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Inelastic scattering reaction as a probe for monopole, dipole and quadrupole excitations

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Abstract. The study of collective motions within atomic nuclei, such as monopole, dipole, and quadrupole excitations, is crucial for understanding nuclear structure and properties, which provide insights into the spatial distribution and dynamic nature of protons and neutrons in nuclei. By analyzing the angular distributions of these modes excited via inelastic scattering reactions, we can determine the transition characteristics and deformation lengths of nuclei. Specific case studies, including quadrupole excitations and dipole excitations indicating exotic cluster structures in light nuclei, highlight the utility of modern experimental setups like the solenoidal spectrometer and the active target detector.

1 Introduction

The collective motion of nuclei refers to the phenomenon where all or most of the nucleons (protons and neutrons) within an atomic nucleus move in a coordinated manner. These excitation modes are important for explaining a range of nuclear phenomena, reflecting the distribution of protons and neutrons within the nucleus and contributing to our understanding of nuclear structure and properties. For example, quadrupole excitations refer to a type of vibrational mode where the shape of the nucleus oscillates between different ellipsoidal forms. These excitations are associated with changes in the spatial distribution of the nuclear charge and mass, provide key insights into the shape and dynamic nature of nuclei. Dipole excitations typically involve the oscillation of the proton distribution against the neutron distribution within the nucleus and are intimately connected to the local isospin symmetry breaking. Monopole excitations in nuclei are fundamental symmetric oscillations where the entire nucleus expands and contracts uniformly, providing critical insights into the incompressibility of nuclear matter [1].

Direct reaction is a powerful experimental tool to study the interplay between single-particle structure and collective motion of nuclei. These collective excitations may be excited with sizable cross sections via inelastic scattering reactions. The angular distributions of monopole, dipole and quadrupole excitations show different features, so the transition polarity of the atomic nuclei can be determined by the by comparing to the calculated differential cross sections with the reaction models, such as the distorted wave Born approximation (DWBA) method (see 1). The deformation length can be determined by the amplitude of the differential cross sections, according to the method in Ref. [2]. In this paper, the different aspects probed with inelastic scattering reactions induced by light ions will be discussed, including quadrupole, dipole and monopole excitation.

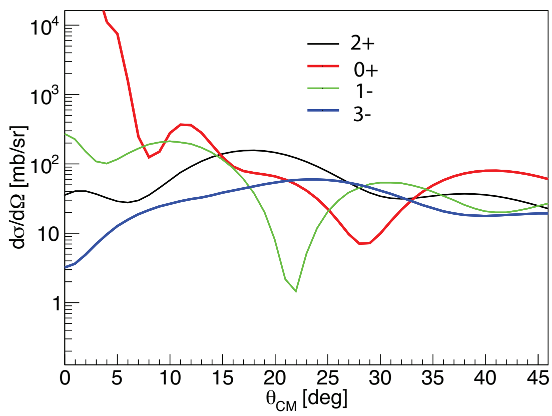

Figure 1. Left: Calculated differential cross sections of deuteron inelastic scattering on ^{16}C at 25 MeV/u with the DWBA method, assuming the final states are 2^+(black line), 0^+(red line), 1^-(green line) and 3^-.

2 Quadrupole excitations

For certain nuclei with an inert core, the degree of valence-neutron coupling can also be described by the different neutron and proton contributions to the quadrupole transition. It is determined by the ratio of neutron and proton quadrupole matrix elements $M_n/M_p = N\delta_n/(Z\delta_p)$, where δ_n and δ_p are the neutron and proton deformation lengths, respectively [2]. The effect of decoupling of the valence

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neutrons could be weakened in nuclei with an inert core coupling to the valence neutrons, which results in a large M_n/M_p ratio. This phenomenon has been observed in a number of light nuclei, including ^{20}O [3], ^{15}B [4], ^{17}B [5], ^{38}S [6], ^{21}O [7], ^{20}C [9] and ^{16}C [10].

With the HELIOS spectrometer [11], the elastic and inelastic scattering of ^{15}C on deuterons has recently been measured at the ATLAS beam line in inverse kinematics [12]. The elastic scattering differential cross sections were analyzed with the optical model. From the inelastic scattering differential cross sections to the first excited state, a matter deformation length =1.04(11) fm δ_d=1.04(11)fm was extracted. The quadrupole transition yielded a neutron-to-proton matrix element ratio M_n/M_p = 3.6(4). Neutron effective charges and core-polarization parameters for ^{15}C were determined and discussed. These findings were compared with results from *ab-initio* no-core configuration interaction calculations. The results indicate a moderate core decoupling effect of the valence neutron in ^{15}C, similar to its isotone ^{17}O, which aligns with the interpretation of other neutron-rich carbon isotopes. It also shows the capability of solenoidal spectrometer for measuring the inelastic scattering reactions with light nuclear probe.

