

TIME ODD MEAN FIELD WITH DENSITY DEPENDENT  
MESON INTERACTION

متوسط المجال ذو الزمن الفردي مع تفاعل الميزونات المعتمدة على  
الكثافة

By

SAJA A. TITI

, 2017

Thesis committee: Dr. Hazem Abu Sara (Principal advisor)

Dr. Ismael Badran (Member)

Dr. Wafaa Khater (Member)

This Thesis was submitted in partial fulfillment of the requirements  
for the Master's Degree in Physics from the Faculty of Graduate  
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## DEDICATION

To the memory of my father, who taught me passion and ambition. For my mother for her continuous love and support, and to my sisters and brothers for their encouragement. To my fiance for his exceptional support during my study in past two year. To my amazing friend.

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## ABSTRACT

Time odd mean fields have been investigated over the last few years. The effect of time odd mean field on physical observables in nuclear system with broken symmetry using CDFT with non-linear meson coupling model have been studied. It was shown that the effect of this field come in form of additional binding. In our study, we analyze the physical observable for light odd-mass nuclei with using density dependent meson - interaction model with DD-ME2 parameter. We found the addition amount of binding energy for odd-mass light nuclei are less than 1.5 MeV for most of nuclei. The effect of time odd mean field on Single particle energy states are studied. Also, we investigated the effect of the shape of nuclei on time odd mean field.

## ملخص

لقد تم دراسة متوسط المجالات ذو الازمنة الفردية في السنوات القليلة الماضية. تأثير هذه المجالات على الكميات الفيزيائية التي يمكن قياسها في الانظمة النووية المتأثرة بحالة التماثل غير الكامل تم تحليلها باستخدام نظرية CDFT معتمد على النموذج غير الخطي لاقتزان الميزونات. لقد وجد ان تأثير هذه المجالات كان على شكل زيادة في طاقة الربط النووية للنيكونات. قمنافي هذا البحث بدراسة هذه الكميات باستخدام نموذج اخر وهو اقتزان الميزونات المعتمدة على الكثافة، باستخدام معاملات DD-ME2 لقد وجدنا ان هناك ايضا زيادة في طاقة الربط النووية، ولكن هذه الزيادة هي اكبر من تلك التي تم حسابها باستخدام النموذج غير الخطي وتصل هذه الزيادة ل اقل من 1.5 ميجا الكترون فولت في معظم الانوية الخفيفة التي تمت دراستها. تأثير هذه المجالات على مسارات الطاقة الاحادية للنيوكونات، ومدى تاثر هذه المجالات بشكل الانوية ظواهر تم دراستها ايضا.

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## CHAPTER 1

### INTRODUCTION

Over the years self consistent many-body theories were developed, with the purpose to study the structure of atomic nuclei and related nuclear phenomena at low energy. They provide a theoretical tool to explore the nuclear chart and categorize it into known and unknown regions.

Both density functional theory (DFT) and effective field theory (EFT) provide new tools that overcome the difficulties that faces many-body theories, leading to a better understanding of nuclear forces and achieve a better description of atomic nuclei[1]. EFT is frequently applied to inter-nucleon interaction and field theory at finite density. In 1965 density dependent functional theory has been introduced in the frame work of Kohn-Shame density functional theory by solving the quantum many-body problem in terms of energy density functional, the dependence of energy on the densities, currents and other derivative related to them became a significant way to view the distribution of nucleonic matter, spin, momentum and kinetic energy [3, 2]. It provides a successful description of atoms, molecules, condensed matter and was later applied to other fields in chemistry and physics[4].

Self consistent mean field approximations which basically result from averaging nucleon-nucleon interaction over the state of individual nucleons, is a basic concept of every DFT,

and provides a universal base to numerically calculate ground state properties of atomic nuclei [5, 6, 7, 8].

Different self consistent mean field models based on non-relativistic and relativistic realization became a standard tool of modern nuclear structure studies. Self-consistent Hartree-Fock (HF) and Hartree Fock Bogolibov (HFB) models that is based on effective interaction, finite range Gogny forces and a zero-range skyrme, represent a non-relativistic energy density functional (EDF) approaches, leads to describe high level of nuclear structure properties [8, 9].

In the seventies of last century Wileta and his group proposed a new concept to describe the nuclear structure. They suggested to start with relativistic Lagrangian, that included mesonic and nucleonic degree of freedom and contained strong coupling constant. The theory became known as relativistic quantum field theory[5, 10]. Covariant density functional theory (CDFT) is a relativistic model based on Dirac's formalism [6, 8, 11]. Relativistic self consistent mean field theory is able to explain many nuclear properties for low and medium mass nuclei.

Covariant density functional theory (CDFT) has been applied to study large number of nuclear properties and has been successful in describing many nuclear phenomena. It was very successful in the description of atomic nuclei behavior in extreme conditions such as high spin and deformation ( Super- and hyper-deformation). Superdeformation (SD) was discovered thirty years ago in  $^{152}\text{Dy}$ [12]. There has been many studies of nuclear SD; and has been discovered in different mass regions and extensively studied experimentally [13] and theoretically. Hyperdeformation (HD) is another important phenomena in nuclear

structure, which will enable to enrich our knowledge of nuclei at extreme conditions of very large deformation and fast rotation. CDFT was very successful in describing and predicating the experimental observation of discrete HD bands, in the  $Z = 40 - 58$  part of the nuclear chart. The spin at which HD bands become yrast was identified, and it was predicted that  $^{107}\text{Cd}$  was the best candidate to observe discrete HD bands [14, 15]. It shows a great success in describing ground state properties of nuclear structure, and large rang of finite nuclei in the nuclear chart [5, 16].

The fission barrier was also studied using covariant density functional theory. The barrier height was calculated for even-even nuclei in the actinides region and superheavy region of the nuclear chart. For the actinides it was found that triaxiality lower the height of the inner barrier by 1 - 4 MeV and the results were comparable to experimental data [18], and no effect of on it for superheavy nuclei [17].

The ground state properties for nuclei are calculated using energy functional that have Time-even or Time-odd densities and current in the framework of Skyrme EDF theory [19]. Time even mean field operation appear in many static properties, which can be studied experimentally. For example neutron and proton rms radii, binding energy for both spherical and axially deformed nuclei. It was found that these properties are sensitive to time-even mean fields. The result of the calculations agree with the experimental results [19, 20, 21, 22]. This agreement is the reason why properties of time-even mean field are well known and defined. However, the properties related to time-odd mean field is less known.

Time-odd mean field appear in nuclear system with broken time-reversal such as odd mass nuclei and rotating nuclei. Many of the rotating nuclei properties have been extracted using Hartree-fock cranking approach based on effective skyrme interaction and Time-odd mean field have been studied in rotating superdeformed nuclei. However, the results were not compatible with the experimental data, and showed a dependence on the type of skyrme interaction[7, 20, 23, 24, 25, 26].

Time odd-mean field plays an important role in the development of density functional theory [23]. Binding energy in odd mass nuclei, pairing correlation in the odd A and odd-odd nuclei is few of the nuclear properties related to time-odd mean field. In 2001 Duguet and Bouché [27] studied the characteristic of odd nuclei using skyrme Hartree-Fock-Bogolubov, they did this using mean field calculation of even-even nuclei and study how the process of adding a nucleon affected the mean field function and energy. The result showed that there is creation of quasi particle which affect on binding energy by breaking the time reversal invariance [20, 27, 28]. Magnetic moment, the strength and energy of Gamow-Teller resonance [20, 29], fusion process[20, 30], are another nuclear properties that has been studied.

Different progress have done over the years to improve approaches based on skyrme interaction and other approaches like, the following are short overview for some of significant improvements: in 1998 Rakhimov et al[31]. Modified Skyrme Lagrangian to include  $\sigma$ -meson field. They attempted to introduced interaction scale which is independent on the medium (scale invariance). The study showed great successes in normal interaction, and the invariance break in bad way in strong interaction.

In 1999 Typel and Wolter [32] studied the ground state properties using a density dependent meson-nucleon vertices's in the framework of CDFT. The density dependent of meson-nucleon coupling for  $\rho$ -,  $\sigma$ -,  $\omega$ -meson was introduced.

In 2003 Wenhui et al.[33] introduced new sets of parametrization for the relativistic mean field Lagrangian. PK1, PK1R and PKDD, These sets of parameterizations was able to describe the properties of nuclear matter and nuclei in and far from beta stability line. This type of parametrization used to describe stable and unstable nuclei, and nuclei from light to heavy mass region. In 2005 Lalazissis et al. [34] introduced DD-ME2 parametrization and applied it to superheavy nuclei.

In 2008 stone and Reinhard[20] investigated both even-even nuclei and odd A-nuclei, using Skyrme density functional, in both static and dynamic nuclei. The result of even-even nuclei shows a good agreement with the experimental data, while the odd-odd one shows a significant deviation which indicate that another set of parametrization and another models needed for better description.

Despite of understanding the Time-odd mean field in Skyrme density functional theory, much less progress has been done using CDFT. This can be related to many reasons, for example Time odd mean field and basically RMF theory are fully Lorentz invariant, so that it does not require any additional coupling constant. Time-odd mean fields as shown in the Dobaczewski, and Dudek [7] study provided a non-specific information and so that they not well defined in non-relativistic density functional theory and need another parametrization set.

In 2010 Afanasjev et al. [6] studied the time odd mean fields in CDFT, in odd-mass nuclei. They studied the effect of time odd mean field on binding energy, which have always tendency to increase the binding energy in way independent of the choice of the parametrization. Different phenomena related to time odd-mean field are also investigated. In the same year they published another paper which studied the rotating nuclear system [35]. In both papers they used non-linear parametrization of the RMF lagrangian.

As mentioned above, time odd mean fields are vary important for proper description of many nuclear phenomena, and the effort paid to understand this fields within the frame work of CDFT and their impact on nuclear phenomena recently become significant. Despite that there still much more problem not solved.

The aim of this thesis is to investigate the effect of time-odd mean field on the physical observable in nuclear systems with broken symmetry using CDFT with density dependent meson-interaction which will be represented by the parameter set DD-ME2.

This thesis is organized as follows: in CHAPTER (2) contains the formalism of the model in covariant density functional theory in rotating frame with general terms and definition. In CHAPTER (3), investigation of the properties of Time-odd mean field with additional parametrization and their effect on physical observable in non-rotating frame. In CHAPTER (4) summary and main result will be presented.



## CHAPTER 2

### FORMALISIM

#### 2.1 General Concept of Covariant Density Functional Theory

Covariant density functional theory as shown from recent studies [6, 35] provide a very successful description on microscopic behavior and properties of ground and excited state of nuclei. Three types of models have been developed to provide a realistic density functional, non-linear meson coupling, density dependent meson-coupling constant and point coupling models with density dependent vertices. In this thesis, density dependent meson-coupling model will be used [34].

##### 2.1.1 Mesons

Mesons are subatomic particle, and have an integer spin so that they categorized as a bosons. In covariant density functional theory nucleons (proton and neutron) are considered to be a point like particles and interact with each other by the exchange of several mesons. these mesons are defined by three quantum numbers; spin (J), parity (P) and isospin(T). The mesons that participate in this interaction are:

1. Scalar  $\sigma$  mesons, which are responsible for the attractive force between nucleons.

The quantum numbers of the  $\sigma$ -meson are (J = 0, T = 0, and P = +1).

2. Vector mesons  $\omega$ , which are responsible for the repulsive part of the nucleon interaction. the quantum numbers of the  $\omega$ -meson are ( $J = 1, T = 0, P = -1$ )
3. Vector  $\rho$ -mesons, which are responsible for the isospin dependence of the nuclear force. The quantum numbers of the  $\rho$ -meson are ( $J = 1, T = 1, P = -1$ ).

