Nuclear Safeguards and Environmental Monitoring: A Survey

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Abstract

This survey paper comprehensively examines the suite of scientific methods and technologies employed for monitoring and analyzing nuclear materials and environmental samples. The focus is on ensuring compliance with nuclear non-proliferation agreements and understanding isotopic compositions through advanced techniques like mass spectrometry and radiometric analysis. These methodologies are crucial for detecting, quantifying, and comprehending the distribution and behavior of radioactive isotopes in various contexts. The paper systematically explores the role of nuclear safeguards and environmental monitoring in global security, emphasizing the significance of precise isotope measurements for compliance verification and environmental impact assessments. Key advancements in nondestructive assay methods, such as Passive Gamma Emission Tomography and Muon Scattering Radiography, are highlighted for their contributions to enhancing monitoring capabilities. The integration of particle analysis techniques and the strategic application of radioactive isotopes are discussed as central to advancing nuclear safeguards and environmental studies. Additionally, the paper addresses challenges and innovations in maintaining radiopurity and managing radioactive waste, as well as the role of neutrino detectors as non-intrusive monitoring tools. The survey concludes by underscoring the importance of continuous refinement of analytical methods and interdisciplinary collaborations to enhance nuclear security and environmental sustainability. Future research directions are suggested, emphasizing the need for improved isotope detection technologies and comprehensive environmental monitoring frameworks.

1 Introduction

1.1 Importance of Nuclear Safeguards and Environmental Monitoring

Nuclear safeguards and environmental monitoring are essential for global security and environmental protection, serving to verify compliance with nuclear non-proliferation agreements like the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) to prevent the diversion of nuclear materials for non-peaceful purposes [1]. Advanced technologies, such as the Passive Gamma Emission Tomography (PGET) system, enhance the sensitivity of spent fuel inspections, thereby strengthening monitoring capabilities within the NPT framework [2].

The TRIP facility at KVI exemplifies the production of short-lived radioactive isotopes at low kinetic energies, which are crucial for adhering to nuclear safeguards and conducting precision studies in fundamental physics [3]. Verification of contents in sealed dry storage casks containing spent nuclear fuel remains a significant challenge, emphasizing the need for robust safeguards to prevent nuclear material misuse [4].

Accurate measurement of trace concentrations of naturally-occurring and cosmic-ray-induced radioactive isotopes is vital for low-background experiments integral to dark matter searches and neutrino studies [5]. The Kamiokande Collaboration's investigation into production rates of radioactive iso-

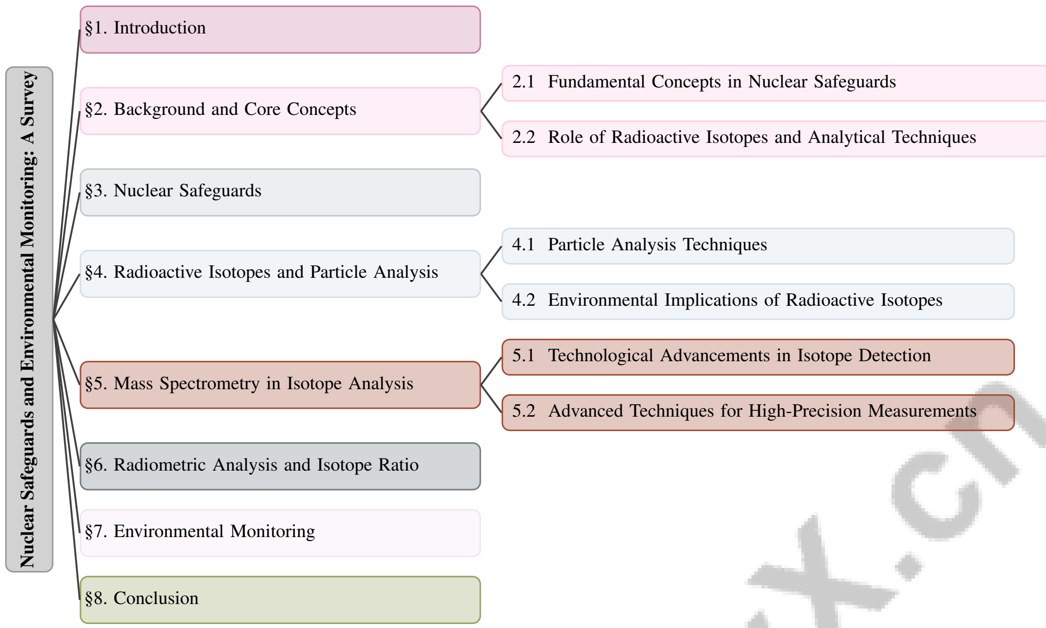

Figure 1: chapter structure

topes via cosmic-ray muon spallation is critical for understanding background events in neutrino detection, underscoring the necessity for precise environmental monitoring [6].

