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Jelena Vesić *

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Tracking Detectors in Nuclear Physics: An Overview

Jelena Vesić [1,*]

Jozef Stefan Institute, Jamova cesta 39, 1000 Ljubljana, Slovenia; jelena.vesic@ijs.si

Abstract: Advances in accelerator technology have enabled the use of exotic and intense radioactive ion beams. Enhancements to tracking detectors are necessary to accommodate increased particle rates. Recent advancements in digital electronics have led to the construction or planning of next-generation detectors. To conduct kinematically complete measurements, it is essential to track and detect all particles produced as a result of the reaction. Furthermore, the need for high-precision physics experiments has led to significant developments in the detector field. In recent years, highly efficient and highly granular tracking detectors have been developed. These detectors significantly enhance the physics programme at dedicated facilities. An overview of the charged-particle tracking detectors in low-energy nuclear physics will be given.

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1. Introduction

Advances in accelerator technology have enabled the use of exotic and intense radioactive ion beams. Tracking detectors are essential for accurately reconstructing the precise trajectories of nuclei. This is crucial for determining the kinematics of nuclear reactions and investigating the nuclei's structure. In the coming decades, progress in understanding nuclear structure properties and in general the field of low-energy nuclear physics will depend on high detection efficiency, high counting rate capabilities, and excellent time and position resolution of the tracking detectors. This has sparked the development of high-precision detectors and novel experimental techniques for the spectroscopy of γ-rays and particles. An overview of the charged-particle tracking detectors in low-energy nuclear physics will be given.

2. Tracking Detectors

The upcoming facilities such as FAIR (Facility for Antiproton and Ion Research) [1] and SPIRAL2 (The Système de Production d'Ions Radioactifs en Ligne de 2e generation) [2], will provide low-energy beams of radioactive isotopes with energies below 10 MeV/nucleon. The emittance of these new beams will necessitate the use of beam tracking detectors to accurately recreate the precise impact position of the nuclei on the experimental target. Nevertheless, due to their thickness, conventional detectors produce a significant amount of energy and angular straggling. To overcome that, the SED (Secondary Electron Detector) concept can be used. The fundamental concepts of emissive foil detectors have been understood since the 1960s [3]. The primary advantage of these detectors is that only the thin, emissive foil is in the path of the ions. This, in turn, minimises energy and angular straggling. The SED detector consists of two main parts: the emissive foil and the secondary electron detector. The emissive foil is a thin film of material, typically made of carbon or Mylar, positioned along the path of ions. The incoming ions cause the ejection of secondary electrons (SE) from the foil [4]. The electrons are then directed towards a secondary electron detector. SED provides information on the time and position of the secondary electrons, allowing for the determination of the ion's trajectory through the detector. Low-pressure gaseous detectors are frequently employed in nuclear physics. The detector operation at low pressure enables the use of thin windows. The ions traverse the detector and are identified through the ionization of the gas. In the case of a multi-wire proportional counter (MWPC), the process of ionization is enhanced during the avalanche regime, allowing for precise measurements of both time and position [5]. The SED detector reported in [6] has a comparable design to MWPC; it uses a thin emissive foil that is connected to a low-pressure gas chamber. The SED is not allocated along the path of the beam; instead, it identifies the cloud of secondary electrons ejected from an emissive foil. Both an electric field and a magnetic field direct the secondary electrons from the foil to the detector. The magnetic field is necessary to achieve a good position resolution [7]. The detector has a large effective area of 40x10 cm^2, and a thickness of only 250 mg/cm^2 (aluminized Mylar). It showed a good time and position resolution of 300 ps (FWHM, for heavy ions) and 1.4 mm (FWHM), respectively. The position resolution improved to 1 mm (FWHM) when using a smaller detector [6]. Additionally, it was reported that thinner foils, as low as 50 mg/cm^2 (carbon foils), can be used to further minimize straggling. The SED was used in VAMOS (VAriable MOde Spectrometer) [8] experiments and was employed in experiments with fission fragments. The performances attainable at SEDs in low-pressure conditions were comparable to, or even superior to, those achieved under atmospheric pressure. Micromegas (Micro-Mesh Gaseous Structure) detectors were invented in the nineties, and they have since gained significant popularity in the fields of particle and nuclear physics [9], [10]. Micromegas detectors consist of two distinct regions divided by a micromesh. The first region is a drift gap spanning several mm, characterized by a low electric field. The second region is an amplification gap spanning several tens of microns, characterized by a high electric field. When a charged particle traverses the gaseous detector, it primarily generates ionization electrons within the drift gap. The particles move towards the micromesh and are then transferred to the amplification gap, where they undergo a process called avalanche multiplication. Therefore, a signal can be detected either on the micromesh or on certain strips located on the other side of the amplification gap, facing the mesh. Nevertheless, the operational characteristics vary when the pressure is low. The fast charge collection results in exceptional timing characteristics and the ability to handle high counting rates. The advantages of wire chambers have been repeatedly established, particularly at normal pressure rather than at low pressure. The objective of the study in [11] was to assess the operational capabilities of the wire chamber detector under low-pressure conditions (several Torr) and to compare its performance with that of traditional wire chambers. Wire chambers are highly effective when operated under low-pressure conditions [12]. Significant progress has been made in enhancing the time resolution of micromegas detectors operating at low pressure (about 4 Torr). A series of micromegas detectors were tested in the laboratory under low-pressure conditions, revealing a good time resolution of 130 ± 30 ps, comparable to the findings reported from wire chambers [11]. The successful results achieved in prior experiments, which demonstrated high counting rate capabilities and excellent time resolution, have inspired the development of a new real-size 2D prototype wire chamber and a 2D bulk Micromegas operating at low pressure [13]. The spatial resolution of the Micromegas in the SED configuration was tested for the first time at low pressure (below 20 mbar) [13]. Various tests were conducted to analyse both prototypes' time and spatial properties. The spatial resolution in the horizontal (x) direction was found to be 0.90 (0.02) mm (FWHM) for the real-size prototype and 0.72 (0.08) mm (FFWHM) for Micromegas. For the real-size prototype, the time resolution was approximately 110 (25) ps. The specification requirements for the SED detectors are 150 ps for time resolution and 1 mm FWHM for spatial resolution S3-LEB (The Super Separator Spectrometer, Low Energy Branch, GANIL [13]). Spatial resolution requirements are set by the demand for the spectrometer to reach a mass resolution of 1/300, which is directly dependent on the SED trajectory reconstruction.

