CHAPTER I

INTRODUCTION

In nuclear spectroscopy, one studies the nuclear energy levels, their excitations and decay mechanisms and other related properties. Conventional nuclear spectroscopic methods like the shell model treats the nucleus as a many-body system with valence nucleons around the inert core moving over a set of active single particle states(N) defined by a mean field. The number of ways in which the m valence particles can be distributed over N single particle states is just $d(m) = \binom{N}{m}$, the total dimensionality of the many-body space. One can then project out various subspaces from this space as needed. For example, one can construct a many-body subspace with fixed J and T (the total angular momentum and isospin), two quantities that are conserved by the nuclear Hamiltonian (H). Then one constructs Hamiltonian matrices in such model m-particle subspaces, from its (1+2) -body form, and diagonalises the martices to obtain eigenvalues and eigenvectors. These then provide detailed information about the spectra, transition strengths, etc. for the nuclear system. However this conventional approach to spectroscopy becomes prohibitively difficult for nuclei, heavier than the light ones, due to rapid increase in the model space dimensionality. Moreover, it is important to ask whether the essential statistical aspects of the detailed structure calculations can be obtained by some easier approximate methods. Spectral distribution method[1),2)] (SDM) is one such global statistical procedure, rich in its structure, developed and applied for a wide range of nuclear problems. This theory dispenses with the need to construct nuclear eigenfunctions and exploits certain underlying simple features originating from the many-particle nature of the model spaces. It overcomes the major practical limitation faced in diagonalising matrices of large dimensions in the conventional shell model and with its recent advancements[3] is now capable of handling calculations in large model spaces across several major shells. In spectral distribution theory one first recognises the role played by the central limit theorem[4] (CLT) of statistics in the many particle model spaces, by virtue of which the eigenvalue distribution for most (1+2) -body realistic Hamiltonians in large shell model space assumes a characteristic form, close to the asymptotic Gaussian. This again implies[1],[2] asymptotic forms in the Hamiltonian basis for expectation values of operators like the sum rule operators and transition strengths. Another important aspect[5] of the theory is the separation of the average smoothed behaviour and the small fluctuations about it for both the eigenvalue density and transition strength. These two can be calculated by very different methods. In this thesis we shall discuss only the average properties and not the estimates of fluctuation. In SDM the averages of the products of the low powers of the Hamiltonian and excitation operator needed for the density and strengths in many-particle spaces, can be related to the averages of the same operators in some defining few-particle spaces, exploiting the underlying group structure resulting in "propagation of information"[1],[2]. The applications[1],[6] of SDM to date include calculation of binding energies, excitation spectra, level densities, spin cut-off factors, orbit occupancies, sum rules and excitation strengths of particle transfer, different electromagnetic and beta decay transition operators as well as study of goodness of nuclear symmetries and of the bound on time reversal non-invariant part of nucleon-nucleon interaction. They are evaluated in a parameter-free form using the interaction in spaces specified by particle number and other necessary quantum numbers.

A theoretical study of the Gamow–Teller and M1 excitation strengths and sum rules is useful because of the extensive measurements of Gamow–Teller and M1 transitions carried out over the years by means of (p,n), (n,p) reactions[7),8)] and through the inelastic (e,e′) and (p,p′) reactions[9)]. The experimental results show substantial quenching of the total strength in the low excitation energy region relative to an exact sum rule as well as shell model predictions which take into account configuration mixing[10),11)] only within a single major shell. The phenomena of quenching generated a lot of interest among theorists and experimentalists in their effort to understand the spin excitations[12)] of nuclei properly. Whereas careful and detailed study of the excitation strength distribution can answer questions relating to the origin of the quenching of the strength observed experimentally, reliable estimates of the strength sum itself is required to predict the amount of quenching. One such detailed study[13)] of the strength distribution using the formalism of random phase approximation (RPA) was carried out by Osterfeld, Cha and Speth. For a statistical description of the GT and isovector M1 giant resonances, the important quantities one needs to find are the sum rule strength, the form of the resonance and the parameters needed to quantify it. In this thesis we use the spectral distribution theory to study these aspects. The Gamow–Teller strength function is useful in many other contexts[14)], one of them being in the evaluation of beta decay and electron capture rates of the fp shell nuclei for the presupernova and supernova evolution. The calculation of these decay and capture rates are important ingredients in the Si burning stage of stellar evolution which subsequently influence the gravitational collapse and shock formation in the supernovae.

The thesis is organised as follows. In chapter II we present a brief review of some of the results of the spectral distribution method. Only those aspects of the theory are presented which we need for the applications described in the subsequent chapters. Section 2.1 introduces the spectral distribution method explaining the nature of the eigenvalue density distribution of the Hamiltonian in large shell model (SM) spaces and its evaluation in terms of the low-order moments. The section also discusses various partitioning of the model vector space we need. Section 2.2 and 2.3 discuss the polynomial expansion of strength and expectation value of operators in the framework of SDM and section 2.4 gives some results of the recently developed strength density formalism. Section 2.5 gives the strength and expectation values in multipole form and finally section 2.6 discusses the methods of evaluation of the operator averages and their propagation from the few particle to many particle spaces.

