NOVA SCHOOL OF SCIENCE & TECHNOLOGY

DEPARTMENT OF PHYSICS

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BSc in Physics Engineering

LIGHT FRAGMENT DETECTION USING RESISTIVE PLATE CHAMBERS

CONTRIBUTION TO GSI EXPERIMENT S249

MASTER IN PHYSICS ENGINEERING

NOVA University Lisbon

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Abstract

This will be my abstract.

Keywords: Resistive plate chamber, Quasi-free scattering, Gaseous detectors, One keyword more, The last keyword

Resumo

Este vai ser o meu resumo.

Palavras-chave: Câmara de placas resistivas, Dispersão quase livre, Detetores gasosos, A última palavra-chave

Contents

Acronyms

CALIFA	CALorimeter for In-Flight detection of gamma-rays and charged pArticles *(p. 10)*
DAQ	Data Acquisition *(pp. 13, 14)*
FAIR	Facility for Antiproton and Ion Research *(p. 3)*
FRS	FRagment Separator *(p. 10)*
GLAD	GSI Large Acceptance Dipole *(p. 10)*
GSI	GSI Helmholtzzentrum für Schwerionenforschung *(p. 10)*
NeuLAND	New Large-Area Neutron Detector *(p. 10)*
R3B	Reactions with Relativistic Radioactive Beams *(p. 10)*
RPC	Resistive Plate Chamber *(p. 10)*
Super-FRS	Super FRagment Separator *(p. 3)*
ToFD	Time-of-Flight Detector *(p. 10)*

1

Introduction

"The important thing in science is not so much to obtain new facts as to discover new ways of thinking about them."

Sir William Lawrence Bragg

1.1 Introduction

Since the birth of Nuclear Physics, with the discovery of the atomic nucleus by Ernest Rutherford in 1911 [1], this area has proved to be a fascinating field for scientific research displaying a rich variety of quantum phenomena. Many features of the nucleons in the nucleus exhibited are similar to the structure and behavior of atomic electrons in the atom. Similar descriptions for energy levels and shells, spins and angular momentum have emerged.

But there are some differences:

1. The dominating force inside the nucleus is the strong force rather than the electromagnetic one.

2. Since the strong force is short range and attractive, the potential in which the nucleons exist is created by all the other nucleons in contrast to the force between the atomic electrons and the spatially separated positive charge of the nucleus.

Two fundamental models—the liquid-drop model and the shell model—represent key milestones in this development. Their reconciliation explains many nuclear phenomena, particularly the emergence of magic numbers and the behavior of exotic nuclei.

1.1.1 The Liquid-drop Model

The liquid-drop model, first formulated comprehensively by Weizsäcker and discussed in detail by Bethe and Bacher in 1936 [2], treats the nucleus analogously to a charged droplet of incompressible fluid. This model emphasizes collective properties of the nucleus, such as binding energy, surface tension, and Coulomb repulsion among protons.

The semi-empirical mass formula (also called the Bethe-Weizsäcker formula) captures essential trends:

$$B(A, Z) = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_A \frac{(N-Z)^2}{A} \pm \delta(N, Z)$$

where each term accounts for volume, surface, Coulomb, asymmetry, and pairing effects respectively.

While successful at explaining global nuclear properties—such as the approximate binding energy per nucleon—it could not account for observed anomalies in nuclear stability, such as nuclei at specific nucleon numbers (2, 8, 20, 28, 50, 82, 126) exhibiting enhanced stability: the magic numbers.

1.1.2 The Shell Model

The limitations of the liquid-drop model led to the proposal of the shell model, notably formulated by Maria Goeppert Mayer and J. Hans D. Jensen independently in 1949 [3]. Their work, expanding on the early suggestions of Elsasser, showed that nucleons move in quantized energy levels within a mean potential well created by all other nucleons—analogous to electrons in atomic orbitals.

Initially, it was thought that a simple three-dimensional harmonic oscillator potential could describe the structure. However, it was soon realized that including a strong spin-orbit coupling term, where the nucleon's spin couples to its orbital motion, was critical to reproduce the magic numbers observed experimentally [3, 4].

In particular, spin-orbit splitting lifts the degeneracy of orbital states, energetically favoring high-angular-momentum states (e.g., $j = l + 1/2$), thus producing large energy gaps at specific nucleon numbers—those corresponding to the magic numbers.

