



**Development of $(p,p'\gamma)$ detection capabilities at
iThemba LABS through the study of low-lying
 $E1$ strength in ^{58}Ni**

by

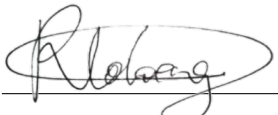
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A dissertation submitted to the Faculty of Science, University of
the Witwatersrand, Johannesburg, in fulfilment of the
requirements for the degree of Master of Science.

April, 2022

Declaration of authorship

I, **Refilwe Emil Molaeng**, hereby declare that this thesis titled **Development of $(p,p'\gamma)$ detection capabilities at iThemba LABS through the study of low-lying $E1$ strength in ^{58}Ni** is my own original work. It is being submitted for the Degree of Master of Science to the University of the Witwatersrand, Johannesburg. It has not been submitted previously for any degree or examination to any other university.

Signature: 
Refilwe Emil Molaeng

Date: April 25, 2022

*This work is dedicated to my loving parents, **Goitsemanang** and **Onkokile**
Molaeng.*

“Mmatla kgomo ya gaabo kodumela o etse mhata sediba”

A Tswana proverb

Abstract

The principal aim of this study was to explore the $(p,p'\gamma)$ detection capabilities at 0° at the iThemba Laboratory for Accelerator Based Sciences (iThemba LABS) in South Africa. This was done through the study of the low-lying dipole strength of ^{58}Ni with a proton beam of $E_p = 80$ MeV. The inelastically scattered protons were measured with the K600 magnetic spectrometer positioned at 0° , while the subsequent γ decay was measured with the Ball of hyper-pure Germanium and Lanthanum bromide detectors (BaGeL) at backward angles at distances ranging from 17-20 cm away from the target.

Low-lying dipole strength, commonly known as the Pygmy Dipole Resonance (PDR), appears in nuclei with neutron excess and can be pictured macroscopically to result from oscillations of these excess neutrons against an inert core with $N \simeq Z$. By its nature, the PDR may elucidate the formation of the neutron skin in nuclei.

Proton inelastic scattering experiments at very small angles including 0° favour electric dipole excitations allowing for the extraction of the full low-lying $E1$ strength. Detecting these protons in coincidence with the subsequent γ -ray decay further improves the selectivity to very low spin transfer, allowing for resolved excited states between 3 and 10 MeV and multipolarity identification. Moreover, the high-energy resolution high-purity germanium detectors used in decay studies allow for an improvement of the standard energy resolutions obtainable with magnetic spectrometers.

The coincidence matrix obtained for this study indicated a decay to the ground state and the first excited state. Since this experiment was an initial test of the $(p,p'\gamma)$ detection capabilities at 0° , the beam time was limited and so, the statistics obtained are low. As a result, the p - γ angular correlations and hence, the spins and parities of the excited states, could not be determined. However, a total of 19 excited states were identified in this work and were found to be in agreement with those from the National Nuclear Data Center. Only two of these states were identified to have $J^\pi = 1^-$. The results of this study were compared with previous $(\alpha, \alpha'\gamma)$ and (γ, γ') studies and yielded good agreements overall.

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Chapter 1

Introduction

The iThemba Laboratory for Accelerator Based Sciences (iThemba LABS) is a multidisciplinary research facility that focuses on the development, operation and use of particle accelerators and related research equipment [1]. Experimental nuclear structure and different reaction mechanisms at moderate-to-high excitation energy and angular momentum have been studied extensively at this facility for over 40 years. Light-ion scattering experiments are measured with the K600 magnetic spectrometer, while γ -ray spectroscopy has been largely performed with the AFRican Omnipurpose Detector for Innovative Techniques and Experiments (AFRODITE) γ -ray array. The K600 magnetic spectrometer is one of the only two facilities in the world (the other being the Grand Raiden magnetic spectrometer at the Research Center for Nuclear Physics (RCNP) in Japan) that is capable of measuring inelastic reactions at extreme forward angles including 0° with high energy-resolution (≤ 100 keV) at medium beam energies [2]. Such measurements have the advantage of providing selectivity to low angular momentum transfer excitations. This selectivity can be further improved by coupling the magnetic spectrometers with γ -ray detectors, allowing for the detection of the subsequent γ -ray decay. Studies of γ -ray emission provide direct and precise information about the location and properties of the excited states, and so, this type of experimen-

tal set-up allows for the characterisation of the decay path for low multipolarity excited states [3]. Measuring the subsequent γ decay in coincidence with the inelastically scattered probe allows for the effective separation of nearby excitations, the determination of branching ratios, the assignment of multiplicities and the investigation of the isospin character in nuclei of interest. γ -ray spectroscopy can be performed with high-resolution semiconductor detectors such as High-Purity Germanium (HPGe) detectors and high-efficiency scintillators such as LaBr_3 detectors.

The iThemba LABS facility has been developed constantly to improve the selectivity of 0° measurements and include particle and γ -decay coincidence measurements. In December 2012, an experimental test was conducted at the iThemba LABS. Two HPGe detectors from the AFRODITE array were successfully coupled with the K600 magnetic spectrometer for the detection of an $(\alpha, \alpha'\gamma)$ reaction on ^{24}Mg at 160 MeV. This experiment allowed for the separation of the excitation-energy peaks of interest and the determination of branching ratios [4]. In 2016, the spectrometer was coupled with 8 HPGe detectors from the AFRODITE array to perform an $(\alpha, \alpha'\gamma)$ reaction on deformed ^{154}Sm at 120 MeV [5]. The results showed that a detailed spectroscopy of $E1$ excitations below the particle threshold was achievable [6].

In the present study, the iThemba LABS K600 magnetic spectrometer was coupled with a ball of 12 high-resolution HPGe detectors from the AFRODITE array and 5 high-efficiency Cerium-Doped LaBr_3 ($\text{LaBr}_3:\text{Ce}$) detectors. This combination of detectors is commonly referred to as the Ball of Germanium and Lanthanum bromide detectors (BaGeL). The aim of the present study was to investigate the $(p, p'\gamma)$ detection capabilities at 0° at iThemba LABS using a beam with $E_p=80$ MeV. Since this set-up favours low-spin transfer, the study was conducted through the investigation of low-lying $E1$ strength in ^{58}Ni . This region of interest has been studied previously in ^{58}Ni using different techniques and probes [7–10], meaning

that the experimental results from the present study could be compared to these pre-existing data.

The low-lying $E1$ nuclei response referred to above is commonly known as the Pygmy Dipole Resonance (PDR). It is described as an out-of-phase oscillation of the neutron skin and an $N = Z$ core. It is attributed to a concentration of $J^\pi = 1^-$ states located around the particle threshold in both stable and unstable nuclei. This resonance lies well below the Giant Dipole Resonance (GDR), but it is sometimes challenging to distinguish them from each other owing to fragmentation and fine structure [11]. Although theoretical and experimental evidence for this low-lying strength has been established, a comprehensive picture of its systematics still needs to be drawn. Therefore, continuous development of different experimental techniques, such as the one developed in this study, is important to provide additional information for a better understanding of the properties and nature of the PDR. The most important challenge in the interpretation of the PDR states is the establishment of the characteristic transition densities and isospin character [12]. Using hadronic probes such as protons and alpha particles at energies of 80 MeV and 120 MeV, respectively, can provide this information [12]. Furthermore, the $(p,p'\gamma)$ reaction is well suited for the study of nuclei with high neutron thresholds such as ^{58}Ni [13]. It also has improved sensitivity to the inner transition density in comparison with the $(\alpha,\alpha'\gamma)$ reaction. This means that complementary information to that obtained from α -particle inelastic scattering and electromagnetic excitation can be obtained from the present study for the case of ^{58}Ni if the $(p,p'\gamma)$ detection capabilities of the K600-plus- γ -array system are adequate at 0° at iThemba LABS.

As mentioned earlier, this study seeks to test and develop the $(p,p'\gamma)$ detection capabilities of the K600 magnetic spectrometer coupled to a Ball of HPGe LaBr₃ detectors (BaGeL) at iThemba LABS. This was done through an investigation into the low-lying $E1$ strength of ^{58}Ni using proton inelastic scattering at $E_p = 80$ MeV.

To achieve the aim of this research, the following specific objectives were carried out:

- A background-free $(p,p'\gamma)$ excitation energy spectra for the ^{58}Ni isotope from the K600 magnetic spectrometer was acquired at zero degrees.
- A coincident γ -decay spectra of ^{58}Ni was acquired from the γ detectors. In this study, only the γ events from the HPGe detectors were analysed.
- A 2-dimensional matrix between the γ decay and the excitation energy was constructed and decays to the ground state and the first excited state were identified.
- The identified excited states were compared to those from the National Nuclear Data Center (NNDC) and previous experiments, thus assigning some to the PDR.

The layout of this dissertation is as follows:

Chapter 2 provides a detailed overview of the PDR. A brief discussion of various experimental techniques and probes used to excite the PDR is provided. Previous studies on the low-lying $E1$ strength in ^{58}Ni are also presented.

Chapter 3 presents a detailed description of the experimental tools used and procedures followed for the successful running of this experiment. This includes all procedures from beam production to the detection of the inelastically scattered protons and γ decay following de-excitation of the target. The data acquisition system of the experiment is also described.

Chapter 4 gives the details of the offline extraction of the relevant experimental information from the data files provided by the data acquisition system. Further offline analysis steps taken to optimise the data are also presented.

Chapter 5 presents and discusses the analysed data. The coincidence matrix and the corresponding excitation and γ -decay energies are presented. Comparisons to previous studies that use α particles and γ rays as probes are also discussed.

Chapter 6 presents a summary of the results and their implications. Recommendations for future experiments are also given.

Chapter 2

Literature review

The atomic nucleus (and the behaviour of its constituents) has attracted a lot of interest from experimental and theoretical physicists since its discovery by Ernest Rutherford in 1911. To study how the protons and neutrons comprising a nucleus behave, the nucleus should be subjected to an external perturbation and its response should be examined [14]. Many theories have been put forward to explain the different observed phenomena and, in some cases, to predict certain behaviours of the nucleus. For example, several resonance-like structures can be observed when nuclei interact with photons, electrons, or hadrons [11]. These resonances can be grouped into different categories of multipoles depending on how the nucleus responds to the perturbation. One of the ways in which these multipoles are categorised is by the angular momentum transfer (L). For example, $L = 0, 1$ and 2 correspond to the monopole, dipole and quadrupole resonances, respectively. A multipole pattern also exhibits isoscalar and/or isovector properties depending on the isospin (T) changes of the nucleus [15]. This chapter gives an overview of the phenomenon of interest in this study, which is the PDR (Pygmy Dipole Resonance), and the different techniques that are used to study it. Two previous studies conducted on the PDR of ^{58}Ni are also presented and discussed in this chapter.

2.1 Pygmy dipole resonance

Experimental studies of resonances started more than 75 years ago when W. Bothe and W. Gentner [16] observed an enhanced photo-dissociation cross section in certain nuclei. A reasonable estimation of the resonance energy and cross section was given by A. Migdal in a seminal work [17], where he explained the enhanced cross section as a dipole oscillation of the protons against the neutrons in a nucleus. Not long after that, G.C. Baldwin and G.S. Klaiber [18] managed to measure photofission cross sections using Bremsstrahlung from a betatron and, for the first time, the near-Lorentzian shape of the resonance referred to as the GDR (Giant Dipole Resonance) was established. The observed cross section in the energy range of the GDR exhausted nearly 100% of the sum rule for isovector electric dipole transitions [11]. It was concluded that the remaining dipole strength had to be small, which finally led to the idea of the lower-energy dipole strength commonly known as the PDR. Figure 2.1 shows how the $E1$ strength splits into the PDR and the GDR.

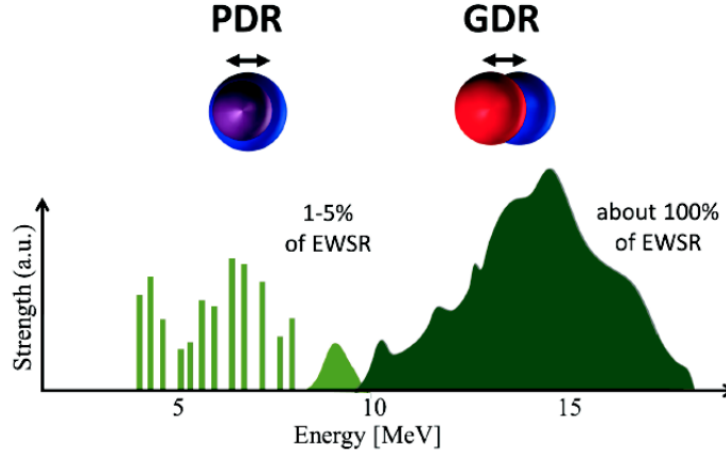


Figure 2.1: Schematic distribution of $E1$ strength in an atomic nucleus showing the splitting of the $E1$ strength into the Pygmy Dipole Resonance (PDR) and the Giant Dipole Resonance (GDR) [19].

A basic description of the electric dipole excitation is given by the three-fluid

hydrodynamical model. Within this model, two independent electric dipole resonances are naturally found, one originating from the out-of-phase oscillation of all protons and neutrons (i.e. the GDR) and the other originating from the out-of-phase oscillation of the neutron skin and an $N = Z$ core (i.e. the PDR) [20]. The PDR in particular is attributed to a concentration of $J^\pi = 1^-$ states located around the particle threshold in both stable and unstable nuclei [19,21]. PDR-like excitations are expected to be enhanced in neutron-rich, unstable isotopes since they have a larger neutron excess [19].

First investigations into the $N = 82$ isotones using $(\alpha, \alpha'\gamma)$ reactions have indicated, in comparison to photon scattering experiments, a splitting of the low-lying dipole strength [22]. The strength separates into two groups: the lower-lying part, which is excited by both isoscalar and isovector probes, and the high-energy part, which is excited only by electromagnetic probes [23]. It has been proposed that only the lower-lying part should be attributed to the PDR, i.e. an excitation mode that is clearly distinct from the GDR in contrast to the higher-lying $E1$ strength with transition densities on the way to the GDR. However, the amount of low-lying dipole strength that should be assigned to the PDR in order to calculate the total strength of this excitation mode is not yet known [22].

Like other multipole excitations, the electric dipole response of the atomic nuclei is partly directly linked to certain properties of the underlying nuclear force [11]. Some theoretical studies of the PDR predict a relationship to the symmetry term of the nuclear binding energy and the nuclear equation of state [24, 25]. The PDR also has implications for neutron capture rates in astrophysical processes, since the $J^\pi=1^-$ states of the PDR act as doorway states in the neutron capture process [26]. The process, commonly known as the r-process, is responsible for the synthesis of about 50% of the elements that are heavier than iron. The equilibrium properties of neutron stars can be modelled through the information carried by the $E1$ strength distribution [27]. The nuclear dipole polarisability, α_D , is suggested

by the studies of Energy Density Functionals (EDFs) using Skyrme forces [28] or a relativistic framework [29] to be a possible observable that has implications on both the neutron skin and symmetry energy. This polarisability can be described as [30]:

$$\alpha_D = \frac{\hbar c}{2\pi^2 e^2} \int \frac{\sigma_{\text{abs}}}{\omega^2} d\omega \quad (2.1)$$

where σ_{abs} is the photoabsorption cross section and ω is the photon energy. From this expression, it is clear that the energy dependence of α_D is inverse and thus α_D depends on the $E1$ strength at low energies. Furthermore, there are existing advanced theoretical methods that can give a realistic description of the $E1$ strength distributions [31] and, therefore, different experimental techniques should also be developed in order to confirm the predictions of those theoretical methods.

2.2 Techniques for excitation of the pygmy dipole resonance

The $N = Z$ core that oscillates against a neutron skin in a PDR mode can be perceived as having an isospin symmetric core. As a result, the PDR should be investigated using different isovector and isoscalar probes that are sensitive to the isospin character of the nucleus [32]. The nature of the response of the states in the PDR region can be obtained by studying the shape of the transition densities. Transition densities give a reflection of the contribution of protons and neutrons to a particular excitation. They can be used to theoretically calculate the oscillation spatial distribution of vibrational states such as the $E1$ excitations, showcasing the notion of isoscalar and isovector excitations. The isovector excitations are associated with the relative out-of-phase motion of the neutrons versus protons which results in a change of isospin ($\Delta T = 1$). The isoscalar excitations on the other hand are illustrated by the neutron and proton transition densities of the same sign, resulting in no change of isospin ($\Delta T = 0$). These microscopic

transition densities can be obtained from the wave function and the X and Y amplitudes derived from Hartree-Fock (HF) plus Random-Phase Approximation (RPA) calculations [32].

By observing the transition densities, it has been shown that, in low-lying regions, nuclei with $N = Z$ have no significant strength of the isovector component, while for all other isotopes there is a significant isoscalar component. As a result, depending on the N to Z ratio, the states belonging to the low-lying region will have different contributions of the isovector and isoscalar components for different isotopes. As an example, the different nature of these states in ^{56}Ni and ^{68}Ni are illustrated in Fig. 2.2. Here, the proton and neutron, and isovector (IV) and isoscalar (IS) transition densities for the low-lying dipole states of ^{56}Ni and ^{68}Ni are compared. At $E = 12.10$ MeV, the proton and neutron transition densities of ^{56}Ni are completely in phase both inside the nucleus and on the surface, while the IS is clearly dominating over the IV transition. The right panel ($E = 10.41$ MeV) of ^{68}Ni depicts the typical behaviour of the PDR where the protons and neutrons are oscillating in phase inside the nucleus but out of phase on the surface. The IS and IV transition densities have the same magnitude on the surface, while on the inside of the nucleus, although in phase, the IS has the major contribution. This illustration further proves that in order to extract the full strength of the PDR, probes with relative contributions of the IS and IV components should be used. As such, protons with their Coulomb component and different mixtures of isovector and isoscalar nuclear components are good candidates to probe the PDR.

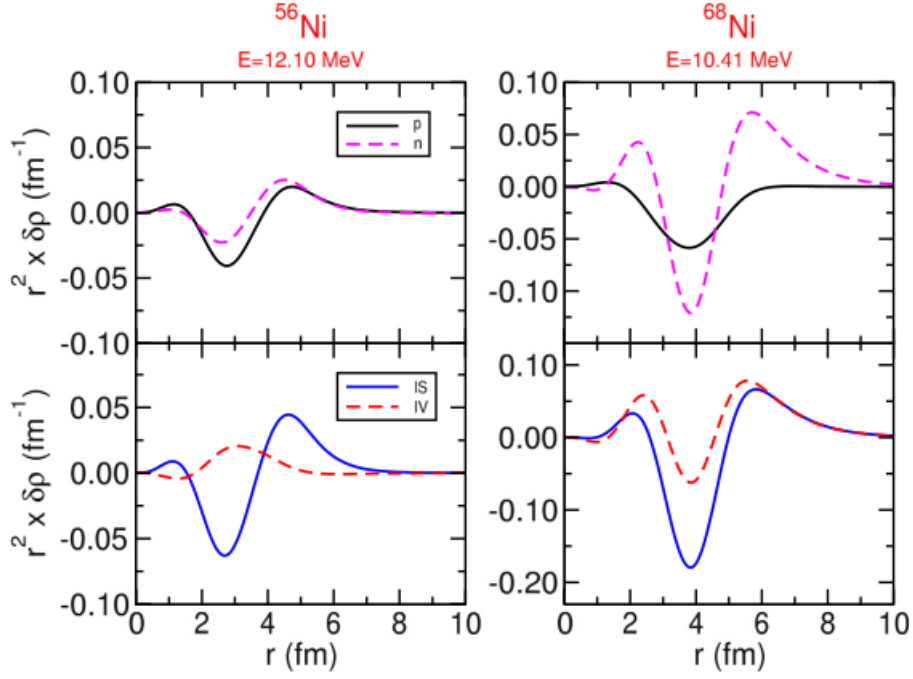


Figure 2.2: Comparison of transition densities of the low-lying $E1$ state for ^{56}Ni and ^{68}Ni [32].

This section gives an overview of some of the major experimental techniques and probes that are used in the study of the PDR. The most important aspects of these different techniques along with their advantages and limitations are discussed. A summary of different excitation mechanisms using different techniques as well as the subsequent decay modes are provided in Fig. 2.3.

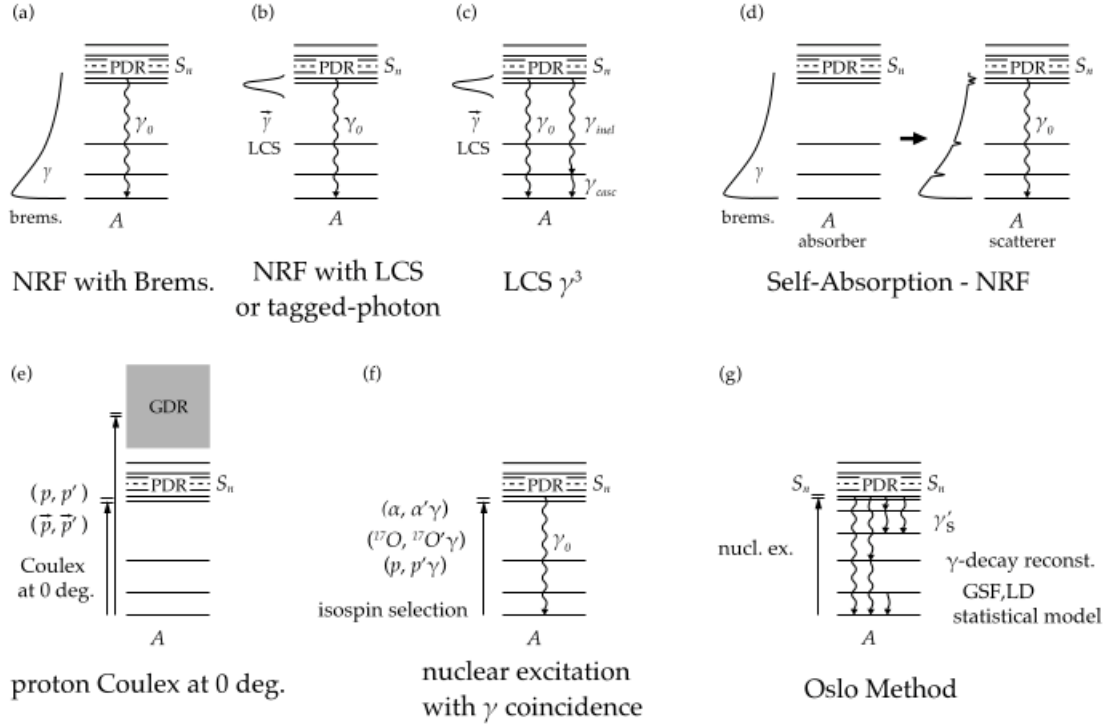


Figure 2.3: Schematic representation of the main experimental methods used in the study of low-lying dipole strength and its decay modes [32].

2.2.1 Nuclear Resonance Fluorescence (NRF)

Low-lying $E1$ states are commonly studied through different Nuclear Resonance Fluorescence (NRF) techniques using real-photon sources with endpoint energies up to the particle thresholds [11]. Unlike in other inelastic scattering experiments, photons are always fully absorbed in the excitation energy resulting in the formation of a resonance state with high selectivity to multipolarity 1 [11]. The excitation mechanism in this technique is well known. Therefore, extracting intrinsic properties like parity, spin or transition densities in a model-independent way from the measured quantities such as the angular distribution and cross section is possible. This subsection gives a brief description of four different NRF techniques used to excite the PDR.