3 Dipole excitations

Dipole excitations have important implications on some basic properties of nuclei, such as the compression properties in the equation of state and the electric dipole polarizability [1, 13]. Different types of dipole excitation modes manifest the isospin asymmetry in nuclear systems at different structure levels. For example, giant dipole resonances (GDR) are located at high excitation energies, which result from the oscillation of neutrons relative to protons, and are usually isovector characterized. Pygmy dipole resonances and soft dipole excitations at lower excitation energies usually refer to resonances arising from the oscillation of valence neutrons or a neutron skin against an $N = Z$ core and have isoscalar characteristics [14]. It was also noted that the weakly bound halo nucleon(s) would undergo low-frequency oscillations against the core, which result in low-lying soft dipole excitations and have isoscalar characteristics [14].

The isoscalar dipole (ISD) transition is also a fingerprint of asymmetric cluster structures. In atomic nuclei, α clustering is a well-established phenomenon [15, 16]. Low-lying enhancement in the dipole transitions induced by the cluster excitation generally occurs over a wide range of nuclear systems, ranging from medium-heavy nuclei to light nuclei including ^{9}Be, ^{10}Be, ^{12}C, ^{16}O [17–20], and actinides [21, 22]. Recently, the dipole resonance in ^{10}Be nucleus located just below the α -emission threshold, has been observed in deuteron inelastic scattering reactions off ^{10}Be. Deformation lengths were inferred from differential cross sections using coupled channel calculations. This 1^- state at 7.27 MeV exhibits isoscalar characteristics, providing new evidence for the pronounced α cluster structure in ^{10}Be. The Gamow coupled channel approach supports this interpretation and suggests that the near-threshold effect plays a significant role in this excitation energy domain.

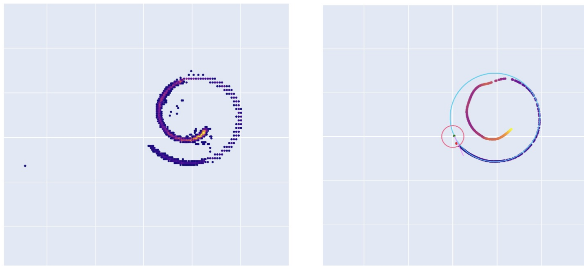

Figure 2. Left: Hit pattern of a deuteron event in the ^{16}C+d scattering reaction at about 11.5 AMeV in a 3 T magnetic field. Points are colored by the amplitude of the signal observed in the corresponding pad; Right: Circle fit was used in the cluster trajectories to estimate vertex position and to calculate $B\rho$ value of the particles.

The experiment was carried out at the ReA6 reaccelerator beam facility of the National Superconducting Cyclotron Laboratory (NSCL). The scattered deuterons were measured using the Active-Target Time Projection Chamber (AT-TPC) [23], which has a large effective thickness owing to the detector length of about one meter and allows direct reactions to be carried out with hundreds of particles per second. In Fig. 2, we show one of the events observed in this kind of measurements.

4 Monopole excitations

In a monopole excitation, all nucleons (both protons and neutrons) move coherently, causing the nucleus to oscillate in size while maintaining its spherical shape. This can be visualized as the nucleus "breathing," hence the term "breathing mode" is used to refer to monopole transitions [25]. It is also known as the fingerprint of the cluster structure. For example, the $3/2_3^-$ state of ^{11}B at E_x = 8.56 MeV has been studied intensely [24] due to its potential analogy with the Hoyle state. One important support is the measured large monopole strength for this state, which is reproduced by the calculations of nuclear cluster models that also predict enhanced dipole strengths. The AT-TPC coupled with the magnetic field of HELIOS also provide a powerful experimental tool for studying the monopole transition in nuclei via inelastic scattering measurement. One of the physics goals of the measurement was to study the monopole transition strength of ^{16}C nucleus, which was known for the well-developed cluster structure [26].

5 Summary

Direct reactions, in particular inelastic scattering reactions, are very powerful for studying the collective properties of nuclei away from the stability. The next-generation radioactive beam facilities is capable of producing sufficiently intense beams of exotic nuclei close to the drip

Table 1. The ratio of neutron and proton matrix elements M_n/M_p, effective charges and $M_n/M_p/(N/Z)$ of ^{15}C and ^{17}O, taken from Ref. [12]

nuclei	M_n/M_p	e_n	$M_n/M_p/(N/Z)$
^{15}C	3.6(4)	0.4	2.4(3)
^{17}C	2.63(4)	0.42	2.34(5)

lines, including Facility for Rare Isotope Beams (FRIB) at Michigan State University (USA), HIE-ISOLDE at CERN (Switzerland), and the future Heavy Ion Accelerator Facility (HIAF) at Huizhou (China). These beams coupling with the state-of-art detectors, such as the AT-TPC, HELIOS and SOLARIS are ideal experimental equipments for these direct reaction experimental studies.

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