The modified energy level filling, based on this strong spin-orbit interaction, led to a successful explanation for the pronounced nuclear stability at nucleon numbers:

$$2, 8, 20, 28, 50, 82, 126$$

for both protons and neutrons separately [3, 4].

1.1.2.1 Magic Numbers and Shell Closures

In the shell model:

- A closed shell means that all available states at a given energy are filled.
- Nuclei with both proton and neutron numbers equal to magic numbers (so-called doubly magic nuclei, e.g., ^{16}O, ^{208}Pb) exhibit especially high binding energies, spherical shapes, and relatively low excitation spectra.

Haxel, Jensen, and Suess [4] provided a succinct explanation showing how a strong spin-orbit coupling splits the energy levels such that filling up the states naturally reproduces the magic numbers.

1.1.2.2 Extension to Exotic Nuclei

The classic shell model was originally built based on stable, near-β-stable nuclei. However, advances in experimental techniques have allowed the study of exotic nuclei — nuclei far from stability, with unusual neutron-to-proton ratios.

In these systems:

- Traditional magic numbers can weaken or even disappear [5].
- New magic numbers (e.g., $N = 16$, $N = 34$) can emerge [5].
- Nuclear deformations become more common, especially near the so-called "island of inversion" (around $N = 20$) [5].
- Phenomena like neutron halos emerge [5].

This phenomenon has led to the concept of shell evolution, where the shell structure depends on the balance between the nuclear force components (central, spin-orbit, and tensor interactions) and changes with proton-neutron ratios.

1.1.3 Conclusion

In summary, the liquid-drop model offered a macroscopic view of nuclear behavior, while the shell model introduced microscopic structure and quantization effects that explain nuclear stability at magic numbers. The discovery of exotic nuclei has highlighted that the shell structure itself is dynamic and evolves under extreme conditions, demonstrating the richness and complexity of nuclear structure beyond the stable valley.

1.2 The FAIR Facility

Facility for Antiproton and Ion Research (FAIR)

FAIR

Super FRagment Separator (Super-FRS)

Super-FRS

1.3 Author's Contribution and Thesis Overview

2

Direct Reactions as Spectroscopic Tools

"Nature hides her secrets because of her essential loftiness, but not by means of ruse."

Albert Einstein

"The art of simplicity is a puzzle of complexity."

Douglas Horton

2.1 Introduction

The structure of atomic nuclei—how protons and neutrons arrange themselves in shells, how they correlate, and how these features evolve across the nuclear chart—has been at the heart of nuclear physics for decades. To unravel this structure, nuclear physicists have long relied on direct reaction mechanisms, in which a projectile interacts with a target nucleus in a controlled and selective way, producing clean signatures of specific internal configurations. Among these, transfer reactions and knockout reactions have historically provided the foundational experimental pathways for exploring the single-particle nature of the nucleus.

2.2 Transfer Reactions

Nucleon transfer reactions, such as (d,p), (p,d), or (t,α), involve the exchange of one or more nucleons between the projectile and the target. In the classic (d,p) reaction, for instance, a neutron is transferred from a deuteron to the target nucleus, leaving the residual system in a state that reveals the properties of the added neutron orbital.

These reactions have played a central role in defining the shell model: by measuring angular distributions and comparing them to reaction theory (e.g., using the distorted wave Born approximation, DWBA), one can extract:

- The orbital angular momentum l of the transferred nucleon (via angular distribution patterns),
- The spectroscopic factor, quantifying the overlap between the initial and final nuclear states.

Transfer reactions are best suited for stable or long-lived nuclei at relatively low energies (5–50 MeV/u), where they benefit from high cross-sections and well-developed theoretical frameworks. However, they become experimentally challenging for short-lived isotopes and high-Z systems, especially where targets cannot be fabricated.

2.3 Knockout Reactions

With the advent of radioactive beam facilities, transfer methods began to be complemented—and in some cases replaced—by nucleon knockout reactions, particularly in inverse kinematics. In a knockout reaction, such as (A, A–1), a high-energy projectile nucleus collides with a light target (e.g., ^{2}Be, C, or H), and a single nucleon is suddenly removed from the projectile.

Knockout reactions operate in the sudden approximation: the interaction is fast enough that the removed nucleon doesn't reconfigure its wavefunction during the process. The resulting residual nucleus and its kinematics encode the structural information of the pre-existing configuration.

By measuring the momentum distribution of the residual fragment and comparing it with theoretical predictions (e.g., via the eikonal reaction model or Glauber theory), one obtains:

- The l-value of the knocked-out nucleon (from the width and shape of the distribution),
- The spectroscopic strength, linked to orbital occupancy.