2.2.1.1 NRF with Bremsstrahlung

The Bremsstrahlung beam used in these experiments (Fig. 2.3(a)) is produced by impinging an electron beam on a radiator target such as niobium. At ELBE [33] and S-DALINAC [34], the maximum electron beam energy reached for NRF experiments is 13.2 and 10 MeV, respectively. The maximum γ -ray energies that can be reached depend on the energy of the electron beam. With Bremsstrahlung, there is a continuous energy spectrum, which means that a large excitation-energy region can be studied during one experimental setting. Even though the photon spectrum is calibrated, this continuity also means that the exact energy of the incident photon is not known and so, the energy of each event cannot be extracted [32]. However, the assumption is always that the detector measures the decay of the populated states to the ground state since the photon is fully absorbed (i.e. the photon energy is directly equal to the excitation energy). This assumption neglects the feeding from higher-lying states because the measured quantity is the product of the photo-absorption cross section and the branching ratio of the γ decay to the ground state. Statistical decay simulations may be employed to correct branching ratios and the feeding scheme so that the photo-absorption spectrum is reconstructed [32]. The most recent studies of the PDR using Bremsstrahlung were conducted at ELBE [33] and the S-DALINAC [34]. In both setups, a high photon flux and large-volume HPGe detectors were combined. Excellent sensitivity for the energy of the PDR was provided through the addition of active Compton suppression and massive shielding. NRF with Bremsstrahlung beam has been used extensively to study the dipole strength distribution in stable $N = 82$ isotones [35–38]. The finalised systematic survey on the PDR of these isotones were conducted for a semimagic nucleus ^{136}Xe [36]. For all these isotones, a resonance-like fragmentation around the $E1$ was observed in the energy region between 5 and 8 MeV. The analysis showed that this fragmentation decreased with N , while the overall low-lying $E1$ increased. This was an indication that the total

strength is dependent on the N to Z ratio.

2.2.1.2 NRF with tagged photons

Improvements for the Bremsstrahlung experiments mentioned above can be developed using tagged photons (Fig. 2.3(b)). Tagged-photon beams are also produced via Bremsstrahlung, but, in this case, one photon per electron is produced through a sufficiently thin radiator target [32]. The energy of these tagged photons is measured from the coincidence between the scattered Bremsstrahlung electron and the γ rays emitted by the nucleus of the radiator target. The detectors for the scattered electrons are placed at 0° behind the radiator target. The following equation is used to determine the remaining energy of the scattered electron $E_{e'}$

$$E_\gamma = E_0 - E_{e'} \quad (2.2)$$

where E_γ is the energy of the produced photon and E_0 is the energy of the electron beam. From this equation, it is evident that the energy of the tagged photons also shows characteristics of continuity but, because of the coincidence measurements, the energy of the individual photons is known. The downside of this method is that the rate at which electrons are detected behind the radiator is limited, which means that the tagged-photon flux measured also becomes limited. Consequently, the achievable reaction rate becomes small.

2.2.1.3 NRF with laser Compton backward scattering

The Laser Compton backward Scattering (LCS) photon beam is produced through the collision of low-energy laser photons with highly relativistic electron beams. As opposed to the previous NRF experiments discussed, LCS provides an adjustable narrow-energy-range photon beam with mono-energies. The back-scattered pho-

tons (at 180°) have the maximum energy given by approximately;

$$E_{\gamma'} = 4\gamma^2 E_{\text{laser}} \quad (2.3)$$

where γ is the relativistic Lorentz factor for the electrons and E_{laser} is the energy of the initial laser photon. The polarisation of the laser beam is maintained in the scattering process, which allows for the produced photon beam to be polarised close to 100%. A polarised beam is advantageous for identifying the spin and parity of the resonance state. This advantage has been exploited to establish the E1 character of the PDR [39–41]. Currently, two operating facilities that use this method are the Teras storage ring [42] and HI γ S at Duke University [40,41,43]. At the latter institution, the electrons drive a free electron laser, while at the former, an external laser is used to provide photons. For the provision of high electron flux for efficient Compton scattering, the electrons are stored in a ring in both facilities. At HI γ S, the rewards of this quasi-monoenergetic photon beam are utilised in a γ^3 setup (Fig. 2.3(c)) [44]. In this particular setup, cascade decays are measured for the data where the photon beam energy is not the same as the detector γ -ray energy. The investigation is typically aimed at the decay of several low-lying states to the ground state. In some cases, γ – γ coincidence measurements may be taken. In [40], a decay of the low-lying 2^+ state to the ground state on ^{138}Ba has been observed. This means that this first excited state could have been populated by the decay of a primary state at $E_i = E_\gamma$. However, those primary transitions were not observed. It was concluded that it is possible that the majority of the low-lying 2^+ states could be as a result of inelastic cascades decay from the 1^- states. Thus the intensity of decay of the 2^+ could be used to extract the cross sections for the 1^- contributions.

2.2.1.4 Self-absorption NRF

The first self-absorption experiment was performed using Bremsstrahlung photons at the S-DALINAC to investigate the decay pattern of low-lying dipole states of ^{140}Ce [45]. As opposed to the NRF techniques mentioned above where the decay of the excited states to the ground state is measured, this technique measures an absorption spectrum when a photon beam is bombarded on a thick absorber (shown in Fig. 2.3(d)). The measured spectrum shows absorption lines at the resonance energy of the target. A direct measurement of the ground-state transition width is evident for pronounced absorption lines. Furthermore, the intensity of the transmitted spectrum is reduced with respect to the original one because of the attenuation effects of the atoms.

2.2.2 Hadronic probes

NRF experiments are much more selective to low spin transfer but they do not provide full access to the strength of the PDR in both stable and unstable nuclei [11]. Therefore, it becomes imperative to use different techniques to probe different components of the nucleus. Alpha particles, owing to their isoscalar internal structure, are appropriate for probing the isoscalar component of the nucleus, while intermediate-energy protons will excite the Coulomb component and different mixtures of isovector and isoscalar nuclear components. This makes these hadronic probes, at intermediate energies of 80 MeV and 120 MeV, respectively, a valuable complementary tool to populate the states of interest and make it easy to distinguish between excitations belonging to the GDR and the PDR since the PDR lies well below the GDR [11, 32, 46] and the GDR above the PDR is a pure isovector excitation. Selectivity to low-spin excitation using hadronic probes can be achieved through particle- γ decay coincidence measurement. This method will be further explained in Sec. 2.2.2.2.

2.2.2.1 Coulomb interactions with protons at 0°

Relationships between cross sections and transition strength can be applied more appropriately for cross sections measured at 0° than at larger angles, where cross sections are extrapolated. Coulomb excitations at angles very close to zero (Fig. 2.3(e)) dominate the total cross sections of electric dipole states, while at angles a little larger than 0° , this cross section is dominated by nuclear excitation [32]. Through Coulomb excitations via proton inelastic scattering at intermediate energies, the resulting cross sections are well described by a one-step reaction with DWBA calculations [12, 32]. Since the cross section is dominated by Coulomb scattering at 0° , it is possible to extract the $E1$ strength in a model-dependent way. Protons at relativistic energy excite the nuclei via a virtual photon, thereby allowing for investigation of the isovector component of the excitation. This powerful technique was first performed successfully in 1991 at the Research Center for Nuclear Physics, Osaka University [47], and is also widely used at iThemba LABS [3]. Unlike NRF experiments or (γ, xn) reactions, protons probe the full excitation strength for all the decay channels. At RCNP, a proton beam of 295 (392) MeV can produce a measured excitation-energy spectrum that goes from ≈ 5 (7) MeV to ≈ 23 (32) MeV. This implies that the measured cross section spans excitation energies across the particle separation energy up to the high-energy tail of the GDR. (p, p') reactions at zero degrees have been constantly developed to further increase sensitivity to low-spin excitations and reduce background contributions significantly. As is the case in this study and for other hadronic probes mentioned in Sec. 2.2.2 above, this can be done by measuring the subsequent gamma decay of the excited states in coincidence with the scattered protons.

2.2.2.2 Particle- γ coincidence

In this experimental technique, depicted in Fig. 2.3(f), a magnetic spectrometer is used to analyse the scattered particles while γ -ray detectors are used to detect

the γ -ray decay in coincidence. This technique allows the experimentalist to measure the energy loss of the inelastically scattered particles (which translates to the excitation energy) and the subsequent γ decay of the excited nucleus. The coincidence data can be sorted into a matrix where one axis represents the energy loss of the probing particle during the scattering process, and the other axis represents the energy of the γ rays measured in coincidence. The high energy-resolution of the HPGe detectors used in this type of experiment is exploited to determine the spin and parity of the excited states, while the known transitions obtained by NRF measurements are used as complementary information. Possible background contributions and cascade decays are excluded by selecting decays to the ground state only. This is done by imposing the condition $E_x \simeq E_\gamma$.

The first study to perform coincidence measurements in order to overcome the disadvantages introduced by hadronic probes was by T.D. Poelheken et al. at KVI Groningen [7]. In that experiment, a 120 MeV alpha beam was bombarded on a ^{58}Ni , ^{208}Pb , ^{40}Ca and ^{90}Zr target. The inelastically scattered alpha particles were measured with the QMG/2 spectrograph, while the subsequent γ decay was measured with a NaI(Tl) detector. The coincidence condition between the alpha particles and γ rays favoured low-spin states and the scattering cross section for discrete $J^\pi = 1^-$ levels in the above-mentioned four nuclei could be determined. The $\alpha - \gamma$ angular correlation could also be analysed. The ^{58}Ni results of this study along with those of a more recent study will be presented and discussed in Sec. 2.3.1 and 2.3.2, respectively.

Another approach of studying the dipole strength distribution through particle- γ coincidence was developed at the University of Oslo, Norway. In their experiments, reactions such as $(^3\text{He}, \alpha\gamma)$ and $(^3\text{He}, ^3\text{He}'\gamma)$ at beam energies between 30-45 MeV are used to excite the low-lying strength. The scattered particles are measured with Si telescopes while the subsequent γ decay is measured with NaI detectors [48]. The Oslo method enables the experimentalist to simultaneously extract

the γ strength function and the level density from excitation-energy-tagged γ -ray spectra [49,50]. The γ strength functions extracted using this method are strongly affected by the $E1$ dipole response up to the neutron separation energy. The states are excited through nuclear reactions, either transfer or inelastic scattering at low energies. The coincidence matrix between the γ decay and the excitation energy is constructed and the γ -ray strength function is determined through a statistical decay model [48]. This γ -ray strength is interpreted as a representation of the transition strength between the states with fixed multipolarity (usually $E1$) [32]. The corresponding nuclear level density is calculated theoretically as an additional fitting function.

2.3 Previous studies on the low-lying $E1$ strength in ^{58}Ni

The studies discussed in this section both employed coincidence techniques through coupling of a magnetic spectrometer with γ detectors in order to explore the low-lying strength in ^{58}Ni . The identification of the isospin structure in the PDR, especially the isoscalar contributions, is one of the most important pieces of information that is needed to form a coherent picture of the PDR. Hence, in these two studies, a beam of alpha particles (isoscalar probe) was used to probe the PDR. In Sec. 5.3.1 of Chapter 5, the results of the current study will be compared with those presented in this section.

2.3.1 $^{58}\text{Ni}(\alpha, \alpha'\gamma)$ with a NaI(Tl) detector and the QMG/2 spectrograph

As mentioned in Sec. 2.2.2.2, an experiment was conducted by T.D. Poelheken et al. in 1992 to study the low-energy isoscalar $E1$ strength in ^{58}Ni , ^{208}Pb , ^{40}Ca and ^{90}Zr . This study aimed to improve the selectivity to low-spin excitation

while giving access to the full isoscalar part of the PDR. The diagonal loci on the two dimensional matrix of γ energy versus excitation energy shown in Fig. 2.4 illustrates a decay to the 0^+ ground state and the 2^+ first excited state of ^{58}Ni . This means that this study did not only favour excitations with low spin transfer but it also allowed for individual decay channels to be studied by applying a gate on the diagonal loci. The multipolarities of the excited states could be determined from the established α - γ correlations. A total of 6 states between 6 MeV and 10 MeV were recorded and denoted as the Isoscalar Low Energy Dipole Resonance (ISLED R). As can be observed from the two-dimensional matrix, the diagonal loci are relatively thick, indicating the poor energy resolution of the NaI detectors. As a result, this setup could not be used where nuclei with high level densities were of interest.

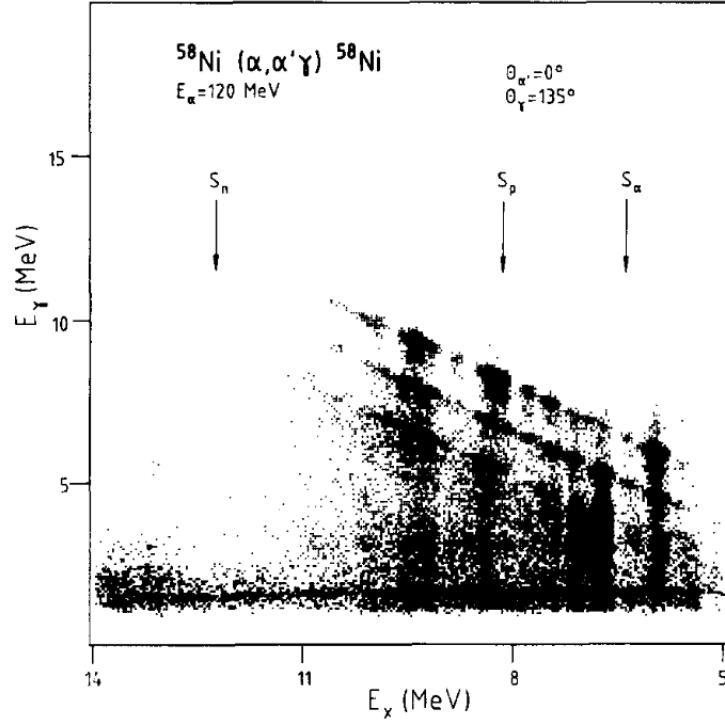


Figure 2.4: Two-dimensional matrix of the γ -ray decay energy versus the excitation energy in ^{58}Ni for $\theta = 135^\circ$ [7].

2.3.2 $^{58}\text{Ni}(\alpha, \alpha'\gamma)$ with HPGe detectors and the Big-Byte Spectrometer

In 2002 Harakeh, Wörtche, and Zilges proposed that the KVI Groningen Big-Byte Spectrometer (BBS) be coupled with HPGe detectors [52]. A series of experiments commenced from October 2002 using a larger array of high-volume HPGe detectors after a successful feasibility test using two small-volume HPGe detectors. In 2006, Savran et al. [8] used the newly developed coincidence setup at the KVI Groningen Big-Byte Spectrometer to perform an $(\alpha, \alpha'\gamma)$ experiment at 136 MeV on ^{58}Ni . As can be seen from Fig. 2.5, the diagonal lines on the two-dimensional matrix are relatively thin, indicating the improved energy resolutions of the HPGe detectors. In addition, the detection of γ decay after proton/neutron emission has been observed, which means that the decay of excitations above particle threshold could be studied successfully. The results were found to be consistent with those of Poelheken et al. The same selectivity to low-spin transfer states can be observed from the dominating transitions to the 0^+ ground state and the 2^+ first excited state of ^{58}Ni . The strong, isolated $J^\pi = 1^-$ state at $E_x=6.023$ MeV has been observed in both studies.

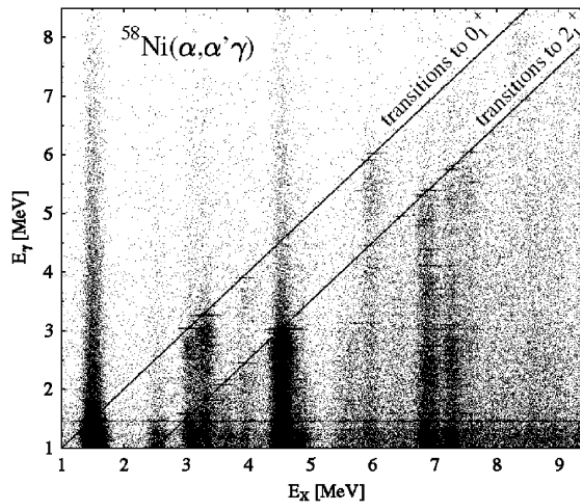


Figure 2.5: Two-dimensional matrix of the γ -ray decay energy versus the excitation energy in ^{58}Ni for $\theta = 135^\circ$ [8].

Chapter 3

Experimental details and techniques

A $(p,p'\gamma)$ reaction was measured for the first time at iThemba LABS using the K600 magnetic spectrometer coupled with BaGeL (an array of HPGe and LaBr detectors). Over the years, (p,p') reactions such as the one studied in [3] have been used extensively at iThemba LABS to extract the excitation-energy spectrum of various isotopes. However, these measurements did not provide any information with regards to the decay of the excited states. In this study, the coincidence condition between the K600 magnetic spectrometer and the γ -ray detectors allowed for the simultaneous detection of the (p,p') reaction and the subsequent γ decay of the excited states. This chapter gives a description of the equipment and techniques used in the experiment. The first section of this chapter (Sec. 3.1) presents an overview of the iThemba LABS Separated Sector Cyclotron (SSC) facility along with the injector cyclotrons used at iThemba LABS. Section 3.2 reports on the K600 magnetic spectrometer and the details related to the set-up of the spectrometer (such as the 0° mode) that were critical for the successful running of the experiment. Described in Sec. 3.3 is BaGeL and the specifications in relation to its configuration. The last section (Sec. 3.4) presents the

data acquisition system, which includes the electronics involved in obtaining the experimental data files and the software used in the process.

3.1 iThemba LABS SSC laboratory

The K=200 SSC at iThemba LABS is a variable-energy machine that is capable of accelerating protons to a maximum energy of 200 MeV. It provides ion beams to the subatomic physics, radioisotope production and radiation biophysics research groups. There are two main facilities that are used to perform subatomic physics research, namely, the K600 magnetic spectrometer, which is the backbone of the present study, and the γ -ray spectroscopy facility, which consists of a selection of γ -ray detectors that can be arranged in different configurations. In this experiment, an 80-MeV proton beam was extracted from the SSC and delivered to the K600 magnetic spectrometer through a high-resolution double monochromator system that consists of the X, P1, P2 and S beamlines. A schematic representation of the iThemba LABS SSC laboratory is given in Fig. 3.1. The K600 magnetic spectrometer with its components will be explained in detail in Sec. 3.2.

The SSC consists of four identical C-shape sector magnets, each with a sector angle of 34° [53]. The injection radius is 0.952 m and the extraction radius is 4.156 m. The pre-accelerated beam that is injected into the SSC is supplied by one of two injector cyclotrons, namely, a K8 Solid Pole Cyclotron 1 (SPC1) and a K11 Solid Pole Cyclotron 2 (SPC2). Both the pre-accelerators have four magnetic sectors, two 90° dees (hollow semicircular structures) and an extraction radius of 0.476 m [54]. As their names suggest, the K8 SPC1 and K11 SPC2 were designed to accelerate protons to a maximum beam energy of 8 MeV and 11 MeV, respectively. SPC1 has an internal Penning ionisation gauge ion source, while the SPC2, which was used for the present experiment, uses either of the two available ion sources, which are the Electron Cyclotron Resonance (ECR) ion source and

the polarised proton ion source. The beams are injected axially into the SPC2 with a spiral inflector. Three interchangeable inflectors are available to cover the range of energies and species. A proton beam of 80 MeV was provided by the SSC facility for the duration of this experiment. This specific beam energy is widely regarded as an intermediate energy in nuclear structure studies and was chosen looking at the fact that at intermediate energies, protons excite the Coulomb and different mixtures of isovector and isoscalar nuclear components [11, 32, 46] whereas protons at higher energies will mostly excite the isovector component of the nucleus. Therefore at this intermediate proton beam energy, we can get a better picture on the region of the PDR since different mixtures of the nuclear components will be accessed.

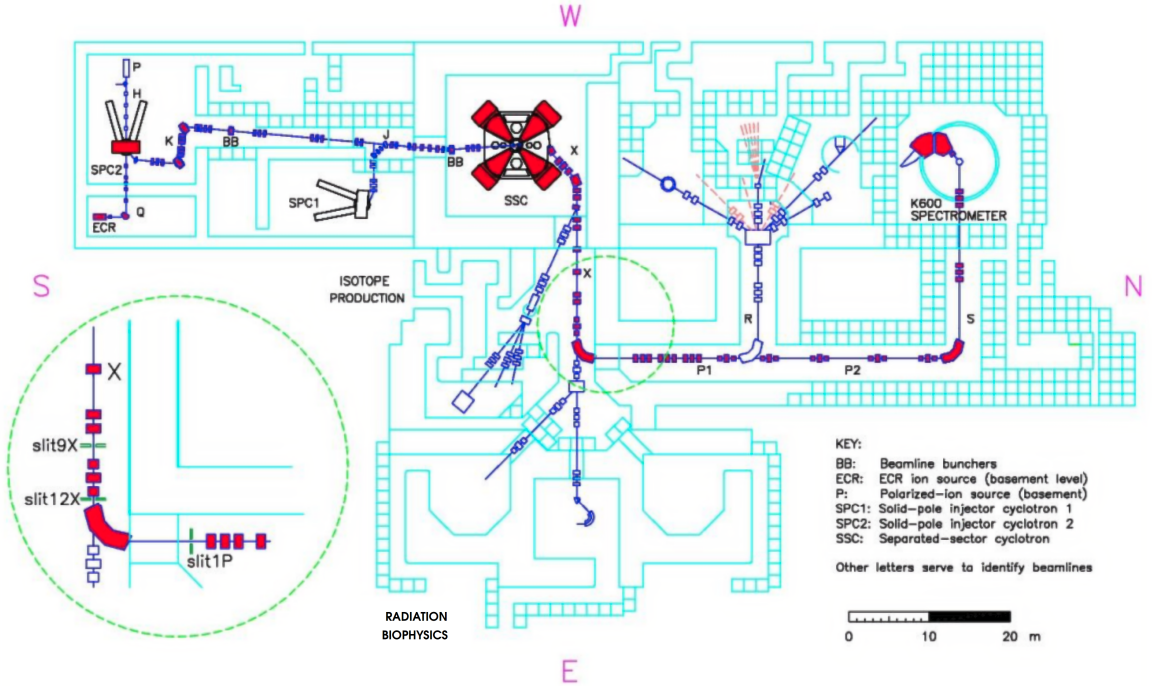


Figure 3.1: The layout of the iThemba LABS SSC laboratory [3].

3.2 K600 magnetic spectrometer

The K600 magnetic spectrometer of iThemba LABS is a large tracking system that consists of magnets and position-sensitive detectors. A schematic representation of this spectrometer is provided in Fig. 3.2 and illustrates all the major components involved in the detection process. It is composed of five main elements, namely, a quadrupole magnet, two dipole magnets (D1 and D2) and two trim coils (K and H). The quadrupole is positioned at the entrance of the spectrometer and its purpose is to focus the beam vertically at the focal plane. It acts as a converging ion-optical lens in one direction and a diverging ion-optical lens in the perpendicular direction; that is, it focuses the beam in one direction and defocuses it in the other.

Following the quadrupole magnet are the two dipoles. The function of these dipole magnets is to allow the momentum dispersion of the charged particles at the focal plane to be varied. This is done by changing the ratio of the magnetic field of the two dipole magnets. In terms of ion-optical relations [55], a dipole separates particles with different energies similar to how white light separates into its components when it passes through a glass prism. The H-coil and the K-coil are located inside D1 and D2, respectively, and they are used to fine tune the horizontal focus at the focal plane. The different shapes of these coils gives rise to different inherent magnetic characteristics. The shape of the K-coil results in a dipole and a quadrupole component and is used to correct first-order kinematic variations of momentum with the horizontal scattering angle θ (described by the ion-optical variable $(x \mid \theta)$). The shape of the H-coil gives rise to a dipole as well as a hexapole component, and is used to correct second-order kinematic variations $(x \mid \theta^2)$.

At the turning axis of the spectrometer lies the scattering chamber. This is where target materials are enclosed during experiments for collision with the beam from

the accelerator facility. The scattering chamber contains the target ladder with six target positions. The inelastically scattered protons from the scattering chamber are collimated by selecting one of the different collimator holders in the collimator ladder, which is positioned at the entrance of the quadrupole magnet where the collimator carousel used to be. A schematic representation of the collimator ladder is shown in Fig. 3.3. In the absence of a collimator, the angular spread of the proton beam would increase and result in scattering off other materials inside the spectrometer. Consequently, a significant amount of background would be observed in the focal-plane spectra.

