

## Structure of neutron-rich nuclei around $A \simeq 100$

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**Abstract.** Neutron-rich isotopes of Mo ( $Z = 42$ ) around  $A \simeq 100$  have been investigated within the formalisms of cranked Nilsson Strutinsky and CHFb, to study several interesting features of nuclear structure in this mass region. The total energy/routhian surfaces have been generated for the isotopes of Mo ranging from  $A \simeq 96 - 112$ , as a function of deformation ( $\beta_2$  and  $\gamma$ ) for ground state and higher angular momentum states. Results of calculations using two different formalisms have been compared and combined to have a better understanding of the underlying mechanism of shape evolution.

**Keywords.** Nuclear structure; CHFb; Nilsson Strutinsky calculations;  ${}_{42}^{96-112}\text{Mo}$ .

**PACS Nos** 21.10.Re; 21.60.Jz; 27.60.+j

### 1. Introduction

Information [1–3] obtained so far indicate that the nuclei in the Sr–Zr–Mo region around  $A \simeq 100$  have several appealing features in their nuclear structure. These nuclei show rapid changes in structure-dramatic variation in quadrupole collectivity has been observed in isotopes of Sr–Zr nuclei. For  $Z > 40$  (Mo, Ru, Pd) nuclei, the shape transition is less dramatic but they show softening of the nuclear energy surface to triaxiality. The rapidity in shape change results in shape coexistence in these nuclei. Moreover these nuclei have shown a richness of various structural effects at high angular momentum ( $\omega$ ). There is also evidence of pairing collapse evident through the moment of inertia value which is almost equal to the rigid body value. So in the  $A \simeq 100$  region, there is an extremely favourable condition to study many different nuclear structural characteristics in a narrow range of isotopes and isotones. This is a fertile territory for testing various theoretical models.

Most of these nuclei are neutron rich and despite different experimental efforts [1,2], detailed experimental information on high-spin properties of  $A \simeq 100$  nuclei are still scarce.

We plan to systematically study neutron rich  ${}_{42}\text{Mo}$  isotopes ( $N = 54-70$ ) within Nilsson Strutinsky formalism [4] to study the equilibrium deformations in their ground states and their evolution with spin. Similar calculations have been started within CHFb with pairing plus quadrupole interaction [5,6], for studying the microscopic origin of the onset of deformation and self-consistent determination of the evolution of pairing gap and deformation with spin. Total energy surfaces have been generated for these nuclei within

HFB and higher angular momentum states for  $^{96}\text{Mo}$  and  $^{104}\text{Mo}$  have been calculated using CHFb. Detailed microscopic calculation of higher angular momentum states of other nuclei is in progress.

## 2. Formalism

The main assumption of Nilsson-Strutinsky approach [4] is that the total energy of a nucleus can be decomposed into two parts,

$$E = E_{\text{macro}} + E_{\text{micro}}, \quad (1)$$

where  $E_{\text{macro}}$  is the macroscopic energy and  $E_{\text{micro}}$  is the microscopic shell correction energy calculated from a non-self-consistent average deformed potential (modified harmonic oscillator potential). Pairing is included only for  $I = 0$ . Rotation is introduced in cranking approximation corresponding to rotation around one principal axis.

In the cranked HFB model, the hamiltonian  $H_\omega$  is cranked about an axis (here, x axis) perpendicular to the symmetry axis (here, z axis) of the nucleus

$$H_\omega = H - \omega \hat{I}_x - \lambda \hat{N}, \quad (2)$$

where the different terms have their usual meanings [6].  $H$  is given by the pairing plus quadrupole model hamiltonian of Baranger and Kumar [5]. Evolution of pairing gap and deformation with spin is calculated self-consistently in this model.

