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INTRODUCTION

Basic concepts of nuclear spectroscopy and the importance of the optical model in analysing experimental data are briefly described in the first three sections of this chapter. These are followed by a discussion on the usefulness of isospin quantum number and the role of isobaric analog states in nuclear spectroscopy in section 1.4. The advantages of studying (p,n) reactions at sub-Coulomb energies, which forms the "maypole" for the present thesis, are explained in section 1.5. The scope of the present work covering the studies of both the isobaric analog states and the low energy proton-nucleus optical model potential is finally described in section 1.6.

1.1 THE NUCLEUS

Nuclei are aggregates consisting of two types of particles, protons and neutrons, together referred to as 'nucleons'. The forces responsible for the binding of nuclear systems belong to the category of "strong interactions", which comprises the interactions among nucleons, mesons and hyperons collectively called hadrons. The internal arrangements of nucleons in nuclei, generally called 'nuclear structure', depends mainly on the nature of these strong interactions which consist of a formidable sum of central, spin-orbit, spin-spin and tensor components. In addition to the strong interactions, nucleons produce electromagnetic effects (such as in γ -decay processes) and the "weak interactions" which manifest themselves in β -decay of nuclei. These weaker interactions play a minor role in nuclear structure but are important in the study of nuclear phenomena.

Our knowledge about the nature of nuclear forces comes from two different sources - (a) static properties of nuclei like the binding energies, nuclear size and shapes etc., and (b) dynamic processes like the scattering and reactions between nucleons and nuclei or between two nuclei. The bulk properties of nuclei serve to define certain important qualitative features of the nucleon-nucleon interaction like its short range, the existence of a hard core etc. The study of the two-nucleon problem has led to significant progress in our understanding of the nuclear forces. However, the main source of evidence on the details of the nucleon-nucleon interaction and its manifestations on the structure of complex nuclei is provided by the rich body of information relating to the nuclear spectra and the properties of individual levels. Experimental investigation of nuclear reactions and scattering constitutes one of the important sources of such information. On the other hand, a detailed understanding of the nuclear forces is an essential anchor to comprehend the results of experimental investigations.

An important simplification in the description of nuclear phenomena manifested by strong interactions comes from the realisation that nuclei are relatively weakly bound systems.[1] The energy required to remove a nucleon from a nucleus is about 5 - 10 MeV and the average kinetic energy of nucleons in nuclei is of the order of 25 MeV. These energies are small compared with the rest energies not only of the nucleons themselves ($M_n c^2 \simeq 1000$ MeV), but also of the lightest hadrons, the π-mesons ($m_\pi c^2 \simeq 140$ MeV). In the analysis of nuclear bound states and reactions at energies well below the pion production threshold (i.e., for $E \leq 100$ MeV), it is therefore a good first approximation to regard the nucleus as composed of a definite number of nucleons with properties similar to those of free nucleons and moving with non-relativistic velocities. The virtual presence of other particles may then be approximately taken into account in terms of forces acting between the nucleons and it should be possible to construct effective two-body forces suitable for describing nuclear systems.

Even after ignoring relativistic effects and considering only two-body forces, an exact microscopic calculation to predict the results of collisions between nucleons and nuclei, in order to understand the experimental data, has not yet been successful. It requires the solution of the nuclear many-body problem involving the various components of the two-body forces which are not exactly known. However, a full calculation of such a complexity, even if possible, would not be very useful in understanding the basic nature of nuclear reactions and nuclear structure, there being an uncertainty type relation between comprehensiveness and intelligibility.[2]

An approximate but physically transparent solution of the nuclear many-body problem can be achieved by realising two basic facts ; - (i) nuclear forces obey certain conservation laws and give rise to important symmetry properties which are very helpful in characterising nuclear states, and (ii) mean free path for collision between constituent nucleons in the nucleus is large compared to the distance between the nucleons and even, under many circumstances, is larger than the dimensions of the nucleus.[1] These observations have led to the development of effective theoretical tools which have been very helpful in systematizing a large body of experimental data on nuclear levels and in the understanding of nuclear dynamics. Some of these developments relevant for the present work are briefly discussed below.