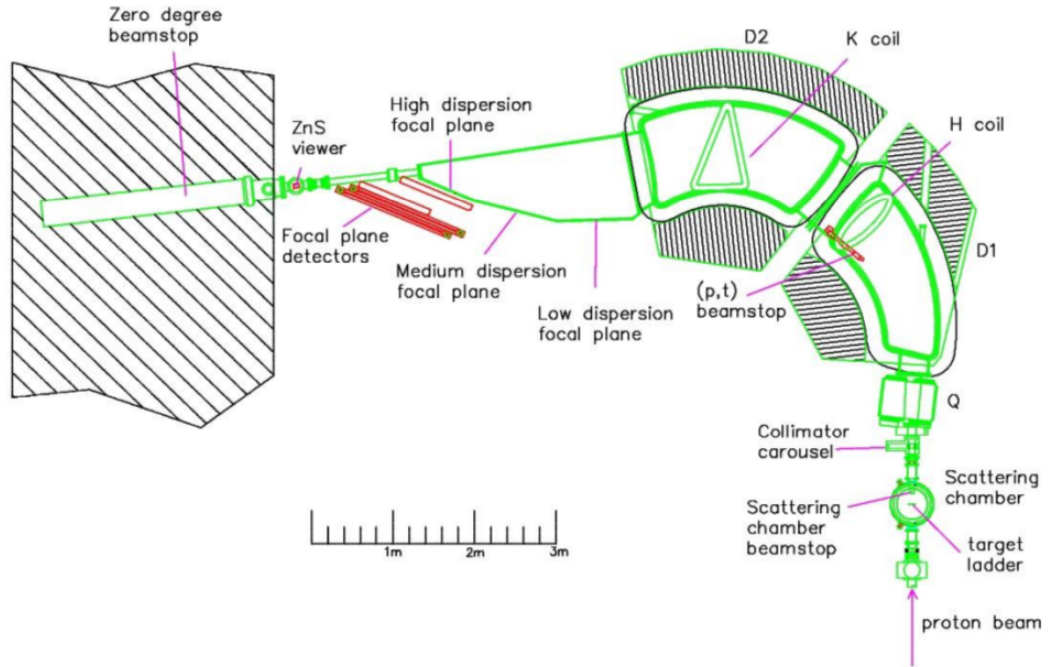


Figure 3.2: Schematic representation of the K600 magnetic spectrometer positioned in the 0° mode [3]. It should be noted that the collimator carousel has been replaced by a collimator ladder.

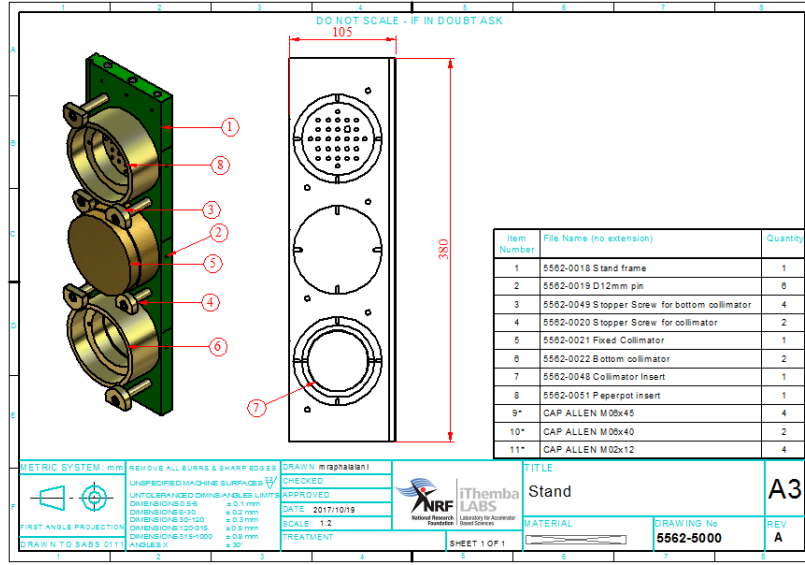


Figure 3.3: An illustration of the collimator ladder and three collimators assembled on the ladder [56].

3.2.1 Focal-plane detectors

In ion-optical instruments, the plane where particles that are scattered at direct angles originating from the same excited nucleus converge is called a focal plane. A focal-plane detector is positioned in this region to detect ions across the focal plane in one or two dimensions [57]. The scattered ions can be detected in any of the three available focal planes: high-dispersion, medium-dispersion or low-dispersion. These different dispersion modes can be exploited depending on the required conditions of different experiments such as the momentum range required. The momentum range of each focal plane is equivalent to the horizontal size of the focal plane (x) divided by the dispersion (D). The high-dispersion mode has access to a limited energy range but with a very high energy-resolution ($\sim 25 - 50$ keV for (p,p')). It is good for separation of the beam from the lowest measurable excitation energy E_x , and it also allows access to lower excitation energies (~ 3.2 MeV) in 0° mode than would be achievable with the other dispersion modes [3]. The medium-dispersion mode has a fair range of accessible

momentum as well as good energy-resolution capabilities. In this mode, a larger momentum range where $p_{\max}/p_{\min} = 1.097$ is covered when compared to the high-dispersion mode where $p_{\max}/p_{\min} = 1.063$. This, as a result, allows for the investigation of a broad excitation-energy region when the spectrometer is operated in medium-dispersion mode. The low-dispersion mode is suitable for use if the experimentalist is interested in a large momentum range; however, this mode gives the worst energy resolution among the three options. The high-dispersion mode used in this experiment resulted in an accessible excitation-energy range of approximately 3.5 - 10.5 MeV.

The two types of detectors that are responsible for the detection of the scattered particles at the focal plane of the K600 magnetic spectrometer are MultiWire Drift Chambers (MWDCs) and plastic scintillators.

3.2.1.1 Multiwire Drift Chambers

The operation of an MWDC is based on the ionisation of gas molecules by radiation. When an energetic nuclear particle enters the hollow gas-filled chamber of the detector, it ionises the medium gas and forms electron-ion pairs. An electric field is applied to drive the electrons towards the electrode that is situated along the center of the chamber while the positive ions are driven to the conductive walls of the chamber. A load resistor is also connected to complete the circuit. A potential drop across the load resistor is measured by a pulse height analyser and is amplified. The measured electronic signal is proportional to the applied voltage and the energy of the radiation, and depends on the type and pressure of the gas medium [58].

The three original drift chambers, developed and built at iThemba LABS (1989-1993) have two different geometrical configurations that correspond to the drift direction of the electrons [59]. The first two drift chambers have the main drift direction of electrons perpendicular to the signal-wire plane and are, therefore,

called the Vertical Drift Chambers (VDCs). In the third drift chamber, the electrons drift in the plane of the signal wires and it is, therefore, called the Horizontal Drift Chamber (HDC). The two VDCs are used to take measurements of the position along the length of the focal plane as well as the angle at which a charged particle crosses the focal plane. The HDC is used to measure particle position in the vertical direction of the focal plane.

Between 2006 and 2009, iThemba LABS manufactured two new VDCs because of the very limited vertical-position detection capabilities of the HDC [59]. Each new VDC, shown schematically in Fig. 3.4 and photographically in Fig. 3.5, has two wire planes in an XU configuration. The X signal wires are perpendicular to the scattering plane, while the U signal wires are angled at 50° with respect to the scattering plane. This configuration is important for determining the particle rigidity and the scattering angle accurately, especially for 0° measurements. The X wire plane of the VDCs is made up of 198 gold-plated tungsten signal wires, while the U wire plane is only made up of 143 similar signal wires. The wires are $20\text{ }\mu\text{m}$ in diameter, and they are placed 4 mm away from one another. Since the applied electric field is inversely proportional to the square of distance to the wire, this means that the smaller the diameter the more the charge multiplication will take place very close to the wire. Furthermore, 199 and 144 field-shaping wires, $50\text{ }\mu\text{m}$ in diameter, also made of gold-plated tungsten are found interspaced at equal distances between the X and U signal wires, respectively. One extra guard wire is found at both ends of the two wire planes. They are $125\text{ }\mu\text{m}$ in diameter and are composed of 80% Ni and 20% Cr. The guard wires reduce current leakage and spontaneous discharge by reducing the electric field at the ends of the VDC. In this experiment, a negative voltage of 3400 V was applied across the field-shaping wires. Three cathode planes, which are 16 mm apart and consist of $20\text{-}\mu\text{m}$ thick aluminium foil, sandwich the wire planes. The inside of the VDCs is isolated from the atmosphere with two $25\text{-}\mu\text{m}$ -thick Mylar planes. The operation of these

detectors is based on the ionisation of a mixture of 90% Ar and 10% CO₂ between the two mylar planes. To determine the position of the events at the focal plane, information on drift time and drift distances of the electrons in the VDC is used. In each cell, drift time is measured from the region where primary ionisation occurs to the region where avalanche occurs. These times are measured relative to the time a pulse is recorded from the scintillator that is situated behind the VDC. To obtain the drift distance, which is the distance travelled by the electron from the signal wire to the position where it first passes through the drift cell, a conversion has to be done from the drift times. This conversion is achieved by a look-up table (discussed in Sec. 4.1.2.2). It is only after accurate drift distances are obtained that accurate focal-plane position coordinates can be determined. In this study, only one VDC was used instead of two. This was done to ensure that the protons do not lose most of their energy in the VDCs before they reach the plastic scintillators since the proton-beam energy was just 80 MeV which falls within the intermediate energy range.

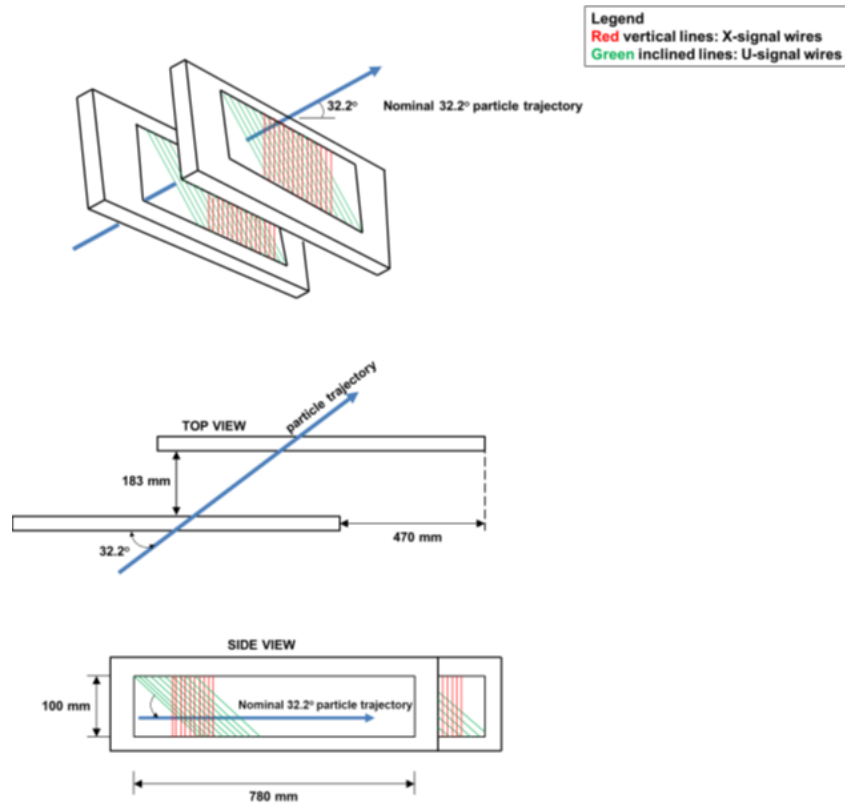


Figure 3.4: A schematic diagram of the K600 VDC focal-plane detectors [15].

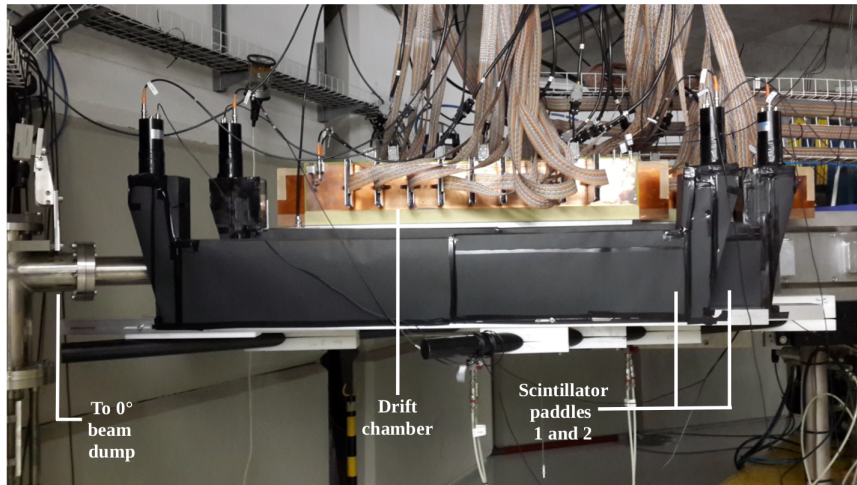


Figure 3.5: The focal-plane detector package of the K600 magnetic spectrometer [60].

3.2.1.2 Plastic scintillator detectors

The two plastic scintillator detectors, wrapped in sheets of aluminised mylar, are positioned just downstream from the drift chambers (also shown in Fig. 3.5) and are very close to the focal plane of the K600 magnetic spectrometer. Scintillator detectors are made up of scintillating materials that can interact with an energetic particle and convert its kinetic energy into detectable light. The scintillation medium should be of good optical quality and transparent for light with wavelengths of its own emission [58]. When an energetic nuclear particle enters the detector, it excites the molecules of the scintillating materials. De-excitation of these molecules results in the emission of visible photons. These photons are then focused to a photo-cathode where they can eject electrons through the photoelectric effect. The ejected electrons are directed to a photo-multiplier tube within the photo-cathode and they are multiplied by changing the applied electric field. The electrons are collected and, thereafter, form an electronic signal that is linearly proportional to the energy that was deposited into the detector.

The plastic scintillator detectors of the K600 magnetic spectrometer are connected to photo-multiplier tubes via 90° twisted pair adiabatic lightguides to both ends of each of the scintillators. These plastic scintillators provide event trigger signals and aid in particle identification through $\Delta E - \Delta E$ particle-identification spectra.

3.2.2 0° mode

The combination of an 80-MeV beam with scattering measurements at 0° was chosen for this experiment so that selectivity to excitations with low angular-momentum transfer can be achieved, thus exciting the PDR. Even though, in this mode, both the unscattered beam and the scattered particles pass through the spectrometer very close to each other due to the small difference in their magnetic rigidity, the spectrometer provides a means by which they can be separated to

achieve a high energy-resolution measurement. The detectors are placed in the high-dispersion focal plane so that the beam can be separated from the lowest measurable excitation energy [3]. Situated inside the concrete wall of the spectrometer vault, after the focal-plane detectors, is a Faraday cup that acts as the 0° beamdump. The unscattered beam from the spectrometer is transported there via the 0° beamline (shown in Fig. 3.5).

3.2.3 Dispersion matching

The momentum spread of the beam affects the obtainable energy resolution with a magnetic spectrometer. As the momentum of the beam from the accelerator increases, the momentum spread also increases linearly. The use of collimators, therefore, ensures that the momentum dispersion is limited. This spread can be further limited by implementing dispersion matching techniques, thereby improving the energy resolution of the spectrometer. During experiments, the beam is set up such that the position and angle of the proton that interacts with the target is independent of the momentum of the proton before the interaction. As a result, the position and angle of the inelastically scattered proton that reaches the focal plane is dependent on the initial beam energy spread thus limiting the energy resolution of the spectrometer [61]. To overcome this challenge, the beamline optics are adjusted so that the beam characteristics match the requirements of the magnetic spectrometer. This is done by separating the protons according to their momentum in such a way that the protons with high momentum will take a longer path in the spectrometer, while the ones with low momentum will take a shorter path, thus achieving an achromatic focus at the focal plane of the spectrometer [62, 63].

When the spectrometer is operated at 0° , the faint beam dispersion matching technique is applied. This is done by placing three beam attenuation meshes between the ECR ion source and SPC2. This results in the reduction of the

number of protons in the beam without distorting the beam profile. The magnet elements in the spectrometer are also scaled such that the faint beam passes directly through the focal-plane detectors. The matching conditions of the beam can then be analysed from the properties of the beam at the focal plane, and the energy resolution can be optimised.

3.2.4 Target ladder information

For this experiment, five targets, ZnS (used as the viewer), ^{24}Mg (used for calibration of the focal plane), ^{12}C (also used for calibration), ^{58}Ni (isotope of interest in this experiment) and an empty target, were mounted at different positions on the target ladder during the experiment. The areal densities of the ^{24}Mg , ^{12}C and ^{58}Ni targets were 0.7 mg/cm^2 , 1.053 mg/cm^2 and 5 mg/cm^2 , respectively. ZnS is a luminescent material that is used as a viewer during K600 experiments at iThemba LABS to check the beam position. The position is adjusted periodically to suit the requirements of the experiment. Figure 3.6 shows the viewer in position on the target ladder. Empty targets are used to determine the background contribution to the acquired spectra (as can be seen in Sec. 4.1.1). ^{24}Mg and ^{12}C have prominent and well-known states, hence they were chosen for calibrating the focal plane. The physics target, ^{58}Ni , was chosen because the target material can be rolled easily and it is not prone to oxidation. Furthermore, as mentioned in the introduction, there are already existing studies of the low-lying strength in ^{58}Ni using different probes [7–10] which can be used for comparison with the data from the present study.

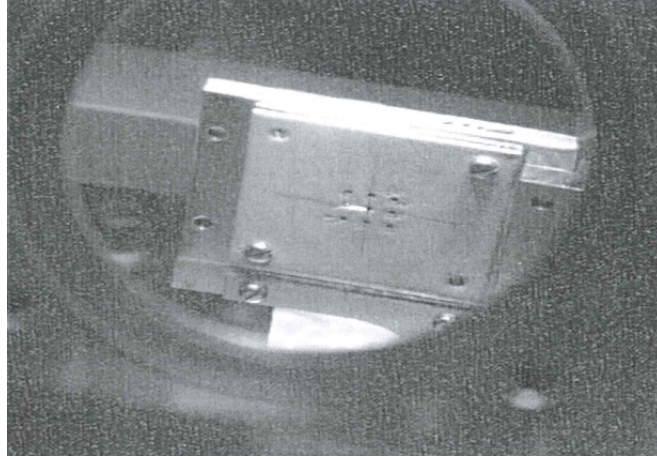


Figure 3.6: Image of the viewer (ZnS) on the target ladder.

3.3 BaGeL detectors

The subsequent γ decay following the excitation of the target was measured with BaGeL, an array of 12 High-Purity Germanium (HPGe) and 5 Cerium-Doped Lanthanum Bromide ($\text{LaBr}_3\text{:Ce}$) scintillation detectors. The BaGeL frame, displayed in Fig. 3.7, is aptly named since it resembles two bagel halves that enclose the scattering chamber during coincidence measurements.

Each HPGe detector is made up of four individual crystals referred to in this work as segments. The detectors take the shape of a clover, hence they are named clover detectors. They are solid state detectors made up of semiconductor material, and their functioning relies on the intermediate band gap between the valence and the conduction band of the material [58]. A semiconductor detector is made up of a p-n junction diode. The positive (p) side and a negative (n) side of a diode are created by adding impurities to a semiconductor material. In between the two sides of the diode, there is a neutral region called the depletion region. It is this depletion region that behaves as a charged-particle or photon detector. A reverse bias voltage is supplied to the p-n junction diode to create a large depletion region and minimise the amount of current in the circuit such that the only significant

measured current is due to the interaction of charged particles and photons [58]. In this experiment, each of the 12 HPGe detectors were fully depleted by a reverse bias voltage of 3000 V. When an energetic nuclear particle enters the depletion region of the detector, it then forms electron-hole pairs. These electrons move through the circuit and lead to a potential drop across a load resistor, and a current pulse is detected. The LaBr₃:Ce detectors are scintillation detectors and their operation was discussed in Sec. 3.2.1.2. A configuration summary of the BaGeL detectors is given in Table 3.1. Six clover detectors were mounted on the left arm of the BaGeL structure and the other six were mounted on the right arm. Three LaBr₃:Ce detectors were mounted on the scattering chamber and the other two were mounted on the right side of the BaGeL frame. θ and ϕ are spherical coordinates from the beam plane.

Table 3.1: The configuration of the BaGeL detectors.

Position	Detector label	Detector model ref.	Dist. from target (cm)	θ	ϕ
Left clovers	L1	Canberra 39	19.5	90°	30°
	L2	Ortec 2	18.5	90°	0°
	L3	Canberra 38	19.5	90°	330°
	L4	Canberra 63	18.5	120°	25°
	L5	Canberra 61	19.5	120°	335°
	L6	Ortec 3	18.5	155°	0°
Right clovers	R1	Canberra 35	17.5	90°	149°
	R2	Ortec 1	17.0	90°	1800°
	R3	Canberra 36	18.0	90°	211°
	R4	Canberra 37	18.0	120°	155°
	R5	Canberra 40	17.5	120°	205°
	R6	Ortec 4	18.5	155°	180°
LaBr ₃ :Ce	LaBr ₃ 1 - #51		20	45°	159°
	LaBr ₃ 2 - #52		20	45°	205°
	LaBr ₃ 3 - #48		13.2	90°	0.°
	LaBr ₃ 4 - #49		20	135°	90.0°
	LaBr ₃ 5 - #50		20	135°	270°

The coupling of the K600 magnetic spectrometer with HPGe clover detectors and LaBr₃:Ce detectors allows for the significant reduction of the background contributions to the spectra, further improves the selectivity to low-spin excitations

and, most importantly, allows for the identification of different decay paths when a gate is applied on the two-dimensional p - γ coincidence matrix.

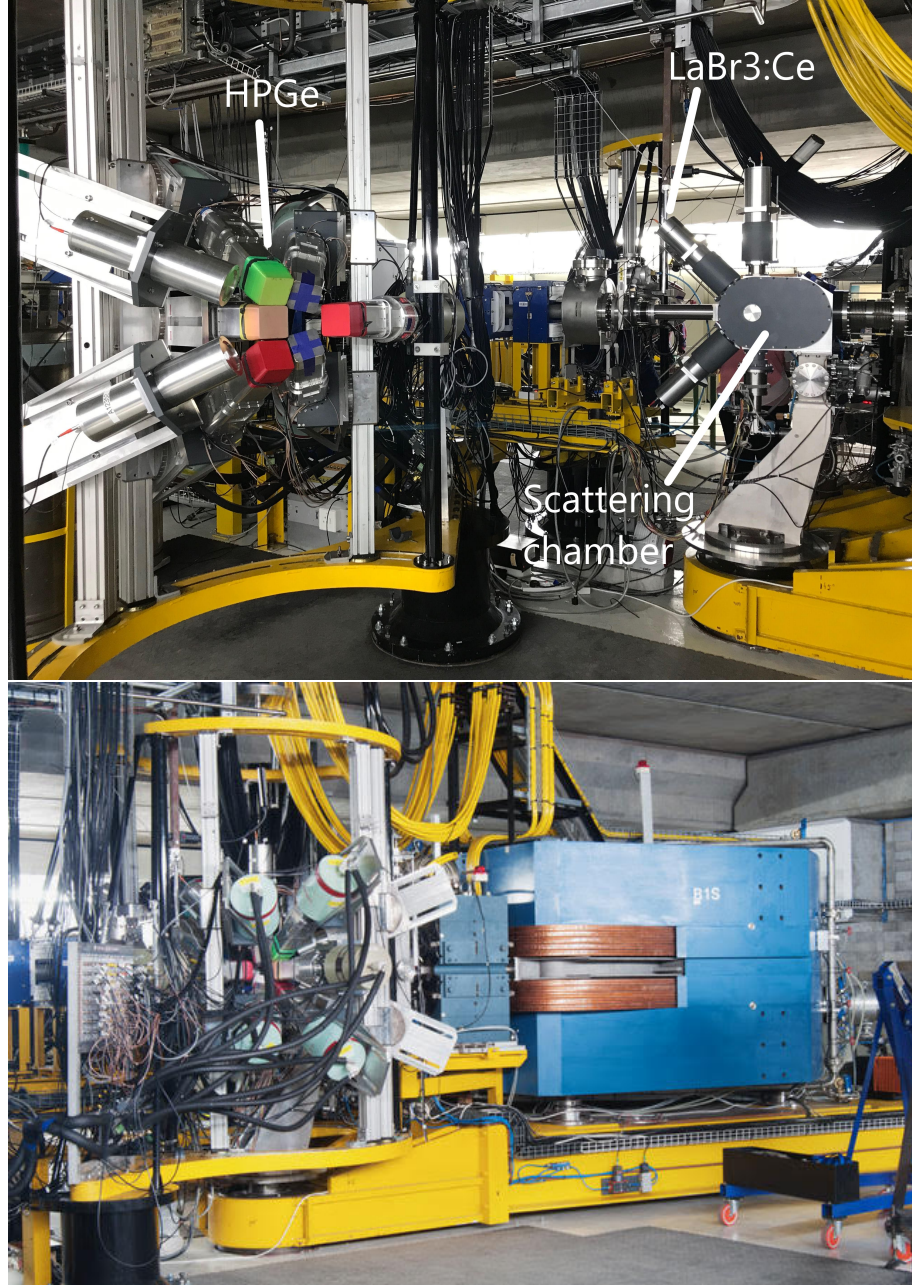


Figure 3.7: The BaGeL frame in the K600 vault showing how the BaGeL structure opens and closes around the scattering chamber and how the γ -ray detectors are arranged on the frame [12].