The large multistep position-sensitive multiwire proportional counters (MWPC) have been developed to detect fission fragments [14]. These experiments are conducted using a versatile scattering chamber at Inter University Accelerator Centre (IUAC) [15], New Delhi. The MWPC detectors have position sensitivity, providing information about both the horizontal and vertical positions of the particles that hit them. The detectors have an active area of 20 x 10 cm^2. The utilisation of a five-electrode geometry results in significant amplification at low pressures, enabling the generation of a fast-timing signal. Additionally, it facilitates the differential energy loss measurement, allowing for the effective discrimination between light and heavy particles. Experimental observations have yielded a timing resolution of 1.7 ns FWHM and a position resolution of 1.1 mm FWHM. R3B stands for "Reactions with Relativistic Radioactive Beams." A NUSTAR (Nuclear Structure, Astrophysics, and Reactions) collaboration performs inverse kinematics nuclear physics experiments. R3B has a setup with high efficiency, acceptance, and resolution for kinematically complete measurements of reactions with high-energy radioactive beams. The setup will be positioned in the focal plane of the high-energy branch of the (Superconducting Fragment Separator) Super-FRS [16] at FAIR. To conduct kinematically complete measurements, it is essential to detect all particles produced as a result of the reaction. Every event necessitates the individual detection of photons, neutrons, light-charged particles, and heavy residues. The Time-of-Flight Detector (TofD detector) [17] is an integral component of the R3B experimental setup. Its purpose is to determine the time-of-flight (TOF) and nuclear charge (Z) of heavy fragments following the reaction in the target. Accurate measurements of the fragments' energy loss (E) as they travel through the scintillator material determine the nuclear charge of reaction products. TofD should detect heavy-ion residues of all charges at relativistic energies. A sophisticated particle-tracking system can accurately identify relativistic ions ranging from hydrogen to uranium in terms of mass and nuclear charge. For Pb fragments, it is necessary to have a relative nuclear charge precision ($\sigma Z / Z$) of less than 0.4% to distinguish Z from Z-1. This imposes an energy-loss measurement with a relative precision $\sigma \Delta E/\Delta E$ better than 1% [17]. Another constraint on the performance of the new ToFD arises from the need to accurately identify residues based on their mass. Furthermore, the main obstacle arises from determining the heaviest residues in the Pb-U region, where the relative mass difference between adjacent nuclei is approximately 0.5%. To resolve the masses, the relative uncertainty in mass must be less than $2 \cdot 10^{-3}$. To achieve the needed mass resolution, it is necessary to measure the TOF of the heaviest residues with a relative error of less than $2 \cdot 10^{-4}$ (sigma) at an average beam energy of 1 GeV/nucleon ($\gamma \sim 2$). With a flight path of around 20 m, the TOF precision for nuclei in the Pb-U region at 1 GeV/ A kinetic energy better than 14 ps is needed. In addition, the ToFD detector must maintain its performance even when exposed to high beam rates of up to $1 \cdot 10^6$ pps (particles per second). The TofD detector has an active surface area measuring 1200×1000 mm^2 and is comprised of four planes of scintillators. Each plane features 44 vertical scintillator bars, each measuring 27x1000x5 mm^3. Photomultipliers are used to read out each bar on both far ends. The width of each bar is adjusted to match the dimensions of a PMT (photomultiplier tube) to eliminate the need for light guides. This allows for a direct connection between the scintillator bars and the PMTs, hence maximizing the efficiency of light collection. The initial results from the in-beam measurements conducted in the FAIR Phase-0 programme demonstrated that the desired objectives, namely achieving a precision of $\sigma \Delta E/\Delta E < 1\%$ in energy loss and a precision of $\sigma t / t < 0.02\%$ in time, have been accomplished [17]. This enables the complete identification of heavy ions up to the lead-uranium region in terms of mass and nuclear charge, in conjunction with a sophisticated particle-tracking system. The R3B setup will also use five detecting systems that rely on plastic scintillator fibres for in-beam tracking [18], [19]. The mass number A of beam-like particles can be calculated by analyzing the deflection of the beam in a magnetic field B, which follows the relation $B\varrho \propto A/Z$. To determine the radius of the trajectories in the magnetic field, it is necessary to measure the position of the particles at different positions. Three fibre detectors with an active area of 10×10 cm^2 will be used for position measurements before and after the target. These fibre detectors will be used to replace the Si detectors in tests with a high beam rate of 1 MHz. The detectors will be composed of square fibres measuring 0.2×0.2 mm^2, arranged in both the x and y directions to provide two-dimensional position measurements. A 40 cm wide fibre detector with a single layer of fibres (only measuring x-position) will be used for the initial position measurement following the magnet. This measurement will act as the reference point for determining the deflection angle. The distance between this detector and the subsequent position measurement is usually several meters, resulting in an angular measurement that is a small fraction of a mrad. Nevertheless, the primary factor influencing the measurement of the angle after the magnet is the angular straggling in the material of the detector. It is intended to use a larger fibre detector (measuring 120×80 cm^2) positioned at the end of the flight path.

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Gas detectors with a surface area of up to 2.6x1 m^2 [19], based on straw-tube technology, are being developed to accurately track the path of evaporating protons. Their positional accuracy is anticipated to range from 100 to 200 µm. Each Straw Tube Wall (STW) of the Proton Arm Spectrometer (PAS) [20] of the R3B collaboration will comprise three layers of straw tubes that are filled with a gas mixture at an overpressure of approximately 1 bar. The tubes are bonded together, with each layer being offset by one tube radius from the preceding layer. For an orthogonal proton track, the detection efficiency is lower near the tube wall but higher in the centre of the straw in the following layer. One plane will be constructed using Mylar tubes with a wall thickness of 60 µm, while the remaining three planes will be made from ultrathin aluminium tubes with a maximum wall thickness of 300 µm. While the angular straggling induced by these tubes is greater than that of the thin Mylar tubes, their impact on the angular resolution will be less due to their proximity to the end of the track.

