Chapter 1

Exotic nuclei

The greatest change in our idea of matter since the time of the ancient Greeks has taken place after the Rutherford scattering experiment(1911). In this experiment it is recognized that an atom consists of a small massive nucleus and a diffused electron cloud around it. The nucleus consists of positively charged protons and neutral neutrons both referred to as nucleons. Further studies showed that the nucleons consist of elementary particles called quarks. Nucleons are strongly bound together in a volume of radius 10^{-15}m (one fermi) which is 10^5 times smaller than a typical atomic radius (10^{-10}m). Nuclear size ranges from about 1 fm for a single nucleon to about 7 fm for the heaviest nuclei. The fact of strong binding over a small volume indicates the existence of a strong, attractive and short ranged force between the nucleons overcoming the repulsive Coulomb force between protons. This force is called the strong interaction and acts on hadrons, particles with the underlying quark structure. This system may seem to be so complex that little could ever be learnt of its detailed structure. However, we have immense number of facts about nuclei and we can understand in great details, concerning about what the individual nucleons do in atomic nuclei, how this leads to the observed nuclear phenomena, how and why these phenomena change from nucleus to nucleus, and how certain nucleons interact with each other in nuclear medium. We have basic models namely the shell model and collective model that provide a framework of our understanding. Nuclear system can be distinguished from atomic ones by at least two remarkable properties which have important consequences on the location of closed shells:

- Nuclei are composed of two fluids, protons and neutrons. Magic numbers can therefore be found for both protons and neutrons leading to doubly-magic nuclei.

- The nuclear interaction is spin-dependent. A strong spin-orbit interaction, which is a surface term, is required to model nuclei. Nuclei close to stability therefore exhibits a sequence of magic numbers of 2, 8, 20, 50, 82 ...

1.0.1 Exotic nuclei

Exotic nuclei refer to β-unstable nuclei with extreme ratios of proton to neutron number on both the proton and the neutron rich sides of stability. In order to form a stable atomic nucleus, an equilibrium between the number of protons and neutrons has to be maintained. This condition is fulfilled for 259 different combinations of protons and neutrons and these nuclei can be found on Earth. In addition, 26 nuclei form a quasi-stable configuration, i.e. they decay with a half-life comparable to or longer than the age of the Earth and therefore are still present on Earth. In addition to these 285 stable or quasi-stable nuclei, some 4000-6000 unstable nuclei are predicted to exist by different models. Close to 2500 nuclei have been observed already and rest are still in *terra incognita*.

Exotic nuclei can be produced in nuclear reactions induced by Radioactive Nuclear Beams (RNB). After production the nuclei of interest are usually separated electromagnetically from the other reaction products before they can be studied. Such studies have led to the discovery of some new phenomena like halo, skin formation, proton radioactivity, the melting of shell structure at existing magic numbers and appearence of new magic numbers. There are two basic methods used to produce Radioactive Nuclear Beams (RNB), one is commonly called Isotope Separation on Line (ISOL) and the other is called in-flight.

In an ISOL-type facility, radioactive nuclei are produced essentially at rest in a thick target, a catcher or a gas cell bombarded with particles from a primary source or driver accelerator. After ionization and selection of a specific mass by electromagnetic devices, these nuclei are accelerated in a post-accelerator. The ISOL method produces high intensity and high quality RNBs generally at energies up to 25 MeV/u. The lifetimes of the accelerated radioisotopes are limited downwards by their extraction time from target and their transfer time to the ion source. In Europe, a broad range of the first generation ISOL RNB facilities have been developed like SPIRAL facility at GANIL Caen, ISOLDE and REX-ISOLDE at CERN's in Geneva, EXCYT facility at LNS, Catania. In North America, ISOL RNB facilities exist at TRIUMF, Vancouver, Canada, ORNL, Oak Ridge, USA and ANL, Argonne, USA. A major ISOL facility which are coming soon are SPIRAL2 at GANIL, France and Rare Isotope Accelerator (RIA) at MSU, USA. Future EURISOL in Europe is also major on coming project.

In in-flight method, an energetic heavy ion beam is fragmented or fissioned while passing through a thin target and the reaction products are subsequently transported to a secondary target after mass, charge and momentum selection in a fragment separator. Since the reaction products are generated in flight, no post-acceleration is required. In-flight facilities are optimum for higher energy (above about 50 MeV/u) beams of very short-lived (down to hundreds of ns) nuclei. Two in-flight RNB facilities are operational one at GANIL and other is FRS at GSI. Flerov Laboratory at Dubna, Russia, operates two cyclotrons, U400 and U400M, whose beams can be fragmented. The resulting nuclei are studied at the separators ACCULINNA and COMBAS. In North America, the NSCL at East Lansing, USA, operates the K1200 superconducting cyclotron which produces heavy ion beams in the 100 to 200 MeV/u energy range. In Japan, the RIKEN laboratory at Saitama includes a heavy ion ring cyclotron, RRC producing beams at energies up to 135 MeV/u and a new fragment separator BigRIPS.