Knockout reactions revolutionized structure studies of exotic nuclei, especially those near the drip lines, by enabling measurements of systems that could only be formed in-flight.

2.4 From Knockout to Quasi-Free Scattering

While both transfer and knockout reactions have yielded profound insights, their selectivity and interpretability face limitations. Transfer reactions are constrained by target availability and are often restricted to stable systems. Knockout reactions, although experimentally versatile, involve complex reaction dynamics with model dependencies that grow in neutron-rich environments and at higher energies.

To transcend these limitations, quasi-free scattering has re-emerged as a uniquely powerful probe. Conceptually close to knockout, but kinematically richer and theoretically cleaner in many regimes, QFS reactions like (e,e′p) and (p,2p) offer direct access to the momentum and separation energy of individual nucleons in their initial nuclear orbitals. In high-energy kinematics, and under the impulse approximation, the scattering process isolates the interaction between the probe and a single nucleon, while the remaining nucleus acts as a spectator.

This progression—from transfer, to knockout, to QFS—represents not just an evolution of experimental technique, but a deepening of our ability to map the quantum landscape inside the nucleus, from its shell structure to the underlying many-body correlations.

2.5 Quasi-free Scattering Reactions

2.5.1 Introduction to Quasi-Free Scattering

Quasi-free scattering (QFS) has emerged as one of the most powerful tools in nuclear physics to probe the single-particle structure and correlations within atomic nuclei. It encompasses a class of reactions in which an incident probe (either an electron or a proton) interacts predominantly with a single nucleon in the nucleus, while the remaining nucleons act as passive spectators. Under kinematic conditions favoring large momentum and energy transfer, and small final-state interactions (FSI), the process can be approximated by the impulse approximation (IA)—a simplification in which the nuclear many-body system is treated as a collection of quasi-free, independent nucleons.

2.5.2 Historical Context and the Electron-Induced Paradigm

The conceptual and experimental foundations of QFS were established in the 1960s, particularly with the pioneering review by Jacob and Maris (1966) [6], which systematized the theoretical framework for electron-induced QFS reactions of the type (e,e′p). In these reactions, a high-energy electron transfers a well-defined amount of momentum and energy to a proton within the target nucleus, which is then ejected and detected in coincidence with the scattered electron. The kinematic constraints of such experiments enable the reconstruction of the missing energy and momentum of the ejected nucleon, which provides a direct spectroscopic window into the bound-state wavefunction.

This formalism was further refined in the 1973 follow-up by the same authors [7], which accounted for distortions in both the incoming and outgoing waves due to the nuclear potential—introducing the Distorted Wave Impulse Approximation (DWIA). These early (e,e′p) experiments, primarily conducted at SLAC and Saclay, provided critical benchmarks for understanding shell structure, spectroscopic factors, and occupancy probabilities, particularly in medium-mass nuclei like ^{16}O and ^{40}Ca. However, the method remained largely confined to stable nuclei due to the limitations in electron beam-target combinations.

2.5.3 Proton-Induced QFS and DWIA Evolution

In parallel, the use of proton-induced QFS—such as (p,2p) or (p,pn) reactions—gained traction as an alternative means to probe the same physics with hadronic probes. While the complexity of the nucleon-nucleon (NN) interaction and stronger final-state interactions initially complicated the analysis, the development of DWIA for hadronic probes enabled the extraction of momentum distributions and spectroscopic observables with comparable reliability. These reactions offered higher cross-sections and better experimental accessibility, though at the cost of increased theoretical uncertainty due to ambiguities in the NN scattering amplitude and optical potentials.

2.5.4 The Modern Era: Inverse Kinematics and Exotic Nuclei

A transformative leap occurred in the 21st century with the advent of inverse kinematics QFS using radioactive ion beams (RIBs) and hydrogen targets. As comprehensively reviewed by Panin et al. (2021) [8], modern QFS experiments at facilities such as RIKEN, GSI/FAIR, and FRIB utilize high-energy beams of neutron- or proton-rich nuclei impinging on proton-rich targets. The resulting reactions—such as (p,2p), (p,pn), or (p,pα)—enable the study of short-lived and exotic systems far from stability, including halo nuclei, nuclei near the neutron drip line, and those within the so-called "island of inversion."