### 2.1.2 Lagrangian density

In covariant density functional theory, the nucleons are point-like particles and interact with each other by exchange of different types of mesons. One can write the Lagrangian density as [5, 6, 8, 9, 34]:

$$\mathcal{L} = \mathcal{L}_N + \mathcal{L}_m + \mathcal{L}_{int} \quad (2.1)$$

The first term of Eq.(2.1) represents the nucleons Lagrangian density and is given by:

$$\mathcal{L}_N = \bar{\psi} \gamma (i\partial - m) \psi \quad (2.2)$$

$\psi$  is the Dirac spinner and  $m$  is the bare nucleon mass,  $\gamma$  are Dirac (gamma) matrices.

$$\gamma^\mu = \begin{pmatrix} 0 & \sigma^\mu \\ -\sigma^\mu & 0 \end{pmatrix} \quad (2.3)$$

$L_m$  represent the Lagrangian of free meson and the photon, it is given by :

$$\begin{aligned} \mathcal{L}_m = & \frac{1}{2} \partial_\mu \sigma \partial_\mu \sigma - \frac{1}{2} m_\sigma^2 \sigma^2 - \frac{1}{4} \Omega_{\mu\nu} \Omega^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega^2 \\ & - \frac{1}{4} \vec{R}_{\mu\nu} \vec{R}^{\mu\nu} + \frac{1}{2} m_\rho^2 \vec{\rho}^2 - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \end{aligned} \quad (2.4)$$

where  $m_\sigma, m_\rho, m_\omega$ , are the rest masses of the mesons, the arrows indicate vector in isospin space, and

$$\begin{aligned}\Omega_{\mu\nu} &= \partial_\mu\omega_\nu - \partial_\nu\omega_\mu \\ \vec{R}_{\mu\nu} &= \partial_\mu\vec{\rho}_\nu - \partial_\nu\vec{\rho}_\mu \\ F_{\mu\nu} &= \partial_\mu A_\nu - \partial_\nu A_\mu\end{aligned}\tag{2.5}$$

Eqs. (2.5) represent the Field tensors of  $\omega$ -,  $\rho$ -mesons and photon. The interaction Lagrangian density is given by:

$$\mathcal{L}_{int} = -\bar{\psi} \left( g_\sigma\sigma + g_\omega\gamma^\mu\omega_\mu + g_\rho\vec{\tau}\gamma^\mu\rho_\mu + e\frac{1-\tau_3}{2}\gamma^\mu A_\mu \right) \psi\tag{2.6}$$

Where  $g_\sigma, g_\omega$ , and  $g_\rho$  are the coupling constants, meson masses  $m_\sigma, m_\rho, m_\omega$ , and  $e$  (proton charge) are parameters contained in the Lagrangian (2.1.2).  $\vec{\tau}$  are isospin matrices,  $\tau_3$  are third component of isospin matrices and equal

$$\tau_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}\tag{2.7}$$

The density dependent have been introduced to the linear model by Boynta and Bomdmer[38], by introducing non-linear terms to the Lagrangian, they replaced the mass term  $\frac{1}{2}m_\sigma^2\sigma^2$  with

$$U(\sigma) = \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{3}g_2\sigma^3 + \frac{1}{4}g_3\sigma^4\tag{2.8}$$

In density dependent models the meson-nucleon coupling has an explicit density dependence. The meson-nucleon vertex function has been determined by adjusting the parameter of an assumed phenomenological density dependent of the meson-nucleon coupling to reproduced the properties of symmetric and anti-symmetric nuclear matter and finite nuclei

[36] and it showed a significant improvement in the description of asymmetric nuclear matter, neutron matter and nuclei far from stability.

Density dependent meson nucleon coupling doesn't have a nonlinear terms in the  $\sigma$  meson, i.e.  $g_2 = g_3 = 0$ . The meson nucleon vertices is defined as:

$$g_i(\rho) = g_i(\rho_{sat})f_i(x) \quad \text{for } i = \sigma, \omega, \rho \quad (2.9)$$

where the density dependence is given by

$$f_i(x) = a_i \frac{1 + b_i(x + d_i)^2}{1 + c_i(x + d_i)^2}. \quad (2.10)$$

for  $\sigma$  and  $\omega$  and by

$$f_\rho(x) = \exp(-a_\rho(x - 1)). \quad (2.11)$$

for the  $\rho$  meson.  $x$  is defined as the ratio between the baryonic density  $\rho$  at a specific location and the baryonic density at saturation  $\rho_{sat}$  in symmetric nuclear matter. The eight parameters in Eq. (2.10) are constrained as follows:  $f_i(1) = 1$ ,  $f''_\sigma(1) = f''_\omega(1)$ , and  $f''_i(0) = 0$ . These constrains reduce the number of independent parameters so that density dependence parameters become only three.

Parametrization of the density dependent model has been developed so that they are able to describe quantitatively the proprieties of nuclear matter and finite nuclei at the same time extreme condition of isospin and density also considered.

This model is represented in the present investigations by the parameter set DD-ME2 [36] listed in Table (2.1) While the previous work was done using non-linear parametrizations [39].

Table 2.1: NL3\* and DD-ME2 parameterizations of the RMF Lagrangian

Parameter	NL3*[MeV]	DD-ME2[MeV]
$m$	939	939
$m_\sigma$	502.5742	550.1238
$m_\omega$	782.600	783.000
$m_\rho$	763.000	763.000
$g_\sigma$	10.0944	10.5396
$g_\omega$	12.8065	13.0189
$g_\rho$	4.5748	3.6836
$g_2$	-10.8093	0.00000
$g_3$	-30.1486	0.00000
$a_\sigma$	0.00000	1.3881
$b_\sigma$	0.00000	1.0943
$c_\sigma$	0.00000	1.7057
$d_\sigma$	0.00000	0.4421
$a_\omega$	0.00000	1.3892
$b_\omega$	0.00000	0.9240
$c_\omega$	0.00000	1.4620
$d_\omega$	0.00000	0.4775
$a_\rho$	0.00000	0.5647

### 2.1.3 The Hamiltonian and Equation of Motion

The CDFT will be used to study the physical observables in which the time-odd mean field plays an important role. Time odd mean field manifest itself in nuclear system with broken time-reversal symmetry in intrinsic frame.

The stationary Dirac equation for nucleon(spinner field)  $\psi_i$  ( $i=1,\dots,A$ ) in intrinsic frame is given by

$$\hat{h}_D \psi_i = \epsilon_i \psi_i \quad (2.12)$$

Where  $\hat{h}_D$  is the Dirac Hamiltonian for a nucleon with mass  $m$

$$\hat{h}_D = \alpha[-i\nabla - V(r)] + V(R)_0 + \beta[m + S(r)] \quad (2.13)$$

Here

$$\beta = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix} \quad (2.14)$$

and

$$\alpha = \begin{pmatrix} 0 & \sigma_i \\ -\sigma_i & 0 \end{pmatrix} \quad (2.15)$$

which are dirac matrices.  $I$  is the 2-by-2 identity matrix, and  $\sigma_i$  are pauli matrices, where  $i$  run from 1-3. The terms included in the Dirac Hamiltonian are expressed as follow: average scalar attractive field determine by mesons  $S(r)$

$$S(r) = g_\sigma \sigma(r) \quad (2.16)$$

also contains magnetic potential terms which originate from space-like component of the vector mesons, space like components of  $\omega$ ,  $\rho$ , and  $A$  are,  $[(\omega^x, \omega^y, \omega^z), (\rho^x, \rho^y, \rho^z), (A^x, A^y, A^z)]$ , respectively.

$$V(r) = g_\omega \omega(r) + g_\rho \tau_3 \rho(r) + e \left[ \frac{1 - \tau_3}{2} \right] A(r) \quad (2.17)$$

This term when implemented in Dirac equation produce the same effect as the magnetic field did, therefor the effect produced by it called nuclear magnetism (NM).

the repulsive time like component of of the vector field  $V_0(r)$

$$V_0(r) = g_\omega \omega_0(r) + g_\rho \tau_3 \rho_0(r) + e \left[ \frac{1 - \tau_3}{2} \right] A_0(r) \quad (2.18)$$

the corresponding meson field and the electromagnetic potential also determine by this

Eqs. [8, 6]

$$\begin{aligned} \{-\Delta + m_\sigma^2\} \sigma(r) &= -g_\sigma [\rho_s^n(r) + \rho_s^p(r)] \\ &\quad -g_2 \sigma^2(r) - g_3 \sigma^3(r), \end{aligned} \quad (2.19)$$

$$\{-\Delta + m_\omega^2\} \omega_0(r) = g_\omega [\rho_v^n(r) + \rho_v^p(r)], \quad (2.20)$$

$$\{-\Delta + m_\omega^2\} \omega(r) = g_\omega [j^n(r) + j^p(r)] \quad (2.21)$$

$$\{-\Delta + m_\rho^2\} \rho_0(r) = g_\rho [\rho_v^n(r) - \rho_v^p(r)], \quad (2.22)$$

$$\{-\Delta + m_\rho^2\} \rho(r) = g_\rho [j^n(r) - j^p(r)], \quad (2.23)$$

$$-\Delta A_0(r) = e \rho_v^p(r), \quad -\Delta A(r) = e j^p(r), \quad (2.24)$$

The source terms  $\rho^n, p_s(r)$ , and  $\rho^n, p_\nu(r)$ , and involve various nucleonic densities currents :

$$\rho_s^{n,p}(r) = \sum_{i=1}^{N,Z} \dagger[\psi_i(r)]\beta\psi_i(r) \quad (2.25)$$

$$\rho_\nu^{n,p}(r) = \sum_{i=1}^{N,Z} \dagger[\psi_i(r)]x_s\psi_i(r) \quad (2.26)$$

$$j_\nu^n(r) = \sum_{i=1}^{N,Z} \dagger[\psi_i(r)]\alpha\psi_i(r) \quad (2.27)$$

The n,p in Eqs. (2.25 - 2.27) stands for neutron and proton respectively. V and S potentials have very different behavior under Lorentz transformation. Relativistic theories containing only a scalar potential and time like component of a Lorentz vector field, while the magnetic potential and V(r) in the Dirac equation and the current  $j^{n,p}(r)$  in the Klein-Gordon equation do not appear in relativistic mean field equations for time reversal systems [6, 5]. For nuclei that have external odd nucleon current will be appear, as acquiescences space like component of vector-meson field  $\omega$  will be induced in the same way current induced magnetic potential. For that the magnetic potential responsible for break time reversal symmetry causing in that way the induction of  $j_\nu^{n,p}(r)$ . Time odd mean field and Nuclear Magnetism are two term used to express this effect.

Space like component of  $\omega$  and  $\rho$  vector field appear in Eq. (2.21) and Eq. (2.23) form the magnetic potential in Eq. (2.17) in the Dirac equation, interaction between different currents contributions related to this spatial component more likely to happened. the nature of interaction different from  $\omega, \rho$ -mesons, more specifically, for  $\omega$  meson all possible combination have attractive interaction (either pp, pn, nn current), for  $\rho$  meson its attractive for (pp and nn currents), but repulsive for (pn) [6].



The coupling constant  $g_\omega$  have large value making the  $\omega(r)$  vector field large and cannot be neglected in the Dirac equation. also the nature of current for  $\omega$  and  $\rho$  are isoscaler and isovector, respectively.

#### 2.1.4 Energy-Density Functional

After obtaining the solution, energy density can be calculated. The total energy of the system is given in Ref [6, 5]. In CDFT the energy can be written as a functional of the density matrix  $\hat{\rho}$  and mesons field  $(\phi_\sigma, \phi_\rho, \phi_\omega)$  and  $A$ , which denoted generally  $\phi_m^3$ .

$$E[\hat{\rho}, \phi] = Tr[(\alpha p + \beta m)\hat{\rho}] \pm \int \left[ \frac{1}{2}(\nabla\phi_m)^2 + U(\phi_m) \right] d^3r + Tr[(g_m\phi_m)\hat{\rho}] \quad (2.28)$$

The total energy is split in different terms for study purpose only, terms are:

$$E_{tot} = E_{part} + E_{cm} - E_\sigma - E_\omega^{TL} - E_\rho^{TL} - E_\omega^{SL} - E_\rho^{SL} - E_{coul} \quad (2.29)$$

Energy contribution come from two parts, fermionic and bosonic degree of freedom, the first two terms,  $E_{part}$  and  $E_{cm}$  represent fermionic contribution, while other term are related to bosonic contribution.

$$E_{part} = \sum_i^A \epsilon_i \quad (2.30)$$

Eq. (2.30) represent the energy of particles moving in the field created by the mesons.

Where  $\epsilon_i$  energy of the  $i$ th particle and sum run over all occupied proton and neutron state.

$$E_\sigma = \frac{1}{2}g_\sigma \int d^3r \sigma(r)[\rho_s^p(r) + \rho_s^n(r)] \quad (2.31)$$

This part represent the liner contribution to the energy of the isoscaler-scaler  $\sigma$  field. Energy time-like component of the isovector-vector  $\omega$  field is,

$$E_{\omega}^{TL} = \frac{1}{2}g_{\omega} \int d^3r \omega_0(r) [\rho_v^p(r) + \rho_v^n(r)] \quad (2.32)$$

Energy time-like component of the isovector-vector  $\rho$  field is,

$$E_{\rho}^{TL} = \frac{1}{2}g_{\rho} \int d^3r \rho_0(r) [\rho_v^p(r) - \rho_v^n(r)] \quad (2.33)$$

Where the energy of space-like component of the isoscaler-vector  $\omega$  field is,

$$E_{\omega}^{SL} = -\frac{1}{2}g_{\omega} \int d^3r \omega(r) [j^p(r) + j^n(r)] \quad (2.34)$$

isovector-vector  $\rho$  field space-like component energy contribution is,

$$E_{\rho}^{SL} = -\frac{1}{2}g_{\rho} \int d^3r \rho(r) [j^p(r) - j^n(r)] \quad (2.35)$$

Coulomb energy represented by

$$E_{Coul} = \frac{1}{2}e \int d^3r A_0(r) \rho_v^p(r) \quad (2.36)$$

in the case of finite nuclei, any relativistic mean fields model has to be complimented by the correction for center of mass motion, the correction for spurious contribution from the center of mass vibration to the energy is

$$E_{cm} = -\frac{3}{4}\hat{h}\omega_0 = -\frac{3}{4}41A^{-1}/3MeV \quad (2.37)$$

The center of mass correction for density -dependent model,

$$E_{c.m.} = -\frac{\langle P_{c.m.}^2 \rangle}{2Am} \quad (2.38)$$

Here  $P_{c.m.}$  is the total moment of nucleus with A nucleons.