1.2 NUCLEAR POTENTIAL : THE OPTICAL MODEL

The relatively long mean free path of the nucleons implies that the interactions primarily contribute a smoothly varying average potential in which the particles move independently.[1] For nucleons bound in the nucleus, a smoothly varying average potential has been highly successful in predicting the binding energies and the systematics of low-lying excited states. Such a one-body potential, popularly known as the "shell model potential" has a real central part and a spin-orbit term of sufficient strength necessary to explain major shell closings.[3]

In the study of nuclear reactions where the incident nucleon is free and can interact with the target resulting in elastic and inelastic scattering and a host of other nuclear reactions, a description in terms of nucleon motion in a central potential with an appropriate spin-orbit coupling is still a good first approximation. For detailed analysis of of reaction channels, the coupling of nucleon motion to the internal degrees of freedom of the target nucleus plays an important role. A one-body real potential can still describe the full spectrum of reaction channels provided one can solve the resulting infinite set of coupled equations where the real potential is used to generate the wave functions of all the channels. It is often a good approximation to truncate the infinite set of coupled equations by adding an imaginary potential to the one-particle Hamiltonian,[4] the total potential becoming complex. The imaginary part of the Hamiltonian is made to account for all the reaction channels which are not included explicitly, the accuracy of the approximation being decided by the number of channels included explicitly and and the strength of coupling between them. The resulting description of nucleon propagation in terms of a complex potential is called the "Optical Model".[1,2,4,5]

The nucleon-nucleus optical model potential is, in general, non-local and energy dependent.[5] For phenomenological analyses this is, however, approximated by an energy-dependent local potential and suitably parametrized in terms of various components,[2] important ones being the real and imaginary parts of the central nuclear potential and a spin-orbit potential. For charged particles as projectiles, one must add the Coulomb potential for an appropriate charge distribution for the nucleus. The parameters of the nuclear potential depend on the incident projectile energy and on the mass and charge of the target usually showing a smooth behaviour. These are described in detail in Chapter 4.

1.3 NUCLEAR REACTIONS AND SPECTROSCOPY

The nucleon-nucleus optical model potential is usually determined from the experimental scattering and reaction data. The elastic scattering differential cross sections, polarizations and reaction cross sections constitute major experimental information to determine the parameters of the one-body nuclear potential. The studies of inelastic scattering and reactions, in addition, also provide useful information on nuclear levels and relevant transition densities.

A knowledge of the mechanism by which a nuclear reaction takes place is important in analysing the experimental scattering and reaction data. Apart from other factors, it is found that the reaction mechanism depends on the incident projectile energy. At very low energies, the projectile takes longer to travel through the nuclear volume thereby undergoing many collisions inside and sharing its energy with a large number of degrees of freedom of the target and thus it establishes a highly complex state of motion, the compound nucleus. Due to the long interaction time, the resulting complex has no memory of the formation channel. The compound nucleus is in an excited state and after some time it emits particles and γ-rays untill it finally reaches the ground state. If only a few reactions are energetically allowed, the incident particle may be emitted with the same energy, this is known as compound elastic scattering.

At moderately high energies on the other hand, the interaction time is much shorter and the incident projectile is able to share its energy with only a few degrees of freedom of the target nucleus leaving it in discrete energy states of lower excitation. Owing to small perturbation, the outgoing wave is appreciably correlated with the incident wave. This results in characteristic diffraction-like pattern in the angular distribution of the ejectile. The elastic scattering at these high energies is essentially determined by the nuclear potential and is called the shape elastic scattering. The shape of the angular distribution, which can be successfully predicted by the optical model, depends mainly on the size of the target nucleus, wavelengths of the projectile and ejectile and the angular momentum transferred in the reaction. Stripping and pick-up reactions are examples of these class of "direct reactions".

Nuclear reactions may thus be broadly classified as compound nuclear or direct, depending on whether or not they pass through an intermediate long lived state. Both processes may simultaneously contribute to the reaction in a particular channel. Though they occur at widely different time scales, it is not possible to distinguish them experimentally. Depending on the incident energy, however, the importance of one may be enhanced much above the other so that essentially only one process may have to be considered. Thus at very low incident energies, the compound nuclear process is important whereas at higher energies the direct reaction contributions dominate.