These experiments exploit complete kinematic reconstruction techniques, coincident γ-ray detection, and high-resolution tracking of all final-state particles. This allows the identification of orbital angular momentum (l) of removed nucleons via momentum distributions, providing a model-independent probe of nuclear shell structure. Moreover, inverse kinematics QFS has facilitated the spectroscopy of unbound states, the quantification of short-range correlations (SRCs), and insights into clustering phenomena in light and medium-mass nuclei.

2.5.5 Benchmark and Current Frontiers

QFS today occupies a unique position among reaction mechanisms, bridging single-particle and correlated many-body dynamics. Benchmarked by decades of electron-induced QFS data, modern (p, 2p)/(p, pn) measurements are now used to:

- Test shell evolution in neutron-rich isotopes,
- Quantify spectroscopic factors and their reduction (quenching),
- Investigate SRCs in asymmetric nuclear matter,

- Map the extent of the island of inversion,
- Explore the nature of unbound and resonant nuclear states.

Theoretical advancements, notably the eikonal DWIA and relativistic frameworks, allow consistent comparisons between experiment and shell-model or ab initio structure predictions. Future developments—such as the integration of machine learning in reaction theory, or the use of polarized beams and targets—promise even finer resolution of nuclear substructure.

3

Experiment

"Somewhere, something incredible is waiting to be known."

Carl Sagan

3.1 Context and Goal of the Experiment

The proposed experiment, detailed in research proposal G-24-00249, aims to investigate the structure of the neutron-rich fluorine isotope, ^{25}F, through one-proton knockout reactions. This study is motivated by the "drastic extension of the neutron drip line for Z=9 compared to Z=8 isotopes," a phenomenon that remains poorly understood [9]. The experiment seeks to elucidate how the ^{24}O core is polarized by the presence of an additional proton in ^{25}F, thereby shedding light on the mechanisms responsible for the observed drip line extension.

The experiment will employ the quasi-free scattering (QFS) reaction ^{25}F(p,2p)^{24}O in inverse kinematics, effectively knocking out a deeply bound valence proton from the ^{25}F nucleus [10]. This approach will utilize the R3B experimental setup, including the high-efficiency neutron detector NeuLAND, to achieve complete kinematic measurements and obtain accurate spectroscopic information on the populated final states of ^{24}O [11]. By analyzing the experimental data, researchers aim to determine the extent to which the single d5/2 proton in ^{25}F modifies the structure of the core nucleons, potentially indicating deformation or polarization of the ^{24}O core [12].

Ultimately, the goal of this experiment is to provide a more detailed understanding of the nuclear structure of neutron-rich fluorine isotopes and the underlying reasons for the extended neutron drip line at Z=9. The results will contribute to a more comprehensive picture of nuclear forces and structure in exotic nuclei, addressing a fundamental question in nuclear physics.

3.2 The GSI Accelerator System

GSI Helmholtzzentrum für Schwerionenforschung (GSI)
GSI
FRagment Separator (FRS)
FRS

3.2.1 Beam

Primary Beam: 40Ar 700 MeV/u
Beryllium Target at FRS -> Creates cocktail beam with 25F
Liquid Hidrogen Target in Cave C in center of CALIFA

3.3 R3B Setup

Reactions with Relativistic Radioactive Beams (R3B)
R3B
Time-of-Flight Detector (ToFD)
ToFD
New Large-Area Neutron Detector (NeuLAND)
NeuLAND
GSI Large Acceptance Dipole (GLAD)
GLAD
CALorimeter for In-Flight detection of gamma-rays and charged pArticles (CALIFA)
CALIFA
Resistive Plate Chamber (RPC)
RPC

3.3.1 Role of each detector

3.3.1.1 MWPCs

3.3.1.2 TwinMUSIC

3.3.1.3 LOS (Large-area Optical System)

Function: Measures the time of flight (ToF) and beam position.
How it works:

- Uses fast scintillators and photomultipliers (PMTs).
- Provides a reference start signal for ToF measurements.
- Crucial for precise velocity determination of incoming beam particles.