### 2.1.5 The Signature, Parity, and Simplex Operator

Time reversal is an operation in which a physical system under going given sequence of events transformed to other system in which exact reverse sequence of events take place. The operation done using an operator known as Time-reversal operator T, its time independent, hermitian single particle operator. An operator under the action of time- reversal could be either even (invariant) or odd (antivariant),

$$T\hat{o}T = \epsilon_T\hat{o} \quad (2.39)$$

where  $\epsilon_T = \pm 1$ . For every operator  $\hat{x}$  have square equal to minus unity as,

$$x^\dagger\hat{o}x = \epsilon_x\hat{o} \quad (2.40)$$

and commute with time reversal  $\tau$  operator, the basis can be chosen as,

$$\hat{x}|n \ \zeta\rangle = \zeta|n \ \zeta\rangle \quad (2.41)$$

where  $\zeta = \pm 1$ . For rotating nuclei the potential exhibit reflection symmetry while the Hamiltonian is only invariant For rotation of  $\pi$  about the x-axis, the rotation operator defined as

$$R_x(\pi) = \exp(-i\pi J_x) \quad (2.42)$$

For wavefunction rotation of  $2\pi$  will not change it except for possible phase factor ( $\pm 1$ ) as,

$$R_X^2(\pi)\psi = r^2\psi = (-1)^A\psi \quad (2.43)$$

The eigenvalue of rotation operator  $R_X^2(\pi)$  called signature. more generally, comparing Eq. (2.41) with Eq. (2.43), the signature is equal  $r^2 = \zeta = \pm 1$  which means  $r = \zeta i = \pm i$ . simplex operator  $\hat{X} = \hat{S}_x$  i.e

$$\hat{S}_x = \hat{R}\hat{P} \quad , i = x, y, z \quad (2.44)$$

$$P = s_x s_y s_z \quad (2.45)$$

again in Eq. (2.41)  $s = \zeta i = \pm i$ .

Defining signature, and parity in nuclear physics very important step to describe the symmetries between proton and neutron, they are good quantum number, which means that they are constant of motion. for a symmetric reflection shape parity and signature are no longer good quantum number, the only good quantum number is the simplex because nucleolus is invariant with respect to rotation of  $\pi$  about x-axis and change in parity, the only one describe this situation are simplex.

### 2.1.6 The Wave-Function

The relativistic mean field Eqs. [2.19 - 2.23] are-coupled set of equation for the unknown field  $\psi_i (i = 1 \dots A)$ ,  $\sigma$ ,  $\omega^\mu$ ,  $\rho^\mu$ , and the coulomb filed  $A^0$ , the method of solving this equation start by initial guess for the potential V and S, usually we choose a Wood-Saxon potential. One solves the Dirac equation for the spinners  $\psi$ , the result are used to calculate the densities  $\rho_s$ ,  $\rho_v$ , which are actually form the source in Eqs. [2.19, 2.20, 2.21, 2.22, 2.23], for calculation of the meson fields their currents have to be solved by iteration, and a new set of potentials (7) and (9), the cycle is repeated until convergence is achieved. A detailed description is presented in Refs. [40, 25].

CDFT was built on the assumption that nucleon are treated point-like particles, Dirac spiners  $\psi$ , they usually decomposed into small and large component [5] as,

$$|\psi\rangle = \begin{pmatrix} f \\ ig \end{pmatrix} = \frac{1}{\sqrt{2\pi}} \begin{pmatrix} f_i^+(z, r_\perp) \exp i(\Omega_i - \frac{1}{2})\phi \\ f_i^-(z, r_\perp) \exp i(\Omega_i + \frac{1}{2})\phi \\ ig_i^+(z, r_\perp) \exp i(\Omega_i - \frac{1}{2})\phi \\ ig_i^-(z, r_\perp) \exp i(\Omega_i + \frac{1}{2})\phi \end{pmatrix} X_{t_i}(t) \quad (2.46)$$

These two components are expanded in terms of three-dimensional axially symmetric harmonic oscillator in Cartesian coordinate characterized by two constants, deformation parameter  $\beta_0 = 0.3$ ,  $\gamma = 0$ , and oscillator frequency  $\hat{h}\omega_0 = 41A^{-\frac{1}{3}}$ , with eigenfunctions  $|n_x\rangle, |n_y\rangle, |n_z\rangle$  in addition of spin degree of freedom  $|s = \pm\frac{1}{2}\rangle$ , obtaining the density  $\rho_{s,v}$  form basis expansion will leads to calculate the sources. The cycle in that way will continue. The self consistent field  $\sigma, \omega, \rho$  can be written as:

$$\sigma(r) = \sum_N \sigma_N \phi_N \quad (2.47)$$

$$\omega(r) = \sum_N \omega_N \phi_N \quad (2.48)$$

$$\rho(r) = \sum_N \rho_N \phi_N \quad (2.49)$$

Where  $N=n_x + n_y + n_z$

$$\Phi_N(r) = \phi_{n_x}(x)\phi_{n_y}(y)\phi_{n_z}(z) \quad (2.50)$$

The number of oscillator shells  $N_F$  and  $N_B$  in which Dirac spinors (fermuonic wave functions), and mesons fields which describe the Bosonic degrees of freedom are expanded should be also identify, usually  $N_F=12$  and  $N_B=16$  are sufficient to calculate ground state properties of light and medium-mass nuclei.

Single particle orbitals are labeled using Nilsson label known also as a asymptotic quantum number, Which are four quantum number preserves in both symmetric and deformed nuclei, basis label usually represented as  $|Nn_z\Lambda\rangle \Omega$ , where N is total number of shell,  $n_z$  is number of oscillator in z direction,  $\Lambda$  is projection of orbital angular momentum, While  $\Omega = \Lambda + \Sigma$  represents summation of projection of orbital and spin angular momentum.

## CHAPTER 3

## THE PHYSICS OF TIME ODD MEAN FIELD THEORY WITH PARAMETRIZATION

Time odd mean field is phenomenon that appears in nuclear system with broken-time reversal symmetry. It appears in odd-even and odd-odd mass nuclei. The extra nucleon breaks spherical symmetry and create non vanishing contribution to the current while in even-even nuclei the current contribution cancels due to the fact that every state is pairwise occupied.

Many nuclear phenomena and properties have been introduced as an open problem because of their strong dependence on time odd mean field. These properties includes: Magnetic moment, band termination, nuclear fission, binding energy of odd mass nuclei, their significant role in nuclei with  $N=Z$  and pairing correlation.

Relativistic mean-field theory (RMF) has been successful to describe a range of nuclear structure phenomena for nuclei along the Valley of  $\beta$  stability and exotic nuclei. As the relativistic mean field model was extended to include effective Lagrangian with density dependent meson nucleon vertex function. We investigate time odd properties in the CDFT with parametrization of the RMF Lagrangian including DD-ME2.

The first step to make calculation related to time odd mean field is to specify nuclear configuration, they are specified by the occupation of available single particle orbitals. The

occupation number  $n$  is either to be 0 or 1, for even-even nuclei all single particle state are pairwise occupied. However, this is not the case for odd nuclei where all single particle state pairwise occupied expect for the last occupied state which will be called blocked state.

Single particle state in the RMF computer code are labeled using Nilson label and signature. The total signature and parity of nuclear configuration is the same as specified by the blocked state. The single particle states are divided into four groups based on their parity and signature ( $r=+i, p=+\pi$ ;  $r=+i, p=-\pi$ ;  $r=-i, p=+\pi$ ;  $r=-i, p=-\pi$ ).

The procedure of the calculations is done in two steps:

- self consistent calculation with time odd-mean field (NM) included, in this step space like component of vector mesons [Eqs. (2.21), (2.23), (2.17)], currents [Eqs. (2.21), (2.23), (2.27)], and magnetic potential  $V(r)$ [Eq. (2.17)] are included.
- self-consistent calculation without time odd-mean field (abbreviated by WNM), in this step spacelike component of vector mesons[Eqs. (2.21),(2.23), (2.17)], currents [Eqs. (2.21),(2.23,(2.27)],and magnetic potential  $V(r)$ [Eq.(2.17)] are discarded.

Taking into account calculation of NM and WNM should be done using same nuclear configuration.

### 3.1 Binding Energy in Odd Mass Nuclei

Theoretical models based on self-consistent mean fields theory such as RMF models have been showed great ability of reproducing the ground state properties of finite nuclei through out the nuclear chart with very limited number of parametrizations. The combination of this theoretical method and computational resources provides sufficient base to



perform calculation forming significant role to understand nuclear structure. One of the properties which have been attracted renewed interest is nuclear mass or binding energy.

Time odd mean fields densities and current contribute with non-vanishing value to ground-state of odd and odd-odd nuclei, since this contribution are essential terms for restoring the local gauge invariance violated by symmetry breaking in intrinsic frame, as a result of this contribution Kramer's degeneracy of single particle state are destroyed[5, 44].

Time odd mean field have direct influence on binding energy, single particle spectra, and nucleon separation energy. These nuclear phenomena are very important and was discussed in [42, 43] for astrophysical application. Nucleon Separation energy plays an important role in estimation nuclear stability near the drip-line[45] and investigation low energy single particle spectra [44].

Understanding the effect of time odd mean field on binding energy of odd and odd-odd mass nuclei become a necessity. The impact of time odd mean field on binding energy has been studied in the CDFT frame work for light odd mass nuclei using non-linear parametrization of the RMF Lagrangian[6], and in non-linear Skyrme EDF [46].

DD-ME2 provides good agreement between calculation and experimental data on ground and excited for many spherical and deformed nuclei [36], so in this part of study we attended to provide an additional investigation on impact of this kind of parametrization on binding energy for wide range of odd mass nuclei.

### 3.1.1 Binding Energy in Even Z Odd N Light Nuclei

It is well known that there are 275 known stable nuclei, where 60% of them are even-even nuclei, while the other 40% are divided equally to odd proton-even neutron or even proton-odd neutron nuclei. How the nuclei evenness and oddness is the key feature to determine the nuclear stability it also related to nuclear properties such as nuclear mass(binding energy).

In this section we present our results for influence of odd mean fields (NM) using density dependent model for effective interaction with DD-ME2 parametrization for even Z, odd N nuclei range from  $10 \leq Z \leq 26$ . For each isotopic chain, the result will be compared to calculation done using Skyrme Hartree Fock [44, 47] and the calculation done using relativistic mean field(RMF) in Ref[6].

The result of these nuclei are presented in Figs. [3.1 - 3.3] in which the effect of time odd mean field (NM) on binding energy are present. It shows the difference in binding energy when NM is included, i.e. ( $E_{NM}$ ) and calculation done without NM ( $E_{WNM}$ ). All of the calculation were done with fixed configuration; that is the configuration was chosen so that it lay between two neighboring even nuclei, the reasons to do that is guarantee that the contribution of current come only from one unpaired nucleon, Here the contribution come from neutron, where proton configuration are fixed for all nuclei. Fig. (3.1) shows the impact of NM on binding energy for four isotopic chains, namely; Ne ( $Z = 10$ ), Mg ( $Z = 12$ ), Si ( $Z = 14$ ) and S ( $Z = 16$ ). For Ne chain, the calculations were performed from  $N - Z = -5$  to 29. The value of the additional binding ranged from few eV for  $^{49}\text{Ne}$  to 550 KeV for  $^{23}\text{Ne}$ . Similar behavior can be noticed for the other three chains. In Mg chain,