The resulting beams from the ISOL and in-flight RNB facilities are highly complementary and both type of facilities are necessary for pursuing the scientific goals of the nuclear physics community.

1.0.2 The proton and neutron drip-lines

One of the main motivations for a new high-performance nuclear physics facility will be the physics at the drip-lines. The largest unknown nuclear territory is on the neutron-rich side of stability but there are also many interesting physics issues on the neutron-deficient side. The observation of proton radioactivity gives some definite points where the drip-line is situated. The two-proton drip-line the limit of proton-rich even-Z nuclei has been reached only up to zinc (Z=30). The situation is even more dramatic on the neutron-rich side of the valley of stability where except for the lightest nuclei we are still far from reaching the neutron drip-line. Indeed, the neutron drip-line is at present known only for elements up to fluorine (Z = 9).

In addition to the experimental efforts to approach the drip-lines for heavier elements, substantial theoretical progress is needed before one can obtain a satisfactory description of the borders of the nuclear chart and learn whether there are stable or long-lived structures beyond the drip lines. As for both light Borromean systems and SHEs the border is not likely to be sharp. Understanding the behaviour of very neutron-rich nuclei could help in elucidating neutron matter properties that are needed for calculations of neutron stars.

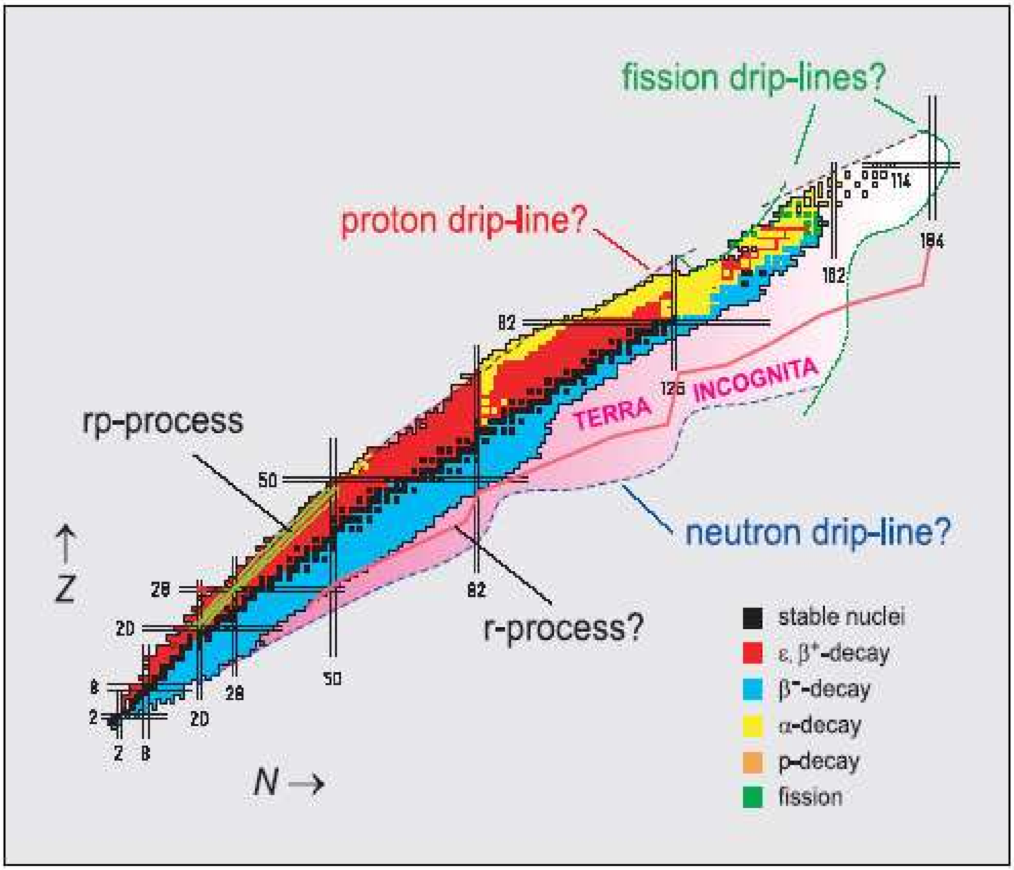

Figure 1.1: Figure of the nuclear chart, the valley of β-stability is indicated by the black squares. A number of important nuclei mentioned in the text and the N=Z line are marked. The horizontal and vertical lines correspond to the magic particle numbers.