The R3B Si-tracker [21] will encompass the target volume and detect light-charged particles, such as protons. The current detector technology uses double-sided silicon strip sensors that are wire-bonded to the specially designed R3B-ASIC (Application-Specific Integrated Circuit). The vacuum vessel can accommodate a maximum of three layers simultaneously, consisting of one inner layer and two exterior layers. The three layers consist of a total of 30 detectors, with 6 in the core layer and 12 in each of the two outer layers. The entire sensitive area is approximately 0.56 m^2, and there are 116736 front-end channels. The Si-tracker has angle coverage ranging from 6 to 103°. Angles are determined by measuring from the forward direction of the beam axis, with the nominal target position serving as the point of reference. The Si-tracker is an essential tool for studying reactions such as (p,2p) due to its capacity to trace recoils. The system measures the paths of recoiling protons and combines them to determine the primary vertex. The tracking information is combined with data from various sub-detector systems to accurately reconstruct the reaction kinematics. The angular resolution of a computed trajectory is a crucial factor in determining the accuracy of these measurements.

One of the latest advancements in R3B detection systems is a multi-gap Resistive Plate Chamber (RPC) [22]. The RPC detector consists of two multigap RPC modules [23] . The chamber contains twelve gaps measuring 0.3 mm each and is read by strips with a pitch of 30 mm. The RPC was integrated into the FAIR Phase 0 experiment and had the specific objective of measuring nucleon-nucleon short-range correlations (SRC) inside an exotic nucleus (^{16}C). Due to the detector's excellent timing precision, the determination of the momentum of forward-emitted protons with a resolution of around 1% was possible. The RPC had an efficiency of over 95% and a time precision better than 100 ps (which takes into account the contribution of a reference scintillator and the momentum spread of the particles) for forward-emitted particles.

At present, radioactive beams with energy ranging from below the Coulomb barrier to several hundred MeV/nucleon are available. These beams allow for a wide range of research on nuclei located near the drip line. To address the difference in intensity between secondary and primary beams, thick targets and high-efficiency detection methods are required. In this particular case, a type of detector known as an active target detector was created. These detectors use the detector gas as the target, and the ability to accurately determine the reaction vertex in three dimensions enables high resolution even when dealing with thick targets. The reaction products can be measured over nearly 4π. The use of active targets and time projection chambers (TPCs) in nuclear physics experiments spans over a few decades [24], [25], [26]. By employing the detecting medium as a target for nuclear reactions, it is possible to track charged particles, determine the location of reaction points, and subsequently compensate for the energy lost by charged particles within the target. The IKAR configuration at GSI served as the initial active target for nuclear physics experiments [27]. Over time, these kinds of detection systems had better performance than traditional experimental methods because they could identify particles, and track them in three dimensions. In addition, they could detect relatively low amounts of energy. Thanks to recent advancements in micro-pattern gaseous detectors (MPGDs) [28], [29], as well as the development of electronics (such as the General Electronics for TPCs project (GET) [30]) and data-acquisition systems (DAQ) with high data throughput and front-end data processing capabilities, modern active targets and time projection chambers can now achieve much higher channel densities than previously thought possible. The need for active targets and time projection chambers in the nuclear physics community has significantly increased due to the ongoing improvements in the generation and acceleration of short-lived beams of rare isotopes at radioactive ion beam (RIB) facilities worldwide.

The ACTive TARget and Time Projection Chamber (ACTAR TPC) is a novel detector created through a partnership of European laboratories and constructed at GANIL, France. It involves a charge projection plane that is divided into 128 × 128 square pads measuring 2 × 2mm^2. These pads are connected to the GET system. The GET system allows for the digitization of the signal at several frequencies selected by the user. A commissioning experiment using resonant scattering of an ^{18}O beam on an isobutane gas (proton) target was performed [31]. The ^{1}H(^{18}O, ^{18}O)^{1}H and ^{1}H(^{18}O, ^{15}N)^{4}He reaction channels were studied. The reaction channels could be differentiated by the scattered heavy ions in their ground state. The excitation functions in both channels were reconstructed and analysed to determine the centre-of-mass (cms) energy resolutions. The (p,p) channel resolved had a 38(4)keV FWHM, whereas the (p, α) channel had a resolution of 54(9)keV FWHM. Simulations indicate that the resolution is mostly determined by the angular resolution, which is in turn primarily influenced by the straggling of the ions in the gas. The latter could be reduced by substituting the isobutane gas target with pure hydrogen. The obtained resolution is similar to the 45 keV cms energy resolution obtained by the Active-Target Time Projection Chamber (AT-TPC) at Michigan State University. This resolution was measured for the ^{1}H(^{46}Ar, ^{46}Ar)^{1}H reaction [32]. The Active-Target Time Projection Chamber (AT-TPC) was recently constructed and put into operation at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. The AT-TPC is positioned within a 2T solenoidal magnetic field, which causes the paths of charged particles to bend. This bending increases the length of their tracks within the detector and allows for a more precise determination of their energy by magnetic rigidity. The AT-TPC is equipped with GET electronics. In the commissioning experiment of the AT-TPC, isobaric analogue states of ^{47}Ar in the excitation function of the elastic scattering reaction ^{46}Ar(p,p) in inverse kinematics [33], were measured. Using active target technology, excitation functions across a wide energy range were obtained. This was achieved with a cms energy resolution of 46 keV. A higher acceptance of scattering angles by using a true global multiplicity trigger module is expected. In addition, the increased density of proton scattering centres in pure hydrogen gas will improve the statistics of future proton scattering experiments. This improvement is made possible by the installation of a new thick Gas Electron Multiplier (GEM) device in front of the micromegas in the AT-TPC, which provides additional electron amplification [34]