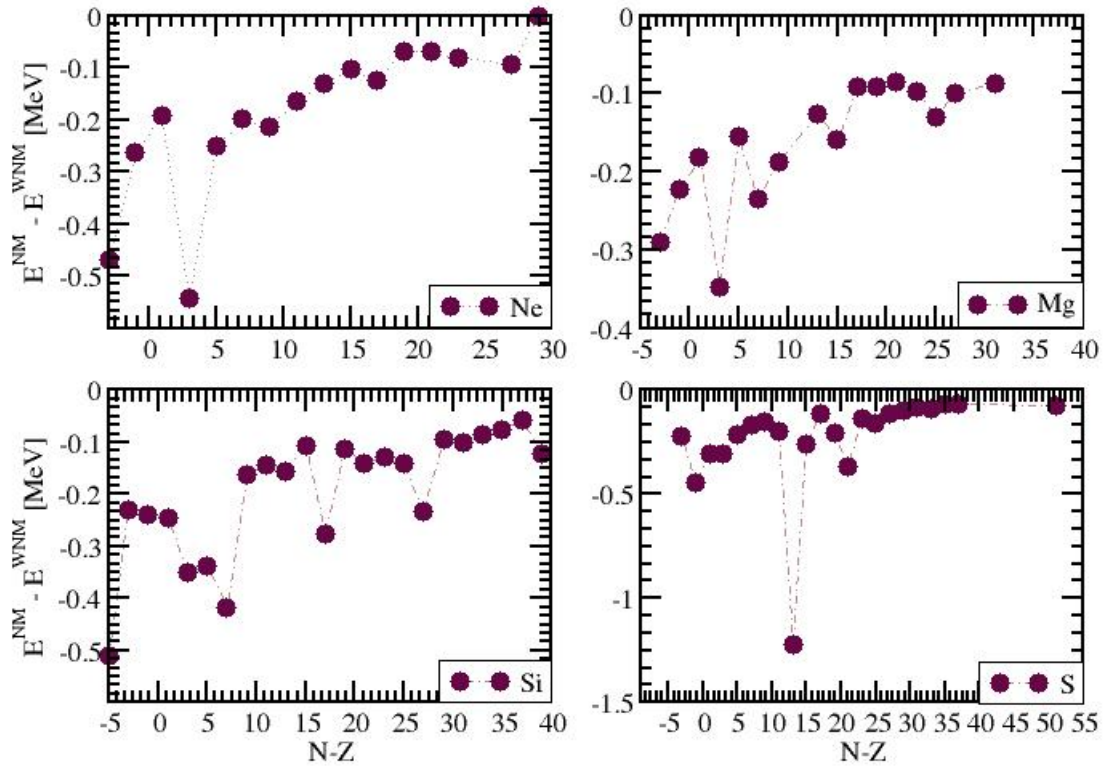


Figure 3.1: Influence of Time odd mean field on binding energy for even  $Z$  (odd  $N$ ), namely, Ne ( $Z = 10$ ), Mg ( $Z = 12$ ), Si ( $Z = 14$ ) and S ( $Z = 16$ ). The calculation done using DD-ME2 parametrization. each chain cover all nuclei from Proton drip line up to Neutron drip line.

the additional binding ranges from 100 to 350 KeV and the maximum value occurs for  $^{27}\text{Mg}$  and for the Si chain the range changes a little to be 100- 500 KeV and  $^{23}\text{Si}$  has the maximum value. It is interesting to see that for S chain the maximum value jumps up to 1.5 MeV for  $^{45}\text{S}$ .

The results obtained for these four nuclei suggests that the effect of NM is stronger for the light nuclei within each chain, that its stronger near the proton dripline, than the heavier nuclei near the neutron dripline. Figs. (3.2) and (3.3) shows the results for Ar ( $Z = 18$ ), Ca ( $Z = 20$ ), Ti ( $Z = 22$ ) and Cr ( $Z = 24$ ). An overall trend is observed that the effect of nuclear magnetism is less than 500 KeV, except of some isotopes. Ar chain have approximately [(100-900)KeV] with two maximum at  $^{45}\text{Ar} = -981.8$  KeV,  $^{47}\text{Ar} = -915.5$  KeV, Ca chain have  $\approx$  [(50-750) KeV] with maximum at  $^{82}\text{Ca} = -748.7$  KeV , where Ti chain have an approximate gain of [(53 - 1500 )KeV] with maximum at  $^{87}\text{Ti} = -1539.8$  KeV . Cr chain has [(0 - 700) KeV] with maximum at  $^{61}\text{Cr} = -686.8$  KeV.

The heavies nuclei, with even Z, is Fe. Isotopes of Fe gained an additional energy [30-520] KeV with maximum at  $^{65}\text{Fe} = -1.2$  MeV. Again the magnitude of additional binding energy are greater for nuclei near proton drip line and decrease as the nuclei have larger mass same as the first group of nuclei.

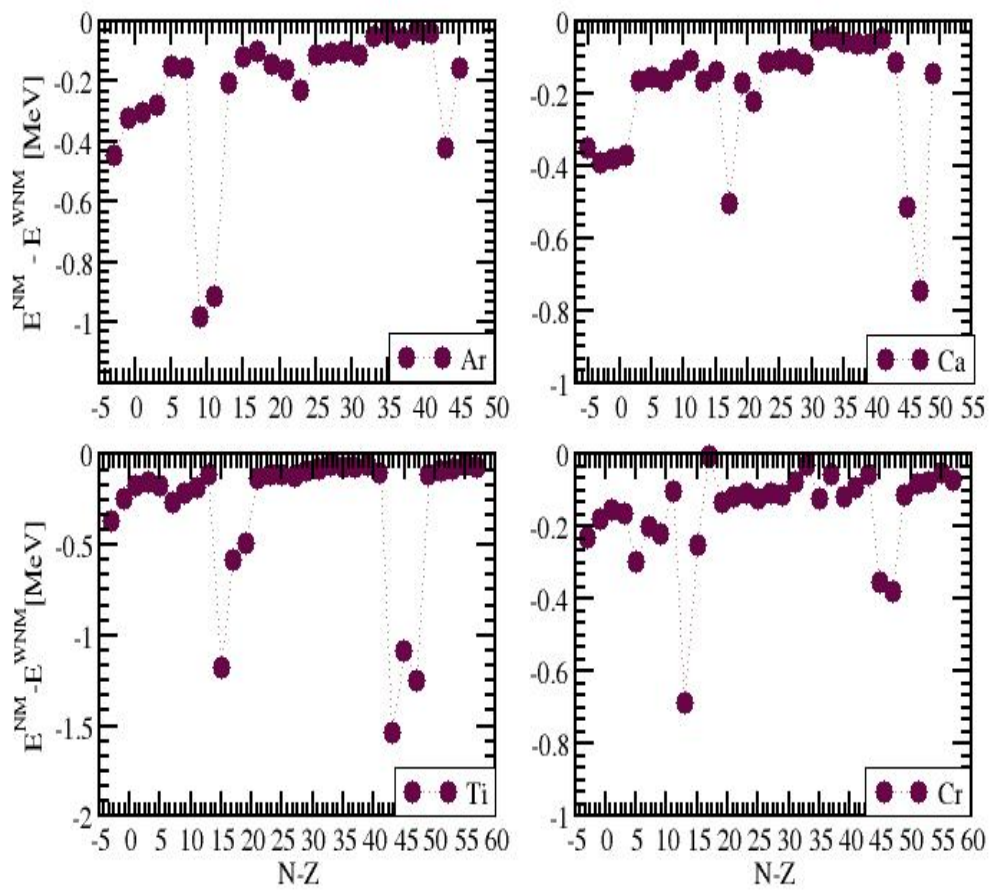


Figure 3.2: Same as Fig. (3.1), but for Ar ( $Z = 18$ ), Ca ( $Z = 20$ ), Ti ( $Z = 22$ ) and Cr ( $Z = 24$ )

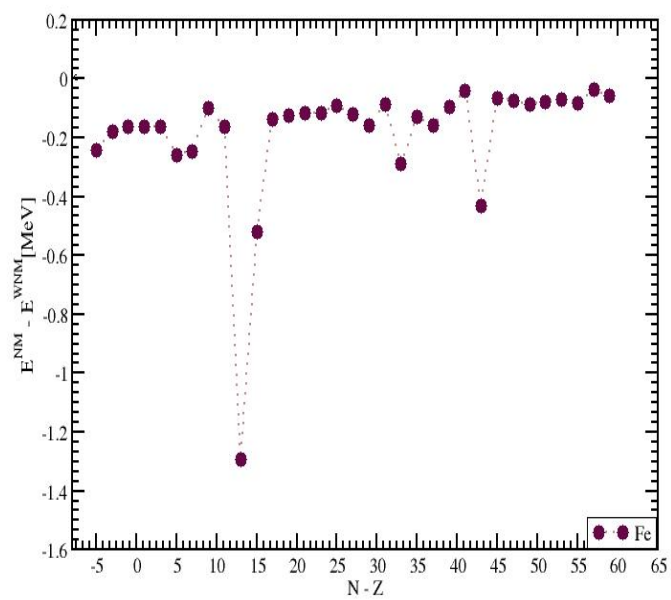


Figure 3.3: Same as Fig. (3.1), but for Fe ( $Z = 26$ ).

### 3.1.2 Binding Energy in Even N Odd Z Light Nuclei

In this section we study the effect of time odd mean field on odd light Z nuclei ranging between  $Z = 11 - 27$  in a similar fashion to what we have done in section 3.1.1

The Fig.(3.4) shows the calculation of Na ( $Z = 11$ ), Al ( $Z = 13$ ), P ( $Z = 15$ ) and Cl ( $Z = 17$ ). Na chain gains an additional binding due to effect of NM around 200 KeV. It can be noticed that the effect of NM is almost independent of the neutron number, as their no change in the additional binding as the number of neutrons changes. Similar behavior can be seen for the Al isotopes. However, <sup>31,39,41</sup>Al deviates from this behavior and gain 700, 400 and 400 KeV respectively.

For P isotopes the additional binding ranged from 160 KeV to 500 KeV and has a maximum gain for <sup>45</sup>P. Most of Cl isotopes gained extra binding energy around [200 - 400] KeV with exception at <sup>37</sup>Cl = 811.4 keV and <sup>56</sup>Cl = 2615.5 keV this isotopes have the highest value of additional energy over all investigated nuclei.

Odd Z nuclei with  $Z = 19-25$  are presented in Fig. (3.5), K ( $Z = 19$ ) isotopes are effected by the same amount due to NM and it is shown by the gain in binding energy. All of the isotopes almost gained around 300 KeV, with two exception value at <sup>58</sup>K = 1388 keV and <sup>87</sup>K = 592.2 KeV This behavior is similar in the case of Sc ( $Z = 21$ ), V ( $Z = 23$ ) and Mn ( $Z = 25$ ).

Sc isotopes have an additional energy round [150 - 400 ] KeV, and for <sup>53</sup>Sc, <sup>57</sup>Sc, <sup>63</sup>Sc, gained around [620 - 750] KeV, only <sup>89</sup>Sc have grater than this value it reach to 860 KeV. V isotopes the effect vary small for most of them [100-170] KeV, expect three of its isotopes <sup>61</sup>V = 1284.1 KeV, <sup>83</sup>V = 501.95 KeV, <sup>87</sup>V = 1254.8 KeV, Mn isotopes have experience

range start from  $^{47}\text{Mn}$  where the calculation showed that it gained no additional binding up to isotopes gained less than 450 KeV,  $^{65}\text{Mn} = 1322.0 \text{ KeV}$  and  $^{65} \text{Mn} = 984.1 \text{ KeV}$  have highest value among other.

Fig. (3.6) represent the last nuclei investigated also its had long chain of isotopes where most of them have between [100 - less than 600] KeV, expect  $^{69}\text{Co} = 1121.3 \text{ KeV}$ .

Generally for all odd Z nuclei, there is an additional binding energy due to NM, the magnitude of this addition is less than 600 KeV, expect for some isotopes which cant get grater than this up to 2 MeV. The magnitude of additional binding in each chain of isotopes is almost constant (*except for some specific isotopes specified above*). The magnitude of additional binding in each isotopic chain is higher for nuclei that lie in the middle between proton and neutron drip lines. However, this is not the case of even Z (odd N) nuclei where the magnitude of additional binding energy is generally higher than it in odd Z nuclei. The minimum value of odd Z nuclei is 100 KeV and for even Z nuclei is only few KeV. Odd Z nuclei gained also the maximum grater than those for even Z. The effects of NM are grater in light nuclei (small A) value and get smaller as the nucleus becomes heavier (large A).



