Study of compression modes in 56Ni using an active target
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Chapter 1

Introduction

In 2015, the nuclear-physics community celebrates the 30th anniversary of the first genuine work on radioactive ion beams [1] used to study the properties of atomic nuclei. However, until the 50’s, the nuclear-physics experiments were constrained to the stable nuclei or the long-lived unstable nuclei (black boxes in Fig. 1.1). With the advent of new types of powerful accelerators, it is possible nowadays to access nuclei with exotic neutron-proton ratios. Furthermore, it is predicted that there are more than 3000 nuclei that could exist in bound states but have not been experimentally observed yet. How the structure and properties of a nucleus change with exotic ratios is still one of the fundamental questions in nuclear physics.

The study of the collective modes in nuclei, the so-called giant resonances, has been one of the important research topics in the field of nuclear physics for several decades. Giant resonances in nuclei, especially for exotic nuclei, are important in understanding some astrophysical phenomena, such as, supernovae explosions, formation of neutron stars etc. Giant resonances are well established for stable nuclei, however, they show different behaviors while approaching nuclei with exotic N/Z ratios. In neutron-rich nuclei, the collectivity of extra neutrons relative to protons can cause soft multipole excitations or pygmy resonances [3][49]. Therefore, it is necessary to extend our knowledge of giant resonances towards exotic nuclei.
CHAPTER 1. INTRODUCTION

1.1 Historical overview of giant resonances

The atomic nucleus is a many-body quantum system. In such system, occurrence of collective oscillations is a natural phenomenon. Giant resonances, which is the subject of this thesis, are prime examples of collective oscillations of nucleons in a nucleus. Giant resonances are characterized by excitation energies higher than the particle-emission threshold and broad widths greater than 2 MeV.

Giant resonances can easily be described by the macroscopic models based on semi-classical concepts. Within the liquid-drop model, giant resonances can be understood as small-amplitude collective oscillations of a nucleus around its equilibrium shape and density. But unlike the only one type of fluid in the liquid-drop model, the nuclear fluid consists of four different types of fluids; protons and neutrons with spin-up and spin-down.

Giant resonances can be categorized depending on three quantum numbers characterizing the transition between the initial and the final state:

- Multipolarity: $\Delta L$
1.1. HISTORICAL OVERVIEW OF GIANT RESONANCES

- Spin: $\Delta S$
- Isospin: $\Delta T$

An isoscalar mode corresponds to protons and neutrons oscillating in phase ($\Delta T = 0$) whereas an isovector mode corresponds to protons and neutrons oscillating out of phase ($\Delta T = 1$). Similarly, an electric mode corresponds to nucleons with spin-up and spin-down oscillating in phase ($\Delta S = 0$) and a magnetic mode corresponds to nucleons with spin-up and spin-down oscillating out of phase ($\Delta S = 1$). In Fig. 1.2 a schematic diagram of different giant resonance modes is shown for the lowest three multipolarities: $\Delta L = 0$ (monopole), $\Delta L = 1$ (dipole) and $\Delta L = 2$ (quadrupole), where $\Delta L$ represents the change in the orbital angular momentum. For each multipolarity, isoscalar-electric ($\Delta T = 0$, $\Delta S = 0$), isovector-electric ($\Delta T = 1$, $\Delta S = 0$), isoscalar-magnetic ($\Delta T = 0$, $\Delta S = 1$) and isovector-magnetic ($\Delta T = 1$, $\Delta S = 1$) modes are shown.

Figure 1.2: Schematic representation of giant resonances for the monopole, dipole, and quadrupole modes. Isoscalar and isovector modes correspond to neutrons and protons moving in phase and out of phase, respectively. Similarly, electric (scalar) and magnetic (vector) modes correspond to nucleons with spin-up and spin-down moving in phase and out of phase, respectively. The notations used are self-explanatory. The ISGDR depicted in this figure is a spurious center-of-mass motion. For details, see Chapter 2.
CHAPTER 1. INTRODUCTION

The first evidence for a giant resonance was found in 1937 by Bothe and Genter by means of photo-absorption by $^{63}$Cu nucleus [5]. This type of giant resonance, obtained by photo-absorption, is called Isovector Giant Dipole Resonance (IVGDR). In 1944, the first theoretical description of dipole oscillation of the nucleus was given by Migdal [6]. A systematic study of the properties of giant resonances began in 1947 [7, 8] when the first betatron came into operation.

In 1971, another type of giant resonance was observed by Pitthan and Walcher [9] which was thought to be a collective $E2$ excitation. It is the Isoscalar Giant Quadrupole Resonance (ISGQR), the energy of which is below the excitation energy of IVGDR.

The first evidence for the existence of Isoscalar Giant Monopole Resonance (ISGMR) was found by Harakeh et al. in 1977 [10, 11] by means of inelastic $\alpha$-particle scattering at 120 MeV on $^{206,208}$Pb, $^{197}$Au and $^{209}$Bi. From its discovery in 1977 up till now, ISGMR has been extensively studied both for stable and unstable nuclei not only by inelastic $\alpha$-particle scattering but also by deuteron scattering [53].

First attempts to identify Isoscalar Giant Dipole Resonance (ISGDR) were made in the early 80’s. Indications of this resonance were reported in inelastic scattering measurements with protons and $\alpha$-particles [12–16]. Although several similar measurements claimed the non-existence of this resonance [17], the first $0^\circ$ measurements for the study of ISGDR were reported by Davis et al. [18, 19] in 1997.