MINOS (Magic Numbers Off Stability) focuses [35] on the spectroscopy of exotic nuclei using proton-knockout reactions. MINOS employs a thick liquid hydrogen target [36] to enhance the luminosity, together with a vertex tracker to maintain accurate vertex resolution for Doppler correction or momentum resolution in in-beam or invariant-mass spectroscopy studies, respectively. The vertex tracker is a TPC that has been hollowed out to form a cylindrical shape. It is equipped with a Micromegas detection pad plane that surrounds the target. During a proton-knockout reaction, such as a (p, 2p) reaction, the protons that are knocked out cause ionization of the gas as they pass through the TPC. The ionized electrons then go towards the detection area, where the signal is enhanced and subsequently recorded by specialized electronics

The ATS (Active Target for Selective Production of Exotic Species (SPES) facility [37]) project at INFN-LNL [38] will offer a reduced-scale ACTAR TPC detector that is optimized for the post-accelerated exotic beams provided by the SPES facility. Meanwhile, the SPECMAT project [39], installed at ISOLDE [40] (The Isotope mass Separator On-Line facility), will use the cylindrical configuration and magnetic field provided by the ISS (ISOLDE Solenoidal Spectrometer) facility to facilitate high-efficiency studies of inverse kinematics direct reactions.

TACTIC stands for the "TRIUMF Annular Chamber for Tracking and Identification of Charged-particles" [41]. TACTIC is a cylindrical, active-target TPC that offers a high level of detection efficiency. It incorporates a "shielding" cathode that captures the ionization produced by the beam,

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enabling larger intensities compared to standard TPCs. The 480 anode signals are collected via specialized electronics. The amplification of small signals is achieved by the utilization of a Gas Electron Multiplier (GEM). The He-CO2 fill gas serves the dual purpose of particle detection and provides a uniform and adjustable target for investigating reactions on alpha particles, such as ^{8}Li(α,n)^{11}B. The compact and uniquely designed start time detector T0 [42], was specifically designed for monitoring hypernuclear particles in the WASA-FRS HypHI experiment at GSI [43], [44]. It uses plastic scintillators that are read by the Multi Pixel Photon counter (MPPC). Even under high photon flux, MPPC has exceptional timing resolution, and its compact dimensions allow for the creation of a small and fast detector when combined with small plastic scintillators. In addition, its popularity has increased due to its reasonable costs, its insensitivity to magnetic fields, and its lower operating voltage in comparison to photomultiplier tubes (PMTs) [45], [46]. The detector's TOF resolution has been examined in relation to the overvoltage and breakdown voltage a maximum counting rate of roughly 3×10^{6} pps per segment, and a maximum beam charge of $Z = 6$. The TOF resolutions between adjacent segments of the detector varied from 44.6±1.3 ps to 100.3±3.6 ps (σ). The specific resolution depended on factors such as the segment, overvoltage values, and beam intensity. The resolution of the TOF between adjacent segments of the T0 counter has been studied concerning several operational factors, including overvoltage, counting rates, and beam atomic charges. The results indicate that the measured TOF resolutions for various adjacent segment combinations of the T0 counter are better than 86.0 ± 1.4 ps when exposed to ^{6}Li beams with beam intensities below 100 kHz. The estimated TOF resolutions of different segment combinations varied by a maximum difference of 41.4 ± 1.9 ps.

The next-generation in-flight magnetic separator, Super-FRS necessitates the use of advanced tracking detectors. Planar detectors composed of scintillating fibres are a reasonable choice due to their reasonable cost, as well as their fast response and high-rate capability. The SciFib prototype [47] comprised 128 fibres with a quadratic cross-section measuring 0.2×0.2mm^{2}. These fibres were connected to two MPPC arrays for the light collection that were then read out using an MPPC ReadOut Board (ROB), designed in GSI. The widths of the two reconstructed horizontal position distributions were comparable to the width observed with the standard FRS (Fragment Separator [48]) TPC detector, up to a rate of 10^{4} 197Au/spill

The GEM-TPC will be included as a component of the standard beam-diagnostics equipment for the Super-FRS. This chamber is capable of providing real-time tracking information for particle identification at frequencies of up to 1 MHz on an event-by-event basis. The essential operational criteria for these chambers include achieving nearly 100% tracking efficiency in high counting rate conditions, achieving spatial resolution below 1 mm, and having a wide dynamic range that encompasses projectiles with atomic numbers ranging from 1 to 92. The present detector comprises two GEM-TPCs housed within a single container, functioning autonomously with opposing electrical drift fields [49]. GEM-TPC consists of three main components: a field cage [50], a GEM stack, and front-end electronics. The GEM stack serves as an amplification stage and is composed of three GEM foils [51] that are separated by a distance of 2 mm each. This arrangement creates two transfer gaps and one induction gap. The last one is positioned between the third GEM foil and the anode strip plane. The operational concept relies on the production of primary electrons in the working gas following the passage of projectiles. The subsequent movement of these electrons, inside a very uniform electric field in the field cage, is directed towards the anode strips. Upon arrival, signals are generated like those of a standard time projection Chamber. However, the primary distinction is in the amplification stage, where the GEM-TPC utilises [49] a triple GEM stack, which allows for modulating the gain. The position resolution achieved in the horizontal plane (x-axis) was between 120 μm and 300 μm, and in the vertical plane (y-axis), it was 125 μm. There are indications that the intrinsic rate capability exceeds the minimum requirement of 1 MHz.