The oscillator shells  $N = 4$  and  $5$  are included in the basis states for both protons and neutrons. The inert core is therefore,  $^{80}_{40}\text{Zr}_{40}$ . The single particle parameter sets ( $\mu, \kappa$  values) are used as suggested by Nilsson *et al* [7] to obtain spherical single particle energies. The pairing and quadrupole force constants are given by

$$G_p = 30/A \text{ MeV}, \quad G_n = 22/A \text{ MeV}, \quad \chi_2 = 80 A^{-1.4} \text{ MeV}. \quad (3)$$

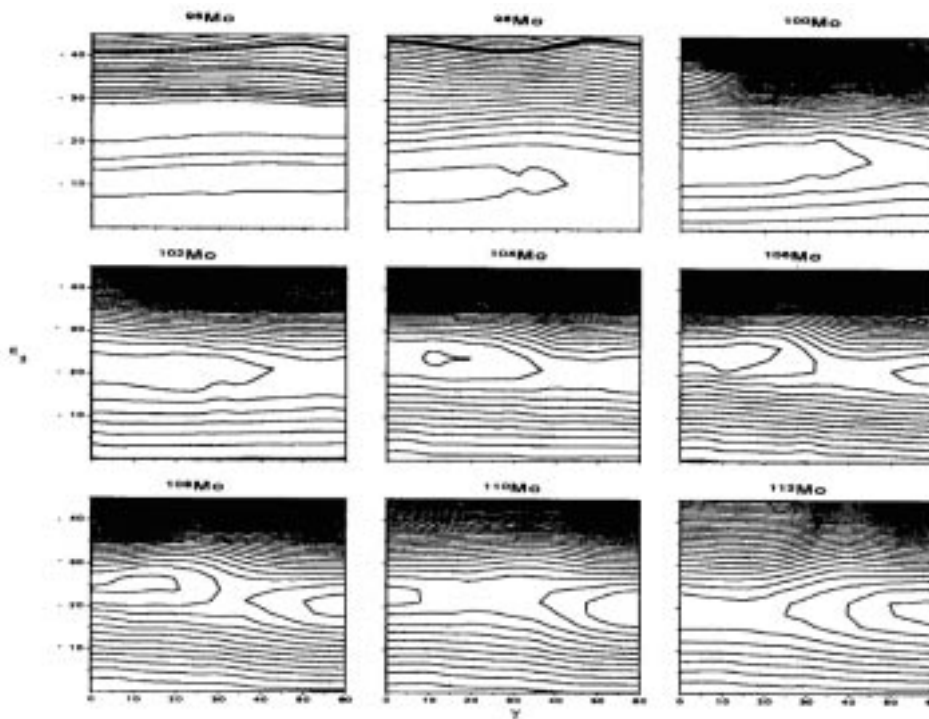
## 3. Results and discussion

Table 1 contains the comparison of our results using two different approaches with previous experimental [8] and theoretical results with extended Thomas Fermi Strutinsky integral method (ETFSI) [9] and finite range droplet model (FRDM) [10].

Figure 1 shows the total energy surface plots for the ground states of  $^{96-112}\text{Mo}$  isotopes as a function of  $\beta$  and  $\gamma$ , within Nilsson Strutinsky approach. The changes in deformation with increasing neutron number is evident from the figure.  $^{96}\text{Mo}$  ( $N = 54$ ) with only 4 neutrons outside the closed  $N = 50$  shell shows small  $\beta$  deformation (table 1). Its total energy surface (TES) is flat against triaxiality indicating extreme  $\gamma$ -softness. As neutron number increases the minimum becomes more confined in the  $\gamma$ -axis, and the  $\beta$  value increases reaching a maximum ( $\approx 0.26$ ) for  $N = 64$ . As  $N$  increases from  $N = 62$ , a second minimum develops for oblate deformation and shape coexistence is predicted for  $N = 66$ . For higher  $N$  isotopes, the first minimum shifts to an oblate shape ( $\beta \approx -0.20$ ).