3.4 Data acquisition system (DAQ)

During detection at the focal plane of the K600 magnetic spectrometer, the trigger signal is produced by a set of electronics that adhere to the Nuclear Instrumentation Module (NIM) standards. The VDC drift time, the time-of-flight (TOF), the measurement of accumulated charge in the scintillator detectors, as well as the accumulated scaler signals are digitised by hardware modules that comply with Versa Modula Europa (VME) standards.

The triggered signals from the wire planes are pre-amplified and discriminated by 16-channel electronic cards located on the VDC Plastic Circuit (PC) board. The signals are transported through 16-channel twisted-pair ribbon cables to the CAEN V1190A Time-to-Digital Converters (TDCs). The TDCs can achieve a resolution of 100 ps. Attached to the scintillator detectors of the K600 are photomultiplier tubes. Signals from these tubes are digitised by a 12-bit current-integrating CAEN V792 charge-to-digital converter. The coincidence of the two scintillator detectors, assumed to have an efficiency of 100% for the detection of energetic charged particles whose mass is one atomic mass unit or greater, forms the trigger signal for the Maximum Integrated Data Acquisition System (MIDAS) [15], which is a data acquisition package that is extensively used in nuclear and particle physics. Once the trigger signal is produced for MIDAS, the relative time that elapses between the cyclotron Radio-Frequency (RF) signal and a coincident scintillator-detector signal, referred to as the particle's TOF is established. It should be noted that the TOF is also the time the proton takes to reach the focal plane from the scattering chamber. This time is important for particle identification purposes as will be discussed in Sec. 4.1.1.

Beam current signals at the beamstop inside the scattering chamber were measured with a Brookhaven Instruments Corporation Model 1000C Current Integrator (CI). The generated output pulse from the CI is discriminated and sent

to the VME scaler module. Together, the known full-scale setting of the CI and the scaler module is used to calculate the integrated current. A pulser and two scaler modules, uninhibited and inhibited, are used to measure the deadtime of the DAQ system. The deadtime per event is approximately $6 \mu\text{s}$. Figure 3.8 shows an overview of the K600 trigger electronics for the VME DAQ system.

The γ rays interacting with the clover detectors generate time and energy signals that are pre-amplified within the clovers. The pre-amplified signals are analysed by three Mesytec Amplifier+CFD (MSCF-16Ch) modules from which the obtained energy and time signals can be fed into the VME DAQ system. The energy output signal from the amplifier is proportional to the amount of energy deposited in the clover detector, while the squared time signal obtained contains the information of the time of the interaction. The amplified energy and time signals are transported by 16-channel ribbon cables to the CAEN Analogue-to-Digital Converter (ADC) and CAEN TDC, respectively. The time and energy signals from the $\text{LaBr}_3\text{:Ce}$ detectors are amplified and discriminated in the LaBr PRO, a custom-made NIM module developed by the INFN-Milan group (Italy), and are then further transported via 16-channel ribbon cables for digitisation at the CAEN ADC and TDC. A schematic representation of the BaGeL electronic system is shown in Fig. 3.9. It is important to note that the data from the $\text{LaBr}_3\text{:Ce}$ detectors were not analysed as part of this work, but their analysis forms part of the future developments and outlook of this study.

The γ -p coincidence measurement is K600-trigger based as explained before. When there is an event at the focal plane that triggers the acquisition system, the γ events in the BaGeL detectors that fall within an appropriately delayed window are recorded and represent the coincidence data. Offline analysis of the data was performed using ROOT, an object-oriented program and library developed by CERN [64].

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Except where indicated,
all logic discriminators have threshold of 100mV

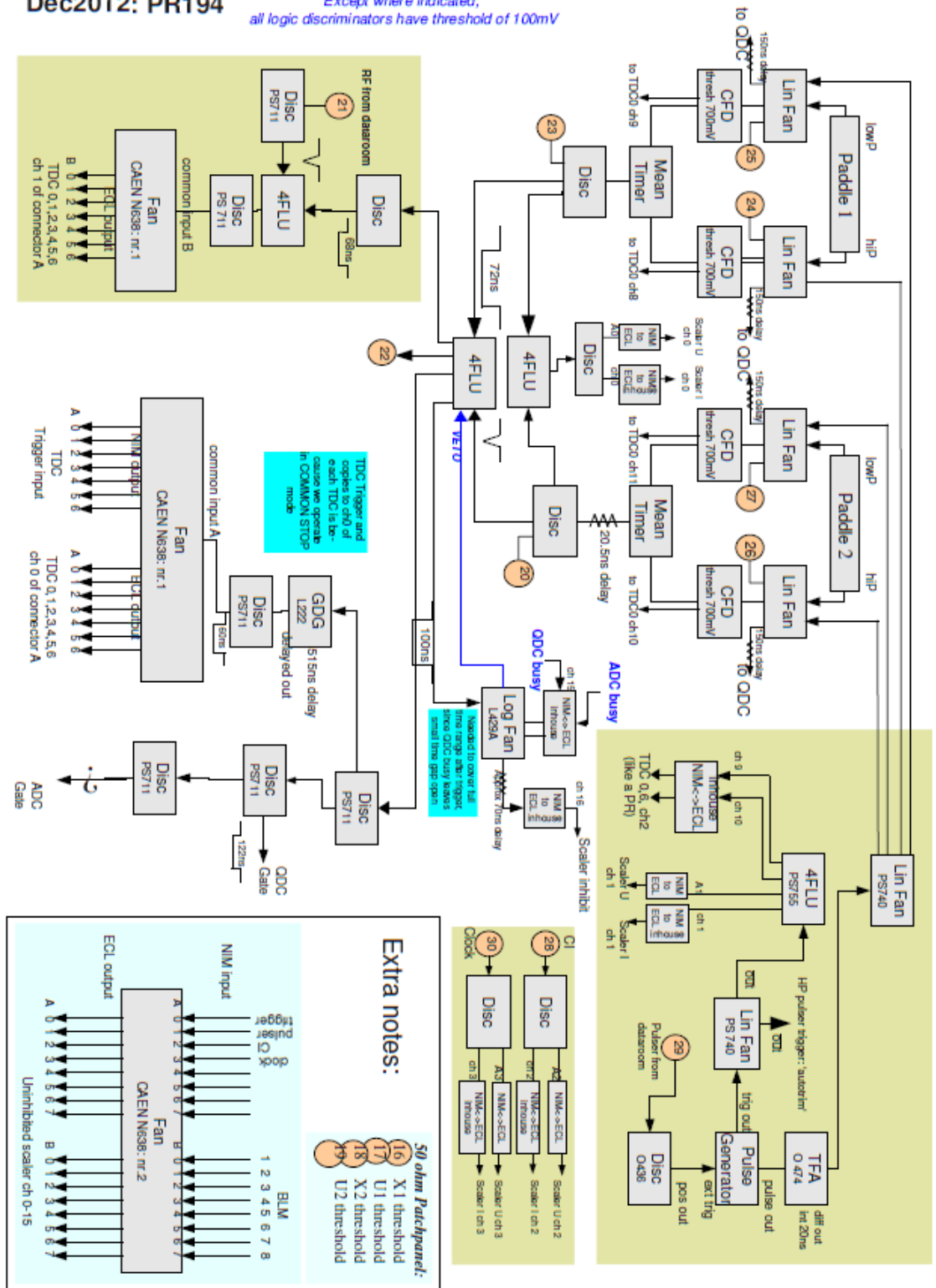


Figure 3.8: A schematic layout of the K600 trigger electronics [65].

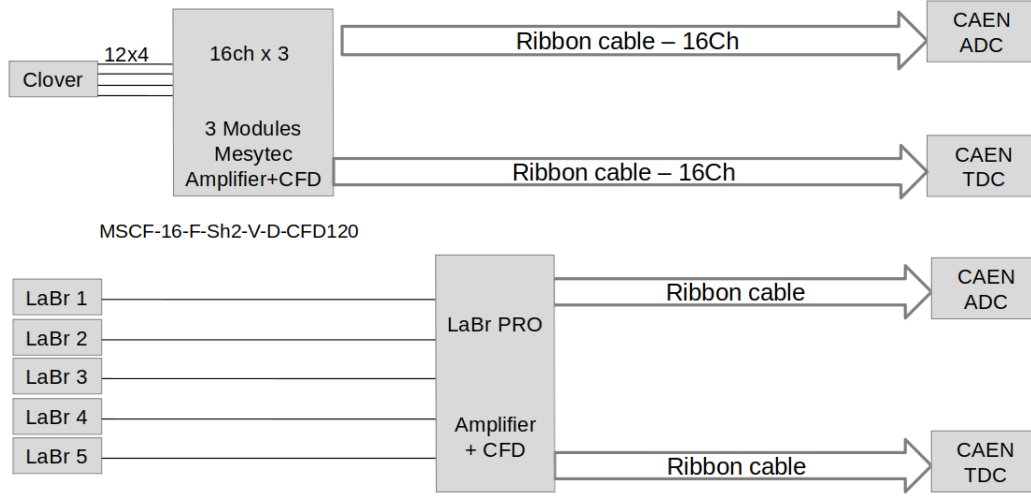


Figure 3.9: A schematic representation of the data acquisition system for the BaGeL detectors [66].

3.5 Estimation of the experiment running time

To estimate the running time of this experiment, the following factors were taken into consideration: Firstly, for an $A = 58$ nucleus, the single scattering yield is $Y(p,p'\gamma) = 124$ events/hour when the beam current is 0.5 nA, the target thickness is 4 mg/cm^2 , the K600 magnetic spectrometer solid angle is 3.5 msr with 0.85 efficiency. Secondly, for 6 HPGe and 6 LaBr₃ detectors at 17 cm from the target, the γ detection efficiency is 1.4 % at 6 MeV with 100% branching ratio to the ground state and the γ -ray coincidence yield is $Y(p,p'\gamma) = 2$ events/hour. In the proposal submitted to the Program Advisory Committee (PAC) of iThemba LABS [12], it was estimated that five days of continuous beamtime will be required. Two days of this time would be dedicated to beam setup, tuning and calibration and the last three days would be used to run the experiment. However the PAC believed that the experiment should be regarded only as a commissioning run and therefore only provided two days of continuous beamtime. About 36.5 hours of that time was used for beam setup, tuning and calibrations. The remaining 11.5 hours was used to take measurements of the data analysed in this thesis.

Chapter 4

Data extraction and analysis

Raw data in the form of event files for each run were obtained using MIDAS. A C++ code developed at iThemba LABS was used to convert the MIDAS data files to ROOT files offline. Before the extraction of useful information from the ROOT data files, e.g., the excitation-energy spectrum or the γ -decay spectrum, specialised scripts developed at iThemba LABS were used offline on ROOT to perform all the necessary data-optimisation procedures as well as for the calibration of the detectors used during the experiment. This chapter is divided into two sections, where the first will cover the data extraction and analysis of the K600 detection system, and the second will cover that of the BaGeL detection system.

4.1 Data extraction and analysis of the K600 detection system

4.1.1 Particle identification

A particle leaves characteristic information behind as it passes through the focal-plane detection system. Different techniques and methods can be used to interpret this information and thus reveal the identity of the particles. The identification

of a charged particle relies on its position in the focal plane, its energy loss in the plastic scintillators, and the time it takes to reach the focal plane from the scattering chamber (the particle's time-of-flight (TOF)). The two methods used for particle identification (PID) in the present study are TOF selection and the ΔE correlation technique, which uses the information related to the energy loss of the particle through the scintillators.

4.1.1.1 Time-of-flight selection

Determining the TOF of a particle is very useful in particle identification because although different types of particles may have similar rigidities, their different momenta will always be related to different TOFs. Software gates were used to isolate the events related to the reaction of interest from beam-halo events. This was done by plotting a histogram of the energy loss of the particles in scintillator 1 as a function of their TOF for an empty frame and for the ^{24}Mg target. By comparing how the energy was lost in the scintillator detector through the ^{24}Mg target and the empty frame, as shown in Fig. 4.1, the inelastically scattered protons of interest could be identified and separated. A software gate as illustrated by the solid black line in Fig. 4.1 (referred to as CUTscint1vsTOF in the figure captions) was applied. To further reduce the background contributions, an additional gate was created from a plot of the energy loss in scintillator 2 versus TOF (Fig. 4.2) referred to as CUTscint2vsTOF in the caption. It should be noted that another gate, CUTTOFvsX1, was created from TOF versus focal-plane position, but at this stage, the background was already significantly reduced by the first two gates and the effects of this new gate were almost redundant.

4.1.1.2 ΔE correlation technique

A fourth gate was created from the energy change correlations of the protons as they move through the two scintillator detectors. This PID selection is based on

the fact that the type of particle and its associated kinetic energy will determines how it loses energy as it interacts with the detector material. Therefore, the way in which the energy of the protons changes as they travel through the two scintillator detectors ($\Delta E - \Delta E$) is used to identify the inelastically scattered protons. Figure 4.3 shows how this PID gate was created from a two-dimensional plot of the energy changes in the two scintillators. It should be noted that the CUTscint1vsTOF, CUTscint2vsTOF and CUTTOFvsX1 software gates were collectively applied on the bottom spectrum of Fig. 4.3.

The effects of these software gates can be observed in Fig. 4.4. The black position spectrum is plotted without any PID software gates and it, therefore, sits on top of a lot of background events. The PID software gates were applied on the blue spectrum where the majority of the beam-halo-related background has been removed. As can be seen in the top panel of Fig. 4.1, there are still some instrumental-background related events as well as some low-energy protons (caused by scattering off the target foil followed by rescattering off any exposed part inside the spectrometer) that fall in our region of interest. Further background subtraction is, therefore, required to remove these remaining background events. This will be discussed in Sec. 4.1.4.

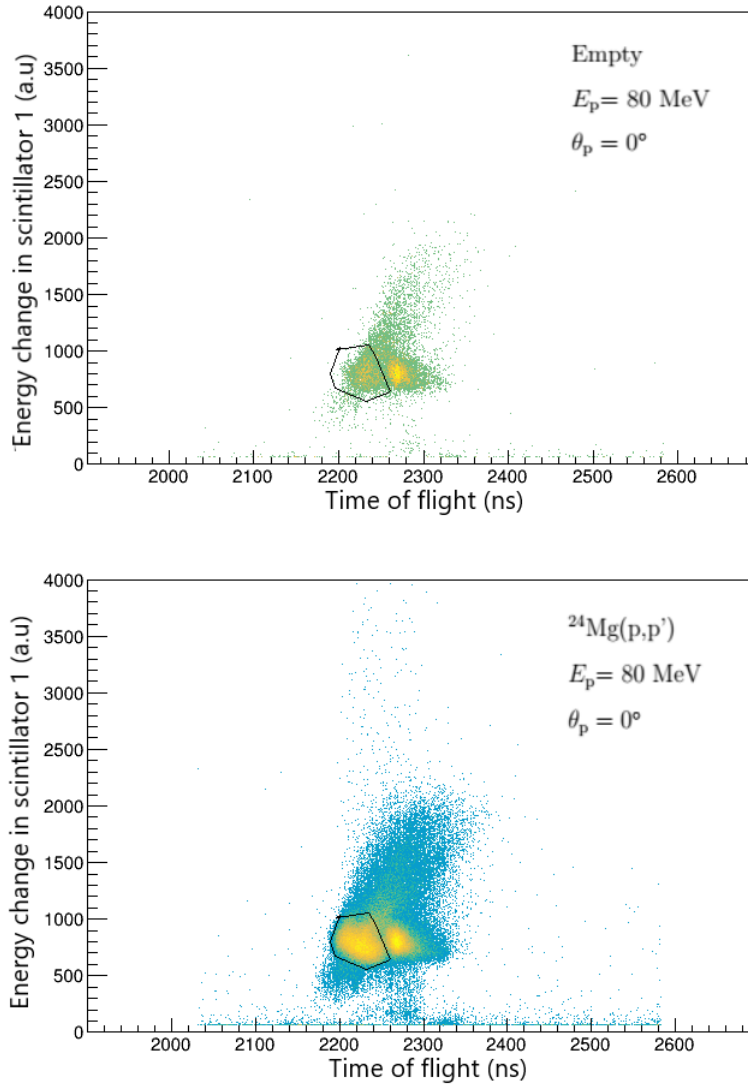


Figure 4.1: A two-dimensional plot of the change in energy of the particles in scintillator 1 as a function of their time-of-flight for an empty target (top) and ^{24}Mg (bottom). The CUTscint1vsTOF software gate selecting the events of interest is shown with a solid black line.

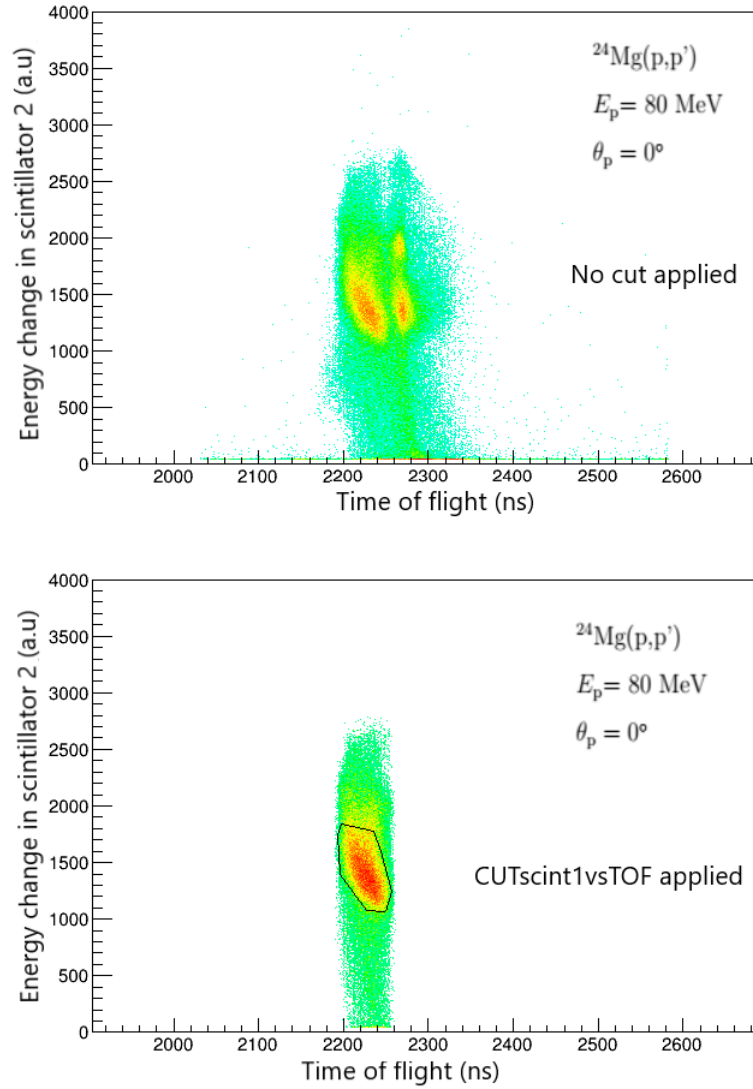


Figure 4.2: A two-dimensional plot of the change in energy of the particles in scintillator 2 as a function of their time-of-flight before the CUTscint1vsTOF software gate was applied (top) and after it was applied (bottom). The creation of another software gate (CUTscint2vsTOF) selecting the events of interest is shown with a solid black line.

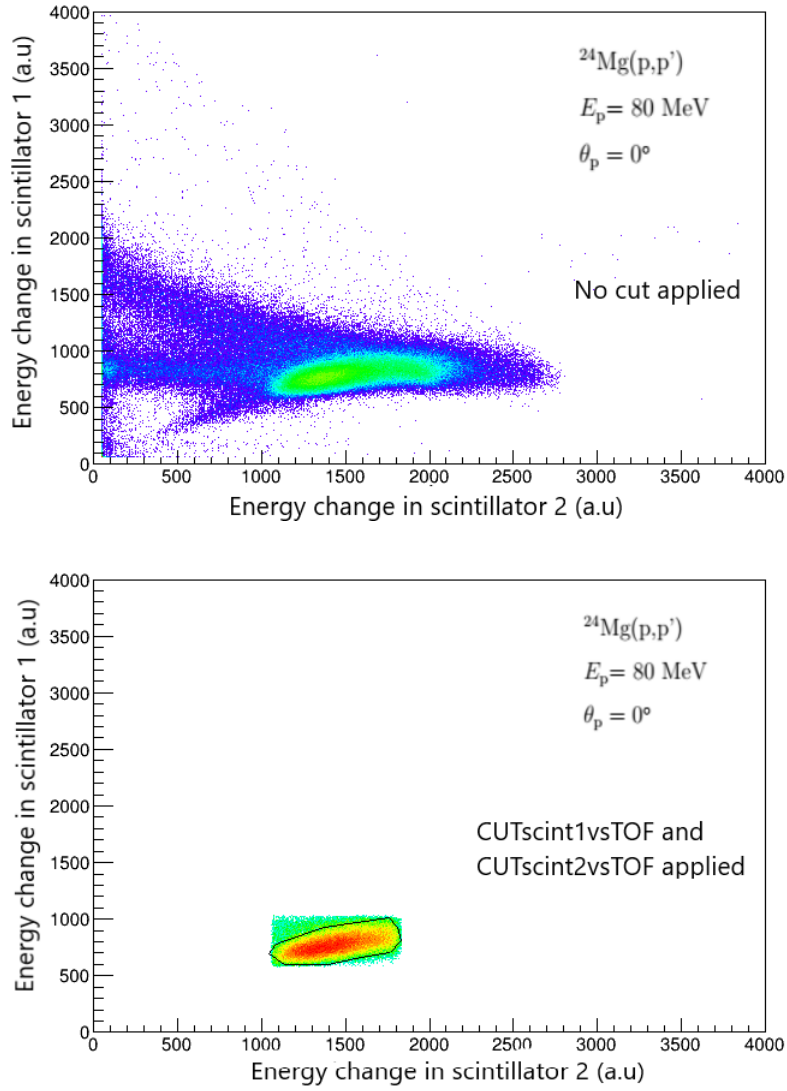


Figure 4.3: A two-dimensional plot of the change in energy of the particles in scintillator 1 vs their change in energy in scintillator 2 before the TOF-related software gates were applied (top) and after they were applied (bottom). An additional software gate further isolating the protons of interest was created and is shown with a solid black line.

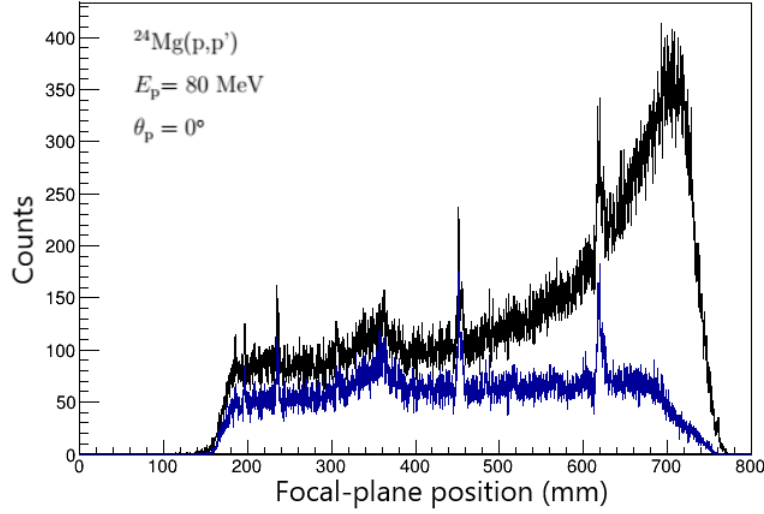


Figure 4.4: Comparison of the position spectra before (black) and after (blue) the particle identification gates are applied. The peaks represents the excited states of ^{24}Mg .