The NUSTAR collaboration, HISPEC/DESPEC (High Resolution In-Flight Spectroscopy/Decay Spectroscopy), aims to investigate the nuclear structure, reactions, and astrophysics questions using high-resolution spectroscopy. Particle identification at RIB facilities requires TOF detectors that provide the optimum time resolution and a high rate capacity. One potential approach being

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explored by the HISPEC/DESPEC collaboration involves using a segmented plastic scintillator as the TOF detector for the high rates. The readout is at both ends, using PMTs [52]. Two versions of this detector, named FINGER, have already been built, put into operation, and used for various experiments in the FRS, GSI. The detector's initial design consisted of 15 strips of BC420 plastic scintillator measuring 14 × 100 × 1 mm^3. A second detector with improved segmentation was constructed based on the results gained from the previous detector. That version was composed of 51 strips of BC420 material, each measuring 4.4 × 100 × 1 mm^3. Because of its segmentation, the detector was able to handle rates higher than 10^6 pps and had an intrinsic timing resolution below 40 ps (σ) [53], [54]. Moreover, the small segment size enabled the determination of position information, which can be used for particle identification. The increased momentum acceptance of the Super-FRS compared to FRS necessitates the construction of a third iteration of this detector, which will have a larger area coverage [55]. This requirement can be met by augmenting the quantity of strips, hence increasing the number of PMTs required and the intricacy of the mechanical design. SiPMs have been considered as the replacement for PMTs. SiPMs have been developed as a contemporary alternative to PMTs. Studies have demonstrated that SiPMs have several advantages, including their insensitivity to magnetic fields (allowing the use of scintillators in the proximity of magnetic spectrometers), cost-effectiveness, and lower voltage requirements. Furthermore, they are capable of achieving time resolutions similar to those achieved with PMTs [56], [57]. An effective method to address the significant segmentation of modern TOF detectors is to employ SiPMs as the readout. A prototype device composed of plastic scintillator strips measuring 4.4 × 100 × 1 mm^3 was tested [58]. The device was equipped with SiPMs of two different sizes for readout at both ends. The test was conducted using a ^{124}Xe beam with an energy of 600 MeV/nucleon. The timing and time-over-threshold data were extracted. The time resolution of the prototype was found to vary depending on the applied voltage and the size of the SiPM. By optimising the voltage, the achieved resolutions of 14.3(10) ps and 10.4(1) ps were for SiPMs measuring 1 × 1 mm^2 and 3 × 3 mm^2, respectively. The results indicated that SiPMs are appropriate for use as readout devices for plastic scintillators in RIB facilities.

In decay spectroscopy experiments, ions are usually stopped in an active implanter, and their subsequent decays are measured. The active implanter's role is to provide implantation times and positions and then detect the times and positions of subsequent decaying particles (α or β) while providing rough energy information to distinguish the decay processes. For fast timing measurements and neutron detection, for example, a time resolution of the implantation detectors lower than 1 ns and the capability to detect and distinguish between ion implantation and subsequent decays are highly demanded. Scintillating fibres are suggested for a Fibre IMPlanter (FIMP) of HISPEC/DESPEC to fulfil these requirements [59]. The basic idea is to stack the implanter from layers of orthogonally running fibre mats, assuming that β and α particles (or their associated secondary electrons) will hit at least one fibre in each of two consecutive layers so that complete position information is available.

Super-FRS at FAIR will produce unique exotic beams at relativistic energies. Slowing down of these ions (using the degrader) will allow to perform experiments at the Coulomb barrier. The HISPEC-10 project aims to use exotic beams with energies of 5-10 MeV/u for spectroscopy studies. The experiments at these energies have an advantage over higher beam energies (HISPEC) experiments because of the larger angular momentum transfer. In addition, transfer, resonance and fusion evaporation reactions can be used to explore realms of the nuclear landscape. Detectors employed for tracking of trajectory and measuring the velocity after the degrader should be as thin as possible to avoid any further energy and angular straggling of the beam. In addition, the tracking detectors should be large enough to cover the whole angular distribution of the slowed-down beam. Two thin transmission-type detectors, MCP (Micro Channel Plates) based, are planned to be used to track slowed-down fragments [60]. The ions impinging the foils produce secondary electrons that are then accelerated towards the MCP. Permanent magnets are employed to compel the electrons to follow circular trajectories due to the substantial distance between the foil and the MCP.

The LISA (Lifetime Measurements with Solid Active Targets) [61] project aims to develop an innovative technique for measuring atomic nuclei's lifetimes. To access the most exotic nuclei, it is necessary to employ thick targets of the thickness of approximately a few gm/cm^2 to maximise the luminosity. To reduce the subsequent deterioration in γ-ray energy resolution, one can replace the passive target with an active one that captures the reaction's position. The LISA experimental methodology relies on active solid targets, which will significantly expand the scope of measurements for excited-state lifetimes and, consequently, the attainable transition probabilities in exotic nuclei. The ion beam separated by the Super-FRS will impinge into a series of diamond detectors, causing direct proton knockout and nucleon removal reactions. The LISA active target will accurately identify the location of the reaction, allowing for the precise determination of the appropriate velocity β in the Doppler correction process. The experimental setup will enable the determination of the ejectile's velocity in the reaction on an event-by-event basis. By using advanced γ-ray tracking detectors like AGATA (The Advanced GAmma Tracking Array) [62], this innovative detector will effectively address the current obstacles to measuring lifetimes using low-intensity beams of unstable nuclei. The Advanced Implantation Detector Array (AIDA) [63], is an HISPEC/DESPEC novel detector system used to assess the decay properties of rare nuclei in RIB facilities. The system consists of stacks of silicon strip detectors, with each stack containing up to eight 8 cm × 8 cm, 128 × 128 strips (16384 pixels) or up to four 24 cm × 8 cm, 384 × 128 strips (49152 pixels) DSSSDs. This setup allows for precise measurement of the positions of implanted ions and their decay products, with accuracy reaching sub-mm. The high pixel density per detector enables the correlation of implantation and decay events at frequencies of about kHz. ASICs are used to handle signals from a large number of strips. These ASICs offer both low and high gain signal processing per strip, with a full scale range of 20 GeV and 20 MeV respectively. The dynamic range of these ASICs is 1000:1 and higher.

The first instance in which TOF measurements have been conducted using integrated electronics with a significant distance between the diamond detectors has been reported in [64]. The TOF capability of diamond detectors (intended to be possibly used as the tracking detectors for Super-FRS) with large surface areas, using polycrystalline samples measuring 20 mm × 20 mm and with a thickness of 0.3 mm, was demonstrated. The detectors, which had segmented Cr/Au electrodes arranged in a sandwich format, were exposed to a 1 GeV/nucleon ^{197}Au beam. When the detectors were placed with a separation distance of 2 cm, they exhibited a TOF resolution σ of 37.5 ps, which was calculated by averaging the results from 16 strip pairs. When TOF measurements were conducted over a particle trajectory spanning 30 m, a resolution of 45 ps was obtained. The detectors were mounted on printed circuit boards (PCBs).