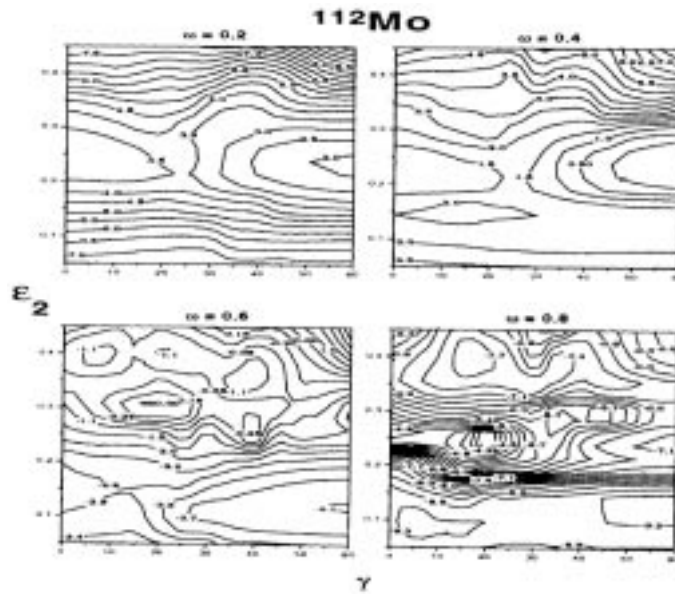
**Table 1.** Comparison of present results with previous results.

A	Expt. [8]	Theory			
		Previous		Present	
		FRDM [10] $\epsilon_2$	ETFSI [9] $\beta$	Nil. Strut. $\epsilon_2$	CHFEB $\beta$
96	0.1720(16)	0.08	0.02	0.08	0.06
98	0.1684(16)	0.180	0.20	0.10	0.08
100	0.2309(22)	0.244	-0.27	0.15	0.10
102	0.326(19)	0.329	-0.27	0.20	0.15
104	0.325(12)	0.349	0.36	0.25	0.18
106	0.353(10)	0.361	0.37	0.26	0.20
108	0.354(41)	0.333	0.37	-0.20	0.20
110	-	0.335	-0.31	-0.20	-0.20
112	-	0.337	-0.31	-0.20	-0.15



**Figure 1.** TES plots within Nilsson Strutinsky approach.

For  $N = 70$ ,  $^{112}\text{Mo}$  isotope, there is a single minimum for an oblate deformation  $\approx -0.20$ , which agrees with previous theoretical result [9].



**Figure 2.** TRS plots within Nilsson Strutinsky approach.

The total routhian surface (TRS) plots for Mo isotopes with  $N < 64$ , for  $\omega = 0.2$  to  $0.8$  show that the extreme  $\gamma$ -soft minimum at ground state shifts towards definite triaxial minimum at  $\omega = 0.2$  with an increase in the  $\beta$  value. But then with increasing rotational frequency the equilibrium shape shifts to oblate.

But for heavier isotopes, the trend in shape evolution changes. Figure 2 shows the TRS plot for  $A = 112$ , Mo isotope. Although the ground state equilibrium shape is oblate (figure 1), the higher rotational frequency generates a second minimum for prolate shape. This shape coexistence prevails until at  $\omega$  about  $0.6$ , the prolate minimum shifts to  $\beta \approx 0.4$ . This is an indication of non-yrast superdeformation. This feature is seen for  $N > 64$ . The spin values associated with the SD shape is  $\approx 50$ .

The total energy surface plots for the ground states of  $^{96-112}\text{Mo}$  isotopes as a function of  $\beta$  and  $\gamma$  have also been generated within CHFB approach.

The changes in deformation with increasing neutron number is similar to figure 1. Smaller values of deformation obtained in the present work compared to the previous results, shown in table 1, indicates that a readjustment of the quadrupole–quadrupole interaction strength is needed.

Preliminary CHFB calculation for higher angular momentum states (up to  $I \simeq 8$ ) show the following interesting results for  $^{96}\text{Mo}$  and  $^{104}\text{Mo}$ . In  $^{96}\text{Mo}$ , neutron alignment takes place ( $\nu g_{7/2}$ ). Neutron pairing gap decreases drastically with spin. In  $^{104}\text{Mo}$ , proton alignment takes place ( $\pi g_{9/2}$ ). Proton pairing gap decreases drastically with spin. Preliminary CHFB results indicate that the rapid onset of deformation in this mass region is a result of strong  $n - p$  interaction in the orbitals with large spatial overlap. The overlapping orbitals are  $\pi g_{9/2} - \nu g_{7/2}$ . The decrease in pairing gap may also be an indication of the pairing collapse predicted in this mass region [3] resulting from a relatively low single particle level density.

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