Study of electric multipole transition probabilities and their importance in reaction dynamics

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The atomic nucleus is a mesoscopic system that exhibits features from both quantum and macroscopic domains. Recent attempts try to model the interactions between the nucleons based on their fundamental quark compositions and involve different many-body terms. Given these considerations, one would expect the structure and interactions of the nucleus to be chaotic and complicated. However, empirical data on level schemes of stable even-even nuclei reveal that the low-lying excited states exhibit a pattern that repeats in different regions of the nuclear chart. A survey of the spin-parity of first excited states in such nuclei shows that they are predominantly 2^+. Also, the first negative parity state in a vast majority of even-even nuclei is 3^-. The characteristic features of these states can be described by the phenomenon of collectivity, or a coherent motion of the nucleons, that can be observed in numerous even-even nuclei across the nuclear chart. Transitions to excited states are commonly expressed in terms of dynamic deformation of the equilibrium nuclear shape - such as surface oscillations for nuclei with spherical symmetry. For axially-symmetric deformations, one thinks of a neutron-proton fluid undergoing homogeneous excitations, with their transition densities in the ratio of N/Z. The measurement of the neutron and proton contributions provides one of the most important tools for understanding the relative importance of valence and core contributions to the collective transitions. It is of particular interest in single-closed-shell nuclei, where low-lying excitations are expected to be composed exclusively of the valence nucleons, if the closed core were truly inert. This is best evidenced by determining the ratio of the neutron and proton transition matrix elements, M_n/M_p, involved in an excitation. This ratio identifies any inhomogeneity between their respective transition strengths [1]. While M_p can be obtained from Coulomb excitation measurements, the determination of M_n requires nuclear interactions, which are subject to complex nuclear models. The validity and applicability of theoretical models rely largely on experimental signatures of accessible quantities that are characteristic of the collective excitations, such as absolute transition probabilities.

One of the most suitable experimental techniques is inelastic scattering in heavy-ion collisions, governed by the combined influence of both Coulomb and nuclear forces. It is the purpose of this thesis to demonstrate (i) the ability of this approach to systematically address crucial aspects of collectivity along an isotopic chain of stable nuclei within single experiments, (ii) the compliance between the results of heavy-ion scattering and conventional techniques, such as level-lifetime measurement, and (iii) the effects of dynamic structural couplings in heavy-ion collisions that influence the cross sections of all reaction channels in a system. In the course of this work, different experiments focusing on the signatures of vibrational collectivity have been performed on the stable even-mass Sn nuclei, which constitute the longest chain of semi-magic isotopes. All measurements have been carried out at the 14UD BARC-TIFR Pelletron-LINAC facility, Mumbai, with arrays of Si surface-barrier and HPGe detectors. Complicated avenues of excitation are included by means of coupled-channels calculations.

A large number of studies have investigated the 2_1^+ and 3_1^- excited states of the tin isotopes in the past few decades, by Coulomb excitation, nuclear resonance fluorescence, level-lifetime measurements, inelastic scattering of electron, proton and α-particle. The transition characteristics are usually inferred through the electric/charge transition probabilities, the $B(E\lambda)$ values, which, in principle, are related to the charge (protons) contributions to the excitation. Such measurements do not include the contributions due to the mat-

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ter distribution (protons + neutrons), which are contingent on the nuclear interactions. The existing estimates of the $B(E2)$ and $B(E3)$ values for the Sn isotopes have a wide range and there are inconsistencies in the existing data leading to different conclusions on the collectivity of the excitation modes. In the light of such discrepancies, unambiguous quantitative assessments of collective properties for the 2_1^+ and 3_1^- states in the stable Sn isotopes is necessitated.

In this thesis work, both the charge and mass transition probabilities for the 2_1^+ and 3_1^- states in the ^{112,116,118,120,122,124}Sn nuclei have been measured by heavy-ion scattering, to understand the underlying contributions from the neutron and proton densities. The dominant feature which provides the key to understand such scattering phenomena is the strong surface-absorption of heavy ions. For conclusive information, measurements have been carried out with a tightly-bound projectile with zero spin and isospin (^{12}C), as well as a weakly-bound projectile with non-zero spin and isospin (^{7}Li), at bombarding energies $E_{\mathrm{c.m.}}/V_{\mathrm{B}} \sim 1.3$. It is thereby observed [2, 3] that such measurements are largely dependent on the size of the probe. The intrinsic M_n/M_p ratios for the 2_1^+ and 3_1^- states in each Sn isotope are deduced by removing the effects of probe size (i.e., considering the probes as point particles) in the extraction of nuclear potential shapes [4].

The experimental identification of collectivity has often been subject to investigating the same nucleus under different experimental probes and techniques to compare the results. The experiments can be classified into two major categories, (i) those that measure the shape of the nuclear potential and (ii) those that measure the shape of the charge distribution in the nucleus. In this context, the $B(E2)$ value for the most-abundant ^{120}Sn isotope has been determined by a measurement of the γ-decay lifetime of the 2_1^+ state, employing the Doppler Shift Attenuation Method with updated techniques. The extracted result [5] gives an improved estimate of the 2_1^+ level lifetime in ^{120}Sn. The corresponding $B(E2)$ value is in excellent agreement with the results obtained from scattering of heavy ions ^{7}Li and ^{12}C. An attempt has also been made to extract the lifetime of the 4_1^+ state, which feeds the 2_1^+ level.

The importance of such realistic estimation of structural parameters and deformation characteristics of the dominant low-lying states in nuclei is realised through investigation of their effects on reaction dynamics in nuclear collisions, by demonstrating a simultaneous description of the elastic scattering channel along with inelastic scattering and one-nucleon transfer channels in the ^{7}Li + ^{120}Sn reaction system, at two bombarding energies. Realistic structural information, such as one-nucleon spectroscopic factors, are deduced by coupling around 30 reaction channels to the entrance channel [6]. New structural parameters have been assigned for transfer to a few of the states in the residual nuclei, whose spectroscopic factors were not known. The same procedure was followed for all the other systems (i.e., ^{7}Li + ^{112,116,118,122,124}Sn) to obtain an unambiguous set of coupling and potential parameters.

As an extension of this work, it has been shown that inelastic couplings can couple to the relative motion between colliding nuclei and significantly affect predictions of fusion cross sections, particularly in systems involving weakly bound projectiles, where different model calculations lead to different conclusions about suppression/enhancement of complete fusion [7]. Such a comparison between experimental and theoretical values of reaction observables can be useful as a test for nuclear reaction models.

Extensive measurements and understanding of the basic collective phenomena in low-lying transitions along an isotopic chain of stable neutron-excess nuclei, with better understood structures, could act as a reference for improved experimental and theoretical studies with unstable isotopes that are expected to be of similar complexity.

References

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