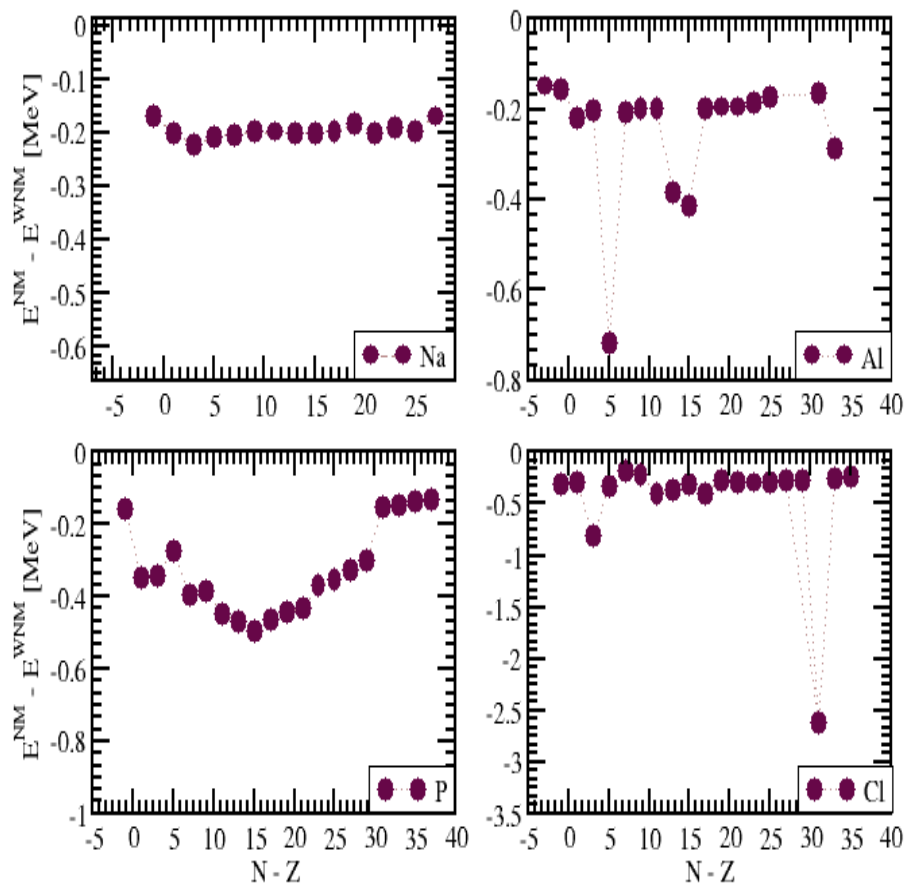


Figure 3.4: Same as Fig. (3.1), but for Na ( $Z = 11$ ), Al ( $Z = 13$ ), P ( $Z = 15$ ), Cl ( $Z = 17$ ).

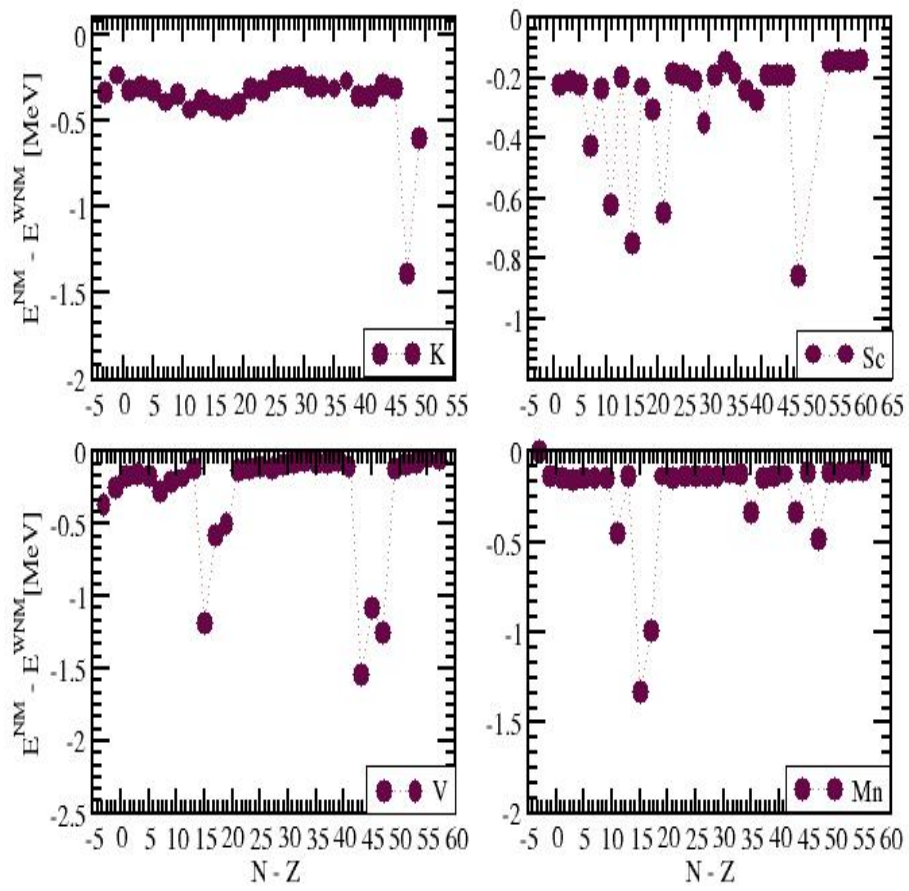


Figure 3.5: Same as Fig. (3.1), but for K ( $Z = 19$ ), Sc ( $Z = 21$ ), V ( $Z = 23$ ) and Mn ( $Z = 25$ ).

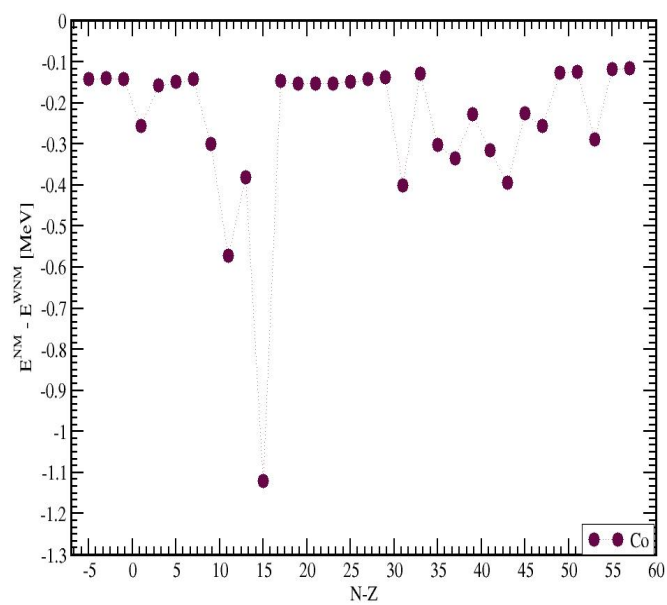


Figure 3.6: Same as Fig. [3.1], but for Cr ( $Z = 27$ ).

### 3.2 Comparison with RMF Non-Linear Model and Non-Relativistic Skyrme EDF

We will compare our results with two different models, mainly with the results of Ref.[6], where the authors used non-linear parametrization of the RMF lagrangian, and Ref.[47], where the authors used non relativistic Skyrme interaction.

Comparing our results with those in Fig.2 of Ref.[6] we notice that both results provide an additional binding, i.e.  $(E^{NM} - E^{WNM} \leq 0)$ . However, our results show that the additional binding is larger.

The magnitude of this additional binding is summarized in table (3.1). In this table we list the range of additional binding for each isotopic chain gained in both calculations. Two significant trends can be noticed, the first one that in case of even Z, all of the nuclei gained an additional binding energy around 500 KeV except for some nuclei which are,  $^{27}\text{Ar}$  have an additional energy  $\approx 800$  KeV,  $^{59}\text{Ti}$  which gained an additional  $\approx 1$  MeV,  $^{61}\text{Cr} \approx 500$  KeV and  $^{65}\text{Fe} \approx 1.1$  MeV. For odd Z nuclei the absolute additional energy is less than 30 KeV in some P isotopes, less than 350 KeV for Na, Al, Cl, K, V, Mn except  $^{37}\text{Cl}$  gained 750 KeV,  $^{61}\text{V}$  gained around 1200 KeV, where Sc and Co gained less than 600 KeV.

In comparison with Fig.2 in Ref.[6], one can see that the results for odd Z and odd N nuclei have the same trend. The variation of the results is more pronounced in odd Z nuclei than in even Z. In our calculations the additional binding in odd Z nuclei is greater than the even Z nuclei, which is the opposite of what is seen in Fig.2 of Ref.[6]

Another significant difference between the DD-ME2 and the NL3 results is the correlation between the additional binding and the mass number. The results of Ref.[6] is inversely correlated with the mass number, where it largest in light nuclei and smallest in

heaviest one. However, this trend doesn't apply generally for all nuclei in our calculation. For odd N this pattern apply for most nuclei expect some of them have an extraordinary additional binding. However, for odd Z nuclei this is not the case where the magnitude of additional binding in each element different from light to heavy; some of them have the maximum variation in the middle and approximately same magnitude at the edge of proton and neutron drip lines.

The position of proton and neutron drip line is very important in nuclear physics because at this lines the nuclear existence ends. Despite that proton drip line is well located using experimental data, the location of neutron drip line for majority of elements is not located and because of limitation in experiment the only way to delineated it using model calculation [48]. The position of neutron drip line is model and parametrization dependent.

We found that for even Z nuclei the position of neutron drip lines of  $^{49}\text{Ne}$ ,  $^{55}\text{Mg}$ ,  $^{67}\text{Si}$ ,  $^{83}\text{S}$ ,  $^{81}\text{Ar}$ ,  $^{89}\text{Ca}$ ,  $^{101}\text{Ti}$ ,  $^{101}\text{Cr}$ ,  $^{111}\text{Fe}$ . While the position of neutron drip lines for calculation done using non-linear NL3 parametrization are  $^{33}\text{Ne}$ ,  $^{39}\text{Mg}$ ,  $^{48}\text{Si}$ ,  $^{53}\text{S}$ ,  $^{53}\text{Ar}$ ,  $^{63}\text{Ca}$ ,  $^{69}\text{Ti}$ ,  $^{81}\text{Cr}$ ,  $^{85}\text{Fe}$ . i.e the calculation indicate that position of neutron drip line shift by [16-32] isotopes in each chain comparing with that number done in ref [6]. However there are some element have shift in proton drip lines by [1-3] isotopes those are  $^{21}\text{Mg}$ ,  $^{29}\text{S}$ ,  $^{33}\text{Ar}$ ,  $^{35}\text{Ca}$ ,  $^{41}\text{Ti}$ ,  $^{45}\text{Cr}$ , compare to position proton drip line  $^{19}\text{Mg}$ ,  $^{27}\text{S}$ ,  $^{31}\text{Ar}$ ,  $^{33}\text{Ca}$ ,  $^{39}\text{Ti}$ ,  $^{43}\text{Cr}$ , located by NL3 parametrization. in other hand position of neutron drip lines in odd Z nuclei are located for each one of them as follow,  $^{50}\text{Na}$ ,  $^{59}\text{Al}$ ,  $^{67}\text{P}$ ,  $^{69}\text{Cl}$ ,  $^{87}\text{K}$ ,  $^{101}\text{Sc}$ ,  $^{103}\text{V}$ ,  $^{105}\text{Mn}$ ,  $^{111}\text{Co}$ , comparing to the position in where NL3 calculation the neutron drip lines located for each of this nuclei at,  $^{39}\text{Na}$ ,  $^{47}\text{Al}$ ,  $^{61}\text{P}$ ,  $^{57}\text{Cl}$ ,  $^{59}\text{K}$ ,  $^{81}\text{Sc}$ ,  $^{73}\text{V}$ ,  $^{83}\text{Mn}$ ,  $^{88}\text{Co}$ , here the neutron drip line

shift by [8-29] isotopes. also proton drip lines are shifted; where located at  $^{21}\text{Na}$ ,  $^{23}\text{Al}$ ,  $^{29}\text{P}$ ,  $^{33}\text{Cl}$ ,  $^{35}\text{K}$ ,  $^{43}\text{Sc}$ ,  $^{45}\text{V}$ ,  $\text{Mn}^{47}$ , compare with NL3 non-linear calculation;  $^{19}\text{Na}$ ,  $^{21}\text{Al}$ ,  $^{25}\text{P}$ ,  $^{31}\text{Cl}$ ,  $^{33}\text{K}$ ,  $^{39}\text{Sc}$ ,  $^{41}\text{V}$ ,  $^{45}\text{Mn}$ ; here proton drip lines shift by [1-4]isotopes.

The effect of time odd mean field on odd light nuclei have been also investigated within Skyrme EDF. Statuta [47] have been study the effect of time mean field using Skyrme energy density functional with SLy4 and SIII on light nuclei with  $10 \leq Z \leq 28$ . The calculation are presented in Fig[7] in upper panel done with SLy4 parametrization, the light nuclei gained additional binding due to NM less than 300 KeV on general in agreement with amount of additional binding presented by calculation done using RMF with non-linear NL3 parametrization. Another study published in 2010 by Pototzky et.al [44] where the effect of time odd mean field on binding energy for odd nuclei with  $16 \leq Z \leq 29$  have been studied using Skyrme Hartree Fouck approach with SKL3 and SLy6 Skyrme forces, this calculation represent that the effect of time odd mean field much small than 1 MeV, and still dependent on parametrization in consistent with those done by Statuta. However, our calculation represent the highest magnitude of additional binding energy due to NM because the model dependence on parametrization with high effective mass, thus the additional binding energy reach up to 2 MeV.

We have also pointed that calculation done using RMF with non-linear parametrization and thats done using Skyrme EDF with SLy6 and SKL3, and our calculation all of them emphasize that there is no enhancement of NM effect at  $N=Z$ . all of the previous calculation we discuss side by side with our calculation expect for some nuclei they agreed that the effect is stronger in lightest nuclei and decrease as the nuclear size increase with some

reservation on some nuclei. Time odd mean field in RMF with density dependent model or non-linear model are always attractive contrary to calculation done using Skyrme EDF where some leading to less (repulsive) or more (attractive) binding depending on type of parametrization.