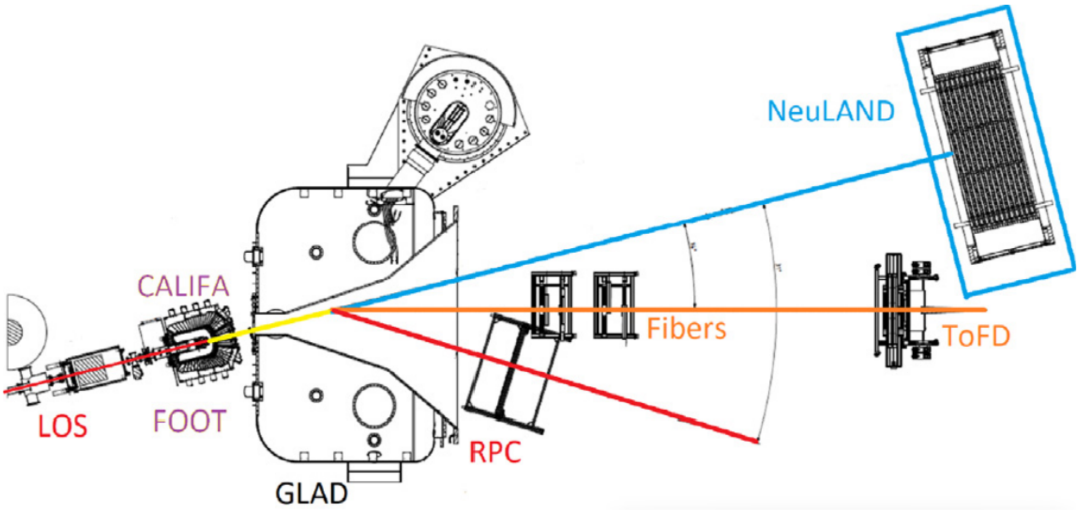

Figure 3.1: Schematic representation of the R3B setup.

Importance: Helps in identifying incoming beam particles before they interact with the target.

3.3.1.4 ROLU

3.3.1.5 CALIFA (CALorimeter for In-Flight detection of -rays and light charged particles)

Function: A gamma-ray and charged-particle calorimeter surrounding the reaction target.

Structure:

- High granularity for precise energy and angle measurements.
- Covers nearly 4 around the reaction point.

Detects:

- -rays from nuclear de-excitation.
- Light charged particles (e.g., protons, alphas).
- Helps in reconstructing excited states of nuclear fragments.

- Technology:

- CsI(Tl) scintillators coupled to SiPMs or PMTs.
- High energy resolution for -ray spectroscopy.

3.3.1.6 FOOTs

3.3.1.7 GLAD (GSI Large Acceptance Dipole Magnet)

Function: Bends charged particles to determine their momentum.

Key properties:

- Superconducting dipole magnet.
- Large acceptance (~80 msr) to handle high-energy reaction products.
- Used in combination with tracking detectors to reconstruct fragment momenta.

Why it's important:

- Essential for measuring momentum distributions, a key observable in QFS and knockout reactions.
- Helps reconstruct the missing momentum of removed nucleons.

3.3.1.8 NeuLAND (New Large-Area Neutron Detector)

Function: Detects neutrons produced in nuclear reactions [11].

Why it's crucial:

- Neutron knockout and quasi-free scattering involve neutron-rich final states.
- Neutron detection is challenging but necessary for reconstructing the full reaction kinematics.

Technology:

- Plastic scintillator bars with time-of-flight (ToF) measurement.
- Very fast response (~100 ps time resolution) to distinguish multiple neutrons.
- Large area (~30 m^2) to maximize detection efficiency.

What it measures:

- Neutron energy via ToF.
- Angular distribution of emitted neutrons.

Advantage:

- Much improved over its predecessor LAND [13], providing higher detection efficiency for multi-neutron events.

3.3.1.9 Fiber Trackers

Function: Track charged particles after the reaction.

Technology:

- Consists of plastic scintillating fibers.
- Read out by SiPMs (Silicon Photomultipliers).

Why it matters:

- Provides precise position information.
- Works in conjunction with other tracking detectors to reconstruct fragment trajectories.

3.3.1.10 ToFD (Time-of-Flight Detector)

Function: Measures the velocity of charged fragments for mass identification [14].

Why it's needed:

- In QFS and fragmentation reactions, products have different masses and need to be distinguished.
- ToF combined with tracking and momentum measurement allows isotope separation.

Technology:

- Plastic scintillators with fast timing resolution (~50 ps).
- High-speed photomultiplier tubes (PMTs) for precise ToF measurements.

3.3.2 Particular Role of RPC

[15]

3.3.3 Main DAQ

Each detector is connected to the main Data Acquisition (DAQ), everytime they have a trigger, they send a trigger request to the main DAQ. If multiple detectors send a trigger request, it is considered an event to register and the main DAQ sends an accept signal, allowing every detector to save that signal.

