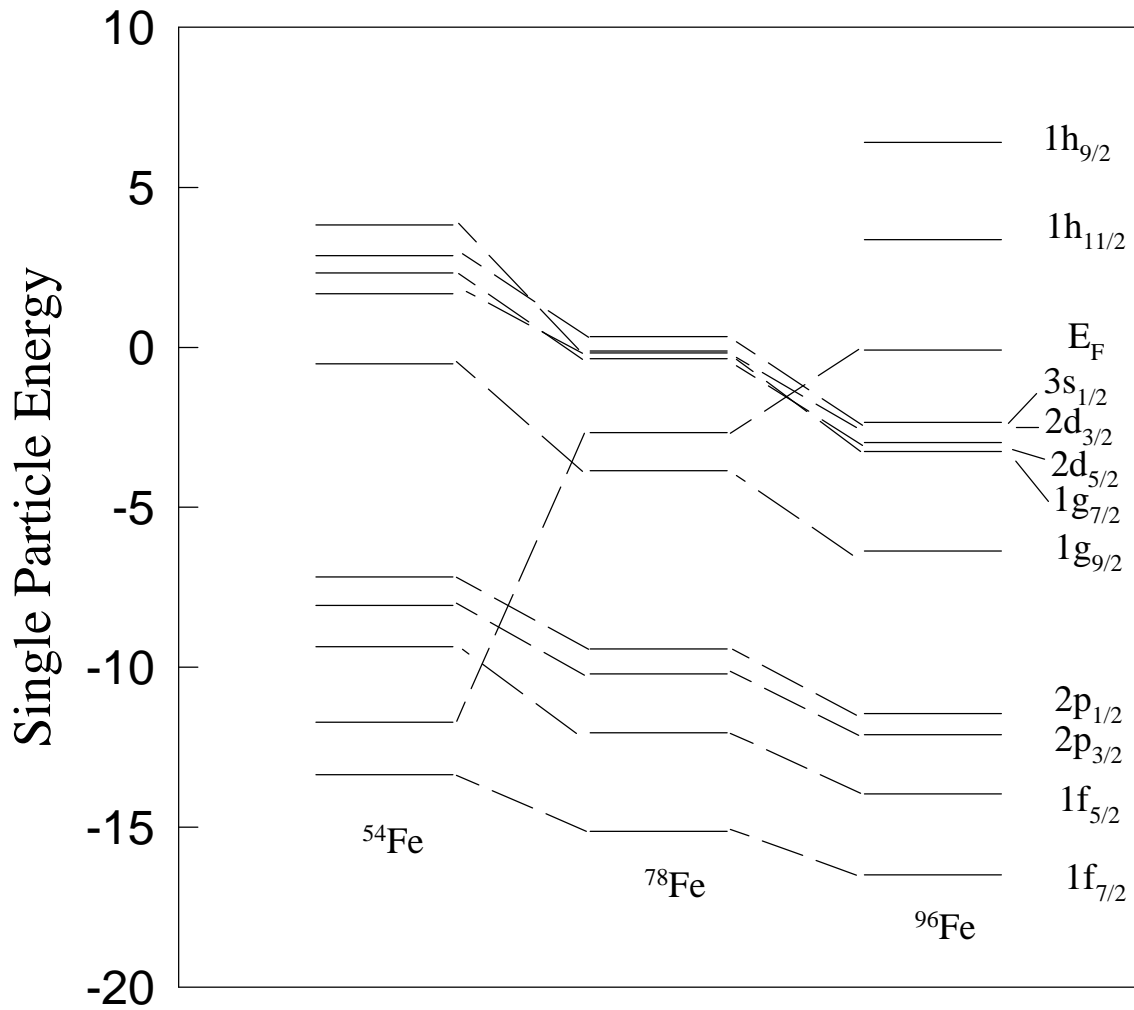


Figure 3: The neutron single particle energy levels of Fe isotopes at zero deformation for $N=28, 50$ and 70 . Here, E_F refers to the Fermi level.