4.1.2 Data extraction from the focal-plane detectors

The K600 analyser uses a ray-tracing algorithm to convert drift distances to focal-plane position coordinates. Before this can be done, however, the measured drift times in the VDC's drift cells must be converted to drift distances using a Look-Up Table (LUT). It is important to note that there is only one LUT per wireplane, which means that one must ensure that the drift times for all the wires in each wireplane fall in a similar time range. One of the factors that cause variations in the measured drift times is the difference in the ribbon-cable lengths that connect the preamplifier output to the TDC. Cable-length offsets are, therefore, applied to correct for these variations first and hence ensure accurate drift-time values. Once this is done, the LUTs can be created and implemented. This section describes how the cable-length offsets were determined and implemented and, thereafter, how the LUTs were created.

4.1.2.1 Cable-length offsets

Cable-length offsets were calculated using a script developed by a K600 collaborator together with a statistically significant white-tune dataset, which is produced by illuminating the whole focal plane uniformly. Since the experiment was part of a larger experimental campaign, the information extracted from a previously analysed white spectrum was used because all of the targets used in the current experiment have strong structures. This process helps with identifying misaligned and/or dead TDC channels. It is important to ensure only events of the particle of interest are selected in order to create a good offset table. This selection was done by implementing the gates created around the protons of interest in the previous section. After the offsets were generated, the runs were re-analysed to verify that the TDC channel vs time histograms were aligned. The results of applying the cable-length offsets are depicted in Fig. 4.5.

4.1.2.2 Look-up-table creation and look-up-table offsets

Once the drift-time characteristics of the VDC are established and corrected, the LUT is created. In this procedure, a specialised script is used to convert the VDC drift times to drift distances for each wire plane. This conversion is obtained from the following equation:

$$y(t) = \left(\frac{dN}{dy} \right)^{-1} \int_{t_0}^t \left(\frac{dN}{dt'} \right) dt' \quad (4.1)$$

where $y(t)$ is the drift distance, $\frac{dN}{dt'}$ is the drift-time distribution and $\frac{dN}{dy}$ is a measure of the spatial distributions of events in the drift cell. The limits of integration t_0 and t are the times of the arrival of the particle in the drift cell and the time at which the pulse appears at the anode, respectively [69]. Since factors such as voltage, gas mixture, the energy and charge state of the ionisation-inducing particles, and the physical condition of the chamber may differ for every

experiment, LUTs should be created for each experiment (and each wire plane).

It may happen that the LUTs also need to be corrected to ensure accurate mapping of the drift times to drift distances. The need for LUT offsets can be assessed using the two-dimensional resolution (Res2D) spectrum shown in Fig. 4.6. If the central regions of these spectra are misaligned, a LUT offset is required. As can be observed in Fig. 4.6 (top), although very subtle, the Res2D spectra only indicate the need for a small offset for the X1 LUT. It should be noted that U1 and X1 refer to the U and X wire planes of the VDC used in this experiment, respectively.

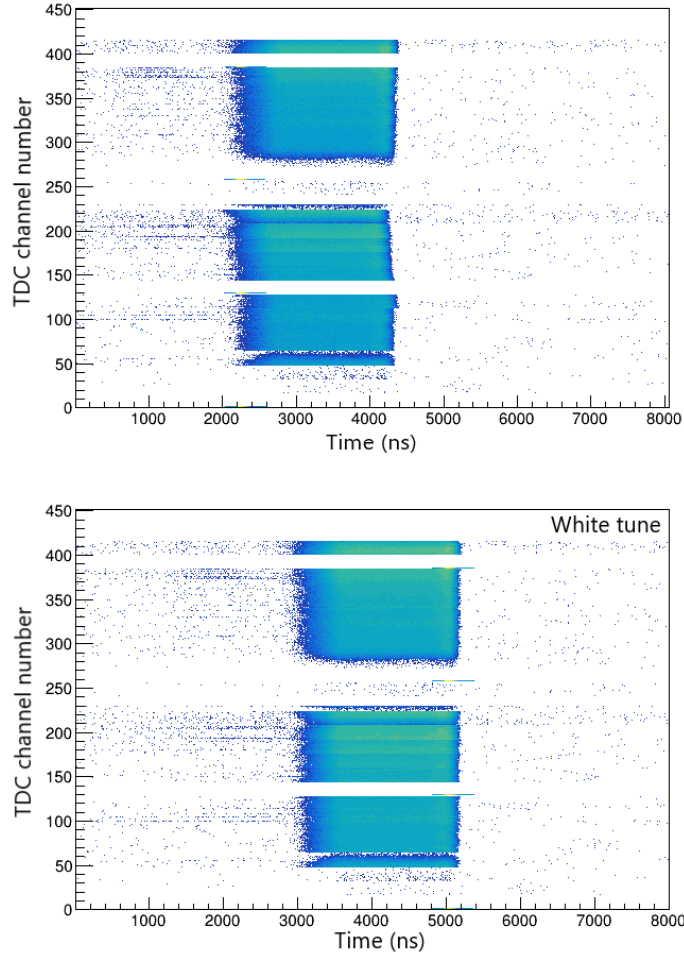


Figure 4.5: TDC channel vs time histograms showing how the TDC channels fail to align before (top) the application of cable-length offsets and how the TDC channels align after (bottom) the offsets were implemented.

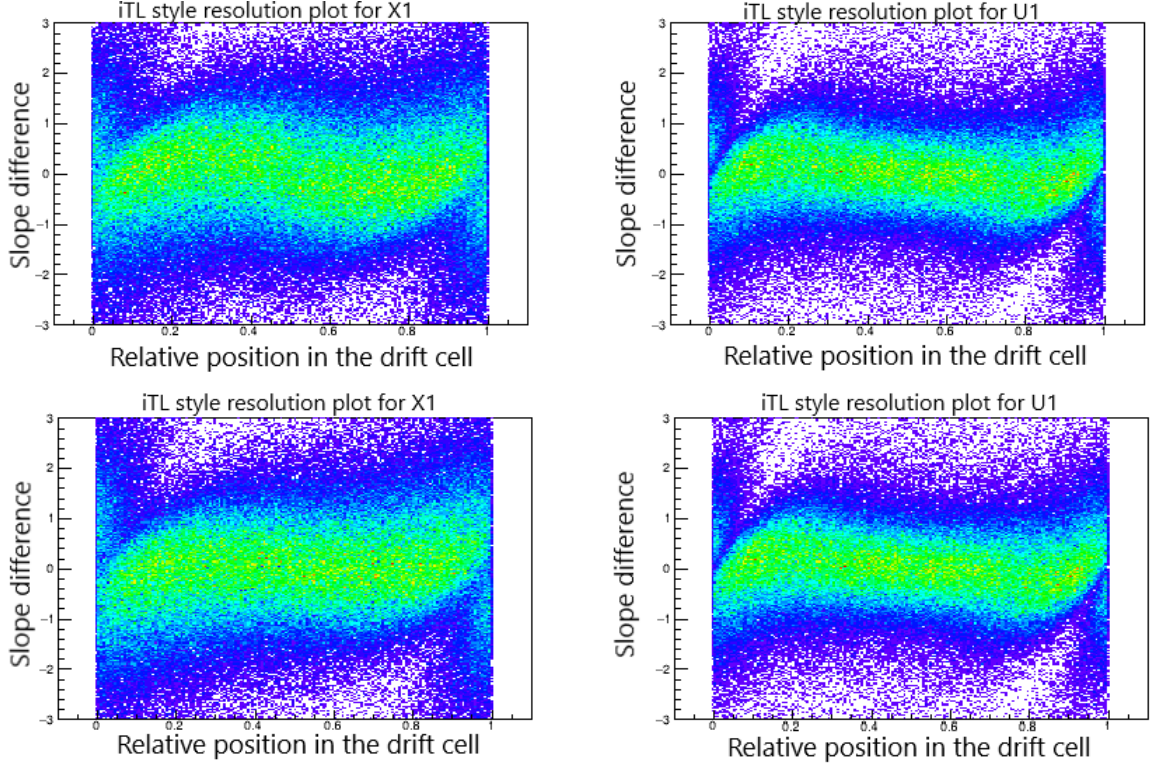


Figure 4.6: A comparison of the two-dimensional resolution spectra of the X1 (left) and U1 (right) wireplanes before (top) and after (bottom) the LUT offsets were implemented. The y-axis represents the difference of the slopes of the drift distances in the first and last wires of the plane.

4.1.2.3 Lineshape corrections

Lineshape correction is an offline procedure to remove the effect of the aberration induced by the spectrometer fields. The momentum distribution of the particles that reach the focal plane can vary, some bending more than others, resulting in different TOFs. This means that certain correction parameters should be determined to account for the TOF dependence of the focal-plane position. The need for these correction parameters is indicated by poorly-resolved slanted states such as the one shown in Fig. 4.7 (top). A well-resolved state gives rise to a straight thinner line. To obtain the lineshape correction parameters, g_i , a polynomial of third order (Fig. 4.7 (middle)) was fitted to regular interval points along the

prominent state in Fig 4.7 (top) as:

$$X_{\text{corr}} = g_0 + g_1(TOF - TOF_{\text{offset}}) + g_2(TOF - TOF_{\text{offset}})^2 + g_3(TOF - TOF_{\text{offset}})^3. \quad (4.2)$$

Using the parameters obtained from the fit, the X1 position was corrected to be

$$X_{Ci} = X_{\text{fp}} - X_{\text{corr}} \quad (4.3)$$

where X_{fp} is the original X1 focal-plane position. The effect of this lineshape correction is shown in Fig. 4.7 (bottom). As can be seen, the state is now much straighter. There is a slight over correction between 2242 and 2248 on the TOF axis, but this has only a minor effect on the overall energy resolution of the state.

While there will be kinematic differences between the $^{24}\text{Mg}(\text{p},\text{p}')$ and $^{58}\text{Ni}(\text{p},\text{p}')$ reactions, the effect of these differences with regard to the lineshape correction is small for scattering angles at and close to zero degrees. To confirm this, relativistic reaction calculations were performed using JRelkin [71] to determine the energy of the particles detected in the focal plane for the $^{24}\text{Mg}(\text{p},\text{p}')$ and $^{58}\text{Ni}(\text{p},\text{p}')$ reactions for the 0 - 2° angular acceptance with $E_p = 80$ MeV. As an example, at 0°, the values obtained for the ^{24}Mg and ^{58}Ni reactions at an excitation energy of 6 MeV were 73.989 MeV and 73.960 MeV, respectively. At 2° deg, these values were 73.985 MeV and 73.958 MeV, respectively. Therefore, the kinetic energy differences over the angular acceptance of the K600 are 4 keV and 2 keV for the $^{24}\text{Mg}(\text{p},\text{p}')$ and $^{58}\text{Ni}(\text{p},\text{p}')$ reactions, respectively. The correction parameters for ^{24}Mg were, therefore, also used for the ^{58}Ni runs.

The effects of the lineshape correction can be seen again in the comparison of the spectra in Fig. 4.8. The bottom spectrum is lineshape corrected and evidently has better resolved peaks. The peak centroids and the standard deviation, σ_{pos} ,

values of the two most prominent peaks of the ^{24}Mg spectrum before and after the lineshape correction is implemented are summarised in Table 4.1. The improved resolution can be seen by comparing the values of sigma for each peak before and after the correction.

Table 4.1: A summary of the ^{24}Mg peak positions and sigma values before and after the lineshape correction was implemented.

	X1-position peak centroid (mm)	σ_{pos} (mm)
Before	452.43	2.45
	619.81	2.59
After	452.19	0.81
	618.42	0.93

4.1.2.4 Data offsets and chaining

Drifts in the SSC fields (due to factors such as day/night temperature changes) and Radio Frequency (RF) changes (due to optimisation of the beam by operators) may affect the TOF and focal-plane positions of the inelastically scattered protons by the time they reach the focal plane. This means that the TOF and focal-plane position have to be adjusted to ensure that all the experimental runs of the same isotope can be chained together, and the results of the particle identification procedure performed on one run can be implemented on all the other runs.

The difference between the centroids of the TOF spectra of each of the ^{24}Mg , ^{12}C and ^{58}Ni runs relative to a reference run was determined, and a table of offsets was produced and implemented. The well-defined peaks of the position spectrum of the ^{24}Mg calibration runs were used to determine shifts in the focal-plane position spectra over time. The position of the same prominent peak in each ^{24}Mg run was determined, and the difference relative to the position of the corresponding peak in the reference ^{24}Mg run was established. The ^{24}Mg position offsets were assigned to ^{58}Ni and ^{12}C runs based on their proximity in time to each ^{24}Mg run. In addition to TOF and X1-position offsets, Y1-position offsets had to be

determined to correct for beam fluctuations present in the vertical plane. The Y1-position spectrum for each of the runs was used to calculate the offsets relative to the reference calibration run.

Once the data offsets were applied, the data runs were chained together so as to increase the statistics for further analysis procedures. To check whether the offsets were applied correctly, peak centroids as well as the sigma values of the chained runs (for TOF, Y1 and X1-position) were obtained and compared to those of single runs. Table 4.2 shows such values for the X1-position spectrum. From the table, it can be seen that the position of the peak centroids of the single 4041 and 4044 runs before the offsets were applied differ noticeably from that of the 4034 run. However, this difference was reduced after the offsets were applied, and the value for the chained runs agreed well with that of the reference run. Furthermore, the sigma values for the chained runs after the implementation of the offsets improved compared to that before the offsets were applied. In Fig. 4.9, the focal-plane position spectrum of the chained runs before the offsets were implemented is compared to that after the offsets were implemented. The well-resolved peaks in the bottom spectrum indicate that the offsets were implemented successfully.

Table 4.2: A summary of the ^{24}Mg peak positions and sigma values before and after the X1 position offsets were implemented.

	Run no:	X1-position peak centroid (mm)	σ_{pos} (mm)
Before	4034	452.21	0.78
	4041	453.40	0.76
	4044	453.50	0.88
	chained runs	452.85	1.09
After	4034	452.21	0.78
	4041	452.22	0.74
	4044	452.21	0.87
	chained runs	452.20	0.83

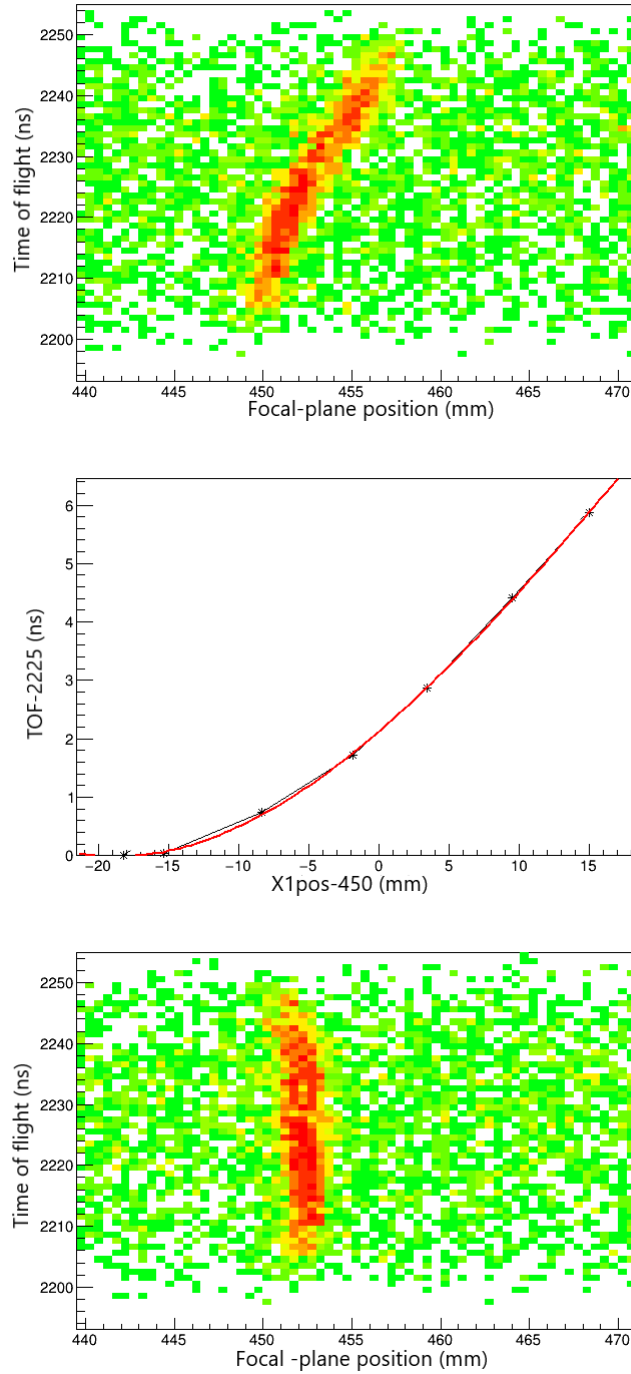


Figure 4.7: A prominent excited state in the TOF vs focal-plane position scatter plot for ^{24}Mg with no lineshape correction applied (top), a third-order polynomial fit on selected points along the lineshape shown in the panel above (middle) and a straighter line with improved resolution after the correction has been implemented (bottom).

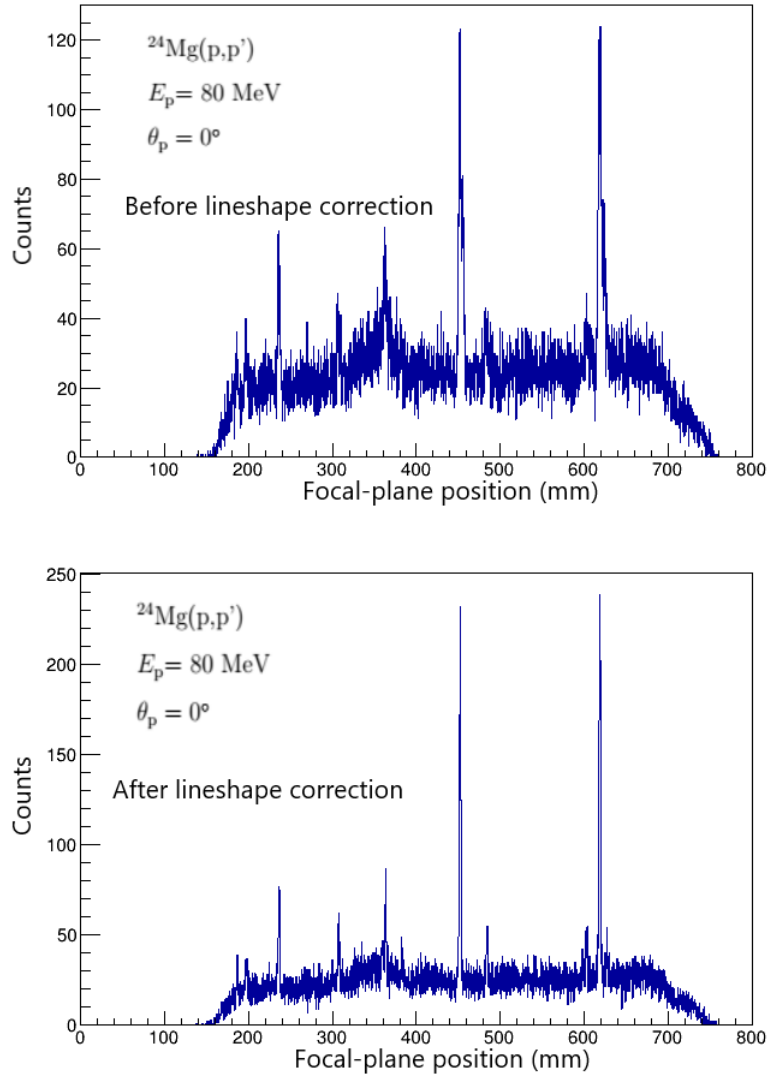


Figure 4.8: Comparison of the focal-plane position spectrum without (top) and with (bottom) lineshape correction.

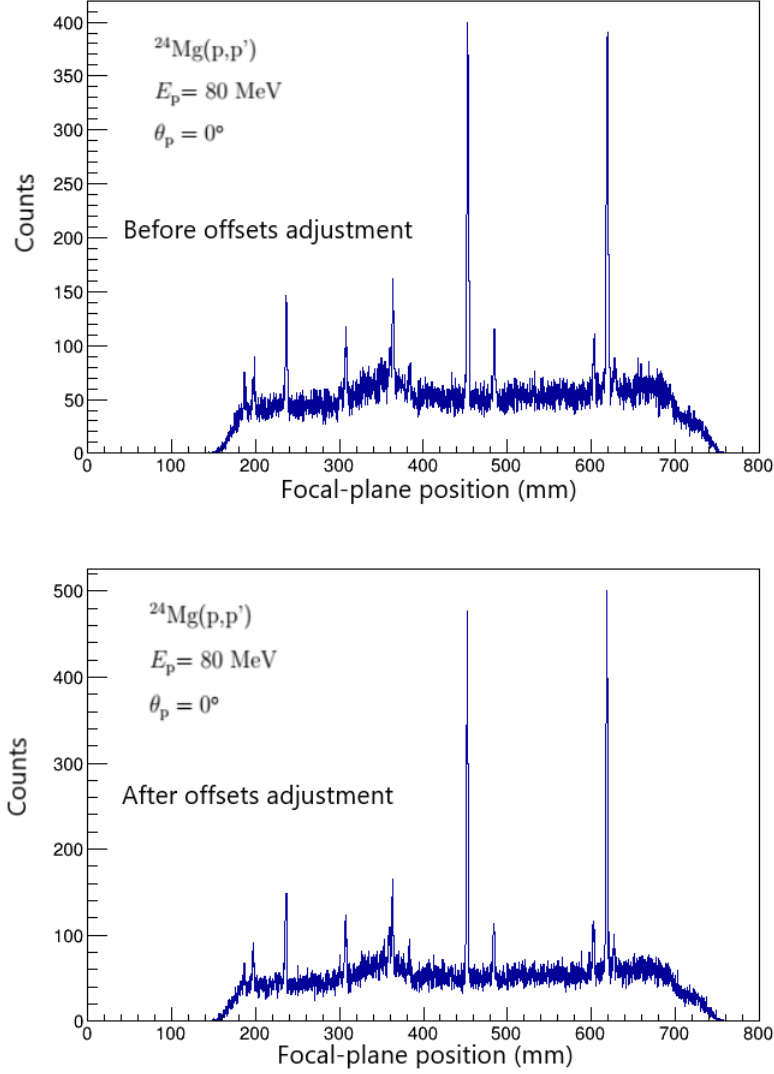


Figure 4.9: Comparison of the focal-plane position spectrum of the chained runs before (top) and after (bottom) position offsets were implemented.

4.1.3 Energy calibration of the focal-plane detectors

Energy calibration of the focal-plane detectors is crucial for converting positions (in mm) on the focal plane to excitation energies (MeV). This process is made up of two subroutines: the first being position-to-momentum calibration through magnetic rigidity and the second being a momentum-to-energy calibration.

4.1.3.1 Position-to-momentum calibration

The ^{12}C position spectrum (shown in Fig. 4.10 (top)) has two well-defined peaks which correspond to the well-known 7.654 MeV and 4.439 MeV states. These values were used to establish a rough relationship between the excitation energy and the focal-plane position of the K600 magnetic spectrometer. This means that a rough MeV per mm value for the focal-plane was obtained so that the focal-plane position peaks in ^{24}Mg (shown in Fig. 4.10 (bottom)) could be matched to excitation energies from the National Nuclear Data Center (NNDC) [70] with improved accuracy for energy calibration purposes. This position-to-energy relationship was established using the following equation:

$$\frac{FPV - SPV}{FPC - SPC}(\text{MeV/mm}) \quad (4.4)$$

where FPV and SPV are the first and second peak values for the excitation energies and FPC and SPC are the first and second peak's centroids (right to left) in the ^{12}C spectrum. Several X1-position peak centroids and their assigned energies from the NNDC for the calibration targets are presented in Table 4.3.

Table 4.3: The focal-plane position peak centroids and their assigned energies from the NNDC [70] for the calibration targets, ^{12}C and ^{24}Mg .