The demand for radiopure materials, such as polymers in rare event physics detectors, highlights the importance of minimizing background signals that could interfere with the detection of rare phenomena, including dark matter and solar neutrinos [7]. Identifying uranium materials based on their production processes is also crucial for nuclear forensics, aiding in provenance determination and enhancing nuclear safeguards [8].

Incorporating cutting-edge scientific methodologies and technologies in nuclear safeguards and environmental monitoring is essential for mitigating risks associated with radioactive isotopes. This integration enhances verification processes to prevent the diversion of nuclear materials from peaceful uses and improves monitoring of environmental contamination through advanced isotopic analysis and trace detection techniques. Such advancements ensure the safety and security of global nuclear activities by providing real-time verification and a deeper understanding of material provenance, thereby bolstering international non-proliferation efforts [8, 9, 10].

1.2 Structure of the Survey

The survey is systematically organized to explore the multifaceted aspects of nuclear safeguards and environmental monitoring. It begins with an introduction that emphasizes the significance of these practices in ensuring global security and environmental protection, followed by a detailed examination of fundamental concepts related to nuclear safeguards, radioactive isotopes, and environmental monitoring. Section three delves into specific methodologies and technologies employed in nuclear safeguards, including mass spectrometry and radiometric analysis for monitoring nuclear materials and ensuring compliance with non-proliferation agreements [1].

Section four focuses on the role of radioactive isotopes and particle analysis in nuclear and environmental studies, highlighting techniques that elucidate isotope distribution and behavior. The subsequent section discusses mass spectrometry in isotope analysis, emphasizing technological advancements and high-precision measurement techniques that enhance isotope detection [11]. Radiometric analysis and isotope ratio studies are explored in section six, which includes discussions on standards-based correction methods and applications of noble gas radionuclides [12].

The survey further addresses the importance of environmental monitoring within the context of nuclear safeguards, examining challenges and advances in radiopurity and waste management, as well as innovative non-intrusive techniques such as neutrino detectors [13]. The concluding section

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synthesizes key points discussed throughout the paper and suggests potential areas for future research, encouraging exploration beyond the topics detailed in the survey [1].The following sections are organized as shown in Figure 1.

2 Background and Core Concepts

2.1 Fundamental Concepts in Nuclear Safeguards

Nuclear safeguards are integral to the global non-proliferation regime, ensuring nuclear materials are confined to peaceful applications and supporting treaties like the NPT. These safeguards rely on meticulous monitoring, accounting, and verification processes to prevent the diversion of materials for weaponization, thus reinforcing global security [2]. Accurate characterization and quantification of radioactive isotopes are essential, particularly in nuclear forensics for determining material provenance [14]. The necessity of maintaining radiopurity in materials used for rare event physics, such as high-performance polymers, underscores the importance of minimizing background noise from contaminants like ^{232}Th and ^{238}U [15].

The historical evolution of nuclear mass understanding, highlighted by Audi, underscores the need for precision in nuclear safeguards [16]. Precision mass measurements, such as those for neutron-rich isotopes like cobalt, are crucial for nuclear structure studies and isotope behavior analysis [17]. Understanding spallation backgrounds in neutrino experiments necessitates precise measurement of isotope production rates in water [6]. Accurately determining decay rates of long-lived isotopes, amidst potential systematic uncertainties, remains a critical focus [18]. The transition to silicon photomultipliers in scintillation detectors enhances gamma radiation measurement precision, improving uranium enrichment analysis [19].

2.2 Role of Radioactive Isotopes and Analytical Techniques

Radioactive isotopes are pivotal in nuclear safeguards and environmental monitoring, offering insights into nuclear material characterization and environmental sample management. Accurate neutron capture cross-section measurements for unstable isotopes, particularly those with short half-lives, enhance nuclear material assessments and environmental impact analyses [20]. Techniques like AMS and ICP-MS have advanced trace isotope detection, essential for effective environmental monitoring and radioactive waste management.

In nuclear safeguards, precise isotope ratio determination verifies the origin and processing history of nuclear materials. Beale's estimator application in SIMS analysis reduces bias in isotope ratio estimation, improving nuclear material evaluations [21]. Combining dry ashing with ICP-MS achieves high efficiency and low detection limits for isotopes like ^{238}U and ^{232}Th, crucial for maintaining radiopurity in rare event physics materials [22].