The conventional method of particle identification involves simultaneous measurements of energy deposition, TOF, and magnetic rigidity. The reliability of such particle identification depends, in particular, on the accuracy of the time measurements. For example, for unambiguous identification of light ions with a mass number around 10, the time resolution can be about 300 ps, and for heavy isotopes like uranium, the time resolution of TOF detectors is more demanding and should be about 30 ps [65]. Such a stringent value poses a challenge to the detector's and the corresponding electronics' properties. Thus, fast radiation-hard silicon strip detectors (SSDs) for the TOF beam diagnostics at Super-FRS have been suggested. The results of the tests of radiation-resistant silicon detectors used for measurements in the Super-FRS and EXPERT projects [66] were presented in [65]. The study's primary focus was to investigate the timing properties of silicon detectors when exposed to radiation from intermediate-intensity Xe and C beams. The time resolution achieved for the detector prototypes exposed to Xe radiation is as low as 20 ps, while for C ions it was 100 ps [65].

A silicon tracker system [67] was specifically designed for conducting experiments using proton-rich RIBs at the SAMURAI [68] superconducting spectrometer of the RIBF (RIKEN RI Beam Factory). The system was specifically developed to achieve the precise reconstruction of angles and identification of atomic numbers for relativistic heavy ions and protons. These nuclei are produced in reactions involving the studies of proton capture reactions relevant to nuclear astrophysics. Highly efficient, exclusive measurements are necessary to compensate for the low intensities and poor quality and purity of secondary RIBs in comparison to primary beam studies. Reaction products are commonly measured in strongly focused forward kinematics due to the high relativistic energy involved. To reconstruct the reaction kinematics, it is critical to track the incoming and outgoing particles in order to extract both the relative energy and the scattering angle. The tracker consists of two sets of single-sided microstrip detectors that measure the coordinates (x, y) at two specific points along the beamline after the target. The system provides particle identification for protons and heavy fragments up to Z = 50, with energy ranging from 100 to 350 MeV/nucleon. The high granularity of silicon detectors is crucial for accurately distinguishing between distinct particle tracks and obtaining precise position information. This is achieved by selecting Si-strip detectors with a little pitch. A 325 μm-thick SSD of the GLAST-type [69] manufactured by Hamamatsu Photonics Company was selected. The silicon implant strip has a width of 56 μm and a pitch of 228 μm. For nuclear reaction research using rare isotope beams at low energies, an active target detector array called ANASEN (The Array for Nuclear Astrophysics and Structure with Exotic Nuclei) has been developed [70]. Its objectives are direct measurements of (α,p) interactions with exotic nuclei in inverse kinematics and measurements of the excitation functions for proton and alpha particle elastic and inelastic scattering. Three distinct types of charged particle detectors comprise ANASEN. For low-intensity radioactive beam tests, the active area's length is 340 mm, and the overall covered area is almost 3π. The readout consists of 480 high-density ASIC electronics channels specifically for the silicon detector and 78 conventional electronics channels for proportional counter and CsI detectors. Because of its cylindrical shape, ANASEN is a good choice for inverse kinematics reaction investigations with high efficiency. The target gas is used as an active gas for a cylindrical gas proportional counter area enabling the determination of the position of the reaction products. The light recoils are detected by a position-sensitive silicon-strip detector array backed with CsI detectors. The specific configuration of the gas detector electrodes and the silicon detector array enables the precise determination of the trajectory of each reaction product for each event. This allows for the determination of the reaction, center-of-mass energy, and final state.

The beams to be delivered at SPIRAL2, primarily consisting of fission fragments, will have a greater mass compared to the current GANIL beams. This means that the level densities will increase. Additionally, the incident energy of the beams will be similar or lower. The GASPARD collaboration [71] was established to construct a novel apparatus that is specifically tailored for the optimal investigation of direct interactions using these beams. Direct reactions play a crucial role in our comprehension of nuclear structure and nuclear astrophysics. Their reaction mechanism has a few degrees of freedom, enabling accurate theoretical calculations that provide essential nuclear structural information. These measurements can also provide valuable information on cross-sections that are significant in astrophysics. Light ion beams have been employed for many years to investigate heavier target nuclei in direct kinematics. The introduction of radioactive beams facilitated the expansion of direct reaction investigations to encompass a wide range of unstable nuclei. In this scenario, the reactions are conducted using inverse kinematics, where the radioactive beam is incident on the light probe. The GASPARD project centers [71] around the idea of a highly granular 4π particle silicon detector that can be seamlessly incorporated into available germanium arrays (AGATA, for example). By detecting gamma rays in conjunction with particles, it becomes possible to utilise thicker targets and achieve a significant improvement in excitation energy resolution compared to detecting particles only. Gamma-ray detection is essential for obtaining spectroscopic data on populated states. GASPARD also incorporates advanced particle identification algorithms that will be able to include special targets, such as a pure and windowless hydrogen target. The current detector configuration consists of a conical-shaped arrangement of eight trapezoidal telescopes in both the forward and backward hemispheres relative to the beam direction. The forward hemisphere has three layers of telescopes, while the backward hemisphere has two layers. Additionally, there is a ring of squared-shaped two-layer silicon telescopes around 90°, providing a solid-angle coverage of 4π. The outside diameter is suitable for the AGATA array. The first layer, composed of small-pitch DSSSDs, is designed to carry out PSD (position-sensitive

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detection), whereas the remaining layers are specifically used for measuring residual energy. The anticipated quantity of electronic channels is approximately 15,000.

The Optimised Energy Degrading Optics (OEDO) [72] beamline is an upgrade of the High-resolution beamline located at the RI Beam Factory in RIKEN. The goal of this beamline is to measure nuclear reactions induced by low-energy RIB(10-50 MeV/u) while maintaining a minimal energy dispersion. The construction of the TiNA [73] silicon detector array was initiated to investigate low-energy reactions at OEDO. TiNA is composed of position silicon detectors and CsI crystals.

