Scenario of weakening of spin-orbit splitting of proton states in exotic Scandium isotopes

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Introduction

Recent advances in radioactive beam facilities ushered in an era of critical experimental observations in the field of properties of exotic nuclei where large imbalance of isospin could be created. Disappearance of conventional shell structure paving the way of new entrants in the field necessitated a fresh look at the physics behind the formation of nuclear shells.

Spin-orbit interaction as initiated by Mayer and Haxel [1] plays a vital role in the shell model. Calcium is a very important nucleus as it can boast of having two doubly shell closed nuclei – ^{40}Ca and ^{48}Ca. Obviously this region drew a lot of interest both from the experimentalists as well as theoreticians [2 - 5]. This paper wishes to shed light through non-relativistic Skyrme-Hartree-Fock theory with the inclusion of tensor interaction on the splitting of shell model orbitals as one moves from stable region to the region of exotic nuclei in Scandium nucleus.

Mathematical Formalism

The tensor interaction in HF theory [6] is given by

$$V_T = T/2\{[(\sigma_1.k^{'})(\sigma_2.k^{'}) - 1/3(\sigma_1.\sigma_2)k^{'2}]\,\delta(r_1 - r_2) + \delta(r_1 - r_2)[(\sigma_1.k)(\sigma_2.k) - 1/3(\sigma_1.\sigma_2)k^2]\} + U\{(\sigma_1.k^{'})\delta(r_1 - r_2)(\sigma_2.k) - 1/3(\sigma_1.\sigma_2) \times [k^{'}.\delta(r_1 - r_2)k]\}, \quad (1)$$

where T and U are tensor coupling strength parameters. Spin-orbit part of the energy density function is given by

$$H_{SO} = C_0^{\nabla J}\rho_0\nabla.\mathbf{J}_0 + C_1^{\nabla J}\rho_1\nabla.\mathbf{J}_1 . \quad (2)$$

Omitting the iso-vector part, the spin-orbit potential component is given by

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

Our aim was to select a good force parameter set which after inclusion of tensor interaction correctly reproduces the location of the centroid energies of neutron 1i and proton 1h shell model intruder states of ^{208}Pb responsible for shell closure and then apply it new region. We have used SKP and SKXce parameter sets to explore the features of exotic isotopes of Scandium.

Results and Discussion

After a thorough optimisation procedure we observed that SKXce parameter set reproduces the result best. The Table 1 displays the result after optimisation of tensor interaction. Tensor coupling constants were optimised by fitting the split energy of 1f shell model state partners in spin-saturated isoscalar nucleus ^{40}Ca, spin-unsaturated isoscalar nucleus ^{56}Ni and spin-unsaturated isovector nucleus ^{48}Ca.

Nucl.	State	Splitting Energy in MeV (Th)	Splitting Energy in MeV (Ex)*
^{40}Ca	ν1f	6.71	5.64
	π1f	6.45	6.05
^{48}Ca	ν1f	8.00	8.01
	π1f	5.17	4.92
^{56}Ni	ν1f	6.63	7.16
	π1f	6.24	7.01

* Data taken from Ref.[7]

Table 1: Table 1. Comparison of splitting of 1f shell model state in ^{40,48}Ca and ^{56}Ni

It must be mentioned here that the whole process of choice of parameter set is pivoted around the reproduction of splitting of π1h and ν1i state of ^{208}Pb. In Table 2 we have presented our calculated results along with the experimental values which supports our views.

Nucl.	State	Splitting Energy in MeV (Th)	Splitting Energy in MeV (Ex.)
^{208}Pb	π1h	4.39	5.56
	ν1i	6.52	6.46

Table 2. Energy difference of 1h proton state and 1i neutron state of ^{208}Pb

Next we have calculated the binding energy and the charge radius of the only stable isotope ^{45}Sc which have been presented in Table 3.

Nucl.	Binding Energy in MeV (Th.)	Binding Energy in MeV (Ex.)[a)]	R_C in Fm (Th.)	R_C in Fm (Ex.)[b)]
^{45}Sc	390.44	387.85	3.5422	3.5443

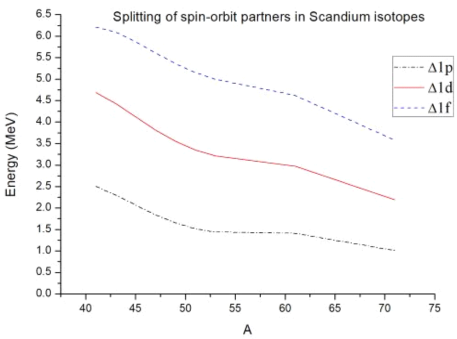
a) – Ref.[8], b – Ref [9]

Table 3. Comparison of calculated binding energy and charge radius of ^{45}Sc with the experimental values

In the cases of Ca isotopes it has been shown earlier that with the increase of neutron number inside the nucleus the neutron-proton interaction changes the amount of splitting between the spin-orbit partner states. Scandium being the next-door neighbouring nucleus plays an important role in the understanding of shell model picture. Though Scandium has shown collectivity through its band structure, we have used spherical approximation to describe its excitation pattern.

It is apparent from the figure 1that as the neutron number increases there is a marked depletion of splitting of shell model states. Specially the states near the closure, viz., 1f state is mostly affected. This change in the pattern of splitting of levels may generate new shell structure for exotic nuclei which needs further investigations. It has also been observed that as one moves towards the exotic region, the charge distribution becomes flattened and gets extended.

Fig. 1 Splitting of spin-orbit proton states of Sc isotopes



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