Advanced techniques, including LIBS and laser spectroscopic helium isotope measurements, expand nuclear and environmental study capabilities. These methods enable real-time nuclear material analysis and precise isotope ratio measurements, supporting non-proliferation compliance and isotopic behavior understanding. Integrating these techniques with innovative detection systems, such as the -ToF detector, offers significant advantages in background reduction and measurement precision, facilitating the study of isotopes with low event rates [23].

Intercomparison of isotope ratio results through standard conversion is vital for consistency across analytical methods, as demonstrated in IRMS uncertainty studies [24]. The Kamiokande Collaboration's dataset provides valuable insights into isotope production rates and decay characteristics, crucial for understanding spallation backgrounds in neutrino experiments [6]. Monitoring gamma emissions from isotopes like ^{54}Mn and ^{60}Co underscores the importance of precise environmental monitoring [18].

Advancements in analytical techniques and strategic isotope application are fundamental to enhancing nuclear safeguards and environmental studies. These initiatives promote global security and environmental protection by implementing advanced monitoring and assessment techniques, such as stand-off neutron detection and antineutrino monitoring, to ensure compliance with international nuclear non-proliferation agreements. Real-time verification of nuclear material usage and potential diversion detection strengthen IAEA safeguards and contribute to the integrity of nuclear facilities worldwide [8, 25, 9].

In recent years, the evolution of nuclear safeguards has become increasingly critical in ensuring the security and integrity of nuclear materials. A comprehensive understanding of these safeguards requires an examination of their hierarchical structure, which can be effectively illustrated through the accompanying figure. Figure 2 presents a detailed categorization of nuclear safeguards into applications and nondestructive assay methods. This figure highlights the advanced analytical methods and detection systems that underpin these safeguards, including mass spectrometry and various monitoring techniques. Additionally, it delineates specific nondestructive assay techniques and the advancements made in precision and reliability, thereby providing a visual representation that complements the textual analysis presented herein. By integrating this visual element, we enhance our discussion of the complexities involved in nuclear safeguards and underscore the importance of these methodologies in contemporary nuclear security practices.

3 Nuclear Safeguards

3.1 Applications in Nuclear Safeguards

Advanced analytical methods are integral to ensuring compliance with nuclear non-proliferation agreements and enhancing the security of nuclear materials. Techniques like Passive Gamma Emission Tomography (PGET) utilize gamma-ray detectors to evaluate the gamma activity profiles of spent nuclear fuel assemblies, allowing for precise monitoring without compromising material integrity [2]. This approach employs sophisticated software to reconstruct cross-sectional images of spent fuel, identify fuel rods, and estimate their activity levels.

Precision mass measurements of neutron-rich isotopes significantly reduce mass uncertainty, facilitating accurate nuclear structure investigations and insights into shell closures, crucial for maintaining nuclear safeguards [17]. Enhanced nondestructive isotopic analysis methods improve energy resolution and analytical capabilities beyond traditional high-purity germanium detectors, essential for precise isotopic characterization required for nuclear material verification [26].

Large-area timing and position-sensitive detection systems offer high detection efficiency and simultaneous timing and position measurements, crucial for comprehensive nuclear material monitoring and adherence to non-proliferation standards [27]. Moreover, replacing photomultiplier tubes (PMTs) with silicon photomultipliers (SiPMs) in handheld gamma spectroscopy systems has improved energy resolution and temperature stability, enhancing the reliability of gamma spectroscopy for nuclear material compliance [19].

In mass spectrometry, methods that measure ion velocities and revolution times during Isochronous Mass Spectrometry (IMS) experiments enhance mass measurement precision, which is vital for isotopic composition analysis in nuclear safeguards [28]. The integration of advanced techniques, such as stand-off neutron monitoring, Neutron Resonance Capture Analysis (NRCA), Neutron Resonance Transmission Analysis (NRTA), and antineutrino detection, significantly enhances the monitoring, verification, and security of nuclear materials. These methods enable real-time assessment of fissile materials without direct reactor access, improving the detection of potential nuclear material diversions and supporting the International Atomic Energy Agency's (IAEA) mission to prevent proliferation and ensure the peaceful use of nuclear energy [8, 25, 29, 9].

Visual representations are pivotal in nuclear safeguards, as depicted in Figure 3. The first figure shows a water channel system with strategically placed poison rods, essential for controlling nuclear reactions. The arrangement of these rods in various colors, such as red, blue, and orange, highlights the precision required in nuclear safety mechanisms. The second figure illustrates a circular structure with a grid of colored squares, emphasizing geometric and spatial considerations in nuclear facility design. Each quadrant's distinct color arrangement reflects the meticulous planning necessary for effective nuclear safeguards, underscoring the importance of detailed design in maintaining control and security within nuclear environments [30, 31].