Calibration target	X1-position peak centroid (mm)	Assigned NNDC E_x (MeV)
^{12}C	359.36	7.6540
	603.03	4.4390
^{24}Mg	196.75	9.8281
	236.04	9.3011
	306.96	8.3579
	452.17	6.4323
	483.70	6.0108
	618.45	4.2382

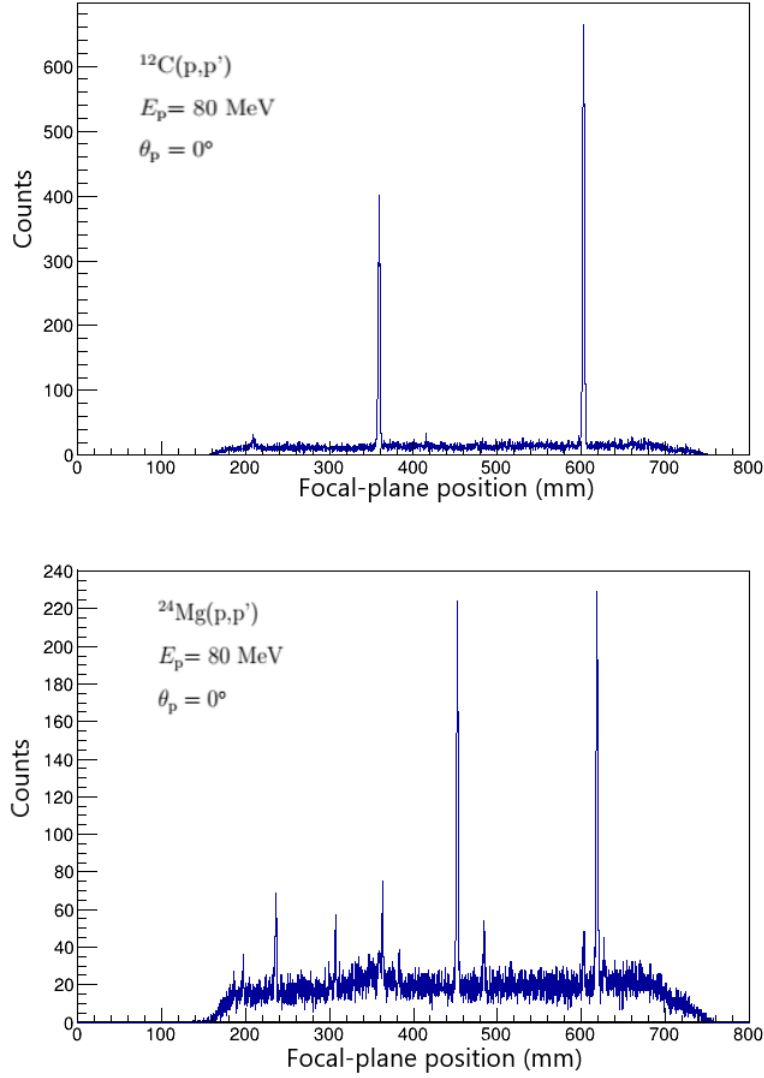


Figure 4.10: Focal-plane position spectra for ^{12}C (top) and ^{24}Mg (bottom).

The calibration subroutine described here involves obtaining the momentum of the protons from their position on the focal plane through magnetic rigidity. The magnetic rigidity, R of a particle with charge Q and momentum p moving through a magnetic field B , with a radius of curvature r is given by

$$R = Br = \frac{p}{Q} \quad (4.5)$$

$$p = QBr \quad (4.6)$$

and the momentum and rigidity are related as follows:

$$p \left[\frac{\text{MeV}}{c} \right] = \frac{c}{1 \times 10^9} QB\rho [\text{e.kG.cm}]. \quad (4.7)$$

JRelkin [71] was used to calculate the $QB\rho$ of the inelastically scattered protons for selected states. Inputs such as the scattering angle, the thickness of the target and the approximate excitation energy corresponding to the focal-plane position of each excited state in the ^{24}Mg spectrum were required in the programme. The obtained $QB\rho$ values were plotted against the K600 focal-plane position values, x_{fp} , as shown in Fig. 4.11. A second-degree polynomial of the form:

$$P = c_1 x_{\text{fp}}^2 + c_2 x_{\text{fp}} + c_3. \quad (4.8)$$

was fitted through the data points and the obtained calibration parameters, c_n , were included in the configuration file used in the analyser to calculate the K600 momentum.

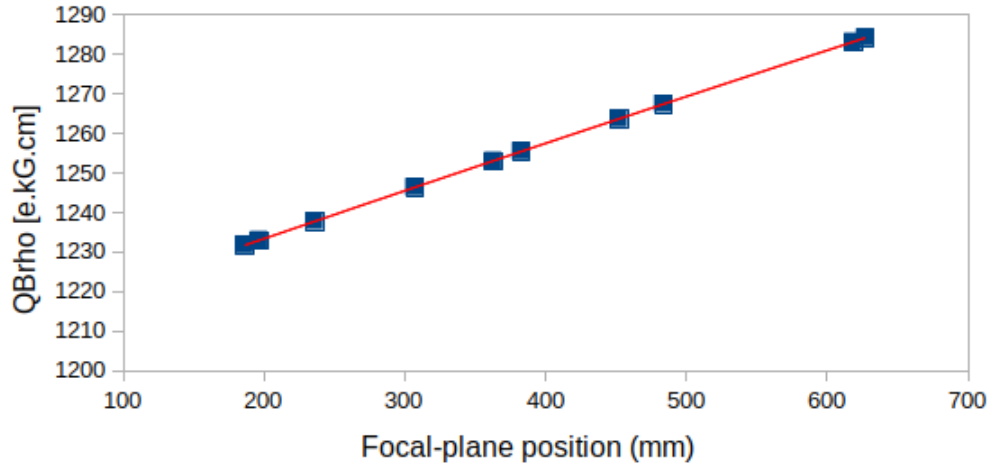


Figure 4.11: A plot of $QB\rho$ values against the K600 focal-plane position values of ^{24}Mg and the second-degree polynomial fitted to the data is shown in red.

4.1.3.2 Momentum-to-energy calibration

The kinematics involved in the calibration of the K600 magnetic spectrometer can be described using a schematic representation as shown in Fig. 4.12. The figure shows a collision between a projectile (1) and a stationary target nucleus (2) in the laboratory reference frame. After the collision, the recoil nucleus (4) moves in the direction specified by the laboratory angle ϕ , while the ejectile (3) moves in the direction given by θ in the laboratory frame.

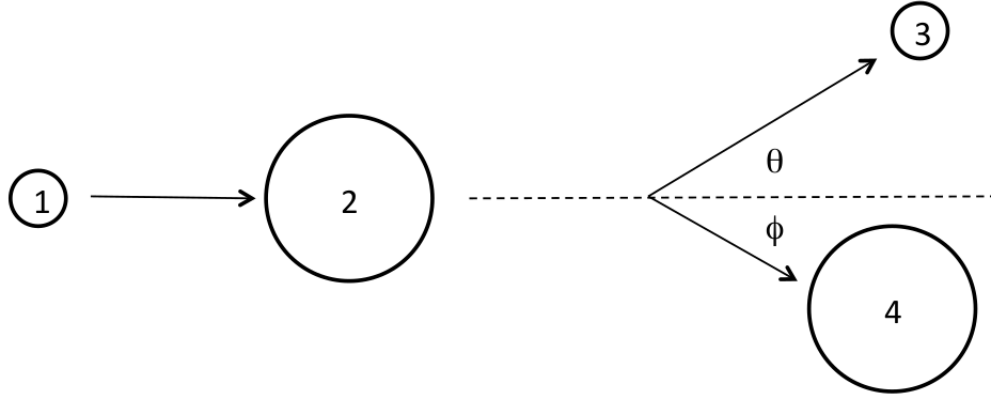


Figure 4.12: A representation of the reaction $1 + 2 \rightarrow 3 + 4$ in the laboratory reference frame.

Using the following equation that describes the kinematics involved in the reaction, the excitation energy of the target nucleus can be obtained:

$$E_x = E_1 + m_2c^2 + \sqrt{p_3^2c^2 + m_3^2c^4} + (p_1^2 + p_3^2 + 2p_1p_3 \cos \theta + m_4^2)^{\frac{1}{2}} \quad (4.9)$$

where E_x is the excitation energy of the target nucleus, m_i and p_i are the mass and momentum of the particles, respectively. The above equation was also implemented in the analyser so that finally an excitation-energy spectrum for the calibration target ^{24}Mg and, subsequently, the excitation-energy spectrum for ^{58}Ni could be obtained. A comparison of the excitation-energy values as calculated by the K600 analyser and the NNDC values for ^{24}Ni is given in Table 4.4.

Table 4.4: A comparison of the excitation-energy values obtained for the focal-plane spectra from the K600 magnetic spectrometer and those from the NNDC [70] for ^{24}Mg .

NNDC J^π	NNDC E_x (MeV)	K600 E_x (MeV)	Difference (keV)
1^+	9.8281	9.8279	-0.13
$2^+, 4^+$	9.3011	9.3043	3.23
3^-	8.3579	8.3592	1.29
0^+	6.4323	6.4324	0.12
4^+	6.0108	6.0149	4.06
2^+	4.2382	4.2404	2.24

The excitation-energy spectra in Fig. 4.13, especially the one in the bottom panel, sits on a continuous background as was discussed in Sec. 4.1.1.2. To determine the energy resolutions of the spectrometer for this experiment, this background contribution must be removed through the approach discussed in Sec. 4.1.4.

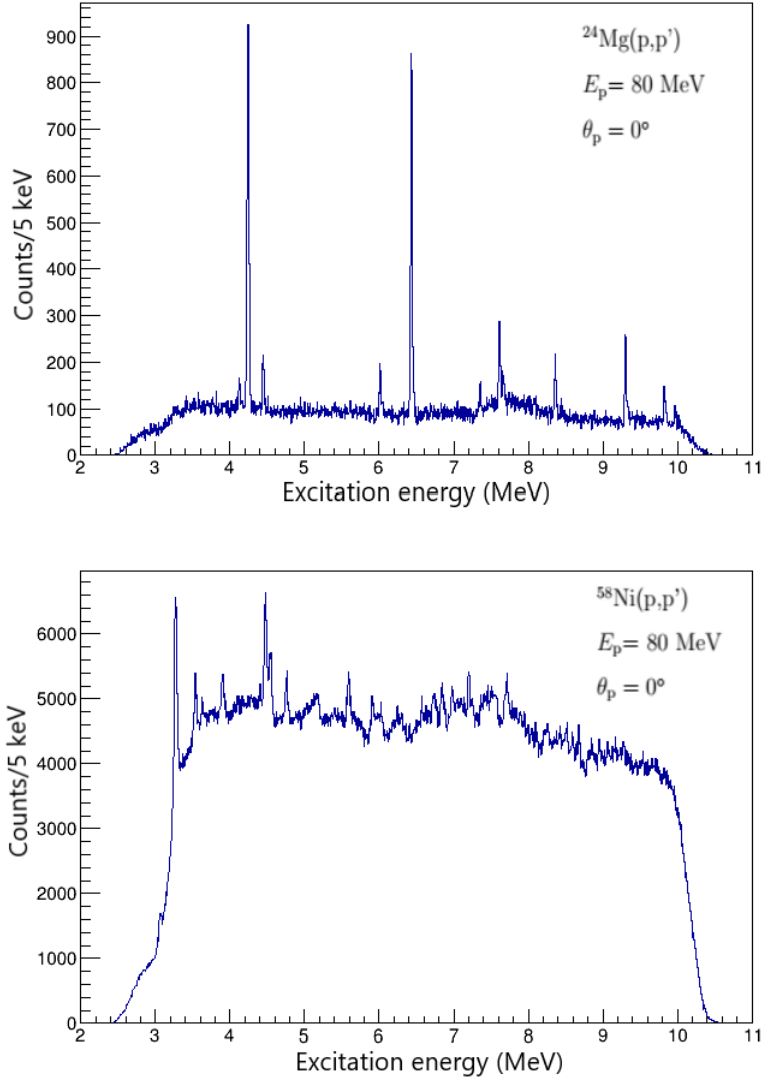


Figure 4.13: The acquired excitation-energy spectrum for the ^{24}Mg target (top) and the ^{58}Ni target (bottom).

4.1.4 Background subtraction

Although the PID techniques described in Sec. 4.1.1 are able to eliminate the majority of the background that is due to beam halo, the more problematic target-related background that appears to be similar to the events of interest cannot be eliminated through PID. To get rid of this type of background, a background

subtraction procedure that is based on the vertical position, $Y1$, of the scattered protons at the focal plane is performed. However, in this experiment there is the advantage of the coincidence measurements. This means that the background can be eliminated by gating the excitation-energy spectrum around the γ -ray detectors, ensuring that only the protons that were detected in coincidence with the γ events are selected.

Nonetheless, the background subtraction procedure was still performed for the K600 data so that the resolution of the spectrometer could be obtained. For this type of background subtraction to be achieved, the spectrometer is operated in vertical focus mode. In this mode, the events of interest are centred around $Y1 = 0$. As a result, beam-halo and target-related background gets distributed evenly across the vertical plane. Looking at the bottom panel of Fig. 4.14, the region outlined in black contains the events of interest and the rest of the spectrum shows how the background events are distributed in the focal plane. These outlines were drawn based on the distribution observed in the projection of the $Y1$ focal-plane position spectrum (in the top panel). Assuming that the very same amount of background is found on the region of interest, a C++ script was used to subtract the background events outlined with pink from the events in the black region. As can be seen from the figure again, the subtracted region was divided into two sections which have a slightly different background distribution. These two sections were added together to ensure that just the right amount of background was subtracted without inducing structure into the region of interest. Figure 4.15 illustrates the results of this procedure. The top panel illustrates the total background spectrum (pink) which was acquired from the addition of the two separate (green and red) background contributions. Finally, the background subtracted excitation-energy spectrum (black) is shown in the bottom panel.

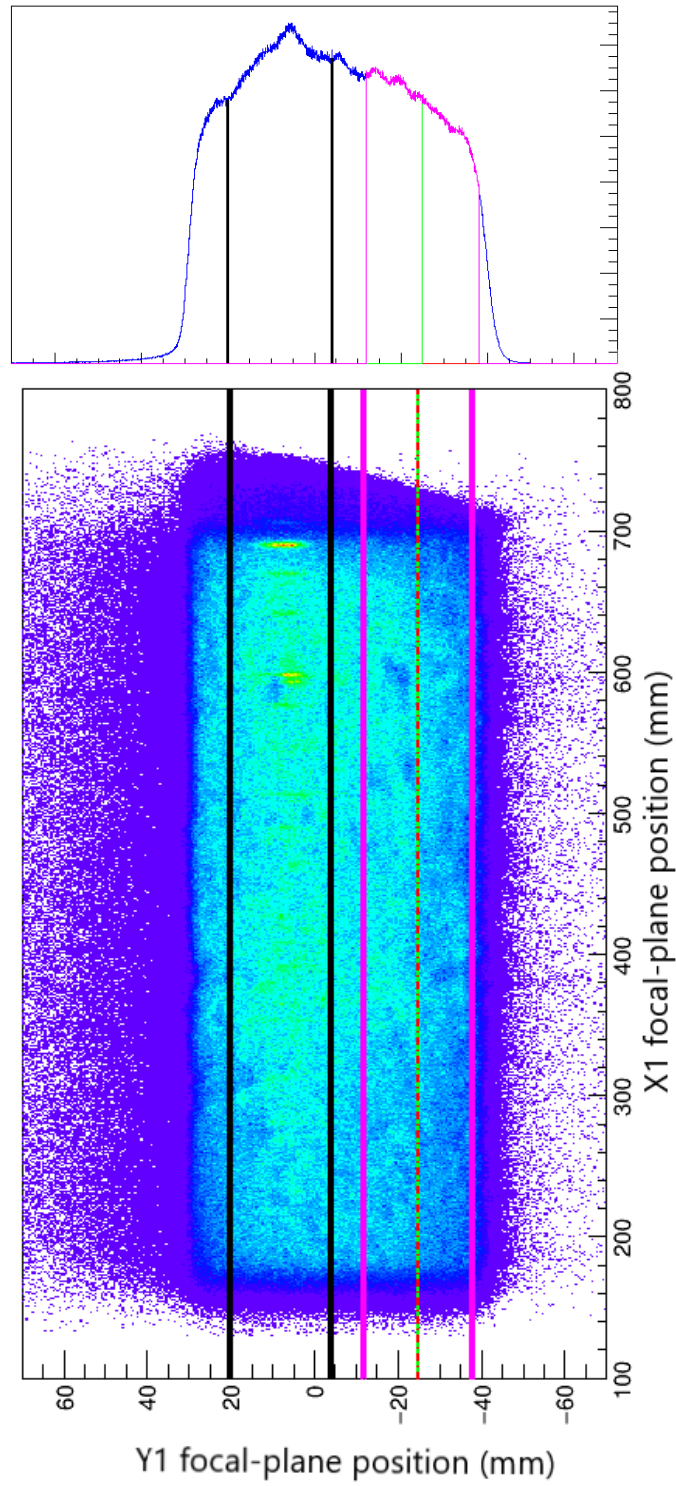


Figure 4.14: Top: Y1 focal-plane projection. Bottom: A two dimensional plot of the Y1 vs X1 focal-plane position. In both spectra, the black region outlines the events of interest while the region in pink shows the background that was subtracted to produce a background-free excitation-energy spectrum.

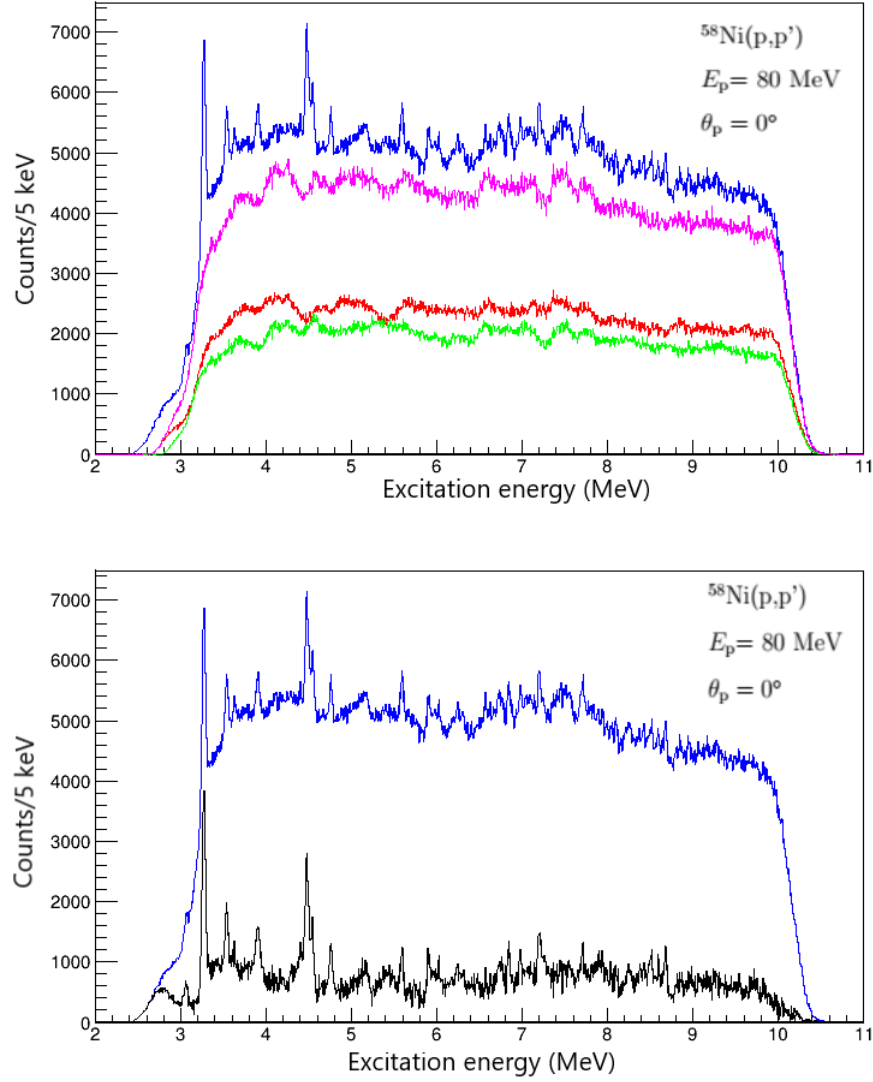


Figure 4.15: The top panel shows the two background contributions in red and green. The raw data are displayed in blue and the total background which is subtracted from the raw data is displayed in blue. The bottom panel shows the comparison of the background subtracted spectrum (black) with the raw data (blue).

4.1.5 Energy resolution of the K600 magnetic spectrometer

The energy resolution is measured as the Full Width at Half Maximum (FWHM) of a peak in the excitation-energy (E_x) spectrum. The energy resolutions of the two most prominent peaks in the ^{24}Mg and ^{58}Ni excitation-energy spectra were calculated in keV as follows:

$$FWHM = 2.355 \times \sigma_{E_x} (\text{MeV}) \times 1000 (\text{keV/MeV}) \quad (4.10)$$

where σ_{E_x} is the standard deviation of the Gaussian distribution related to the statistical fluctuations in the number of events on the excitation-energy spectrum. The energy resolutions of the selected states in each target are summarised in Table 4.5.

Table 4.5: A summary of the centroid, σ_{E_x} and energy resolution, E_{res} , obtained for each of the two most prominent ^{24}Mg and ^{58}Ni excitation-energy peaks.

Target	E_x (MeV)	σ_{E_x} (MeV)	E_{res} (keV)
^{24}Mg	4.2403	0.0123	29.0
	6.4323	0.0110	26.0
^{58}Ni	3.2703	0.0197	46.5
	4.7578	0.0207	48.7

4.2 Data extraction and analysis of the BaGeL detection system.

4.2.1 Energy calibration of the clover detectors

The energy calibration of the clover detectors is a procedure that assigns γ -ray events to specific γ energies following the decay of a known excited state of the calibration source. This is done by describing a second order polynomial, E_γ , as a function of a γ -ray event named GammaRawADC in a channel number of a

specific ADC as follows:

$$E_\gamma = p_0 + p_1\gamma_{\text{RawADC}} + p_2\gamma_{\text{RawADC}}^2 \quad (4.11)$$

Each of the 12 clover detectors is composed of 4 individual crystals; therefore, 48 calibration parameters were extracted from the GammaRawADC when gated on the K600 well-defined $E_x=6.432$ MeV state of ^{24}Mg . However, as can be seen in Fig. 4.16, the ^{24}Mg γ -ray statistics in this experiment were too low to conduct the single crystal calibration. As such, the calibration parameters used in this analysis were obtained from an experiment performed within the same experimental campaign as the one being analysed in this dissertation. Shown in Fig. 4.17 is the calibrated ^{24}Mg γ -energy spectra of that experiment.

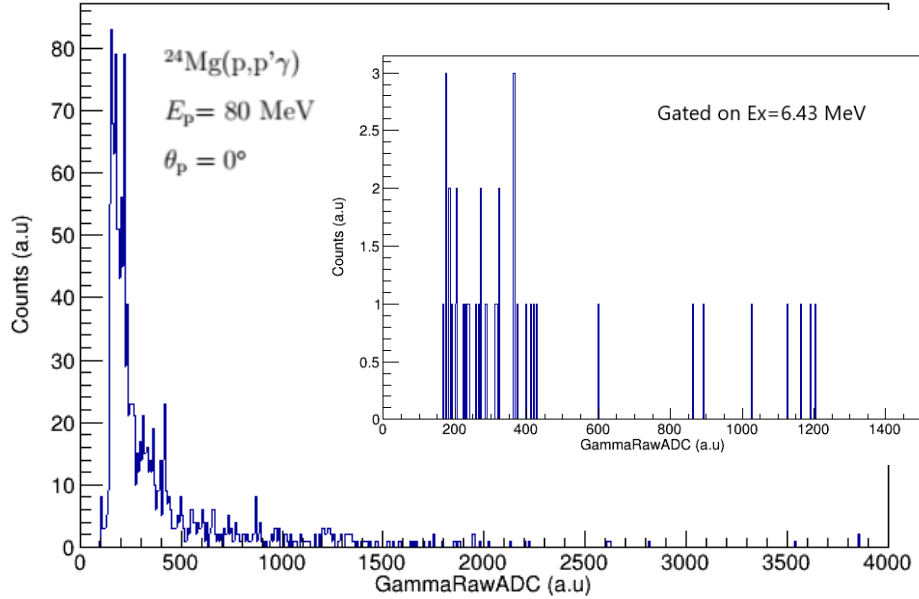


Figure 4.16: The GammaRawADC spectrum for ^{24}Mg . Top right: GammaRawADC gated on the 6.432 MeV excitation energy of the K600 for one individual segment of the clover detectors.