Table 3.1: The effect of time odd mean field on light nuclei with  $10 \leq Z \leq 27$ , column (1) represent light nuclei, column (2) and (3) represent range of additional binding due to effect of NM on light nuclei isotopes, additional binding represented due to calculation done using RMF with NL3 non-linear model and RMF with density dependent DD-ME2 parametrization.

<b>Light nuclei</b>	<b>Non-Linear NL<sub>3</sub> (KeV)</b>	<b>DD-ME2 (KeV)</b>
Ne	around [50-320]KeV	≈[0.00-550]
Na	around [100]	[170-220]
Mg	[50-300]	[100-350]
Al	around [100]	[150-400]
Si	around[50-320]	[100-500]
P	[50-250]	[130-500]
S	[50-300]	[300-1500]
Cl	[0-150]	[170-2610]
Ar	[50-250]	[100-900]
K	[50-250]	[240-1400]
Ca	[100-350]	[50-750]
Sc	[50-100]	[140-860]
Ti	[50-250]	[53-1500]
V	[50-100]	[100-1300]

Continued on next page



**Table 3.1 – continued from previous page**

<b>Light nuclei</b>	<b>Non-Linear NL<sub>3</sub> (KeV)</b>	<b>DD-ME2 (KeV)</b>
Cr	[50-250]	[0.0-700]
Mn	[50-100]	[0.0-1320]
Fe	[50-250]	[34-1300]
Co	[50-100]	[110-1120]

### **3.3 Effect of Time Odd Mean Field (NM) With Density Dependent Parametrization on Changing the Shape of Nuclei**

Triaxial nuclear shapes are used in nuclear physics to describe transitional nuclei; nuclei that are not so strongly deformed. The ground state deformation of axially symmetric nuclei may change and break the symmetry. Gamma angle used to describe the departure from axially symmetry in both static and rotating nuclei, nuclear shape that has  $\gamma = 0^\circ$  or  $60^\circ$  describes axially symmetric prolate and oblate shape respectively. Intermediate  $\gamma$  value between those values describe triaxial symmetric shape[49].

Triaxial degree of freedom plays a significant role in our investigation. Calculation of binding energy due to NM with their dependence on deformation angle is plotted in Fig. (3.7) and [3.8]. Both of them presented and cover all the nuclei from proton drip line up to neutron drip line. For even  $Z$  and odd  $Z$  nuclei separately. Each nuclei between  $Z = 10 - 27$  is shown in separate panel. We found that Time odd mean field (NM) is strongly affected by the shape of nuclei. In Fig. (3.7) for even  $Z$  nuclei most of nuclei near the proton drip

line are found to be triaxial so that they gained an additional binding energy higher than other neighborhood nuclei, in this region small value of  $\gamma$ -deformation leads to significant amount of binding energy. In section 3.1.2 we pointed to nuclei that gained a significant amount of additional binding.  $^{45}\text{Ar}$  and  $^{47}\text{Ar}$  gained more than 900 KeV, as we can see from panel (e) in Fig. (3.7) the value of  $\gamma$ -deformation is  $42^\circ$  and  $50^\circ$  respectively.

$^{65}\text{Fe}$ ,  $^{59}\text{Ti}$ ,  $^{89}\text{Ti}$ ,  $^{87}\text{Ti}$ ,  $^{87}\text{Ti}$  nuclei gained more than 1 MeV are triaxial nuclei. Their deformation angle is  $34^\circ$  and 58, 57, 59 for Ti isotopes as we can see from panel (i) and (j) respectively. The effect of triaxillity of the nuclei become more significant as the nuclei get heavier. However, the NM don't affect on nuclei which found that there ground state are triaxial in calculation without NM. The nuclei become completely triaxiall when  $\gamma = 30^\circ$ , in this angle maximum additional due to trixiillity we get,  $^{65}\text{Fe}$  have nearly  $\gamma \approx 35$  as we can see this maximum.

In Fig. (3.8) odd Z nuclei additional binding energy due to NM with there dependence on deformation angle  $\gamma$  are represent. Panel (a)-(i) represent nuclei with odd Z between 10-27. We found that they are strong in deformation and transitional nuclei more than odd N nuclei. as in the case even Z nuclei, odd Z one with more than 1 MeV are  $^{85}\text{K}$ ,  $^{61}\text{V}$ ,  $^{87}\text{V}$ , the angle of deformation is  $\gamma = 52, 58, 59^\circ$ .  $^{65}\text{Mn}$ ,  $^{69}\text{Co}$  gained more than 1 MeV but with  $\gamma$ -deformation is  $33^\circ, 25^\circ$ .

Calculation of time odd mean field using density dependent model leads to additional binding energy, some nuclei exhibit a significant amount of additional binding reaching more than 1 MeV, this additional magnitude of energy is due to the change of this nuclei shape from prolate to triaxial shape. However, there are two nuclei  $^{65}\text{Cl}$  [panel(d), Fig.

(3.8)], and  $^{45}\text{S}$  [panel(d), Fig. (3.7)] are experience more than (1 - 2) MeV, but we found that they are axially symmetric (prolate shape) and not triaxial shape, the reasons that this nuclei exhibit such amount of additional binding energy because of the calculation of NM and WNM exhibit two different  $\beta_2$  deformation minima,  $\beta_2 = 0.14$  in WNM calculation and  $\beta_2 = 0.23$  in NM calculation, that there are an additional amount of energy due to deformation in addition of additional binding energy own by NM.

### 3.4 Effect of Nuclear Magnetism (NM) on Single Particle Energy State

In this part of thesis we aim to study the effect of time odd mean field on single particle energy state (NM). For that calculation of single particle energy states with NM and without NM are considered for axially symmetric and triaxial nuclei, in each odd N(odd P) nuclei. We analyzed  $^{51}\text{Fe}$ ,  $^{65}\text{Fe}$ ,  $^{69}\text{Co}$ ,  $^{57}\text{Co}$  to guide overall discussion and are presented in Figs. (3.9 - 3.12).

Fig. (3.9) represent axially symmetric (with  $\gamma = 0^\circ$ )  $^{57}\text{Co}$  odd Z nuclei, panel (a) and (b) present neutron single particle energy states, panel (c) and (d) present proton single particle energy states. proton energy states exhibit splitting only in blocked state  $\frac{7}{2}^+ [3 0 3]$  with energy = - 4.10 MeV, one of state are raise up by - 4.39 MeV and the other drop down by - 3.84 MeV with net energy difference between upper and lower ( $\Delta E_{split}$ ) = - 0.55 MeV. neutron energy sates with same structure as blocked state, also experience such splitting.

Fig. (3.10) represent also axially symmetric  $^{51}\text{Fe}$  odd N nuclei, Same as  $^{57}\text{Co}$  nuclei, panel (a) and (b), (c) and (d), present neutron and proton single particle energy state including and without including NM. only blocked state experience splitting;  $\frac{5}{2}^+ [3 1 2]$  with

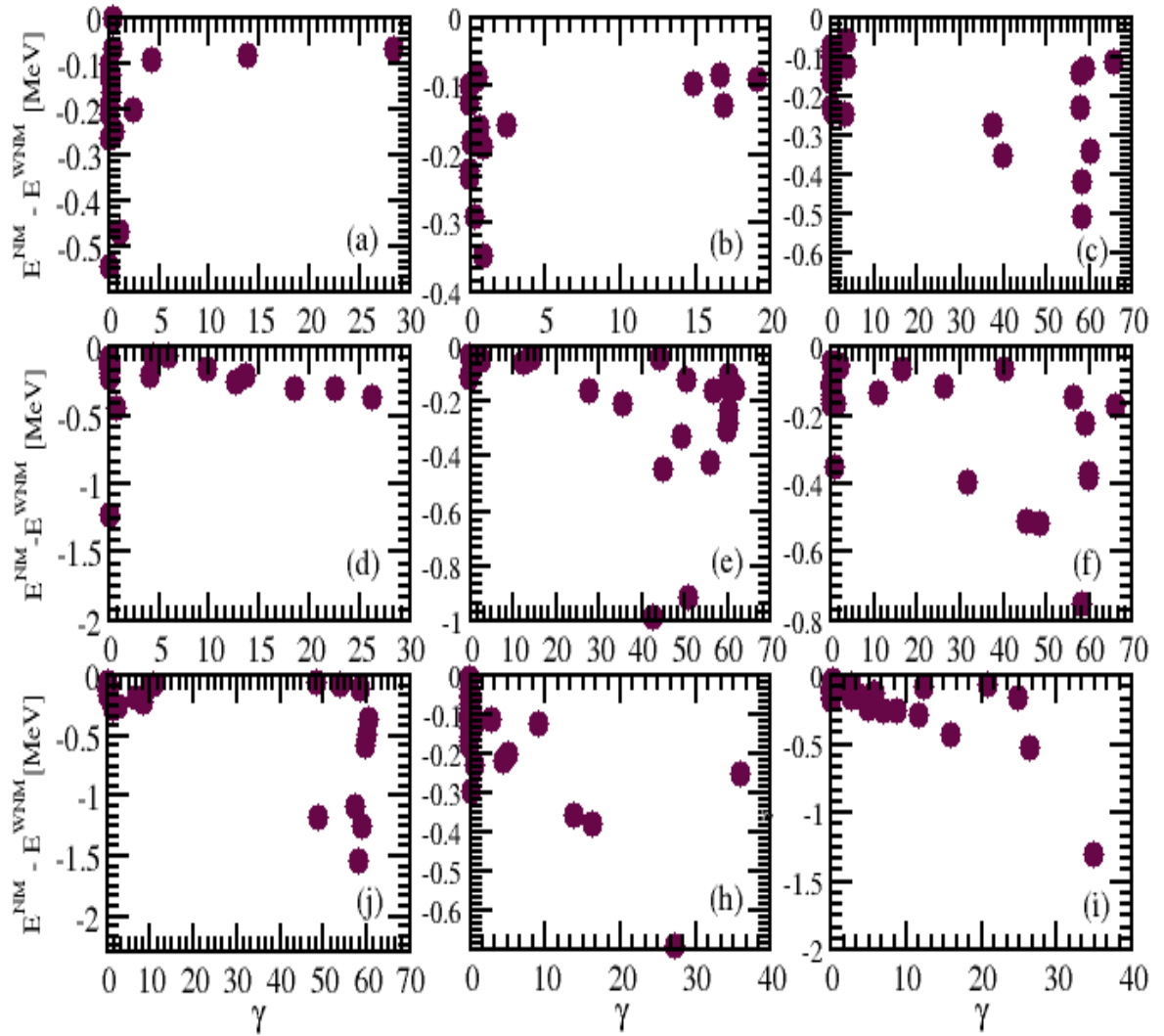


Figure 3.7: Additional binding energy with their dependence on deformation angle gamma (degree) for odd N light nuclei, even Z nuclei between [10-27] are present in each panel from (a) - (i). The calculation cover all isotopic chains from proton drip line up to neutron drip line.