One of the uncertainties that lies in the application of SDM is in the choice of the Hamiltonian. In the past the predictions using SDM were compared with the shell model results. However, except for the A-dependent universal interaction of Wildenthal, shell model calculations for other interactions have not been successful throughout the sd shell. Thus the comparisons of the calculations performed with the highly successful universal sd-interaction provide new stringent tests of the SDM theory. In chapter III we thus present the results of our investigation using SDM, of binding energies, orbit occupancies and smoothed spectra, along with the shell model results and experimental data.

We present the results of our investigation of the strength sums for the Gamow-Teller and isovector M1 excitations in chapter IV. Section 4.1 gives the definition of the operators and their one-body matrix elements. In section 4.2 we give the derivation of two new approximate separate sum rules for β^- and β^+ decays in terms of the orbit occupation probabilities and apply them to (fp) shell. Section 4.3 (4.3A and 4.3B) discusses the extensive systematic evaluation of GT and M1 strength sums by spectral distribution methods using the polynomial expansion as well as the sum rule strength density formalism, for nuclei with arbitrary isospin in fp and sd shell. Through this we understand why the approximate sum rules developed in section 4.2 works well in fp shell but fails badly in sd shell. This section also includes evaluation of GT and M1 strength sums by SDM at different levels of accuracy (going beyond the second term in the polynomial expansion method) and the advantages of the sum rule strength density formalism over the polynomial expansion are discussed. The results are compared with those obtained by the shell model wherever possible. Chapter V then describes the results of our investigation of the strength distribution itself using the strength density formalism for M1 and GT excitations in the sd shell. We point out here, that this method when extended across major shells, can be useful for the study of quenching through configuration mixing. In chapter VI we present a model for the calculation of β-decay rates which uses approximate sum rules developed in section 4.2 and the SDM occupancies. This model is used for obtaining the β^- decay rates for some Co and Cu isotopes needed to be incorporated in the stellar evolution calculations at the Si-burning stage of the presupernova as well as for predicting halflives of neutron rich nuclei with A > 60. Finally in chapter VII we make some concluding remarks and discuss the scope for future work.

REFERENCES FOR CHAPTER I

1). French J B, 1980 in Moment Methods in Many Fermion Systems, (New York : Plenum), edited by, Dalton B J, Grimes S M, Vary J P and Williams S A;

Wong S S M, 1986 Statistical Nuclear Spectroscopy, (Oxford University press, UK)

2). Draayer J P, French J B and Wong S S M, Ann. Phys. (NY) 106 (1977) 472, 503;

French J B and Kota V K B, Ann. Rev. Nucl. Part. Sci. 32 (1982) 35

3). French J B and Kota V K B, Phys. Rev. Lett. 51 (1983) 2183;

Kota V K B, 1990 in Capture Gamma-ray Spectroscopy and Related Topics AIP Conf. Proc. 238, edited by, Hoff R W, p685

4). Mon K K and French J B, Ann. Phys. (NY) 95 (1975) 90

5). Brody T A, Flores J, French J B, Mello P A, Pandey A and Wong S S M, Rev. Mod. Phys. 53 (1981) 385

6). Kota V K B and Kar K, Pramana 32 (1989) 647

7). Rapaport J, Taddeucci T, Welch T P, Gaarde C, Larsen J, Horen D J, Sugarbaker E, Koncz P, Foster C C, Goodman C D, Goulding C A and Masterson T, Nucl. Phys. A410 (1983) 371

8). Goodman C D, 1983 in Proc. Int. Conf. Nucl. Phys., Florence (Bologna : Tipografica Compositori) p165

9). Richter A, 1983 in Proc. Int. Conf. Nucl. Phys., Florence (Bologna : Tipografica Compositori) p189

10). Bertsch G F and Hamamoto I, Phys. Rev. C26 (1982) 1323;

11). Anantaraman N, Brown B A, Crawley G M, Galonsky A, Djalali C, Marty N, Morlet M, Wills A, Jourdain C and Wildenthal B H, Phys. Rev. Lett. 52(1984) 1409.

12). Bertsch G F and Esbensen H, Rep. Prog. Phys. 50 (1987) 607 Goodman C D and Bloom S D, 1984 in Spin Excitation in Nuclei, edited by, Petrivich F, et al (New York : Plenum) p143 ; MacFarlane M H, 1989 in Proc. Int. Conf. Nucl. Reaction Mechanism (Suppl. Vol.), Saha Institute of Nuclear Physics, Calcutta, India

13). Osterfeld F, Cha D and Speth J, Phys. Rev. C31 (1985) 372

14). Fuller G M, Fowler W A and Newman M J, Astrophys. J. Suppl. 42 (1980) 447; 48 (1982) 279