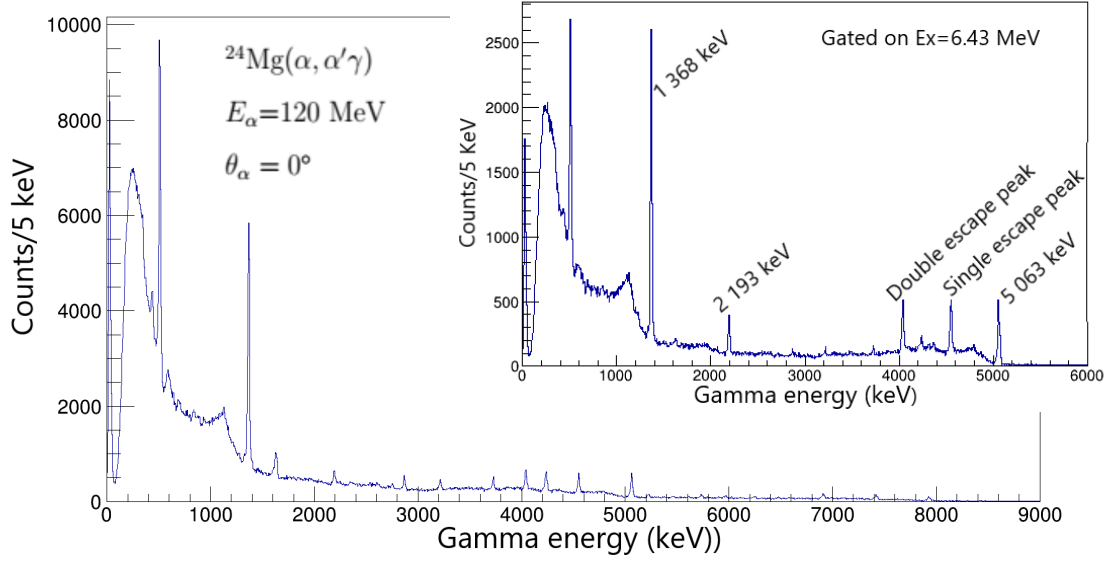


Figure 4.17: The calibrated γ -energy spectra of ^{24}Mg . Top right: γ energy gated on the 6.432 MeV excitation energy of the K600.

4.2.2 Gamma-ray time

Gamma-ray time (referred to as Gammatime in this text) for coincidence measurements is the time difference between the detection of the inelastically scattered protons by the detector system at the focal plane (i.e. the trigger signal) and the detection of the subsequent γ decay by the clover detectors. On some occasions, the Gammatime spectra of different segments of the clover detectors do not overlap due to the different lengths of cables and the electronic path through which each clover time signal needs to pass. Figure. 4.18 (top) shows how the Gammatime of two different clover segments fail to align for ^{58}Ni . A file of offsets using the calibration target, ^{24}Mg , must be produced and implemented to correct for the misalignment. However, since the statistics of the ^{24}Mg for this experiment were low, an offset table implemented was produced from the dataset of PR298, an experiment performed prior to this one at iThemba LABS. After the Gammatime spectra were aligned, the prompt peak was identified. The prompt peak represents the time window of the γ rays that were emitted in coincidence with

the detected protons. This peak was gated on throughout the analysis so that only the γ rays of interest were analysed. As can be seen from Fig 4.18 (bottom), the Gammatime spectra aligned after the offsets were implemented.

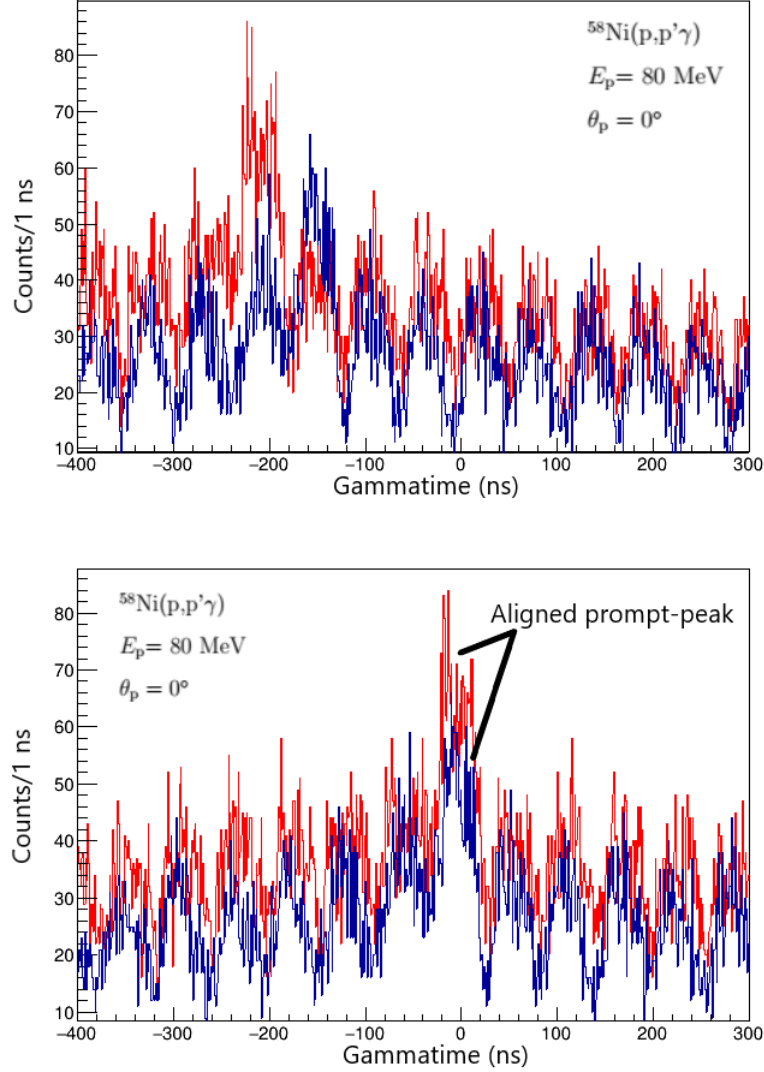


Figure 4.18: Comparison of two Gammatime spectra of two different clover detector segments before the offsets table was implemented (top) and after the offsets table was implemented (bottom).

4.2.3 Addback procedure

The addback procedure reconstructs the total energy released in the clover detector by the possible interactions that could have taken place in the detectors. This is done by adding any γ rays that have been detected in the different segments of the same clover within the prompt Gammatime peak. The first step during the addback procedure was to consider only the γ events detected in coincidence by the different crystals of the same clover. This was done by imposing a condition that these events need to fall within the Gammatime prompt peak (Fig. 4.19). This condition was implemented in the analyser to ensure that only the γ events of interest are selected. The second part of the addback procedure was performed using a specialised script developed at iThemba LABS. It is in this part that for each event, the energies of the γ rays detected simultaneously by the segments of the same clover are added back together to produce the total energy of the initial γ ray. The three possible interactions of γ rays with the detector material being accounted for here are the photoelectric effect, Compton scattering and the formation of an electron-positron pair.

The photoelectric effect is a dominating interaction where the energy of a single γ ray that interacts with the detector material is fully transferred to a single electron in the detector. During Compton scattering, the γ ray deposits a fraction of its energy in the detector material during an interaction. This results in the production of an electron with the partial energy of that γ ray. The remaining energy carried by this γ ray, which is equal to the initial energy of the γ ray minus the energy transferred to the electron, can be deposited in different parts of the clover segments through interactions such as photo-electric effect or the Compton scattering with the detector material. The electron-positron pair is formed when an energetic γ interacts with the detector material. The resulting positron will interact and annihilate with the electron of the detector material resulting in the formation of two 511-keV γ rays. It is in the two latter interactions (Compton and

pair production) that the energy of each initial γ ray could be re-constructed by adding back all the energy fractions that are detected in different segments of the clovers. Furthermore, gating on the prompt peak during this procedure ensured that the γ energies reconstructed are only of the γ rays of interest.

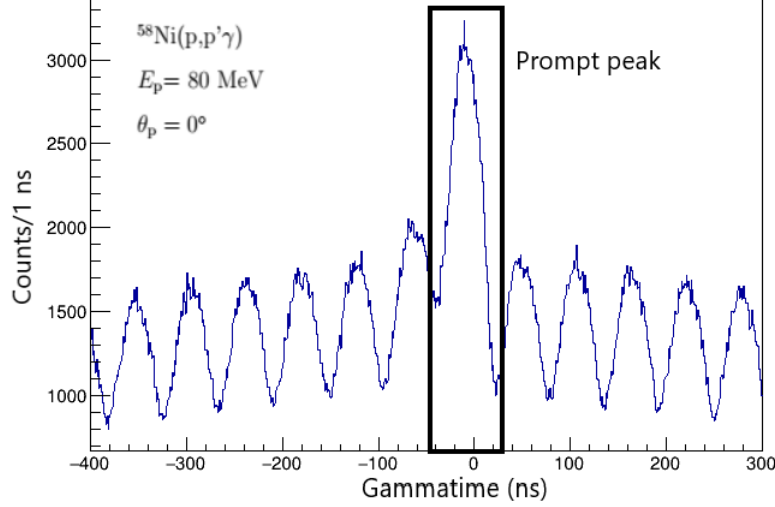


Figure 4.19: The aligned Gammatime spectra of all 12 clover detectors with the prompt peak identified for the addback procedure. The Full Width at Half Maximum (FWHM) of the prompt peak is 37 ns.

It is after this procedure that a γ -energy spectrum with improved photopeaks can be produced from all 4 segments of the 12 clover detectors. This improvement can be observed in Fig. 4.20 where the photopeaks obtained before the addback procedure (blue) are compared with those obtained after (red) the procedure. The addback efficiency which indicates by how much the addback procedure has improved the observed photopeak counts was calculated as

$$\text{Eff} = \frac{A_{\text{addback}} - A_{\text{single}}}{A_{\text{addback}}} \times 100\% \quad (4.12)$$

where A_{single} and A_{addback} are the areas under the photopeaks of the single and the addback spectra, respectively. The areas were calculated using the formula of a pure Gaussian peak with a peak height h and a full width at half maximum w

$$A = 1.064467 \times h \times w \quad (4.13)$$

The attainable addback efficiency for a single photopeak can go as high as 60%; however, for this experiment the efficiency is relatively low due to the low prompt-to-random peak ratio in the Gammatime spectrum. Even so, the effect of the addback on the different photopeaks can still be observed. Table 4.6 summarises the addback efficiencies of two most prominent photopeaks of ^{58}Ni when the spectrum is gated on the decay to the ground state and the first excited state.

Table 4.6: A summary of the addback efficiency of ^{58}Ni after the addback procedure. The spectrum was gated on decay to ground state and first excited state.

γ energy (keV)	Eff (%)
3262.21	19.1
3021.73	25.5

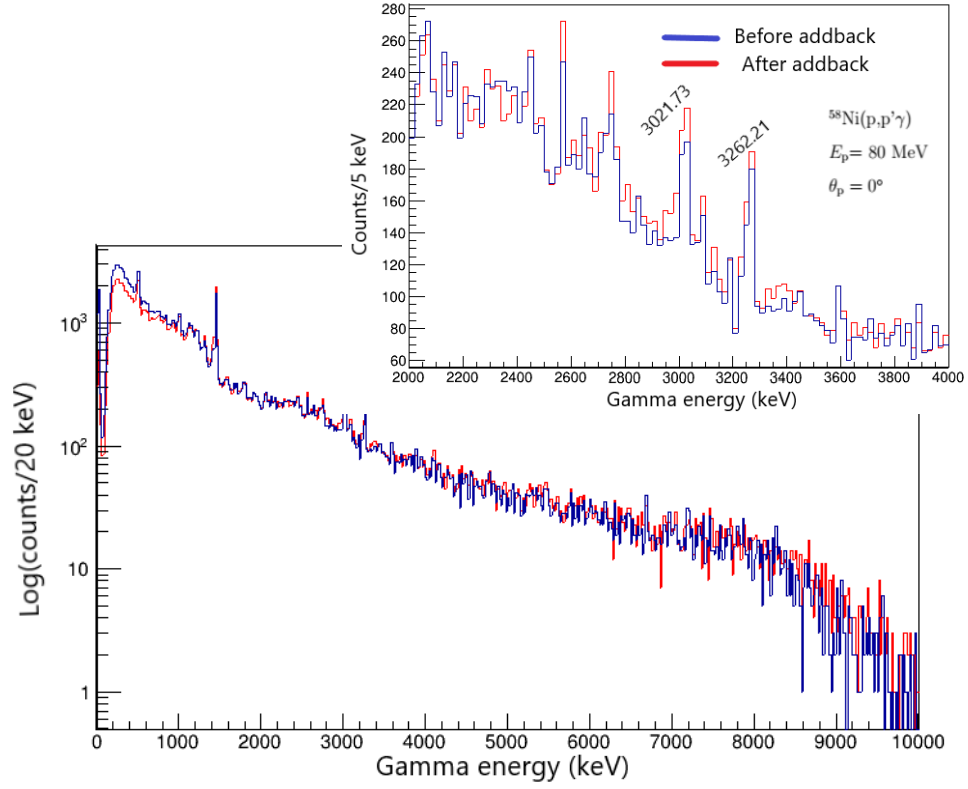


Figure 4.20: The comparison of gamma-energy spectra of the clover detectors before (blue) and after (red) the addback procedure is implemented. As can be observed in the zoomed in spectrum (top), the addback procedure increased the photo efficiency.

Chapter 5

Results and discussions

5.1 Description of the measured $(p,p'\gamma)$ results

5.1.1 The coincidence matrix

The experimentally measured $(p,p'\gamma)$ coincidence matrix shown in Fig. 5.1 (top) is a two-dimensional scatter plot deduced from the energy loss of the inelastically scattered protons versus the energy of the γ rays measured in coincidence. To obtain this matrix, the PID software gates created in Sec. 4.1.1 were applied and the Gamma events of the addback procedure in Sec. 4.2.3 (gated on the prompt peak) were used. To check how much of the random events could be found on the prompt-peak-gated matrix. The matrix in Fig. 5.1 (bottom) was produced by gating on a random Gammatime peak of the clover detectors. This coincidence matrix contains only uncorrelated events of the background contributions. Therefore, by observing the background distribution of this matrix, the real coincidence events in the prompt-peak-gated matrix could be verified. The comparison of the 0^+ ground state γ energy spectrum in Fig. 5.2 further proves that the coincidence events of interest are found in the prompt peak of the Gammatime spectrum. As observed in Fig. 5.1 (bottom) and in the Gammatime spectrum in Fig. 4.19, the amount of background was found to be more prominent in the $(p,p'\gamma)$ reaction

than in the case of $(\alpha, \alpha' \gamma)$ measurements performed in the same experimental campaign. It is suspected that the random gamma rays could originate from scattered protons off the collimator and the elements at the entrance of the spectrometer. Improvement in the γ -detector shielding and a detailed investigation into the specific source of this background will be conducted in the future to minimise its contribution.

Concerning the excitation-energy spectrum of ^{58}Ni in the present work, a γ -detector gate was imposed on the excitation energy so that the spectrum only contains the $p\text{-}\gamma$ events that were in coincidence. As explained in Sec. 4.1.4, to obtain a background-free spectrum, usually a background subtraction procedure is performed on the K600 single events. This technique has been used successfully in (p, p') experiments at iThemba LABS [3]. However, during this procedure, there are possibilities of over subtracting or even introducing new structures to the spectrum. Therefore, gating the excitation-energy spectrum on the γ -ray detectors in order to reduce the background becomes more advantageous. This allows for the elimination of the proton events that were generated by beam halo and the ones that were scattered off the target frame and collimator material. Most of these events were removed in the K600 excitation-energy spectra using the PID cuts explained in Sec. 4.1.1. However, since this method does not include the correlated γ rays, the coincidence condition is required (gating on the γ detectors) to further identify the proton events of interest that were detected in coincidence with the γ rays. The lower panel in Fig. 5.3 shows the excitation-energy spectrum for ^{58}Ni that is not gated on the γ -ray detectors, whereas the upper panel displays the same spectrum but with the gates applied.

The PDR region, between 6-9 MeV, has been outlined in black in Fig. 5.1 (top) and 5.3. Even though some $p\text{-}\gamma$ coincidence structures are present and can be observed in this energy range, the statistics are too low to unambiguously identify the presence of a specific decay pattern, and no $p\text{-}\gamma$ angular distribution could be

determined. As a result, no particular states could be assigned to the PDR. The diagonal lines shown in the top panel of Fig. 5.1 represent the gates on the decays to the 0^+ ground state and the 2^+ first excited state in ^{58}Ni .

To observe a decay to the 0_1^+ and 2_1^+ states, the $|E_x - E_\gamma| < 200 \text{ keV}$ and $|E_x - (E_\gamma + 1454.21)| < 200 \text{ keV}$ conditions were applied to the γ -energy spectrum, respectively. The absolute differences are being considered here because it is possible that some of the $E_x - E_\gamma$ values might be negative but still be within the detection resolution. These gates only select the events that are between each set of diagonal lines. The diagonal lines were opened 400 keV wide in order to ensure that all the coincidence events that are close in proximity to the values within the absolute-value brackets are included. The 1454.21 keV is the energy of the first excited states of ^{58}Ni . Similarly, to observe the excited states that decayed through these channels, the same gates were applied to the excitation-energy spectrum. The resulting spectra (projections of the coincidence matrix) can be observed in Fig. 5.4. The excited states that decayed directly to the 0^+ and the first 2_1^+ level are summarised in Table 5.1. The correlation between the excited peaks present in the K600 spectrum and the γ rays measured in coincidence as seen from the coincidence matrix is evident. A pronounced unresolved multiplet can be observed at 4.5 MeV.

Table 5.1: Transitions observed for decay to the ground state and the 2_1^+ state. A comparison to NNDC values [70] for ^{58}Ni is also provided.

Decay to	E_x label	present work E_x (keV)	NNDC E_x (keV)	E_x diff. (keV)	γ label	present work γ energy (keV)	NNDC γ energy(keV)	γ diff. (keV)
2_1^+	A	3061.91			a	1450.76		
	B	3272.82	3263.66	9.1	b	1803.87	1809.5	-5.63
	C	3535.84	3531.3	4.54	c	2072.63	2076.9	-4.27
	D	3894.21	3898.8	-4.59	d	2441.35	2444.7	-3.35
0_1^+	E	3272.42	3263.66	8.76	e	3264.15	3263.4	0.75

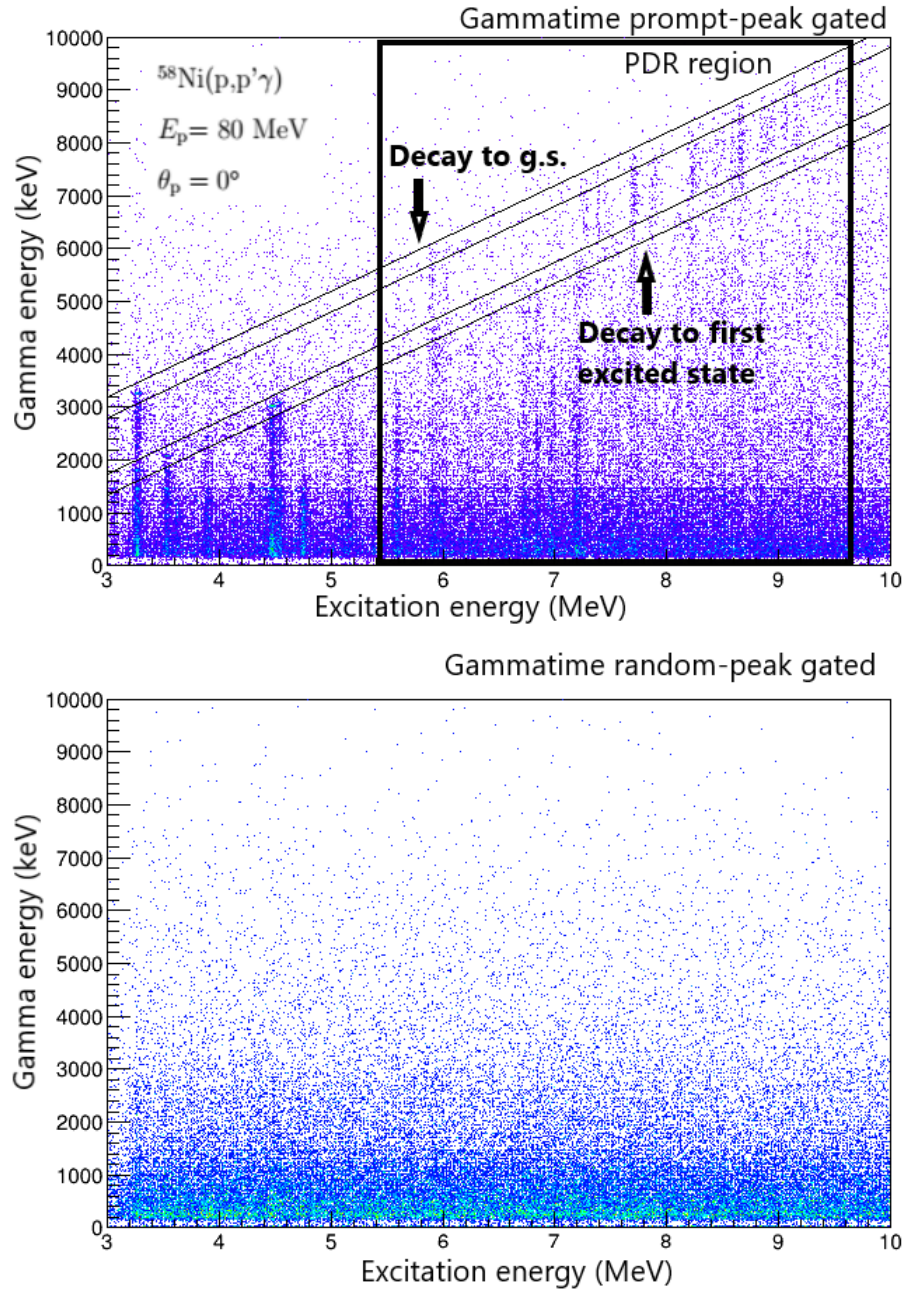


Figure 5.1: A comparison of the coincidence matrix of the detected γ rays and the measured excitation energy in ^{58}Ni when gated on the prompt peak (top) and random peak (bottom) of the Gammatime spectrum.

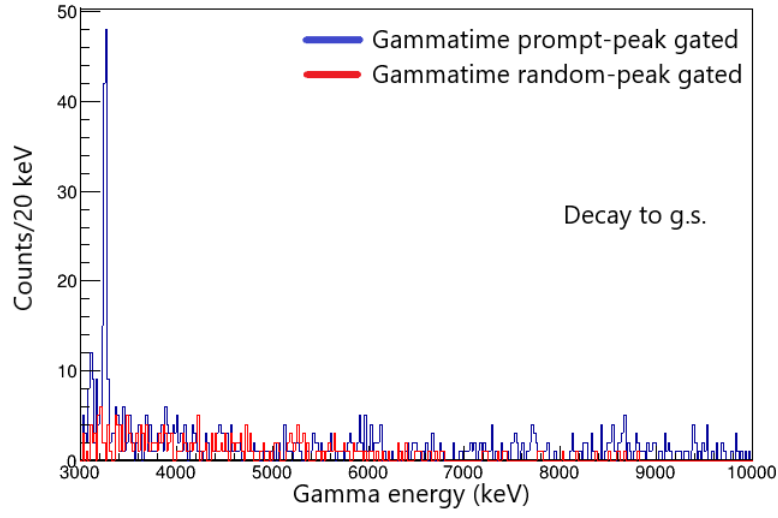


Figure 5.2: A comparison of the 0^+ ground state γ energy spectrum when gated on the prompt peaks and when gated on a random peak. The figure shows that the coincidence events are indeed found at the prompt peak of the Gammatime spectrum.

