Island of inversion around N = 20 isotones and indication of a bubble structure

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Introduction

Charge distribution is one of the important properties of the nuclei. Isotopic as well as isotonic variation of charge radii provide clues for nuclear structure information including closure as well as melting of shell formation and one can get also information about exotic structures like bubble nuclei in the work of Campi and Sprung [1]. Inversion of shell model states has been related to quadrupole deformation[2,3]. But to what extent island of inversion is correlated to deformation is not clear. In this context charge distribution plays a very important role. We shall try to show in this work the correlation between bubble structure and inversion of states through inclusion of tensor interaction in Skyrme-Hartree-Fock theory. Lesinsky et al [4] have shown in great details how the presence of tensor force changes the evolution of the spin-orbit splitting with N and Z. Zou et al [5] have shown the reduction in neutron spin-orbit splitting as on moves from ^{48}Ca to ^{46}Ar. Importance of tensor interaction in Skyrme-Hartree-Fock theory has been explored in the works of Otsuka et al [6-8]. Keeping these findings in view the present scenario in bubble structure of nuclei and island of inversion has been investigated.

Mathematical Formalism

The importance of inclusion of tensor interaction in the Skyrme-Hartree-Fock (SKHF) theory for developmental study of nuclear shells throughout the nuclear chart has been shown [9]. The spin-orbit potential which is the key player in forming groups of single-particle levels leading to formation of shells is given by

$$V_{SO}^{q} = \frac{1}{2r}\left\{\left(C_0^J - C_1^J\right)J_0(r) + 2C_1^J J_q(r) - \left(C_0^{\nabla J} - C_1^{\nabla J}\right)\frac{d\rho_0}{dr} - 2C_1^{\nabla J}\frac{d\rho_q}{dr}\right\} \mathbf{L\,.\,S} \quad (1)$$

After variation and keeping only the iso-scalar part one obtains

$$V_{s.o.}^{q} = \frac{W_0}{2r}\left(2\frac{d\rho_q}{dr} + \frac{d\rho_{q'}}{dr}\right) + \left(\alpha\frac{J_q}{r} + \beta\frac{J_{q'}}{r}\right) \quad (2)$$

where

$\alpha = C_0^J + C_1^J$ and $\beta = C_0^J - C_1^J$ are the tensor coupling coefficients, q stands for proton (neutron) and q' stands for neutron (proton), $\rho_{q(q')}$ is the proton or neutron density, $Jq_{(q')}(r)$ is the proton or neutron spin-orbit density. We have used one set of parameters SKX [10], for our calculations. A schematic pairing force of BCS type has been used to take care of pairing correlation. To get the optimized spin-orbit constant $C_0^{\nabla J}$, variational studies of the spin-orbit splitting of $1f_{7/2} - 1f_{5/2}$, $2p_{3/2} - 2p_{1/2}$ and $1d_{5/2} - 1d_{3/2}$ levels were performed for isoscalar spin-saturated N = Z nucleus ^{40}Ca. Optimization of other tensor constants has been described in [9]. Spherical basis has been used in the calculation as most of the nuclei under consideration have been found to be spherical [11].

Results

It was pointed out by Grasso et al [12] N = 20 region is most suitable for proton bubble formation due to closeness of the $2s_{1/2}$ state and $1d_{3/2}$ state. In Table I the results for the energies of shell model states along with their occupation probabilities have been presented.

Table I

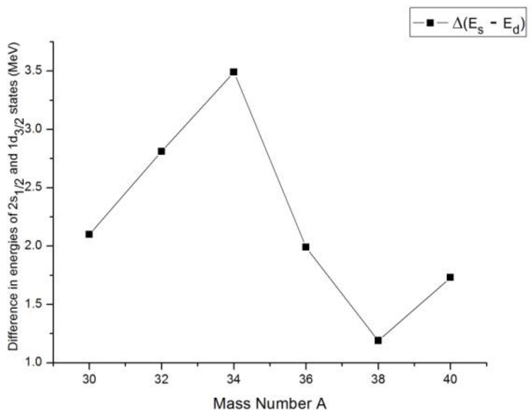
The energies and occupation probabilities of shell model single particle states of even isotones of N = 20 nuclei