All of these saved signals of each detector are then saved in a common *lmd* file containing every detectors data separated by event.

There's a synchronization signal with around 10 Hz to make sure every detector is synchronized.

3.4 Personal Contribution to the Experiment

4

RPC

This is the 4th chapter epigraph.

4.1 Properties

4.2 Build (components, electronics, gas mixture, DAQ, etc.)

DAQ

4.2.1 RPC Build

- Active area of 1550x1250 mm^2 = 1.9 m^2.
- Two modules composed 6 gap RPC glass stacks.
- Gas mixture of C2H2F4 (98%) and SF6 (2%).
- Readout strips 3 cm width (placed in the middle of the two modules).
- Readout in both sides of the strips

4.2.2 RPC Electronics

4.2.3 RPC Gas Mixture

4.2.3.1 Pressure

The working pressure inside the chamber is lower than atmospheric pressure. This ends up being helpful because the atmospheric pressure itself compresses the RPC and makes everything tidy, aligned and without gaps.

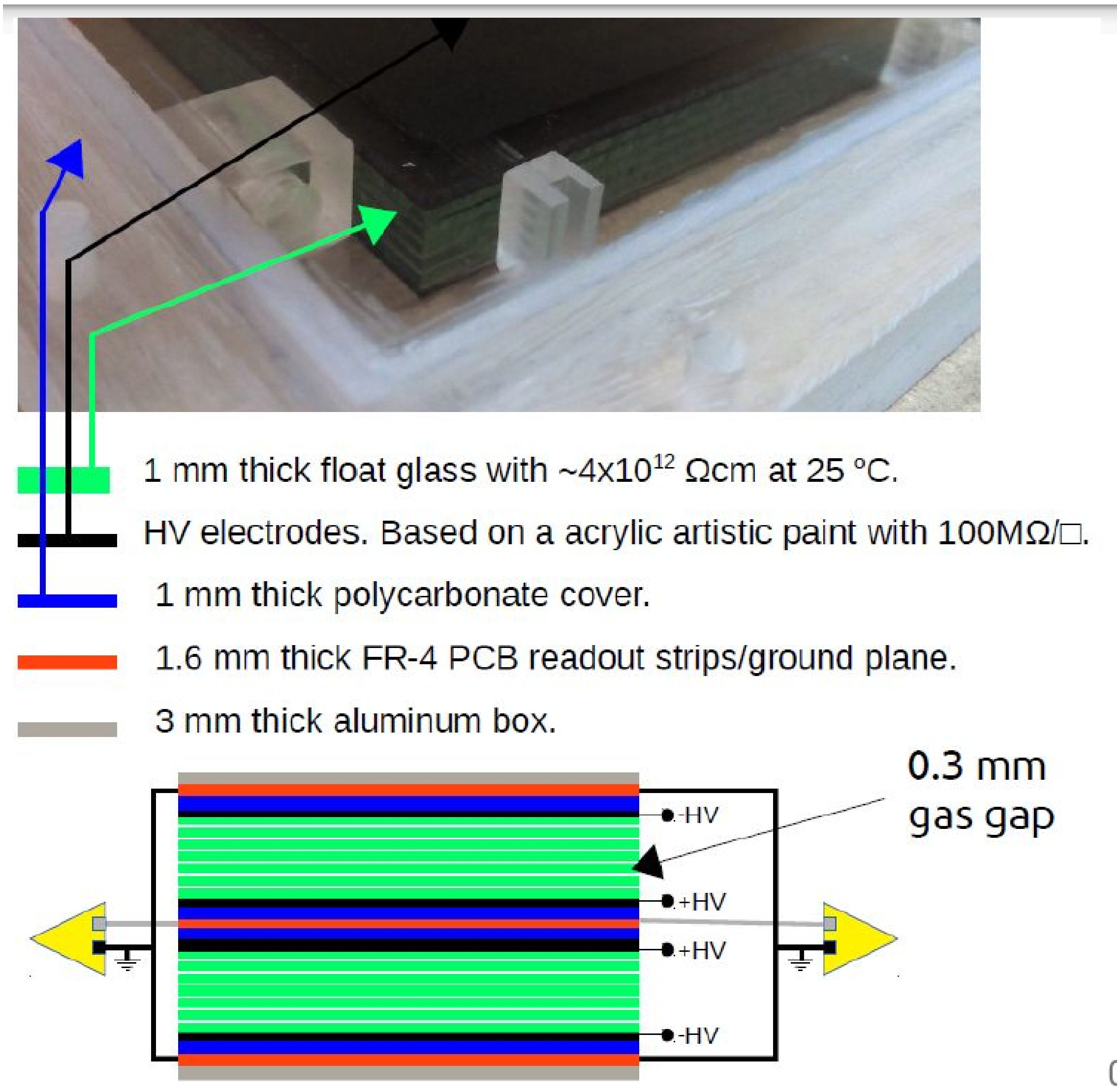

Figure 4.1: Schematic representation of the RPC.