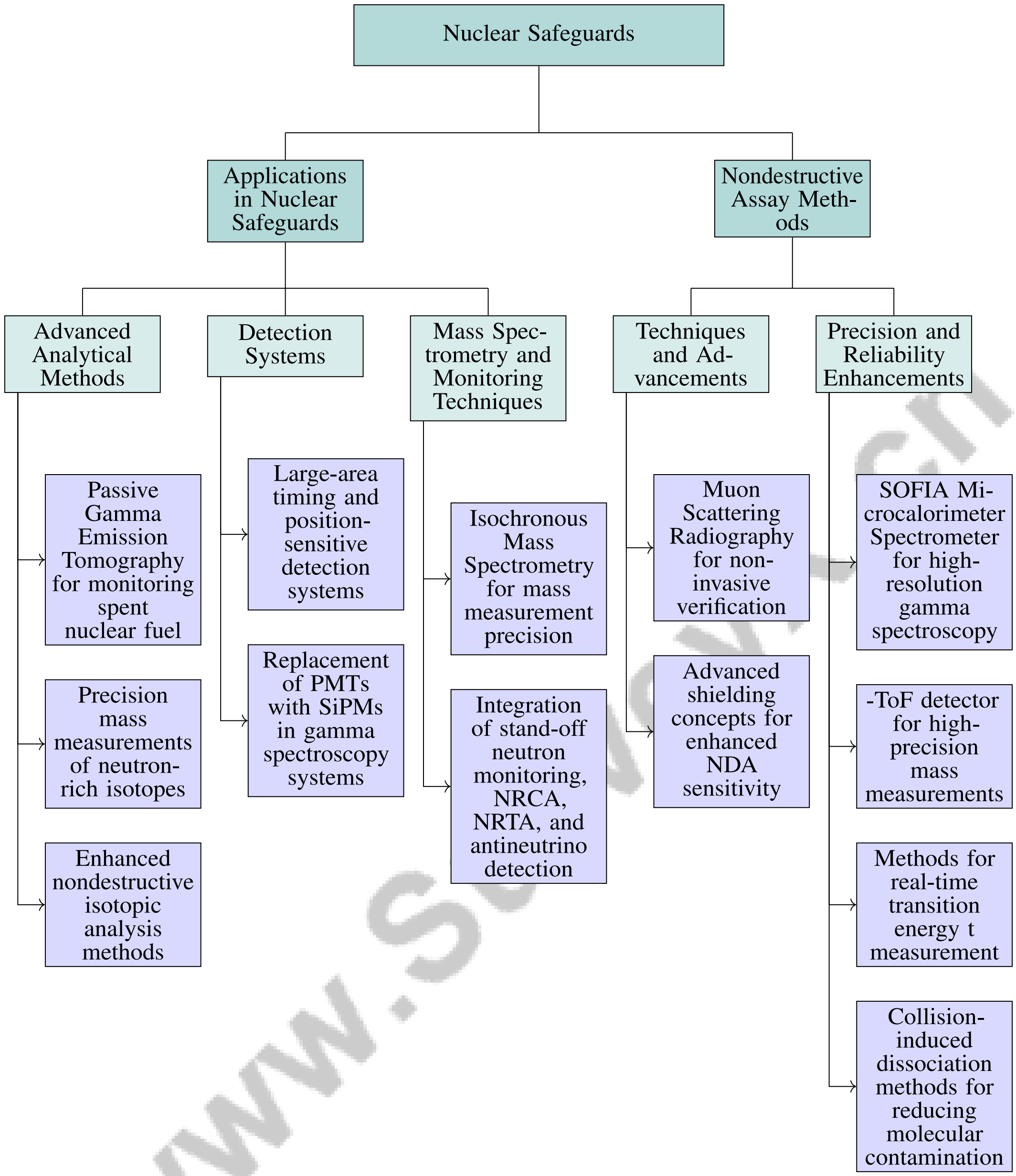
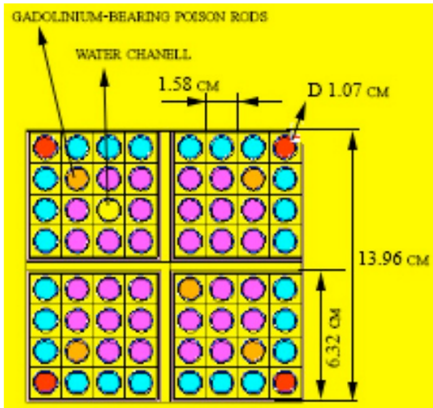


Figure 2: This figure illustrates the hierarchical structure of nuclear safeguards, categorized into applications and nondestructive assay methods. It highlights advanced analytical methods, detection systems, mass spectrometry, and monitoring techniques, along with specific nondestructive assay techniques and advancements in precision and reliability.

