Reduction in Spin-orbit Splitting near Calcium Region Studied Through Skyrme-Hartree-Fock Theory

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Introduction

Importance of splitting of spin-orbit partners of shell model states came in to focus when the shell model was proposed by Mayer and Haxel et al in 1949 [1]. When there is a large imbalance in isospin content of a nucleus, the neutron-proton interaction changes its general character causing a shift in the energy levels. The conventional magic numbers give way to new entrants in the field. It has been observed that depletion of splittings of spin-orbit partner states occurs for some of the exotic nuclei. There are some explanations for this phenomenon already in vogue: - a) a large neutron excess changes the diffuseness of the neutron distribution modifying the spin-orbit interaction [2], b) the neutron-proton monopole interaction determining the character of the spin-orbit interaction of exotic nuclei reduces the splitting of the partner states [3], c) inclusion of tensor interaction in the mean-field type calculation causes a modification in the spin-orbit interaction which culminates into a change in the splitting of spin-orbit doublets [4].

Actually the problem of weakening of the splitting of spin-orbit partner states arose from the studies on erosion of N = 28 shell as one moves from ^{48}Ca to ^{42}Si isotopes.. In the transfer reaction study of ^{46}Ar (d, p) ^{47}Ar via inverse kinematics Gaudefroy et al [5] have deduced a reduction of the shell gap of N = 28 by 330(90) keV and weakening of the spin-orbit splitting of f and p shell model states by 10 (2) and 45 (10)%, respectively. In order to study the weakening of spin-orbit splitting among low- j neutron orbitals as one moves from ^{48}Ca to ^{42}Si, Otsuka et al [3] have introduced the modification of the spin – isospin part of the underlying N – N interaction through tensor interaction. Through relativistic mean-field theory Lalazissis et al [6] have shown that the magnitude of the spin-orbit potential is considerably reduced in light drip line nuclei. With the increase of the neutron number, the effective one-body spin-orbit interaction becomes weaker. However, in the cases of other shell-closed nuclei there is no experimental or theoretical result. Nuclei in the Calcium region need extra attention due to the fact that they have two important shell closures for N = 20 and N = 28 which are manifestations of strong spin – orbit interaction amongst the nucleons. In this work we have undertaken a detailed study of splitting of spin-orbit partners of shell model states below and above the Fermi-surface of neutron rich nuclei in Calcium region through Skyrme-Hartree-Fock theory after the inclusion of tensor interaction, which became quite successful in reproducing the structures of conventional shell closed nuclei.

We have shown in our earlier paper the importance of inclusion of tensor interaction in the Skyrme-Hartree-Fock theory for developmental study of nuclear shells throughout the nuclear chart [7]. The spin-orbit potential which is the key player in forming groups of single-particle levels leading to formation of shells is given by

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

$\alpha = C_0^J + C_1^J \text{ and } \beta = C_0^J - C_1^J$, are the admixture of 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.

Neutron rich Ca-isotopes provide an interesting base to study the changes in the spin-orbit splitting of shell model states. We have included a schematic zero-range pairing interaction also in our calculation.

Results

In Table 1 the splitting of 2p states of $^{40,\,48}$Ca obtained via SKX parameter set after inclusion of tensor interaction is presented in order to highlight the importance of it in the field of spin-orbit splitting.

Table 1: Splitting of 2p (n/p) states in ^{40,48}Ca

State	^{40}Ca		^{48}Ca	
	Th.	Expt.	Th.	Expt.
ν2p	1.63	2.00	1.96	1.77
π2p	1.45	1.72	1.09	2.14

In Table 2 we present a comparative study of locations of the single particle states in ^{47}Ar and ^{49}Ca.

Table 2: Single particle states in ^{47}Ar and ^{49}Ca

State	^{47}Ar		^{49}Ca	
	Th.	Expt.[a)]	Th.	Expt.[a)]
$1f_{7/2}$	-7.72	-8.02	-9.52	-9.95
$2p_{3/2}$	-4.23	-3.55	-5.71	-5.15
$2p_{1/2}$	-2.38	-2.42	-3.61	-3.13
$1f_{5/2}$	-0.07	-0.1	-1.52	-1.15

a) Ref. [5]

The results indicate that as the neutron number increases the splitting of spin-orbit partners decreases. In Fig. 1 we present the change in splitting of 1d shell model state in Ar isotopes. It is clear from the figure that there is a sharp drop

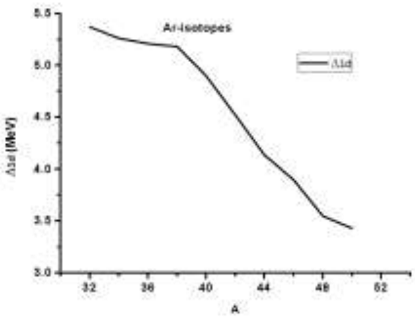

Fig.1 Change of splitting of 1d states of Ar isotopes with increasing neutron number

in the splitting as we cross the landmark of ^{38}Ar when N = 20 is reached. We have extended our calculations to the Calcium region. The results are shown in Figure 2.

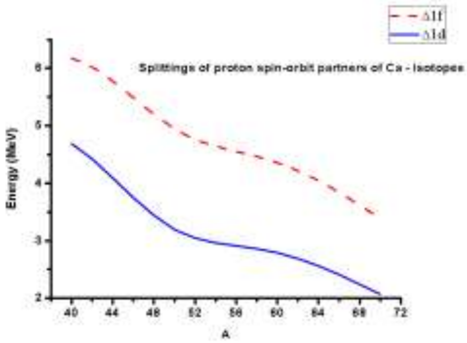

Figure 2. Splitting of 1f and 1d proton states of Calcium isotopes

There is a rapid decrease in the splitting up to A = 50, and after that there is a gradual decrease in the pattern. This vindicates our postulate that tensor interaction has a role to play in the attenuation of the splitting of spin-orbit partners.

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