4.2.3.2 Understanding the Role of the Gas Mixture in Resistive Plate Chambers (RPCs)

The gas mixture used in the Resistive Plate Chamber (RPC) at R3B consists of:

- 98% $C_2H_2F_4$ (Tetrafluoroethane, also known as R-134a, or Freon)
- 2% SF_6 (Sulfur Hexafluoride).

This specific gas combination plays a critical role in ionization, charge transport, avalanche formation, and quenching mechanisms inside the RPC. Below, the physics behind each component and their contributions to RPC performance are presented.

4.2.3.3 Role of $C_2H_2F_4$ (Tetrafluoroethane - Freon)

Primary Function: Ionization Medium and Avalanche Formation

$C_2H_2F_4$ is the main working gas, meaning that it provides the environment in which the ionization and charge multiplication take place.

Key Physics:

1. Ionization by Charged Particles

   - When a charged particle (e.g., a proton, electron, or ion) passes through the RPC, it ionizes the gas molecules, creating free electrons and positive ions.
   - The number of ionization events depends on the stopping power (dE/dx) of the particle.

2. Electron Acceleration and Avalanche Formation

   - The electric field inside the RPC accelerates the free electrons, leading to electron impact ionization.
   - This results in an avalanche process, where an initial electron triggers a chain reaction of ionization events.
   - $C_2H_2F_4$ has a moderate first ionization energy (11.7 eV), making it an efficient medium for this multiplication process.

3. High Electron Attachment and Low Diffusivity

   - Unlike noble gases (which have high electron mobility), $C_2H_2F_4$ has moderate electron attachment properties.
   - This prevents excessive diffusion of electrons, leading to more localized avalanches.
   - The electron mean free path is controlled to ensure controlled charge multiplication.

Why $C_2H_2F_4$ is Used Instead of Noble Gases?

- Noble gases like argon have too high a mobility, leading to excessive charge spread and loss of spatial resolution.

- $C_2H_2F_4$ is a polyatomic gas, meaning that it has multiple molecular vibrational modes, which help in absorbing excess energy and controlling the growth of the avalanche.

4.2.3.4 Role of SF_6 (Sulfur Hexafluoride)

Primary Function: Quenching Agent and Sparking Suppression

Although only 2% of the mixture, SF_6 is crucial for ensuring that the detector operates in a controlled avalanche mode rather than a full electrical breakdown (streamer mode).

Key Physics:

1. Electron Capture and Avalanche Control
   - SF_6 is a strong electronegative gas, meaning it has a very high affinity for capturing free electrons.
   - This limits the size of the avalanche, preventing uncontrolled charge growth.
   - By capturing electrons, SF_6 reduces the risk of streamer formation, which would cause sparking and damage the RPC.
2. Suppression of Discharges
   - SF_6 raises the dielectric strength of the gas mixture.
   - This prevents full electrical breakdown, where a single avalanche could trigger an arc discharge across the plates.
3. Quenching of Excited Molecules
   - SF_6 also helps in the de-excitation process by absorbing excess energy from excited $C_2H_2F_4$ molecules.
   - This prevents UV photon emission, which could trigger secondary avalanches and reduce timing resolution.

4.2.3.5 RPC Operating Regimes and How the Gas Mixture Affects Them

Three Operating Modes of an RPC:

1. Avalanche Mode (Preferred Mode)
   - The gas mixture ensures that charge multiplication occurs in a localized and controlled way.
   - SF_6 limits the avalanche size, allowing the detector to operate in a stable mode with high timing precision.
2. Streamer Mode (Unwanted)
   - If SF_6 were absent or insufficient, excessive charge buildup could lead to a transition from an avalanche to a streamer discharge.
   - This would reduce spatial resolution and could permanently damage the RPC electrodes.