Compound nuclei may exist in many excited states, and their reactions show characteristic resonant behaviour at appropriate energies. If the incident energy is low, these resonances are frequently well separated and can be studied individually. At somewhat higher energies, the resonances crowd together and overlap so that they cannot be individually identified, though the cross sections fluctuate with energy. At lower experimental resolution, the cross sections appear to vary smoothly with energy. Such a smooth variation is also observed at still higher energies. The cross sections calculated from a complex potential vary smoothly with energy and are thus to be compared with the smoothly varying or energy-averaged experimental cross sections. The statistical analysis of compound nuclear fluctuations lead to important information on level widths and spacings.[2]

Direct reactions such as stripping, pick-up etc. are most frequently used for the spectroscopy of single particle states of nuclei. Reactions in which a nucleon is deposited in the nucleus, like the (d,p) and (d,n) stripping reactions, give information concerning the unfilled single particle levels of the residual nucleus; while those in which a nucleon is removed from the nucleus such as the (p,d) pick-up and (p,2p) knock-out reactions tell us about the filled levels of the target nucleus. The energy spectrum of the ejectile thus directly reflects the level structure of the residual nucleus. Similarly quasi-elastic (p,n) reactions are useful in studying the isospin dependence of the nuclear potential and the isospin purity of the nuclear levels.[2]

The experimental differential cross section for reactions like stripping and pick-up is related to the theoretical form factor which can be calculated using the detailed direct reaction theories such as Distorted Wave Born Approximation and others. The form factor contains all the angular and energy dependence. The ratio of the experimental differential cross section and the theoretical form factor, called the "spectroscopic factor", is a direct measure of the single particle purity of the final (or the initial) state; if it is unity, the state is pure single particle, while a value less than unity indicates that the single particle strength has been spread over two or more states. Thus a measurement of the angular distribution of the ejectile provides a quantitative estimate of the spectroscopic factor. A comparison of the experimental angular distribution and the theoritical form factor helps to determine the quantum numbers of the ejectile and hence that of the single particle state under consideration. Techniques for determining the spectroscopic factor are described in more detail in Chapter 3.

1.4 NUCLEAR ANALOG STATES

Nuclear forces obey a set of symmetry and conservation laws which are very helpful in analysing nuclear phenomena and in systematizing nuclear states. An important type of symmetry is associated with the existence of the two states of the nucleon (neutron and proton) with closely related properties This degeneracy reflects invariance properties of the strong interaction, referred to as "isobaric symmetry"[1] and suggests that nuclear forces are charge independent. Nuclear states can thus be classified according to an "isobaric spin" quantum number and they can be subjected to a generalized Pauli principle in the extended space-spin-isospin degrees of freedom.

The validity of isospin quantum number and the charge independence of nuclear forces can be tested by a comparative study of the spectra of isobars. The rotational invariance in isospace implies that the Hamiltonian commutes with the total isospin T. The stationary states can thus be labelled with the quantum number T and the states form a degenerate multiplet consisting of (2T+1) components. Isobaric multiplet structure is found to be a general feature of the nuclear spectra, thus providing abundant experimental evidence for the charge independence of nuclear interactions.[1] The degeneracy between the multiplet components with different T_z is lifted by the Coulomb forces.

The isobaric invariance is violated by the electromagnetic interactions. For the lightest nuclei, these effects are relatively small and mainly give rise to small energy splitting between the isobaric multiplets. The discovery of well defined isobaric multiplet structure in heavier nuclei[6] has revealed that the strong Coulomb interactions are rather ineffective in breaking the isobaric symmetry even in the heaviest nuclei. This can be understood from the fact that the Coulomb field varies rather slowly over the nuclear volume. The wave functions of the individual protons are only little affected and the main result of the Coulomb field is to add to the nuclear energy a term depending on the number of protons (T_z) without violating the T - quantum number.

In medium and heavy nuclei, the large neutron excess implies that the ground state must have minimum isospin $T = T_0 = T_z$. This feature of the spectra reflects important systematic effects in the nuclear binding that favour low values of T. The lowest states with $T = T_0 + 1$, which are analogs of the low lying states in the neighbouring isobars, occur at excitation energies well above the proton emission threshold and have been found to give rise to well defined sharp resonances in proton induced reactions like (p,p), (p,p'), (p,γ) and (p,n) etc.

The study of isobaric analog resonances has provided an extensive body of evidence regarding the validity of isospin symmetry in heavier nuclei. The resonance structure in proton induced reactions can be represented[7] by a smoothly varying direct amplitude and a resonance amplitude of Breit-Wigner form. The ratio of the observed proton reduced width and the single particle value provides a measure of the single particle parentage factor observed in neutron pick-up reactions. Thus isobaric analog resonance spectroscopy provides a powerful tool supplementing the stripping and pick-up reactions in the study of nuclear levels.