1.0.3 Features of exotic nuclei

Halo: A neutron halo is characterized by an extremely long tail of the density distribution and a decoupling of a halo neutron (or neutrons) from the other part of the nucleus usually called the core. The existence of a genuine halo depends on the predominance of only two halo particle motions, in s and/or p orbital. Experimentally it is identified by a large interaction- or a reaction-cross section and a narrow momentum distribution of the core fragment of the nucleus. Because of the centrifugal barrier a neutron with a small orbital angular momentum extend the tail of the wave function much more than a neutron with a large orbital angular momentum. Conditions for the formation of halo have been studied by Jensen and Riisager [Rii00]. They found an interesting behaviour of loosely bound neutron(s). When one neutron is bound weakly to a core, an rms radii of the density distribution of this neutron diverges to infinity as the separation energy goes to zero if it is in s- or p-orbital. A neutron in a higher orbital does not show this divergence. ^{11}Li and ^{11}Be are the most studied halo nuclei and are providing test grounds of nuclear models [Tan96].

Skin : By definition the difference between halo and skin is the difference in the slope factor in the density tail that is related to the separation energy [Tan92]. Appreciable neutron halos appear only in nuclei with an extremely small separation energy of the last neutron(s); 0.3 MeV in case of ^{11}Li and 0.5 MeV for ^{11}Be. The two-neutron separation energies are 0.97 MeV for ^{6}He and 2.13 MeV for ^{8}He. Therefore, the terminology "skin" is more appropriate for ^{8}He. It is more arbitrary to call the excess neutron on the surface either as a halo or a skin for ^{6}He. The neutron skin and proton skin are common phenomena in unstable nuclei. However, skins do not exist (or are extremely small if at all) in stable nuclei. It also suggests that a considerable number of neutrons can be included in a neutron skin. In contrast, a neutron halo is expected to include only a few neutrons in the last orbital.

Proton radioactivity phenomena: The unstable radioactive nuclei can be classified into seven categories depending on their decay modes: (i) α emitters, (ii) β^{+} emitters,(iii) β^{-} emitters, (iv) fissioning nuclei, (v) one-proton (1p) emitters, (vi) two-proton (2p) emitters, and finally (vi) exotic-cluster emitters. Protons are charged particles, and therefore they are sensitive to the charge of other protons which create a Coulomb barrier. This barrier prevents protons from quickly leaving the atomic nucleus even if they are unbound. The tunnelling probability depends on the available energy and the height of the Coulomb barrier, which in turn depends on the nuclear charge Z. The delay associated with the tunnelling process allows for the observation of 1p and 2p radioactivity. Even if protons are unbound by, e.g., 1 MeV, the tunnelling of the combined Coulomb and centrifugal barrier is not instantaneous, i.e. the nuclear deacy is delayed by a measurable amount of time. The discovery of ground-state 2p radioactivity has been observed in two experiments, one performed in 2000 at SISSI/LISE3 facility of GANIL [Gio02] and another performed at the FRS of GSI in 2001 [Pfu02]. The observation of ground-state 2p radioactivity for

^{45}Fe, ^{54}Zn and possibly for ^{48}Ni allowed this type of radioactivity to be established as a new nuclear decay mode. Other candidates like ^{59}Ge, ^{63}Se or ^{69}Kr might be reached in the near future [Bla08].