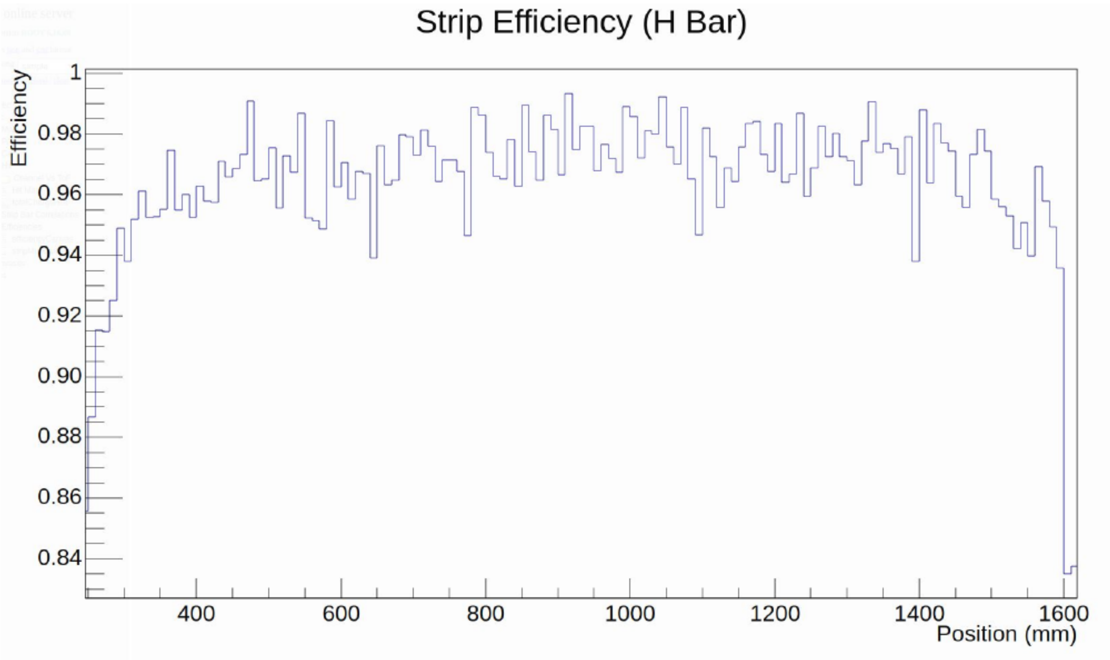

Figure 4.2: RPC Strip Efficiency

3. Breakdown Mode (Detector Failure)

   - If the gas mixture fails to prevent excessive charge growth, the detector enters a self-sustaining discharge, which can permanently damage the plates.

4.2.3.6 Final Thoughts

This 98% $C_2H_2F_4$ + 2% SF_6 mixture is carefully chosen to:

- Optimize avalanche growth for fast timing resolution.
- Prevent streamers and discharges that could damage the RPC.
- Ensure high efficiency in detecting charged particles.
- Provide a fast recovery time, allowing the RPC to operate at high rates.

4.3 Previous Experiments and Results

First Beam time at R3B:

RPC efficiency higher than 95 %. Good synchrony between RPC and the other detectors. Detector and DAQ were stable during the two weeks of beam time.

4.4 Preparation for an Experiment

Before each experiment Flash the RPC with SF_6 to dry out the interior. An alternative (SF_6 is expensive) is to use Nitrogen. One has to be careful with the flashing pressure because if it's too high it can inflate the RPC and damage it. This process takes about a week.

When preparing to insert the gas mixture in the RPC, to check if there are no leaks, one opens the gas bottles with the mass controllers closed and then closes the bottles and checks if the pressure drops in the gas line.

Then insert the gas mixture, place one vertical NeuLAND bar on each side and calibrate in coincidence with cosmis rays. This enables us to adjust the voltage of the electrodes and find the working point of the RPC. This process takes about a week.

4.5 Calibration

5

Simulations

Whenever there is a problem, it usually lies between the chair and the monitor.

5.1 Geant4

5.2 ROOT

5.3 R3BRoot

5.4 Plots

5.5 Conclusions for the Experiment

6

Results

This is the results chapter epigraph.

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A

NOVAthesis covers showcase

This Appendix shows examples of covers for some of the supported Schools. When the Schools have very similar covers (e.g., all the schools from Universidade do Minho), just one cover is shown. If the covers for MSc dissertations and PhD thesis are considerable different (e.g., for FCT-NOVA and UMinho), then both are shown.

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B

Appendix 2 Lorem Ipsum

This is a test with citing something [**ecoop12-dias**] in the appendix.

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I

Annex 1 Lorem Ipsum

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