States\Nuclei	^{40}Ca	^{38}Ar	^{36}S	^{34}Si	^{32}Mg	^{30}Ne
$1d_{5/2}$	20.33	13.79	15.38	16.43	17.20	17.64
Occ. Prob.	1.0	0.985	0.984	0.928	0.619	0.310
$1d_{3/2}$	14.26	8.31	8.65	9.40	10.99	12.24
Occ. Prob.	1.0	0.597	0.164	0.022	0.037	0.030
$2s_{1/2}$	5.99	9.51	10.64	12.89	13.80	14.33
Occ. Prob.	1.0	0.859	0.728	0.187	0.112	0.061

S.P. energies are all negative

The difference in energies of $2s_{1/2}$ and $1d_{3/2}$ states has been plotted in Fig. I from where we c an see that a change takes place at ^{34}Si which indicates a probable case of inversion.

Figure I



We have calculated the binding energy per nucleon and charge radii of even isotones N = 20 nuclei starting from ^{32}Mg. The calculated results along with experimental values [13,14] are shown in Table II.

Table II

Binding energy per nucleon and Charge radii of N = 20 even isotones

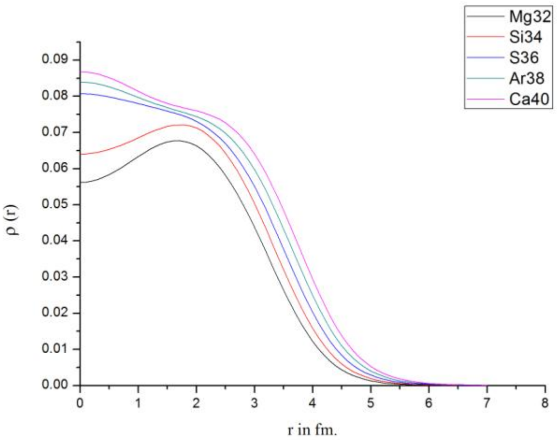
Nuclei	B.E./A (Th)	B.E./A (Ex)$^{a)}$	R_c (Th) in fm.	R_c (Ex) in fm$^{b)}$
Ca^{40}	8.43	8.55	3.4715	3.4764
Ar^{38}	8.51	8.61	3.3914	3.4020
S^{36}	8.50	8.57	3.2964	3.2982
Si^{34}	8.30	8.34	3.1975	
Mg^{32}	7.78	7.80	3.1042	3.1863
Ne^{30}	7.55	7.04	2.96	

a) Ref.13, b) Ref. 14

It is apparent from the table that the calculated values are quite close to the experimental values thus vindicating the importance of inclusion of optimized tensor forces in SKHF theory. It needs mention that in case ^{32}Mg the calculated value of charge radius is somewhat on the lower side.

From Table I one can see a drastic drop in the occupation probability of $2s_{1/2}$ state from ^{34}Si down to ^{30}Ne. Only in case of ^{36}S we can compare the occupation numbers from experiment [15]. In case of $1d_{5/2}$ experimental value is 5.95(our value 5.90), for $1d_{3/2}$ experimental value is 0.31(our value 0.64) and for $2s_{1/2}$ experimental value is 1.63(our value 1.46). As we know that depletion in occupation probability of s-state is a requirement for the development of nuclear bubble, so, we feel ^{34}Si is a good candidate for bubble nucleus. In order to explore the situation we have calculated the charge distribution of N = 20 isotones. The results are shown in Fig. II.

Figure II



From the Figure II it is evident that in the central region of the charge distribution of ^{34}Si and ^{32}Mg we can observe a depression instead of elevation compared to ^{38}Ar and ^{40}Ca indicating formation of bubble structure with a hollow inside. Thus we see formation of bubble structure in the inversion region takes place. This phenomenon needs further consideration.

Summary

Through inclusion of optimized tensor interaction in the SKHF theory we have explored the region of N = 20 nuclei to check whether one can get an idea of formation of bubble and whether an inversion of position in energy levels takes place there. The results show ^{34}Si to be a prospective candidate for both the situations.

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