The GRIT project (Granularity, Resolution, Identification, Transparency) [74] is about building a state-of-the-art portable Silicon detector array for efficiently investigating direct reactions. The system comprises a novel compact Silicon array with high granularity and a ~ 4π acceptance. The detector will be easily incorporated into other arrays like AGATA and PARIS [75] . The array comprises a series of stacked double-sided silicon strip detectors (DSSSD), with each stack consisting of two or three layers (three layers in the forward direction, two in the backward direction). This configuration yields over 7000 electronic channels of information. An integrated preamplifier, iPACI [76], has been developed for the GRIT array using the AMS 0.35 μm BiCMOS technology. This preamplifier is capable of providing charge and current information and is designed to handle a huge number of channels, exceeding 7000. The detector will be able to distinguish between the various masses of the incoming particles.

The DIAMANT [77], [78] is a highly granular and compact array made of CsI(Tl) scintillators. It is designed to be positioned at the centre of a gamma-ray array such as AGATA. This instrument is used for the detection of light-charged particles, such as alpha particles, protons, or deuterons, that are emitted during fusion-evaporation or transfer reactions. The array comprises a variable number of CsI(Tl) scintillators, ranging from 64 to 96, depending on the setup. Each of the detectors is equipped with charge-sensitive preamplifiers that operate in a vacuum. The preamplifiers are installed on a flexible printed circuit board (PCB) called FlexiBoard, which also serves as a self-supporting framework for the array. The primary component of DIAMANT is a rhombicuboctahedron, with two opposing square faces left vacant to allow the passage of the beam. The FlexiBoard may be unfolded from its quasi-spherical form, allowing easy access to the detectors. Downstream of the main structure, there are additional sets of detectors known as ForwardWall and ChessBoard. These sets consist of 8 and 24 detectors respectively. Their purpose is to enhance the level of granularity in the forward direction of the array. The DIAMANT was recently successfully integrated with the EAGLE [79] and NEDA [80] detection systems for the first time. The physics case for the commissioning and initial experiment was selected to be ^{57}Cu [81]. The case was selected to study an intricate balance between individual and collective motion within the atomic nucleus.

The MUGAST array [82] consists of the MUST2 detectors [83] positioned in the forward hemisphere, as well as additional detectors in the backward hemisphere. The MUST2 array [83] uses both dE-E and TOF approaches to identify particles. The detectors are composed of silicon strips of Si(Li)-CsI telescopes with thicknesses of 300 μm, 5 mm, and 4 cm, respectively. It is suitable for high-resolution measurements across an extensive range of energies, from 500 keV to 400 MeV. The integration of the MUGAST Silicon array with the AGATA array and VAMOS spectrometer presents a distinctive possibility to conduct unique experiments, enabling the precise determination of energy and momenta of all reaction products using radioactive beams.

The FAZIA array [84] is a recently developed detector specifically built for detecting charged particles in the Fermi energy range. It consists of three stages of telescopes: a 300 μm thick silicon detector, a 500 μm thick silicon detector, and a 10 cm CsI(Tl) detector. It encompasses 192 silicon-scintillator telescopes designed to detect and identify charged fragments generated in heavy ion fixed target reactions at beam energies ranging from 15 to 100 MeV/u. The pulse shape analysis (PSA) approach enables the identification of ions based on their charge and mass, even in cases where the usual ΔE-E method cannot be used. As a result, it significantly reduces energy thresholds. The telescopes provide accurate energy measurements for particles ranging from a few MeV protons to a few GeV heavy ions.

CHIMERA is a 4π detector array consisting of 1192 Si-CsI(Tl) telescopes, designed to detect both charged particles and γ-rays. The 4π coverage of the Si–CsI(Tl) telescopes and their ability to efficiently detect both charged particles and γ-rays over a broad solid angle can yield interesting results. It has been coupled with FARCOS, a correlator that possesses excellent energy and angular resolution.

The Silicon Tracker for Radioactive Nuclei Studies (STRASSE) [85] at SAMURAI Experiments [67], RIBF, RIKEN is a recently developed detection system that is currently being built. It is designed specifically for measuring quasi-free scattering (QFS) at energies of 200-250 MeV/nucleon. The system comprises a charged-particle silicon tracker connected to a specialised thick liquid hydrogen target, which can be up to 150 mm long. The system is designed to fit into large scintillator or germanium arrays compactly. The ultimate goal of the tracker is to achieve a reaction vertex resolution of less than 1 mm and a missing-mass resolution below 2 MeV in σ for (p,2p) reactions when used in conjunction with the CsI(Na) CATANA (CAesium iodide array for γ-ray Transitions in Atomic Nuclei at high isospin Asymmetry) array [86].

At the REX-ISOLDE facility [87] numerous successful transfer experiments have been conducted using the TREX [88] setup in combination with the γ-detector array MINIBALL [89]. T-REX is composed of compactly arranged position-sensitive ΔE-E telescopes, which cover up to 66% of the solid angle. The setup allows for the identification of light reaction products and the measurement of their angular distribution across a wide range of polar angles. The energy upgrade of the ISOLDE facility, High Intensity and Energy ISOLDE (HIE-ISOLDE) resulted in changes not just to the beam's energy definition, but also to its time structure and emittance, improving both. This led to a notably distinct set of criteria for the detectors, which must have the capability to handle heavy, neutron-rich beams with energies up to 10 MeV/u. An in-depth examination of these criteria, relying on the knowledge gained from the successful TREX array, resulted in the development of an enhanced successor, the Highly Integrated setup for Transfer Experiments at REX (HI-TREX) [90]. The readout will be performed through the FPGA (Field Programmable Gate Array.)-based GEAR platform for reading the data from the SKIROC2 ASICs. The trapezoidal shape of the sensors was chosen as a compromise between optimizing the detector array for specific physics scenarios and compatibility with the current infrastructure. Due to the lack of commercially accessible silicon sensors, a project was initiated to build a new detector. This project centres around the use of thin double-sided silicon strip detectors (DSSSDs) that have an exceptionally shallow entrance window