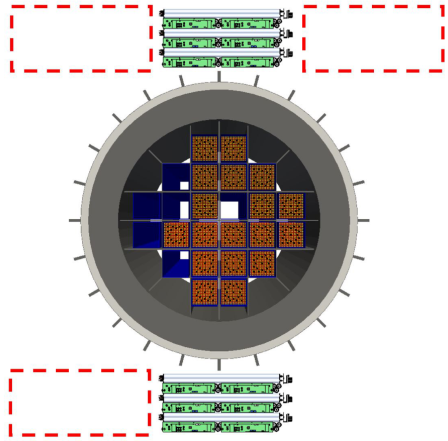
3.2 Nondestructive Assay Methods

Nondestructive assay (NDA) methods are crucial for analyzing nuclear materials, enabling comprehensive monitoring and verification without altering their physical or chemical state. These methods address the limitations of conventional techniques, often hindered by the heavy shielding required for nuclear materials. Techniques like Muon Scattering Radiography (MSR) provide non-invasive verification, overcoming these limitations [31].

Advanced shielding concepts, incorporating multiple layers and vetoing techniques, effectively reduce cosmic-ray backgrounds while preserving the ability to detect low-energy decays, enhancing NDA sensitivity and accuracy in challenging environments [32]. The SOFIA Microcalorimeter Spec-



(a) Water Channels and Poison Rods[30]



(b) Diagram of a Circular Structure with a Grid of Orange and Blue Squares[31]

Figure 3: Examples of Applications in Nuclear Safeguards

Method Name	Measurement Techniques	Technological Advancements	Application Context
MSR[31]	Muon Scattering Radiography	Muon Tracking Detectors	Nuclear Safeguards
LBGPC[32]	Muon Scattering Radiography	Sofia Microcalorimeter Spectrometer	Nuclear Non-proliferation
SOFIA[26]	Gamma Spectroscopy	Sofia Instrument	Nuclear Safeguards
-ToF[23]	Muon Scattering Radiography	-ToF Detector	Nuclear Non-proliferation
OMTE[28]	Two Tof Detectors	Real-time Determination	Ims Experiments
CID[33]	Muon Scattering Radiography	Sofia Microcalorimeter Spectrometer	Nuclear Non-proliferation

Table 1: Summary of nondestructive assay methods highlighting their measurement techniques, technological advancements, and application contexts in nuclear safeguards and non-proliferation. The table provides a comparative analysis of various methodologies, including Muon Scattering Radiography and Gamma Spectroscopy, alongside the technological innovations that enhance their effectiveness.

trometer exemplifies advancements in high-resolution gamma spectroscopy, enabling nondestructive isotopic analysis with improved precision [26].

The -ToF detector, utilizing a multi-reflection time-of-flight mass spectrograph, achieves high-precision measurements of atomic masses and decay properties, further enhancing NDA capabilities [23]. Recent methodologies that measure transition energy t in real-time address variability affecting mass measurements, thereby improving nondestructive analysis reliability [28]. Additionally, collision-induced dissociation (CID) methods significantly reduce molecular contamination in radioactive ion beams, supporting the precision of mass spectrometry and the nondestructive analysis of nuclear materials [33]. These advancements in NDA techniques are essential for ensuring compliance with nuclear non-proliferation agreements and maintaining nuclear material integrity, thereby bolstering global nuclear security efforts. Table 1 presents a detailed comparison of nondestructive assay methods, emphasizing their measurement techniques, technological advancements, and specific application contexts in the realm of nuclear material analysis.

4 Radioactive Isotopes and Particle Analysis

The examination of radioactive isotopes and particle analysis methodologies is crucial for understanding isotopic behaviors and ensuring nuclear safeguards and environmental monitoring. This section explores advanced particle analysis techniques that enhance our comprehension of isotopic distribution and behavior.

4.1 Particle Analysis Techniques

Particle analysis techniques are vital for studying radioactive isotopes, providing insights crucial for nuclear safeguards and environmental monitoring. Techniques at the TRIP facility, including magnetic separators and radio frequency buncher coolers, exemplify sophisticated approaches in isotope measurement [3]. Laser-Induced Breakdown Spectroscopy (LIBS) enables detailed isotopic composition analysis, using argon gas to create an aerosol from molten salt, which is essential for material compliance and environmental assessments [34].