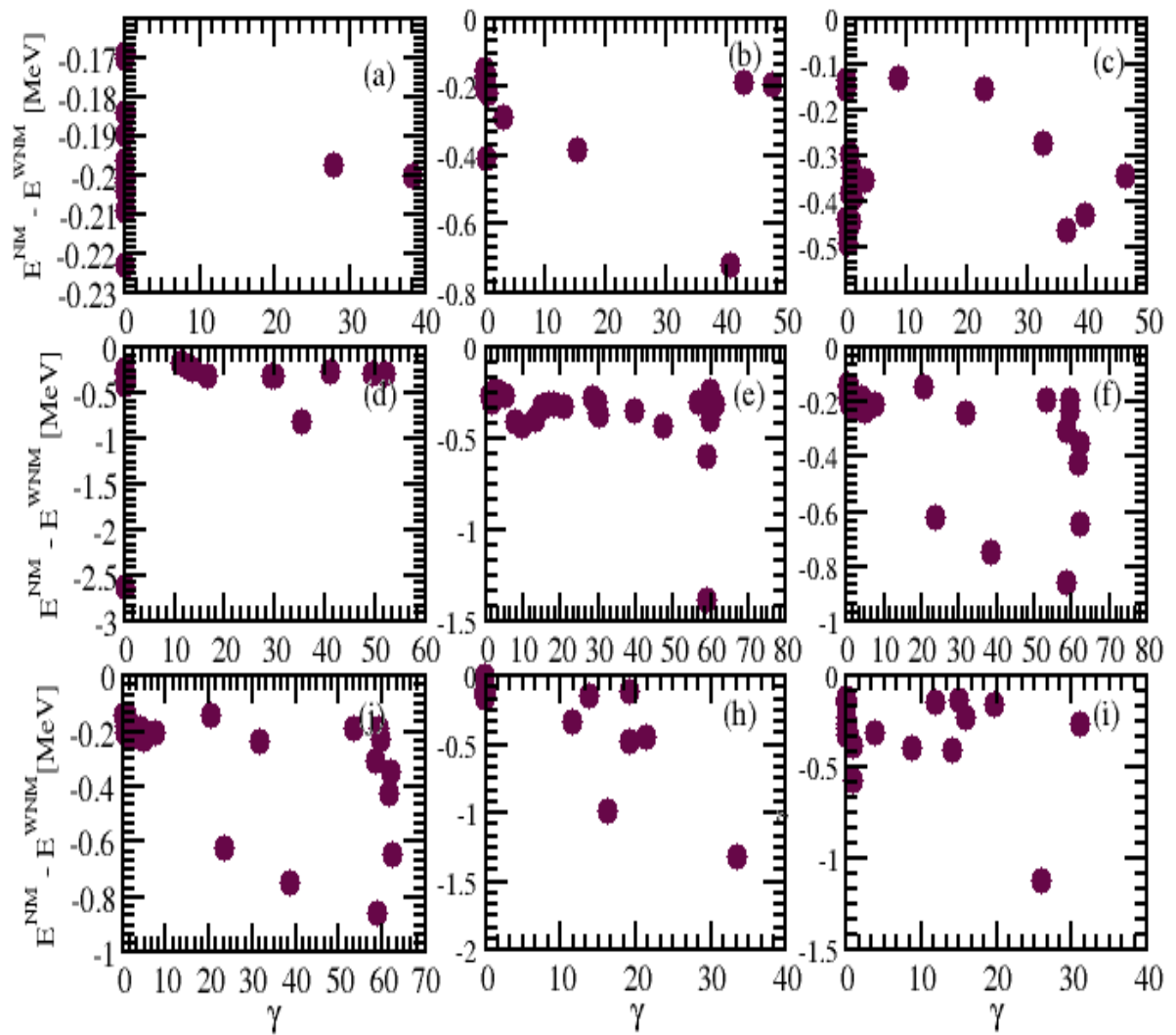


Figure 3.8: Same as Fig. (3.7), but for odd  $Z$  light nuclei between [10-27].

13.15 MeV split into  $E = 13.44$  and  $12.87$  MeV, apparently again one raise up and one drop down with  $(\Delta E_{split}) \approx -0.6$  MeV. For proton single particle energy state splitting appear states  $\frac{5}{2}^+[2\ 0\ 2]$ ,  $\frac{5}{2}^+[3\ 1\ 2]$  with  $\Delta E_{split} \approx -[0.4 - 0.5]$  MeV in each state respectively.

In Fig. (3.11 - 3.12) show single particle energy state for triaxial  $^{69}\text{Co}$  ( $\gamma \approx 26^\circ$ ) and  $^{65}\text{Fe}$  ( $\gamma \approx 34^\circ$ ) nuclei. Fig. (3.11) same as Fig. (3.9), but for  $^{69}\text{Co}$ . Neutron and proton exhibit splitting in all of its single particle energy state, not only blocked state  $\frac{7}{2}^+[3\ 0\ 3]$ . For odd N  $^{65}\text{Fe}$  this behavior is still applicable; all single particle energy state of proton and neutron Fig. (3.12) panel (a) and (c), comparing to panel (b) and (d) affected by NM and split including block state  $\frac{1}{2}^+[4\ 2\ 0]$ ; in this state one raise up by  $6.77$  MeV and one drop down by  $5.86$  MeV with  $\Delta E_{split} \approx 0.9$  MeV.

Generally, Time odd mean fields break kramer's degeneracy in blocked states, that's why this states exhibit such splitting. single particle energy state in all axially symmetric nuclei (with  $\gamma = 0$  or  $60^\circ$ ) both odd N and odd Z nuclei exhibits an splitting in blocked state as result of NM with magnitude  $\Delta E_{split}$ , this magnitude depend on each nuclei separately, leads to raise up one state and drop the other with each by  $\approx \frac{\Delta E_{split}}{2}$ , also for odd N nuclei proton energy state, and for odd Z nuclei neutron spectra exhibit splitting in all energy state has same  $\Omega$  number. However since  $\Omega$  is not good quantum number in triaxial nuclei and each state are mixed state of different  $\Omega$  basic state, we found that all the proton and neutron energy state including blocked state are split.

In all above figure we deal with only occupied state. In Fig. (3.13) occupied and unoccupied single particle energy state of proton with same structure as blocked state presented for  $^{93}\text{Co}$  nuclei as function of there splitting energy, state with different signature

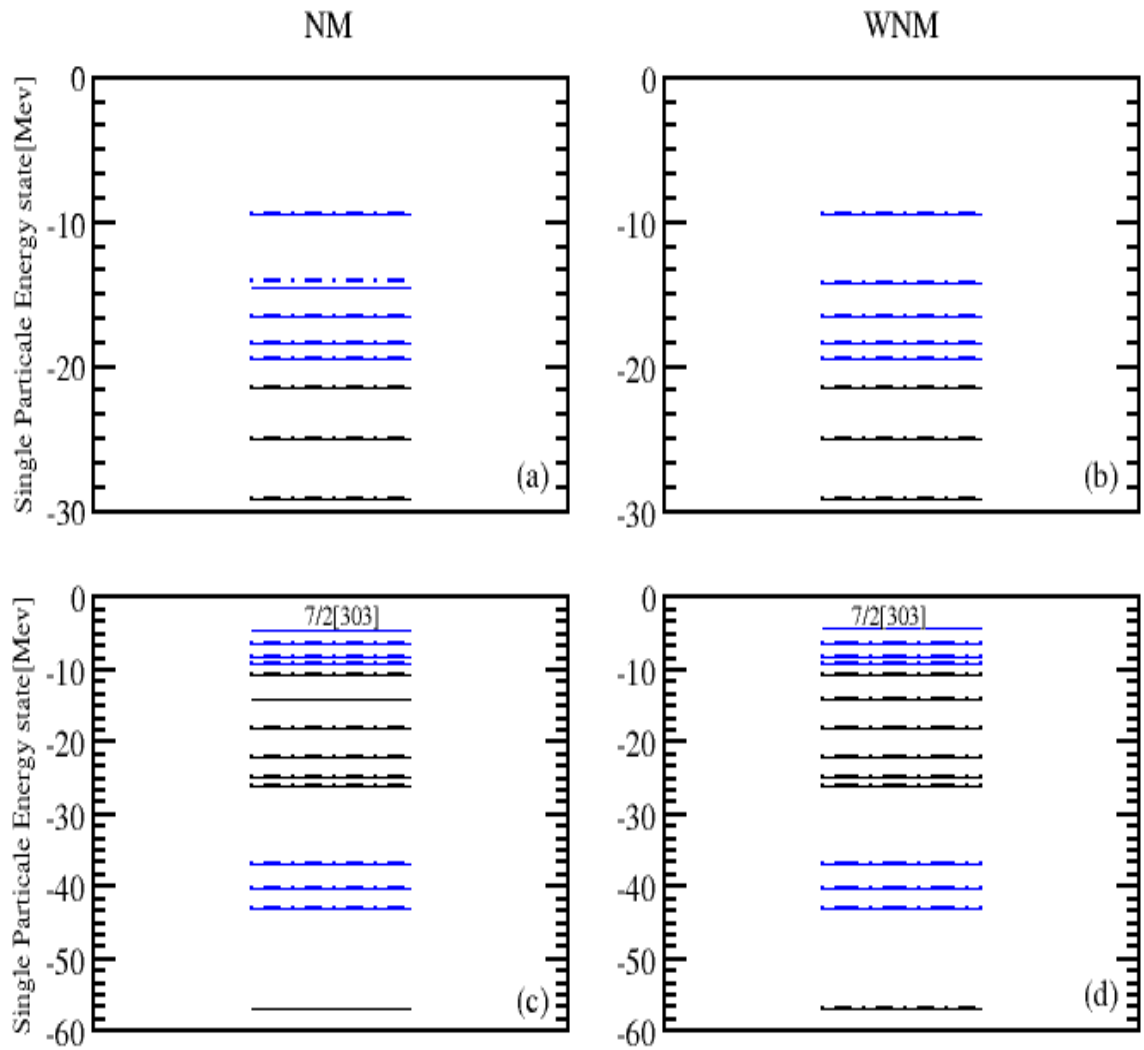


Figure 3.9: Single Particle Energy State of  $^{57}\text{Co}$ . panel (a) and (c) present single particle energy state for proton and neutron with calculation including NM, panel (b) and (d) present single particle energy state for proton and neutron without including NM. state with black solid (dotted) line are state with (+p+i), (+p-i), blue solid(dotted) line are state with (-p+i), (-p-i).

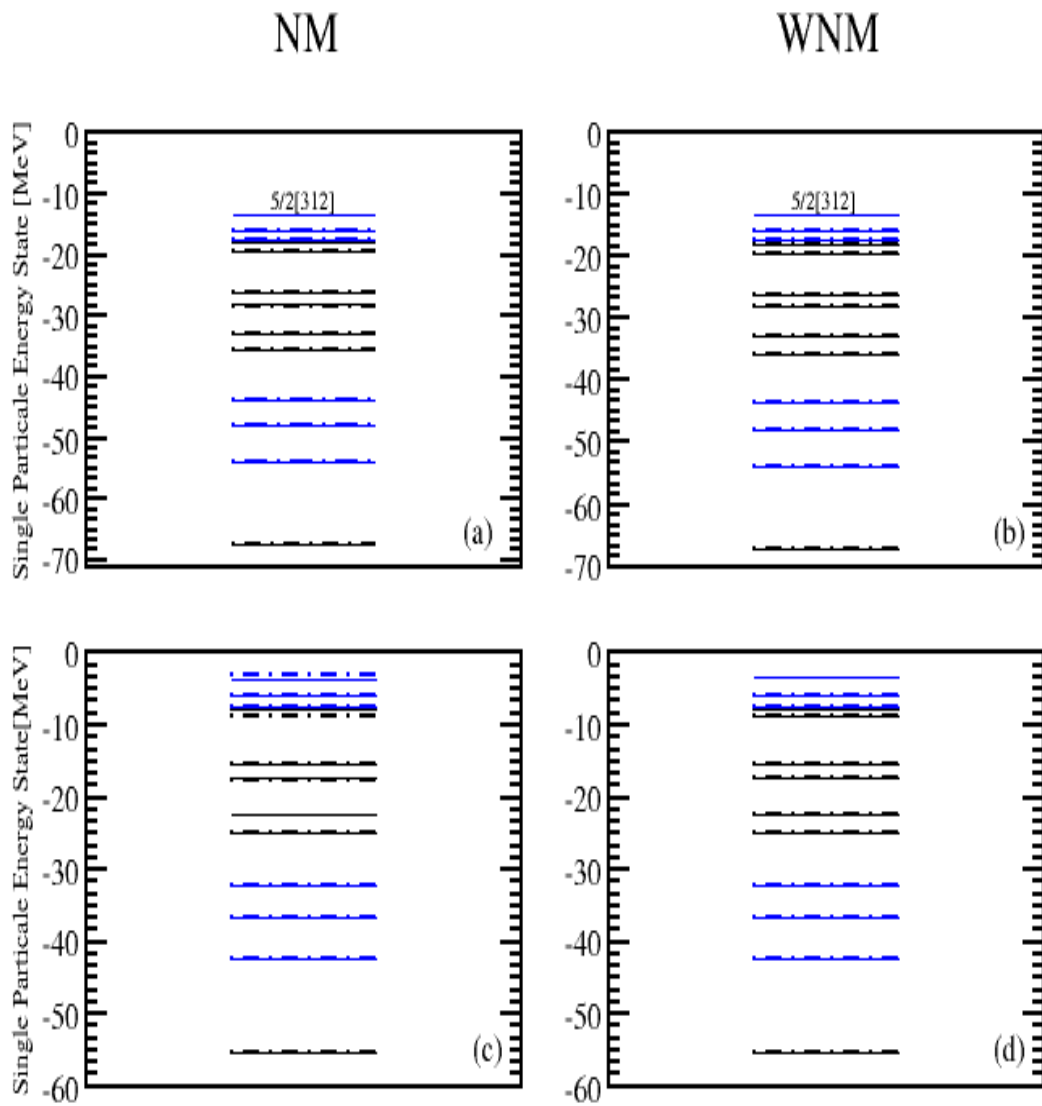


Figure 3.10: Same as 3.9, but for  $^{51}\text{Fe}$  (odd N number).