1.5 ADVANTAGES OF (p,n) REACTIONS AT SUB-COULOMB ENERGIES

Low energy (p,n) reactions proceeding through the formation of compound nucleus provide useful experimental data for investigating the proton-nucleus optical model potential and for the spectroscopy of isobaric analog states in the compound nucleus.[8,9] The following are the main advantages of studying (p,n) reactions below the Coulomb barrier.

(i) Next only to elastic scattering, (p,n) reaction is perhaps the simplest to study experimentally. It combines the merits of both charged particle and neutron induced reactions. In the entrance channel, the best possible energy resolution can be obtained for the incident beam of protons using an electrostatic accelerator and in the exit channel the absence of Coulomb forces increases the compound nucleus decay widths and the resulting enhancement in (p,n) cross section facilitates easy measurement.

(ii) At incident proton energies near the Coulomb barrier, the elastic scattering diffraction patterns begin to lose their details. Forward angle data are Coulomb dominated and at backward angles the data are ~~adulterated~~ contaminated with compound elastic contributions. The absorption cross section remains the only useful information for the investigation of proton-nucleus optical model potential. Admittedly, the single ~~datum~~ quantity σ_{abs} at a given incident energy ~~is a~~ provides meagre information compared to the distribution of elastic scattering and polarizations. Compensation comes from the fact that σ_{abs} can be fairly accurately measured at these low energies. When the proton energy is below the Coulomb barrier but still a few hundred keV above the (p,n) threshold, neutron emission is the major decay mode of the compound system so that $\sigma_{p,n} \approx \sigma_{abs}$.[8] Measurement of (p,n) excitation functions are straight forward. These excitation functions contain considerable information on the nucleon-nucleus optical model potential if the parameters are treated in a consistent and continuous manner with those obtained at higher energies. Perhaps one can visualize these functions as playing the leading role below the barrier while the diffraction patterns play the leading role above. The conversion of $\sigma_{p,n}$ to σ_{abs} usually requires only small corrections for γ-ray emission at energies near the (p,n) threshold and that can be made using the known radiation strengths from neutron capture experiments. Corrections for proton re-emission are small.

(iii) One of the beneficial effects of the Coulomb barrier is that, by virtue of its height relative to the spreading width from absorptive potential, the barrier can quasi-bind a single particle state.[10] Thus the single particle resonance may be sharpened sufficiently to be observed as a function of proton energy for a given nucleus. These size resonances may be observed in experimental strength functions obtained from the (p,n) excitation functions by factorizing the dominant Coulomb penetrability contributions. Collective and shell effects are then expected to be revealed in these strength functions as a function of target mass.

(iv) If the incident proton energy required to produce the isobaric analog resonance is far below the Coulomb barrier, the proton penetrability is too small to produce a resonance with appreciable proton width in elastic scattering experiments. This, combined with the limited experimental resolution, causes the resonance amplitude to be insufficient to identify structure from the elastic scattering data. An example of this sort of problem has been clearly seen in the study[11] of proton induced reactions on ^{92}Mo.

Since neutron penetrabilities tend to be large and are unaffected by the Coulomb barrier, (p,n) reactions provide a sensitive means for the identification of resonances so long as the proton bombarding energy is above the (p,n) threshold. The (p,n) cross section is usually sufficiently large to identify resonances in spite of the fact that neutron emission can occur only through isobaric spin admixtures in either the compound system or the final nuclear state.

(v) An experimental measurement of total (p,n) cross section at smaller energy interval (much less compared to the average widths of compound nuclear resonances) serves two purposes at the same time.- (a) isobaric analog resonances can be seen in the fine structure excitation functions and these can be shape analysed to deduce the spectroscopic factors, and (b) the excitation function averaged over suitable energy interval to smoothen out compound nuclear fluctuations can be analysed using the optical model.

(vi) (p,n) reaction cross sections are basic inputs in the calculation of nucleosynthesis and hence are of great value in Astrophysics.(21)

1.6 SCOPE OF THE PRESENT WORK

The present study has been undertaken to exploit the above-mentioned advantages of (p,n) reactions at sub-Coulomb energies for the spectroscopy of compound nuclear states at high excitation and the systematic investigation of low energy proton-nucleus optical model potential. The measurement of total (p,n) cross section as a function of energy at finer steps provides an oppurtunity to study the isobaric analog states observed as resonances in the (p,n) excitation functions. The excitation functions suitably averaged over an energy interval to smoothen out the fluctuations due to compound nuclear resonances can be used for optical model analysis.