The production and analysis of tritium-substituted methane through catalytic processes illustrate advancements in isotopologue concentration, vital for isotope distribution studies [35]. The SOFIA method, employing a multiplexed detector array, enhances isotopic analysis with high energy resolution and fast measurement rates [26]. Cosmogenic radionuclide production studies show good agreement between measured and theoretical isotope production rates, crucial for dark matter searches [36, 37].

Particle analysis techniques also enable the detection of ultra-low potassium contaminations in materials, achieving high sensitivity [38]. A customized setup with a low energy accelerator and a 4 BaF2 detector array advances neutron capture measurements on isotopes with short half-lives, providing insights into isotopic dynamics [20]. These methodologies support nuclear safeguards and environmental monitoring, enhancing our understanding of isotopic behavior and compliance with international agreements [8, 39, 40].

Figure 4 illustrates the complexity and precision of particle analysis techniques. The first image shows electron motion within a ring-end cap electrode system, essential for precision measurements [41]. The second figure highlights an algorithm for analyzing unlabelled data, focusing on isobaric contaminants [42]. The third image depicts a particle detector system, emphasizing the strategic placement of Time-of-Flight detectors [43]. These examples demonstrate ongoing advancements in particle analysis.

4.2 Environmental Implications of Radioactive Isotopes

Radioactive isotopes significantly impact ecological and geochemical processes. Noble gas radionuclides enhance environmental monitoring by tracing water movement and oceanic processes, contributing to understanding global cycles [10]. Despite advancements, questions remain about material activation yields and cosmic ray exposure effects on isotopes [44].

Ultra-low background liquid scintillation counting (ULB LSC) techniques expand isotope applications in environmental monitoring and nuclear accident tracking [45]. Tritium-substituted methane analysis enhances understanding of tritium chemistry, crucial for evaluating environmental impacts [35]. Identifying rare earth elements and impurities as provenance signatures highlights the complexity of isotopic measurements [8].

Isotopes like ^{96}Zr, with long half-lives, influence ecological processes over geological timescales, serving as markers for long-term environmental changes [46]. Studying isotopes in environmental contexts provides insights into their behavior and ecological impact, employing advanced techniques to trace radionuclides, assess pollution, and identify uranium signatures, thus enhancing our understanding of radioactive materials' dynamics and their potential effects on human health and the environment [41, 47, 8, 10, 40]. Integrating advanced analytical techniques is vital for understanding these dynamics and ensuring environmental protection amidst nuclear activities.

5 Mass Spectrometry in Isotope Analysis

Mass spectrometry plays a crucial role in isotope analysis, driven by ongoing technological advancements that enhance measurement capabilities. This section examines significant innovations in isotope detection, including the use of position-sensitive ion detectors in Penning trap mass spectrometry, the NAUTILUS instrument for spatially resolved trace isotope analysis, and phase-imaging ion-cyclotron resonance techniques that improve precision and speed [48, 49, 42, 50, 51].

5.1 Technological Advancements in Isotope Detection

Recent advancements in mass spectrometry have significantly improved isotope detection and analysis, supporting nuclear safeguards and environmental monitoring. Ultra-high-resolution microcalorimeter gamma spectroscopy enhances nondestructive isotopic analysis by providing superior energy resolution compared to traditional detectors [26]. The electrostatic mirror-type foil-MCP detector achieves high precision in timing and position measurements, crucial for monitoring isotopic distributions and compliance verification [27].

The transition from traditional photomultiplier tubes to silicon photomultipliers (SiPMs) in gamma spectroscopy systems has transformed the field, offering compactness, lower voltage requirements, and insensitivity to magnetic fields, thereby enhancing reliability across various environments [19]. Additionally, a method for online measurement of transition energy t has improved mass measurement accuracy in Isochronous Mass Spectrometry (IMS) experiments [28]. These innovations not only broaden the applications of mass spectrometry but also enhance the precision and reliability of isotopic analyses. The technique, particularly atomic mass spectrometry, is renowned for its superior sensitivity and accuracy in elemental analysis, bolstered by advancements in laser-induced breakdown and ablation methods. Innovations in instrumentation and software integration are driving productivity and miniaturization, expanding applications across scientific disciplines [49, 50].

5.2 Advanced Techniques for High-Precision Measurements

Advanced mass spectrometry techniques have substantially refined the precision and accuracy of isotopic measurements, essential for nuclear safeguards and environmental monitoring. Innovations such as position-sensitive ion detection in Penning trap mass spectrometry and the NAUTILUS instrument, combining secondary ion mass spectrometry (SIMS) with single-stage accelerator mass spectrometry (SSAMS), have markedly improved resolution and accuracy [21, 49, 51, 50]. The CHIP-TRAP project, utilizing dual precision traps, further enhances isotopic measurement precision by minimizing external noise.

