Experimental investigation of the structure of nuclei with Z,N $\sim$ 28

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Introduction

The magic number 28 is the first shell closure that is originated due to the inclusion of spin-orbit ($\vec{l}.\vec{s}$) coupling term in the nuclear Hamiltonian. There are some debate on the strength of this shell gap from theoretical as well as experimental point of view. From Nuclear Shell Model, the active nucleonic orbitals governing the structure of nuclei are $1f_{7/2}$, $2p_{3/2}$, $1f_{5/2}$, $1p_{1/2}$ and intruder $1g_{9/2}$ orbital. Again from Nilsson Model, $f_{7/2}$ and $g_{9/2}$ orbitals have shape driving effect which can bring deformation in the system. The coupling of $2p_{3/2}$ and $1g_{9/2}$ orbitals, which are $\Delta j = 3$ and $\Delta l = 3$ orbitals, can also bring octupole correlation in the system.

The density of states of these nuclei are low and the presence of shape driving orbitals in the configuration space result in drastic change in structure of nuclei with little change in N or Z. Several nuclear structures including deformed and spherical shapes had already been observed in these mass region which include deformed rotational bands at higher excitation in ^{56}Ni, coexistence of prolate and oblate shapes and gamma vibration at lower excitation in even-even ^{56}Fe and ^{58}Fe and spherical shape in odd A ^{55}Fe. The question is whether the observed deformation in these even-even nuclei are due to the softness of the core or due to the contribution of the shape driving $g_{9/2}$ orbital in the nuclear wavefunction, which had been observed in odd A nuclei of Cr and Fe isotopes.

In the present thesis the structure of odd-A ^{57}Fe ($Z = 26, N = 31$), ^{55}Mn ($Z = 25, N = 30$) and odd-odd ^{54}Mn ($Z = 25, N = 29$) have been studied, to investgate the effect of odd nucleons on the shape coexistent ^{56}Fe core, using gamma ray spectroscopy technique. The issue about the nature of the $Z = N = 28$ shell gap has also been addressed in the present thesis with a different perspective.

Experimental details

The alpha induced fusion evaporation reactions were used to populate the nuclei of interest. The experiment was performed at VECC, Kolkata taking α beam of 34-MeV from K-130 cyclotron. The details of the experiment and data analysis techniques have been reported in [1]. The lifetime measurements of some of the states have been done using Doppler Shift Attenuation Method (DSAM).

Results and Discussions

The level schemes of these nuclei have been significantly modified by the placement of several new transitions, new levels, precise spin-parity assignments of all the levels and lifetime measurements of some of the levels of ^{57}Fe. The I^{π} assignments have been made through R_{DCO}, Δ_{IPDCO} and Polarization (P) measurements.

Odd-Odd ^{54}Mn

The detailed results obtained in ^{54}Mn are published [1]. One of the interesting aspects obtained in the present work is the identification of a few low-lying negative parity states in this odd-odd nucleus which have been interpreted as the octupole phonon states coupled to the ground and low-lying excited states [1]. New E3 and E1 transitions are observed to decay from these states. The 6^-, 1138 keV state becomes, so far, the lowest known octupole phonon states in this mass region.

The low-lying positive parity states in ^{54}Mn correspond to spherical structure, manifested as single particle excitations. The detailed

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study of the configurations of both yrast and non yrast states have been made through shell model calculations [1]. With the increase in frequency, the deformed band structures based on multi-hole, multi-particles configuration have been observed which is also corroborated by the TRS calculation that predicts oblate shape at higher excitations for this nucleus [1].

Odd-N ^{57}Fe

Different band structures, implying different nuclear shapes, have been observed which insights the effect of odd neutron/s in upper fp orbitals and $g_{9/2}$ orbital on the shape coexistent core of ^{56}Fe.

The states at lower excitation have the characteristics of gamma vibration decaying to the main band by $\Delta J = 1, 2$ transitions, having similar kind of moment of inertia [2]. The γ values obtained in ^{57}Fe using Davydov model from experimental energies and intensities are 17° and 18° respectively which are corroborated well by the Total Routhian Surface calculation, that predicts $\gamma = 19°$.

A new M1 band has been observed at excitation energy of 3.1 MeV which has the characteristics of magnetic rotation (MR) [3]. The lifetime of all the states in this band have been measured from which the transition probability B(M1) values have were deduced. The B(M1) values are seen to decrease with increase in spin, which is the crucial evidence of magnetic rotation. With this observation, ^{57}Fe become the lightest nucleus to posses magnetic rotational band and it is the first nucleus in the lighter mass region where magnetic rotation has been conclusively established from decreasing nature of B(M1) values with spin. The assigned configuration of this MR band is $(\pi f_{7/2})^{-2}(\nu p_{3/2} f_{5/2} p_{1/2})^3$. This is also the first time when MR band is formed with only fp orbitals. Shears Mechanism with Prinicipal Axis Cranking (SPAC) calculations repoduce the experimental energies and transition rates very well, making this MR band as a unique one indicating the purity of holes and paricles configuration across $N = Z = 28$ shell closure which points out the robustness of this shell closure. These results are under review in PLB [4].

The odd neutron in $g_{9/2}$ orbital bring axial deformation, prolate shape, in the system which is manifested by decoupled rotational band. The band crossing has been observed for the first time in this nucleus. The lifetime measurements of all the states in this band have been done using DSAM technique and B(E2) values have been deduced [5].

The transitions with enhanced E1 and D_0 have been obtained indicating the presence of octupole correlation in the system.

Odd-Z ^{55}Mn

The deformation based on $\pi(f_{7/2})$ orbital has been established in the present work [6]. The plot of E_x vs I fits well with the rotational equation. The rotational band is based on $\pi[312]5/2^-$ Nilsson orbital. Observation of both the signature partners suggests strongly coupled band, which is obvious from the fact that the odd proton occupies the high Ω Nilsson orbital. Total Routhian surface calculation corroborates the experimental findings. Band crossing has also been observed in ^{55}Mn for the first time. Similar kind of deformation has been identified in ^{57,59}Mn isotopes. An octupole phonon state has also been observed in this nucleus like its isobar ^{55}V and near by odd-odd nuclei.

Conclusion

Several nuclear stuctures, based on fp and $g_{9/2}$ orbitals across $N = Z = 28$ shell closure, for nuclei with $Z < 28, N > 28$ have been established. The robust nature of $N = Z = 28$ shell closure has been indicated.

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