For ^{55}Mn, previous studies[12,13] of the isobaric analog resonances have either concentrated on the (p,γ) channel or on the relative yield in the (p,n) channel using a long counter. Absolute (p,n) cross sections have been measured using only thick targets[14] but the data are not reliable, having an error of 30% or more.[15] For ^{80}Se target, the isobaric analog resonances have been investigated in proton elastic scattering[16] but the spectroscopic factors thus obtained do not compare well with those obtained using the (d,p) reactions on the same target.[17] Moreover, in both the ^{55}Mn and ^{80}Se cases, the maximum energy used has been limited to observing the analogs of the first few excited states only. Studies up to much higher incident energies are important to investigate the usefulness of the isobaric analog resonances as spectroscopic tools at higher excitation.[7]

Extensive studies of elastic scattering, polarizations and reaction cross section data have been carried out in the proton energy range greater than E_p = 10 MeV for nuclei throughout the periodic table and a global set of optical model parameters has been obtained.[2,18] However, much less effort has been put in extrapolating the systematics of the optical model parameters to lower energies. Some initial attempts to investigate the low energy optical model potential for protons have indicated a much larger energy dependence of the strength of the real potential at lower incident energies[8,19,20] as compared with the energy dependence at higher energies. Tentative explanations of this energy dependence has been put forward in terms of the non-locality of the nucleon-nucleus potential.[19] Anomalies in the strength of the imaginary potential as a function of target mass have also been reported[10,20] in analyses over limited mass regions, the imaginary potential showing several peaks across the periodic table. These anomalies are found to be somewhat correlated to nuclear deformation and density of states.[20] A detailed survey of the various attempts is presented in Chapter 4. A systematic investigation of the proton-nucleus optical model potential at sub-Coulomb energies covering a wide mass region, however, has been lacking.

In the studies being reported in this thesis, the total (p,n) reaction cross sections on ^{55}Mn and ^{80}Se targets have been measured as a function of energy from near threshold to about 5.5 MeV at 5 keV interval using a 4π-neutron counter. The experimental details and the features of excitation functions are described in Chapter 2. The excitation function around the prominent resonances have been scanned at finer energy interval to determine the shape parameters of the resonances accurately.

A detailed account of the isobaric analog resonance spectroscopy is presented in Chapter 3. The positions of the analog resonances in the excitation function have also yielded information on the Coulomb displacement energies for the isobaric pair ^{56}Mn - ^{56}Fe and ^{81}Se - ^{81}Br. The resonances have been analysed using Robson's R-matrix formalism(7) to extract the neutron spectroscopic factors for the low lying bound states of the target plus neutron system. Parameter dependence of the spectroscopic factors deduced in such analyses has also been investigated in detail for a typical case of a prominent resonance observed in the reaction ^{55}Mn (p,n)^{55}Fe. The spectroscopic factors obtained in the present study of (p,n) reactions on both the targets have been compared with the corresponding results from (d,p) reaction studies on the same targets and also other previous elastic scattering measurements.

The fine structure excitation functions have been averaged over 100 keV energy interval to smoothen out the compound nuclear fluctuations. A systematic study of the proton-nucleus optical model potential has been carried out using the resulting averaged (p,n) excitation functions for ^{55}Mn and ^{80}Se along with similar data taken from literature on forty three other targets in the mass range A = 40 - 140 measured in the energy range E_p = 2 - 7 MeV. The procedure for the selection of data, methods of analysis and the results obtained are described in Chapter 4. The present method of analysis has emphasized ~~on progressing~~ a step-by-step progress. towards fixing the potential parameters, ~~and~~ reducing at each step the number of parameters varied so that an umambiguous set of optical model parameters could be obtained. A detailed survey of the parameter space has been carried cut and the confidence levels on the parameter values obtained in the analysis have been assigned as discussed in the Appendix.

Importance of the Coulomb correction and isovector contributions to both the real and imaginary potential at these lower incident energies have been investigated in the light of recent findings [63] and the results compared with those at higher energies. The volume integral per nucleon of the imaginary potential obtained for all the forty five nuclei analysed have been examined in detail to derive any systematic trends as a function of target mass and charge and to understand the anomalous behaviour reported in literature.[10,20] A global potential has been deduced for the energy and mass range under consideration and its predictions have been compared with the available experimental data on elastic scattering and reaction cross sections to test its applicability over an extended region of target mass and incident energy.

A summary of the present investigation of sub-Coulomb (p,n) excitation functions and the conclusions derived about the isobaric analog resonance and the proton optical model potential at low energies are presented in Chaper 5.