1.0.4 Problem for the present work

In the present work nuclear structure studies have been carried out for neutron rich exotic nuclei in three regions of nuclear chart. These are neutron rich isotopes of O and F up to A=29 (sd shell), of Fe up to A=66 and Mn up to A=62 (fp shell) and of Ni, Cu and Zn up to A=80 (fpg shell). Experimental data on the energy levels of neutron rich isotopes of O and F have recently been made available up to A=29 using the technique of β-dalayed γ-ray spectroscopy [Mic06][NNDC]. Recently at Legnaro National Laboratories neutron rich Fe isotopes were populated through multinucleon transfer reaction by bombarding a ^{238}U target with ^{64}Ni beam [Lur07]. Analysis of the gamma spectrum of neutron rich Fe isotopes has provided data on their level structures. Experimental data on the neutron rich Mn isotopes from A= 59-63 has been made available by Valiente-Dobón *et al.* [Dob08] through mutineutron transfer reaction on ^{238}U target with 460 MeV ^{70}Zn beam. The first identification of $^{70-74}$Ni and lifetime determination of $^{71-74}$Ni have been carried out through thermal-neutron-induced fission of ^{235}U and ^{239}Pu at Lohengrin recoil spectrometer of ILL-Grenoble [Ber90]. The neutron-rich isotopes $^{68-74}$Ni have been recently produced at the LISOL-Leuven facility in the fission of ^{238}U induced by a 30-MeV proton beam [Fra01]. All these recent available experimental data have motivated to undertake theoretical study of the above mentioned nuclei. All calculations have been performed in the framework of nuclear shell model. The properties calculated are energy levels, wavefunctions, transition rates and quadrupole moments. Two important features of exotic nuclei have been reported in the literature. First is the melting of traditional magic numbers and appearance of new numbers. Second is the variation of single-particle energy levels of proton as more and more neutrons are added to the isotopes - the so called 'monopole shift'. In going from $^{17}_{8}O_9$ to $^{76}_{28}Ni_{48}$ the magic numbers from Z and or N = 8 to 50 is covered. Similarly the N/Z ratio is covered from 1.21 to 1.71. The above two features have been studied in detail for the isotopes considered in the present work.

The two main ingradients of any shell model calculation are the choice of valence space and an effective interaction. The valence space chosen for O and F isotopes is full sd shell with ^{16}O as core with four different interactions viz Preedom Wildenthal, Wildenthal-Mcgrory modified surface delta interaction, SDPOTA and renormalized

Kuo interaction. Large scale shell model calculations have been carried out for neutron rich isotopes of $^{61-66}$Fe with a newly derived effective interaction GXPF1A in full fp space without truncation taking ^{40}Ca as core. Large scale shell model calculations for odd-odd $^{58-62}$Mn isotopes have been carried out in two different sets of model spaces. In the first set valence space is of full *fp* shell consisting of $0f_{7/2}$, $1p_{3/2}$, $0f_{5/2}$, $1p_{1/2}$ orbitals and treating ^{40}Ca as the inert core. Second set of calculations have been performed in valence space *fpg* taking ^{48}Ca as inert core. Yrast levels of Ni, Cu and Zn isotopes for $40 \leq N \leq 50$ have been calculated for two recently available interaction by Nowacki and Lisetskiy using ^{56}Ni as a core. The Hamiltonian has been diagonalized using m-scheme code ANTOINE at SGI-cluster computer at GANIL. The results obtained by taking ^{56}Ni as a core are unsatisfactory viz. large $E(2^+)$ value for very neutron rich nuclei, small B(E2) values in comparison to experimental values and for ^{75}Cu, ^{77}Cu and ^{79}Cu the ground state is $3/2^-$ instead of experimental indication of $5/2^-$. In view of this large scale shell model calculations have been performed for neutron rich nickel, copper and zinc isotopes with $40 \leq N \leq 50$ using ^{40}Ca as a core by including the $f_{7/2}$ orbit. There is earlier version of effective interaction for ^{40}Ca by Sorlin *et al* , but the effective proton single-particle energy for Sc isotopes using this interaction is not correctly reproduced for more neutron rich nuclei. In the present work 28 two body matrix elements of the earlier interaction between $0f_{5/2}0g_{9/2}$ and $0f_{5/2}0g_{9/2}$ states have been renormalized and tuned such that the agreement with the experimental data improves.

The aim of the present work is to

1. test the suitablity of chosen valence spaces and effective interactions for different nuclei over nuclear chart in explaning the experimental data.

2. to compare the predicted values of nuclear properties with the experimental data wherever available.

3. to make predictions for the unknown energy levels and transition rates which can serve as basis for future experiments.

4. to study the variation in the shell structure in nutron rich nuclei in moving from magic number N=8 to N=50.

5. to design an effective interaction for the *fpg* shell which can account for the experimental data for neutron rich Ni, Cu and Zn isotopes.

The present thesis is organized as follows: **Chapter 1**- Exotic Nuclei ; **Chapter 2**- Shell model and techniques of calculation; **Chapter 3**- Shell model study of neutron rich oxygen and fluorine isotopes; **Chapter 4**- Large scale shell model calculations for $^{61-66}$Fe isotopes ; **Chapter 5**- Large scale shell model calculations for odd-odd $^{58-62}$Mn isotopes; **Chapter 6**-Large scale shell model calculation in Ni region: ^{56}Ni as a core ; **Chapter 7**- Large scale shell model calculations in Ni region: ^{40}Ca as a core ; **Chapter 8**- Conclusions and future prospects.