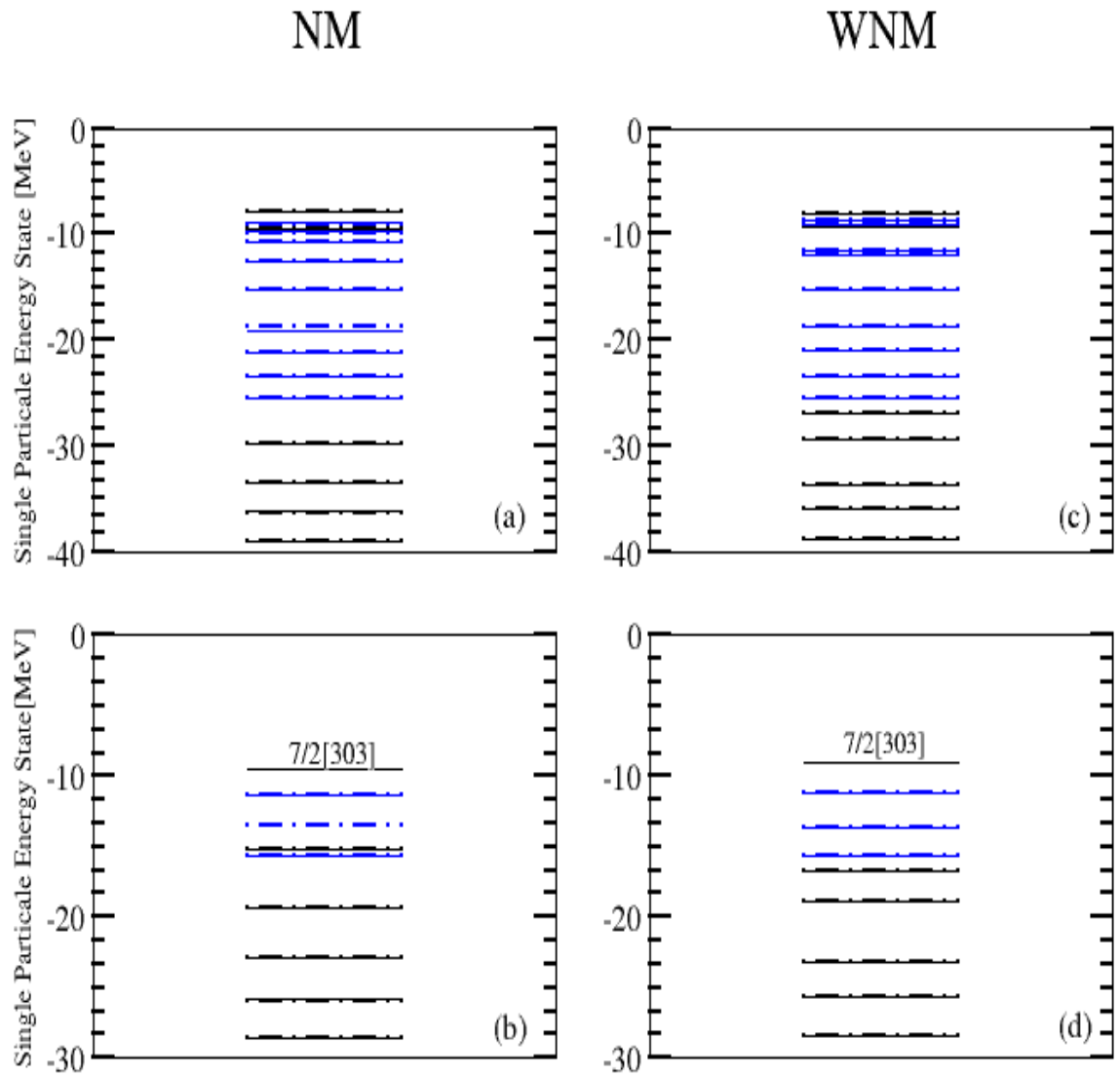


Figure 3.11: Same as Fig. (3.9), but for  $^{69}\text{Co}$  (odd Z number) triaxial nuclei. With block state  $\frac{7}{2}^+[303]$  with positive signature (black soiled line).

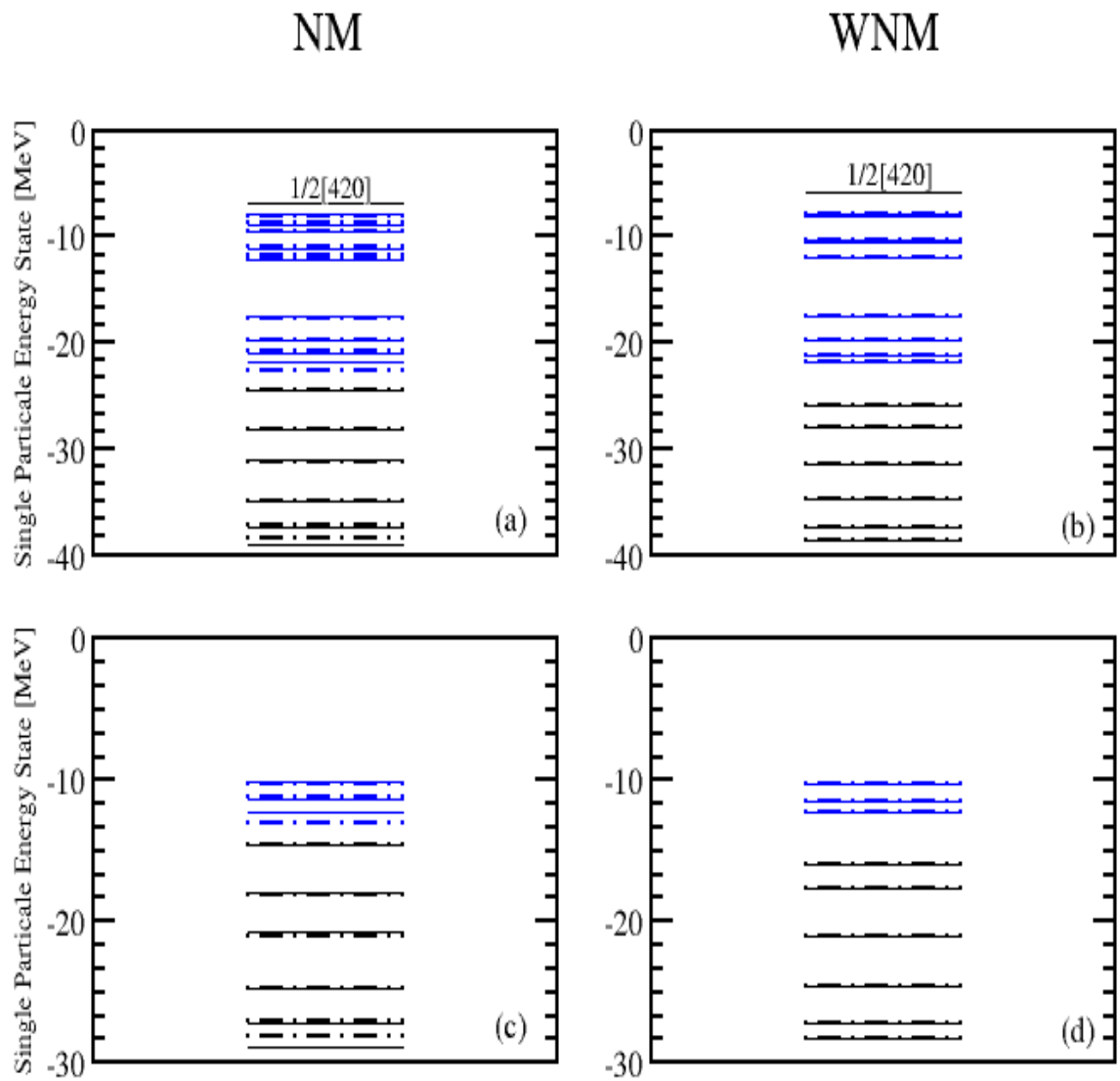


Figure 3.12: Same as Fig. (3.9), but for  $^{65}\text{Fe}$  (odd N number) triaxial nuclei. With block state  $\frac{1}{2}^+[420]$  with positive signature (black soiled line).

also present (state with +i and -i time reversal counter part) as we can see all of them affected by NM in same fit so that they exhibit splitting. and this can be explained using Eq. [2.17]; where the main contribution in magnetic potential come from space like component of  $\omega$ -meson which is basically isospin independent. However all occupied and unoccupied single particle state are split in triaxial nuclei. From Fig. (3.13) we also found that occupied single particle state are more bound than those unoccupied (that have higher energy value than the bound). all of this observation also do not related to signature where state either with (+i) and (-i) experience same influence of NM. Calculation of single particle energy state have been done using RMF with nonlinear parametrization, Fig[10] in ref[6] similar to Fig. (3.13) where the calculation presented are for neutron, occupied and unoccupied single particle energy states for  $^{119}\text{Ce}$  nuclei, calculation done using RMF with non-linear parametrization and RMF with density dependent model are similar in description this situation. However  $\Delta E_{split}$  value are higher than those in calculation using NL3 due to fact that sates are basically gained and additional mount of binding energy due to DD-ME2 calculation.

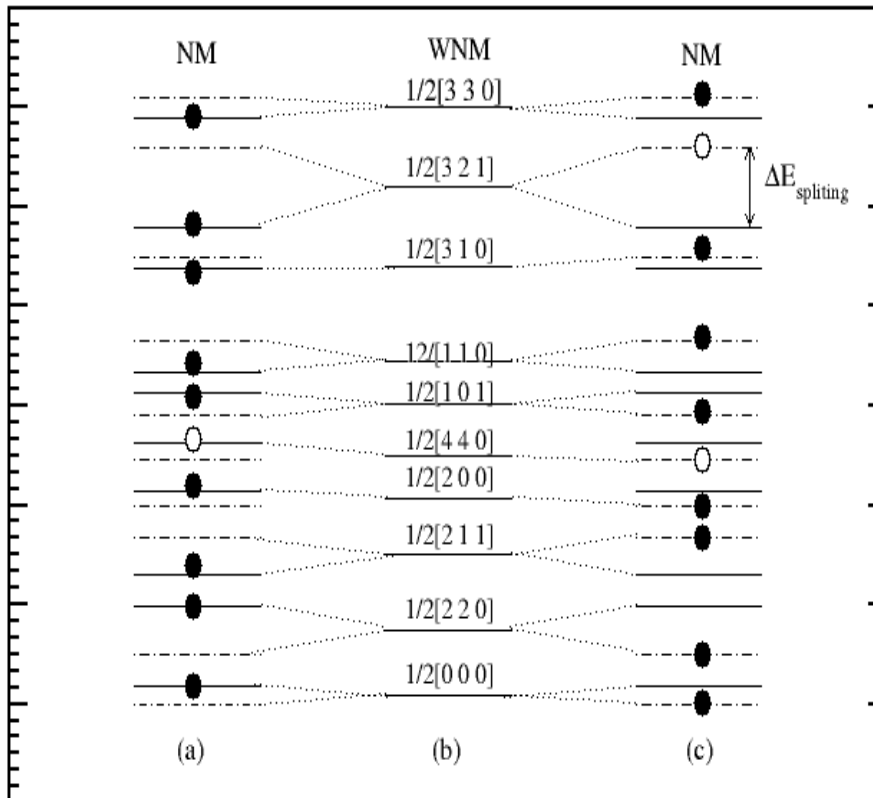


Figure 3.13: Single Particle Energy Proton State of  $^{93}\text{Co}$  as function of energy splitting  $\Delta E_{split}$  with same structure as blocked state  $[1/2\ 3\ 2\ 1]$ . calculation of NM and without NM are presented. state with dot line are state with negative signature (-i), the one with solid are positive signature(+i). column (a) present occupied(filled circle) and unoccupied(open circle) state with and with (+i), column(c) same as (a), but for state with negative signature(-i).

## CHAPTER 4

### CONCLUSION

Time odd mean fields have been studied within the frame work of CDFT using density dependent meson - coupling model with DD-ME2 parameter, the result as follow:

1. Time odd mean field (Nuclear magnetism) affected on light odd mass nuclei, either odd Z or odd N in the same way, they gained an additional binding due to NM in agreement with calculation done using non-linear model which confirm the attractive nature of this fields. However the absolute magnitude of additional binding reach to 1.5 MeV. Odd N nuclei gained higher additional binding than odd Z nuclei.
2. Change the shape of nuclei from axially symmetric nuclei with gamma deformation parameter ( $\gamma = 0, 60^\circ$ ) to triaxial deform nuclei is significant feature in calculation done using DD-ME2; Time odd mean field (NM) is strongly affected by the shape of nuclei. such nuclei gained the largest additional binding among other nuclei. Some of nuclei found to have two different  $\beta$  value (two different minimum), thats result to add extra binding to additional binding reach up to 2 MeV.
3. Single particle energy state with  $\phi = \phi_{block}$  value in axially symmetric nuclei odd N, odd Z nuclei are splits due to NM by  $\Delta E_{split}$ , while all states in triaxial nuclei are splits.

In this thesis, we studied the effect of time odd mean field using density dependent model with DD-ME2 parameter for light nuclei only, and compared them to calculation done with non-linear parametrization, other calculation in heavy and medium mass region needed to complete the whole picture. Calculation with other density dependent parametrization such as DD-ME1, TW99, PKDD, should be done to confirm that additional binding energy weakly depend on relativistic mean field parametrization as non-linear model provide. calculation using point coupling model also proposed as future work to provide better description side by side with description provided by the two previous model.

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