DAPPER stands for Detector Array for Photons, Protons, and Exotic Residues [91]. DAPPER is specifically developed to measure the properties of products resulting from (d,p) reactions conducted in inverse kinematics. DAPPER uses the proton kinetic energy to determine the excitation energy. It employs an array consisting of 128 BaF_2 scintillators to measure the gamma-ray multiplicity, total gamma-ray energy, and the energy of each gamma ray. The photon strength function is derived from this data. The (d,p) reaction serves as a substitute method for measuring nuclei that cannot be measured using the (n,γ) reaction. DAPPER's data provides constraints for predictive models of neutron capture

CsI(TI) detectors are a natural choice for the investigation of reaction dynamics. The study of charged particle energy spectra, specifically the emission of light charged particles like protons and alphas, allows for the investigation of the properties of heavy ion induced fusion and fusion-fission reactions near the Coulomb barrier. The setup at IUAC New Delhi, utilises a detector system consisting of 16 CsI(TI) detectors, each with dimensions of 20 mm by 20 mm and a thickness of 3 mm [92]. A thickness of this extent is adequate for stopping protons with energies of up to 25 MeV, as well as alphas with energies of up to 100 MeV. The alpha energy spectra region of interest, for the aforementioned physics motive, spans from 4 to 30 MeV, while the proton energy spectra region of interest ranges from 2 to 20 MeV. The crystals are detected using a 10 mm by 10 mm photo-diode. The crystals are connected to the photodiode using a square-shaped (non-tapered) Plexiglass light guide that has dimensions of 20mm x 20mm x 7mm. The front surface of the crystal is coated with a 2μm layer of Mylar that has been aluminized on both sides.

Conversion electron spectroscopy and E0 transition measurements are important techniques for studying nuclear structure. In coincidence measurement of electron and gamma ray can be used to unambiguously identify transitions and their conversion coefficients [93]. ICEBall [94] is a mini-orange spectrometer and is composed of six Si(Li) detectors equipped with six mini-orange magnet filters. In mini-orange magnetic filters, electromagnets are arranged in a manner like the segments of an orange. The magnet filters in this arrangement, known as the "orange spectrometer," generate a toroidal magnetic field to precisely guide the electrons. These designs enabled the placement of the source and detector outside of the magnetic field, resulting in enhanced detection efficiency and resolution compared to the solenoidal systems. The Si(Li) detectors have a total surface area of 750 mm^2 and are 5 mm thick. The front surface is covered with a thin layer of aluminized Mylar foil. The magnet filter is placed above the detector using a series of aluminium magnet holders. The existing array of six mini-orange Si(Li) detectors will be substituted with six new thicker Si(Li) detectors. The new magnet filters and detectors will convert ICEBall into the fIREBall [95] array.

SPectrometer for Electron Detection (SPEDE) [96] will be used alongside the Miniball spectrometer at the HIE-ISOLDE, CERN. SPEDE enables the direct detection of internal conversion electrons emitted during flight, without the need for magnetic fields to transport or filter the electrons based on their momentum. Together with the Miniball spectrometer, it allows for the simultaneous detection of γ rays and conversion electrons in Coulomb excitation studies with RIB.

The Silicon And GErmanium (SAGE) spectrometer [97] is used to measure the energies of conversion electrons and γ-rays that are emitted from excited states in nuclei produced in fusion-evaporation reactions. It is used together with the RITU gas-filled recoil separator [98], the great focal-plane spectrometer [99], and the K130 cyclotron [100] at the Accelerator Laboratory of the University of Jyväskylä. Gamma rays are detected using Ge-detectors positioned around the target chamber, while electrons are transported towards the target using solenoid magnets before finally being identified using a segmented Si-detector.

The SPectrometer for Internal Conversion Electrons (SPICE) [101] has been used in combination with the TIGRESS (TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer [102]) γ-ray spectrometer at TRIUMF's ISAC-II [103] facility. The SPICE uses a permanent rare-earth magnetic lens to efficiently gather and guide internal conversion electrons, onto a thick and highly segmented lithium-drifted silicon detector. SPICE combined with the TIGRESS enables the high-resolution in-beam spectroscopy of gamma rays and internal conversion electrons using both stable and radioactive ion beams. Commissioning tests have shown that the design of SPICE effectively reduces the flux of delta electrons, which usually interferes with electron measurements conducted in- beam. The SPES Low-energy Internal Conversion Electron Spectrometer (SLICES) [104] was built specifically for conducting internal conversion spectroscopy at the beta decay station of located at the INFN Legnaro National Laboratory (LNL) in Italy. This spectrometer integrates the superior energy and time resolution of the Si(Li) detector with the selectivity and high efficiency of the magnetic lenses. SLICES is comprised of a large Si(Li) detector that is cooled to a temperature of -150 °C, together with a magnetic transport mechanism. Four fixed N52 magnets, positioned around a central photon shield, focus the electrons onto the detector. To carry out internal conversion studies at iThemba LABS (Laboratory for Accelerator Based Sciences), an electron spectrometer (donated by IPN Orsay, France) that uses a solenoidal magnetic field acting as a lens and a Si(Li) detector has been refurbished [105] and characterized using calibration sources of internal conversion electrons. The spectrometer, equipped with an array of LaBr3:Ce detectors and Low Energy Photon Spectrometers (LEPS) [106], was successfully used for in-beam studies.

3. Conclusions

Particle detectors are an important component of experimental nuclear physics research. Recently, researchers have developed highly efficient and highly granular tracking detectors. These detectors significantly enhance the physics programme in dedicated facilities. Recent advancements in digital electronics have led to the construction or planning of next-generation detectors. Large particle detector systems are essential for understanding the atomic nucleus's characteristics, specifically exotic ones. This quest is very challenging and requires significant work in the field of nuclear physics. Nuclear physicists have significantly contributed to the advancement of particle detectors and their practical applications, particularly in the fields of medicine and national security. Accelerator science and technology, along with detectors, play a crucial role in enhancing the capabilities of nuclear physics. They empower the nuclear physics community to conduct cutting-edge research and develop applications that have wide-ranging societal advantages.

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