The Ramsey method of separated oscillatory fields is instrumental in achieving narrower resonance peaks, leading to precise frequency determinations and improved mass measurement accuracy. Enhanced by the Linear Field Transition Model, this method achieves relative mass uncertainties below 1 ppm, vital for precision applications in nuclear physics, particularly in determining ground-state properties of radioactive isotopes. Techniques such as phase-imaging ion-cyclotron-resonance (PI-ICR) mass spectrometry and laser spectroscopy yield critical data on masses, binding energies, and nuclear properties, contributing to our understanding of nuclear structure and nucleosynthesis processes [52, 41].

Isochronous Mass Spectrometry (IMS) has advanced with B-defined methods, enabling simultaneous measurements of ion velocity and revolution time, thus enhancing mass precision and sensitivity for a broader range of ion species, including those with short half-lives [53, 54, 55, 43, 56]. This advancement allows for better discrimination of isomeric states.

Innovative techniques, such as low-pressure Time Projection Chamber (TPC) technology combined with Thick Gas Electron Multiplier (THGEM) readout, have enhanced Accelerator Mass Spectrometry (AMS) precision, achieving a 2

The development of an electrostatic mirror-type foil-MCP detector enhances timing and position measurement precision, critical for monitoring isotopic distributions in nuclear safeguards [27]. Advanced decay spectroscopy techniques, combined with charge breeding and Penning traps, have enabled high-precision measurements of short-lived isotopes. Collision-induced dissociation (CID) significantly improves the quality of mass measurements by reducing ion beam contamination, facilitating accurate mass determinations of radioactive isotopes, even those far from stability [57, 33].

These advanced techniques, including precision atomic physics methods and tandem inductively coupled plasma mass spectrometry (ICP-MS/MS), collectively enhance isotopic measurement accuracy and sensitivity. This high precision is crucial for applications ranging from nuclear safeguards and forensic analysis to environmental monitoring and fundamental nuclear property studies, supporting critical sectors such as nuclear physics and material analysis [41, 8, 57, 52, 51]. Continuous refinement of these methodologies allows researchers to achieve unprecedented accuracy and resolution, enhancing the reliability and applicability of mass spectrometric analyses across scientific fields.

As shown in Figure 5, mass spectrometry is a pivotal technique in isotope analysis, providing unparalleled precision in measuring isotopic masses and compositions. The scatter plot comparing the vibrational frequencies of ytterbium isotopes with their corresponding masses illustrates isotopic behavior by distinguishing between known and newly measured masses. The second image details a mass spectrometry system, essential for accurately measuring mass-to-charge ratios of ions, while the third image showcases particle tracking in a circular orbit, exemplifying the dynamics of isotopic distributions. Together, these methodologies highlight the sophisticated techniques employed in mass spectrometry, advancing scientific understanding of isotopic phenomena [58, 41, 42].

6 Radiometric Analysis and Isotope Ratio

6.1 Standards-Based Correction and Accuracy Enhancement

Standards-based correction methods are vital for enhancing the precision and reliability of radiometric analysis, especially in isotope ratio measurements critical for nuclear safeguards and environmental studies. Errors introduced during scale conversion can compromise isotopic measurement comparability, necessitating corrections to ensure consistency across analytical techniques [24]. Selecting appropriate metrics is crucial for quantifying decay rate measurement precision and assessing systematic influences, as shown by Angevaare et al. [18]. This approach is essential for refining accuracy in complex datasets where potential errors must be systematically addressed. Mayer et al. emphasize developing high-precision techniques for trace molybdenum isotopes, highlighting the reduction of interfering elements like zirconium to enhance accuracy [46], which is fundamental for compliance verification in nuclear safeguards.

Minimizing destructive techniques in isotopic analysis aligns with the goal of precise isotopic composition determination [26]. Future research, as suggested by Izzo et al., should refine mass measurements and explore the ordering of beta-decaying states in neutron-rich isotopes, broadening these methods' applicability [17]. Integrating advanced standards-based correction methods into radiometric analysis frameworks significantly improves isotope ratio determinations' precision and reliability. Techniques such as Penning-trap and storage-ring mass spectrometry, along with tandem inductively coupled plasma mass spectrometry (ICP-MS/MS) using hydrogen as a collision/reaction cell gas, enhance isotopic composition characterization. This precision is vital for effective nuclear safeguards and environmental monitoring, enabling accurate determinations of critical parameters like masses, binding energies, and isotopic ratios, essential for understanding nuclear structure, fundamental symmetries, and nucleosynthesis processes shaping the Universe's chemical abundances [41, 57].