Establishing the occurrence of isovector giant resonances other than IVGDR turned out to be quite difficult, as both Isovector Giant Quadrupole Resonance (IVGQR) and Isovector Giant Monopole Resonance (IVGMR) are located in the high excitation energy regions implying broad and overlapping distributions. However, the first evidence for IVGQR was found by Pitthan [20] and Torizuka et al. [21] via electron-scattering experiments. The study of IVGQR strength distribution using the ($\gamma$, n) reaction was demonstrated by Sims et al. [22].

The first definitive evidence for IVGMR was reported by Bowman et al. [23] in 1983, where the resonance was studied by the charge-exchange reactions ($\pi^\pm$, $\pi^0$) at a bombarding energy of 165 MeV.

The best probe to study the isoscalar giant resonances is $\alpha$-particle scattering because of two-fold advantages. Since the $\alpha$-particle has zero spin and isospin, the electric isoscalar resonances are predominantly excited. Moreover, since inelastic $\alpha$-particle scattering is a surface reaction, the angular distributions are characteristic of the transferred angular momentum $\Delta L$. 
1.2 Experimental setups for the study of giant resonances

The experimental setups for studying giant resonances vary depending on the nature of the nucleus of interest.

- In case of a stable nucleus, the nucleus is used as a target and the probes ($p$, $d$, $\alpha$-particle,...) are used as projectiles. We call this direct or normal kinematics.

- In case of unstable nuclei, their short half lives forbid these nuclei to be used as targets. Hence, the nucleus becomes the projectile and the probe the target, implying inverse kinematics.

Extensive studies for giant resonances in stable nuclei have been made. Performing experiments with unstable nuclei is a challenge. One of the main challenges is the low production intensity. Therefore, several experimental techniques must be adapted to study the properties of unstable nuclei.

Coulomb excitation

The isovector dipole strength of a nucleus can be studied by Coulomb excitation. For this purpose, the beam of interest impinges on a high-Z target (usually Pb). The fragments are...
detected in the particle detectors. The emitted neutrons from the excited projectile or the excited projectile-like fragments are kinematically focused in the forward direction and are detected in neutron detectors \cite{24, 25}. For detecting the emitted $\gamma$-rays, the $\gamma$-ray detectors (e.g. NaI detectors) surround the target. In Figs. 1.3 and 1.4 schematic diagrams of such experimental setups are shown.

Storage ring

Giant resonances in exotic nuclei can also be studied with the help of storage rings. Since the production rates of the exotic beams are low, a gain in the yield can be obtained by the gain in luminosity of the beam which is achieved through the accumulation and recirculation of the beam in the ring \cite{28}. In Fig. 1.5 the schematic diagram of such a storage ring is shown. For inverse kinematics, the probe or the light particle can be put in the target position as shown in the figure. Usually, a hydrogen or helium gas-jet target is used in this case to study the giant resonances via $(p, p')$ or $(\alpha, \alpha')$ types of reactions. Typical luminosity that can be achieved with the storage ring is of the order of $10^{26} - 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ for some radioactive isotopes.
1.2. EXPERIMENTAL SETUPS FOR THE STUDY OF GIANT RESONANCES

Figure 1.5: Schematic view of the experimental storage ring (ESR) facility at GSI. Picture is taken from Ref. [29].

Active target

An alternative to the above-mentioned experimental setups, which is useful to study giant resonances in unstable nuclei is to use an active-target detector. The active-target technique can be used efficiently for inverse-kinematics reactions. As mentioned above, the production rates of the exotic beams are low, requiring a thick target to get a reasonable yield. But usage of a thick target degrades the energy resolution and also the very low-energy recoil particles may stop inside the target. In the active-target technique, the thickness of the target can be increased without loss of energy resolution. Furthermore, very low-energy (sub MeV) recoil particles can be detected with this type of detector. An example of such a detector is MAYA. The aim of this work is to study the isoscalar giant resonances in neutron-deficient $^{56}$Ni via $^{56}$Ni($\alpha,\alpha'$)$^{56}$Ni* reaction using the active-target detector MAYA. The de-
tails of the experimental setup, analysis procedures, and results are presented in this thesis. Relevant information can also be found from Ref. \cite{30} which was dedicated to study IS-GMR and ISGQR in $^{56}$Ni with deuteron scattering and from Ref. \cite{69} which was dedicated to study soft-monopole resonance, ISGQR, and ISGMR in $^{68}$Ni via deuteron and $\alpha$-particle scattering. In both cases, the experiments were performed using the active-target detector MAYA.

1.3 Outline

In this thesis, we will focus on the isoscalar giant resonances in the neutron-deficient doubly-magic nucleus $^{56}$Ni. The dedicated experiment of inelastic $\alpha$-scattering on $^{56}$Ni was performed at GANIL in May 2011. The outline of this thesis is as follows:

In Chapter 2, the theoretical tools that are commonly used to describe the giant resonance states are described. Some theoretical predictions and experimental evidences of giant resonances in Ni isotopes are also given. Finally, the theoretical predictions for the angular distributions for ISGMR, ISGDR, and ISGQR in $^{56}$Ni relevant to this thesis are presented.

Chapter 3 is dedicated to the details of the MAYA active-target detector and the corresponding electronics.

Chapter 4 describes the tools and methods that were used for the analysis of the data presented in this thesis. It includes the methods for track and scattering-angle reconstruction, beam purification, and filters that were applied to avoid spurious events.

Chapter 5 reports on the details of the simulations performed. It covers the method developed to generate events, determination of experimental resolutions, and discussion about efficiency corrections.

Chapter 6 is devoted to the results obtained from the data analysis. The procedure of getting the angular distributions for different multipolarities of excited giant resonances will be detailed.

Chapter 7 contains the overall summary of the whole thesis and gives an outlook for future experiments.

Finally, the summary in Dutch is given in Chapter 8.