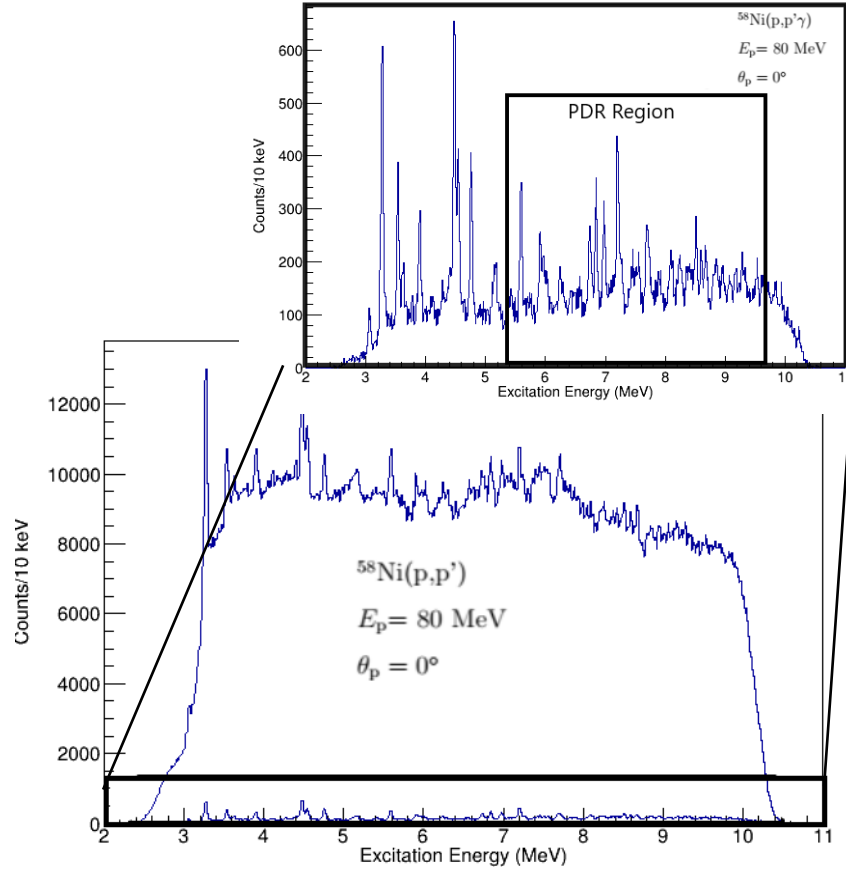


Figure 5.3: The excitation-energy spectra of the $^{58}\text{Ni}(p,p')$ and $^{58}\text{Ni}(p,p'\gamma)$ reactions at $\theta = 0^\circ$. The spectrum on top shows how the background contribution is greatly reduced when the excitation energy is gated on the γ detectors.

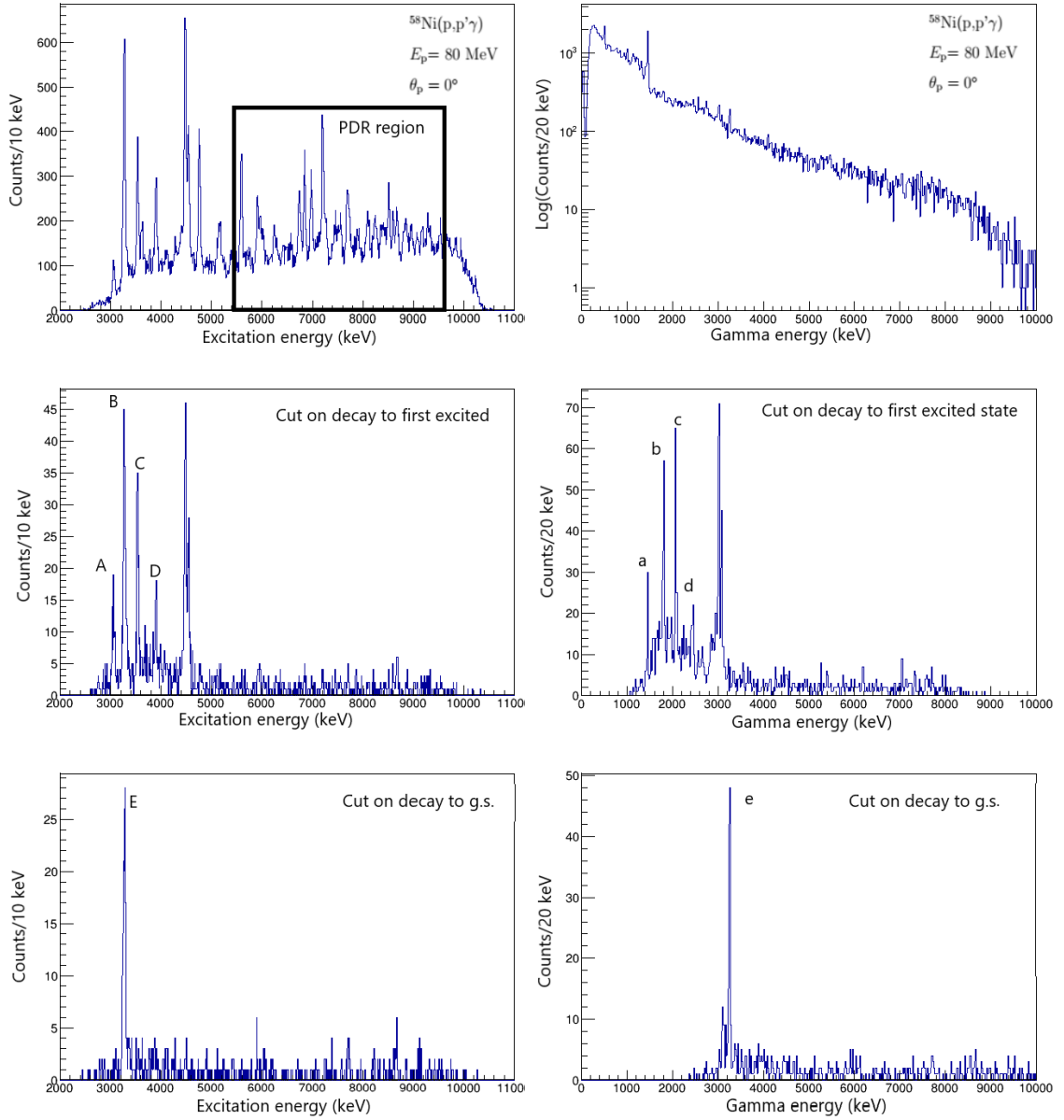


Figure 5.4: The excitation energy (left) and γ decay (right) spectra for ^{58}Ni . The plot also shows the corresponding peak of the excitation and γ energies when gated on decay to the 0^+ ground state and the 2^+ first excited state.

5.2 Excitation-energy spectrum: Extraction of the PDR

Table 5.2 gives a comparison of the excitation energies of ^{58}Ni that were identified in the K600 spectrum with those from the NNDC. Even though the p- γ angular correlations, which were going to provide information on the nuclear spin of the energy levels, could not be determined from the experimental data, when comparing the peak values found in the measured excitation-spectrum of ^{58}Ni with the NNDC values, the spins and parities of the selected states could be assigned. A total of 19 transitions were identified within an energy difference of no more than 10 keV from the NNDC values. At least two observed states just above the proton threshold with values 8.24 ± 0.004 MeV and 8.51 ± 0.002 MeV were identified as 1^- states as shown in Fig. 5.5. These states, also highlighted in gray in Table 5.2, could be considered as part of the PDR in ^{58}Ni .

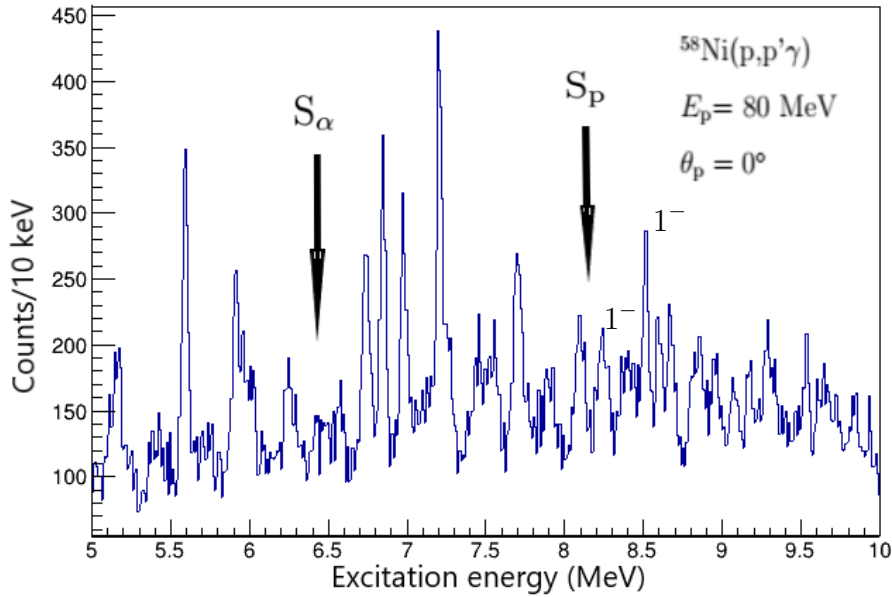


Figure 5.5: PDR region of ^{58}Ni showing the two identified states with $J^\pi = 1^-$.

Table 5.2: A comparison of the excitation energy of the K600 magnetic spectrometer (p,p' γ) with the NNDC values [70] for ^{58}Ni .

NNDC J $^\pi$	K600 E_x (MeV)	NNDC E_x (keV)	Difference (keV)
	3.06 ± 0.002		
2 $^+$	3.27 ± 0.001	3263.66 ± 22	6.34
0 $^+$	3.54 ± 0.001	3531.1 ± 3	8.9
4 $^+$	3.62 ± 0.003	3620.09 ± 22	-0.09
2 $^+$	3.90 ± 0.001	3898.8 ± 4	1.20
4 $^+$	4.76 ± 0.001	4752.2 ± 8	7.8
2 $^+$	5.16 ± 0.003	5156 ± 11	4
2 $^+$	5.59 ± 0.001	5590.3 ± 10	-0.3
0 $^+$	5.93 ± 0.005	5924 ± 10	6
2 $^+$	6.25 ± 0.004	6248 ± 10	2
3 $^-$	6.74 ± 0.002	6735 ± 8	5
3 $^-$	6.85 ± 0.001	6854.5 ± 10	-4.5
2 $^+$	6.98 ± 0.001	6983 ± 5	-3
3 $^-$	7.21 ± 0.001	7210.4 ± 10	-0.4
1 $^+$	7.70 ± 0.002	7709.7 ± 6	-9.7
1	8.10 ± 0.003	8096.3 ± 6	3.7
1 $^-$	8.24 ± 0.004	8237.3 ± 4	2.7
1 $^-$	8.51 ± 0.002	8514.1 ± 4	-4.1
1 $^+$	8.60 ± 0.002	8600.5 ± 7	-0.5
1 $^+$	8.67 ± 0.002	8679.3 ± 8	-9.3

5.3 Comparison with previous experiments

5.3.1 Comparison with ($\alpha, \alpha'\gamma$) experiments

Coincidence measurements on ^{58}Ni were performed by T.D. Poelheken *et al.* [7] at Groningen 30 years ago using the KVI magnetic spectrometer and NaI(Ti) γ detectors. These measurements were performed through an ($\alpha, \alpha'\gamma$) reaction at 0°. Since the resolution of the K600 and HPGe detectors (~ 48 keV and ~ 29 keV, respectively) is better compared to the 250 keV resolution obtained with the NaI detectors, it can be observed from the comparison in Fig. 5.6 that the spectrum generated in the present study from the (p,p' γ) reaction shows many more individual states that could be hidden or not excited in the ($\alpha, \alpha'\gamma$) case.

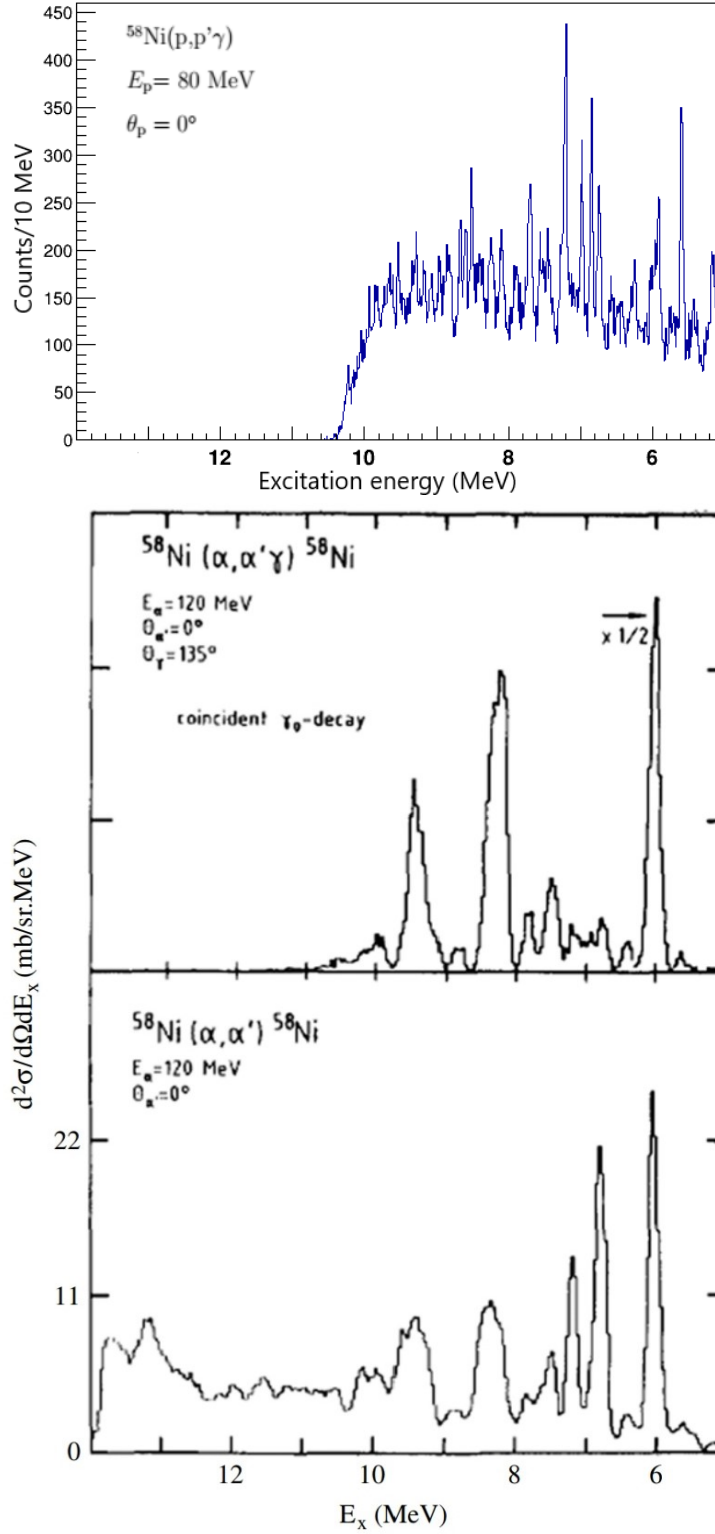


Figure 5.6: Comparison of the K600 ($p,p'\gamma$) and the KVI (α,α') and ($\alpha,\alpha'\gamma$) excitation-energy spectra [7].

This could be an indication that protons and alphas excite different parts of the nucleus and they can, therefore, be used as complementary tools to study the PDR. Owing to the isoscalar internal structure of the α particles, they mostly excite the isoscalar component of the nucleus, while protons at 80 MeV excite both the isoscalar and isovector components of the nucleus. Furthermore, the poor energy-resolution obtained with the NaI detectors has limitations in the applications for the spectroscopy of high-density energy levels.

Another $^{58}\text{Ni}(\alpha, \alpha'\gamma)$ experiment was performed by D. Savran *et al.* [8] in 2006 at the AGOR cyclotron of KVI using the Big-Bite Spectrometer and HPGe γ detectors. These measurements were performed at 3-8° scattering angles and 100-400 MeV incident energies. Compared to the energy resolution of the NaI detectors, the energy resolution of the HPGe detectors was improved by more than one order of magnitude to about $\frac{\Delta E_\gamma}{E_\gamma} = 0.2\%$. The experimental results at $E_\alpha=136$ MeV are shown for comparison with the results of this current study in Fig. 5.7. This comparison is, however, limited due to the low statistics of the $(p, p'\gamma)$ γ -decay spectrum, especially when a cut on the decay to the 0^+ ground state and 2^+ first excited state is applied.

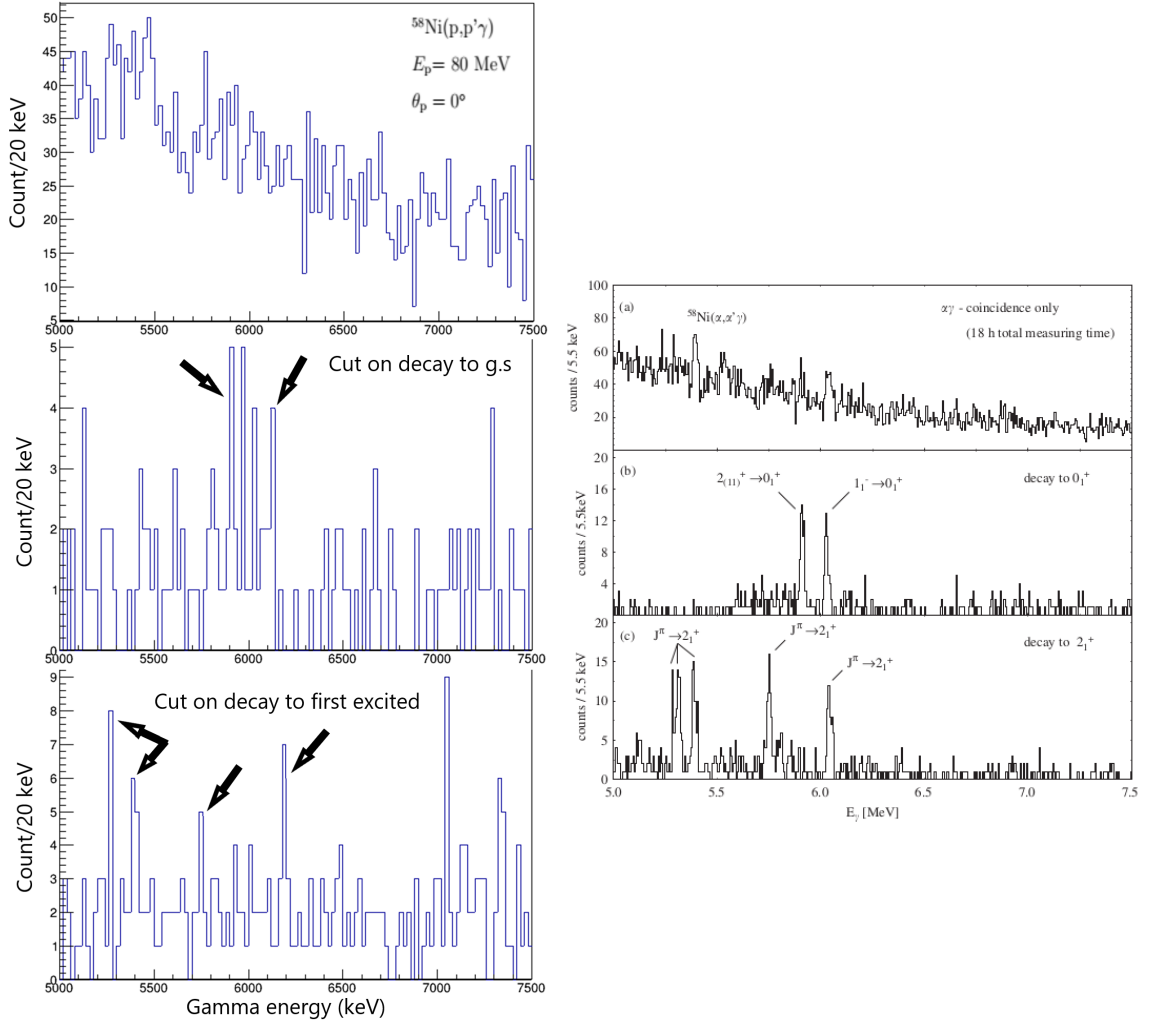


Figure 5.7: Comparison of the K600 ($p,p'\gamma$) and the second KVI ($\alpha,\alpha'\gamma$) γ decay spectra [8]. The arrows on the ($p,p'\gamma$) spectrum gives an indication of where the peaks on the ($\alpha,\alpha'\gamma$) spectrum could be found.

5.3.2 Comparison with a (γ,γ) experiments

Nearly 40 years ago, a $^{58}\text{Ni}(\gamma,\gamma)$ experiment with Bremsstrahlung photons and Ge(Li) detectors was performed at the University of Giessen by K. Ackermann *et al.* [9]. The experiment aimed to study the dipole transitions in ^{58}Ni . Only five

of the ten transitions observed could be assigned parities. Three of these states, namely the 7710, 8240 and 8682 keV states, were observed in the present study. This is summarised in Table 5.3.

An extension of that work was conducted at the 15 MeV linac in Gent 20 years ago also using Bremsstrahlung photons and Ge detectors [10]. The study aimed to investigate the $E1$ strength and its fragmentation below the neutron separation energy. The results showed that the main $E1$ strength is strongest between 5 and 10 MeV and sum up to $60 \times 10^{-3} e^2 \text{ fm}^2$ with an upper limit of $140 \times 10^{-3} e^2 \text{ fm}^2$. This NRF experiment makes a good comparison for this study because it uses a beam of photons with continuous energy from an intense Bremsstrahlung source allowing for a simultaneous observation of all nuclear $J = 1$ states in even-even nuclei that have a strong ground-state transition. Six of the states in the PDR region that were observed in the Gent study were also observed in the present work. This information is summarised in Table 5.3.

Table 5.3: Comparison of the K600 (p,p' γ) with (γ, γ) experiments [9, 10].

Present (p,p' γ) study		Gent (γ, γ) study		Giessen (γ, γ) study	
J^π	E_x (MeV)	J^π	E_x (keV)	J^π	E_x (keV)
	7.70 ± 0.002	1^+	7709.7 ± 0.6	1	7710 ± 3
	8.10 ± 0.003	1	8096.3 ± 0.6		
	8.24 ± 0.004	1^-	8237.3 ± 0.4	1	8240 ± 3
	8.51 ± 0.002	1^-	8514.1 ± 0.4		
	8.60 ± 0.002	1^+	8600.5 ± 0.7		
	8.67 ± 0.002	1^+	8679.3 ± 0.8	1	8682 ± 3

Chapter 6

Conclusions and outlook

A $(p,p'\gamma)$ reaction has been measured for the first time at iThemba LABS and the results validated the possibility of successfully performing $p\text{-}\gamma$ measurements with an intermediate-energy (80-MeV) proton beam. In this experiment, it has been shown that the excitation energy and the γ decay measured on an event-to-event basis allows for sensitive cuts to separate the excitations of interest from the background contributions and track the decay channels of these excitations. The selectivity to low-spin excitation has been observed. Even though the statistics were not high enough in the energy region of the PDR in the produced two-dimensional matrix, some structure could be observed. Since this experiment was a commissioning run and measurements were taken for only about 11.5 hours, in the future, to ensure that sufficient statistics are obtained to be able to extract important information such as the spins and parities on the states comprising the PDR, a longer beam time should be requested. A γ efficiency of $\sim 0.45\%$ at 3.27 MeV was obtained in this experiment and, compared to the 1.4% initially estimated (at 6 MeV) in the proposal for measurements taken in 3 days, it is clear that future measurements will have to be taken over a period longer than 3 days to make up for the now observed low experimental γ efficiency of the setup. As mentioned in Sec. 5.1.1, a detailed investigation should be conducted on the co-

incidence background region for $(p,p'\gamma)$ reactions; however, currently one possible solution that could be implemented is to improve the γ -detector shielding since it is suspected that the random gamma rays could come from scattered protons off the collimator. The comparisons with other experiments conducted using different probes indicate that studying the PDR through $(p,p'\gamma)$ could be as effective as $(\alpha,\alpha'\gamma)$ and (γ,γ) experiments provided that the appropriate scattering angle and incident energy is selected. It is anticipated that the outstanding analysis of the data from the $\text{LaBr}_3\text{:Ce}$ detectors will provide additional information so that the conclusions drawn from this study can be strengthened.

Since it has been observed in the results that the resolution of the HPGe detectors is almost two times better than that of the magnetic spectrometer, developing this detection system can be helpful for future experiments where the interest is in resolving high density nuclear states in complex nuclei.

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