6.2 Applications of Noble Gas Radionuclides and Radiometric Dating

Noble gas radionuclides and radiometric dating are crucial in environmental and nuclear studies, providing insights into radioactive isotopes' temporal and spatial dynamics. These techniques are essential for dating geological and environmental samples, enhancing our understanding of natural processes and human impacts. At the TRIP facility, radiometric dating techniques support environmental and nuclear research [59]. Future research includes improving laser cooling schemes for a broader range of isotopes, enhancing noble gas radionuclide applications in environmental studies [3].

Accurate isotope shifts and hyperfine structure constants measurement is essential for precise radiometric dating, as recent studies demonstrate [60]. This accuracy is crucial for analyzing geo-neutrinos, where precise decay spectra measurements assess radioactive isotopes' environmental impact. Such approaches contribute to understanding radioactive decay's role in natural heat production and geological processes. Noble gas radionuclides are invaluable for environmental monitoring, particularly in tracing groundwater movements and oceanic processes, offering a comprehensive view of water cycle dynamics. A benchmark study on NaI(Tl) crystals' cosmogenic activation illustrates isotopes like ^{22}Na and ^{3}H's relevance in dark matter searches, highlighting their broader applicability in environmental studies [36].

In nuclear studies, producing secondary beams of radioactive particles with narrow energy distributions facilitates experiments enhancing nuclear reactions and isotope behavior understanding [14]. The modified Wiley-McLaren mass spectrometer effectively captures uranium and gadolinium plasmas' dynamics, providing insights into ion compositions and translational temperatures, crucial for nuclear forensics applications. Future research should focus on expanding datasets to encompass various environmental conditions and refining models based on these observations [61]. Studying materials like stainless steel produced by smelting, achieving radioactivity levels comparable to those used in leading neutrino experiments, supports its use in future research [62].

Integrating noble gas radionuclides, such as ^{39}Ar, ^{81}Kr, and ^{85}Kr, with advanced radiometric dating techniques, including Low-Level Counting (LLC), Accelerator Mass Spectrometry (AMS), and Atom Trap Trace Analysis (ATTA), enhances our understanding of radioactive isotopes' complex dynamics in environmental and nuclear studies. These long-lived noble gas radionuclides are valuable for tracing groundwater and ocean water flows, while applying tandem ICP-MS/MS with hydrogen as a reaction cell gas improves detection limits and measurement accuracy of both stable and radioactive isotopes across various industries, including environmental monitoring and nuclear decommissioning [57, 10]. These methodologies support accurate isotopic distributions characterization and their environmental implications, contributing to global efforts in nuclear safeguards and environmental protection.

7 Environmental Monitoring

7.1 Challenges and Advances in Radiopurity and Waste Management

Managing radiopurity and radioactive waste effectively is a critical challenge in nuclear safeguards and environmental monitoring. Detection sensitivity and background interference pose significant obstacles, necessitating continuous updates and validations of measurement techniques to keep pace with advances in material science and detection technology [11, 63]. This is particularly crucial for developing sensitive detectors in rare event physics, where precise radiopurity assessments are essential [15].

Recent progress has enhanced detection capabilities and measurement techniques. The gaseous radiochemical method (FGRM) offers high sensitivity and real-time measurement, beneficial for environmental monitoring [64]. Monte Carlo simulations, especially those involving gamma-ray transport, improve the understanding of photon emissions and their interactions with environmental materials, aiding in experimental design and accuracy, particularly in dark matter detection [65, 36].

Accurate isotopic measurements are vital for radiopurity assessments and waste management, necessitating the calibration of reference materials [66]. Challenges include the lack of suitable commercial standards for isotopes like ^{7}Be and the need to optimize correction methods [67]. Future research should explore the effects of various therapeutic beams and address limitations in mass spectrometry methods, such as the modified Wiley-McLaren method, which lacks adequate mass resolution for isotope ratio analysis under high power ablation [68, 14].

Advancing detection technologies and methodologies is crucial for maintaining radiopurity and managing radioactive waste. This progress not only prevents the diversion of nuclear materials from peaceful applications but also reinforces global nuclear security and environmental protection initiatives. Large-area neutron detectors for stand-off monitoring can verify changes in fissile material composition without direct access to reactor cores, while techniques for identifying uranium signatures enhance forensic assessments and safeguards. Furthermore, cosmic ray muon radiography offers a non-invasive approach to inspecting heavily shielded nuclear facilities, supporting international arms control and non-proliferation efforts [8, 69, 1, 9].

7.2 Role of Neutrino Detectors and Non-Intrusive Techniques

Neutrino detectors are pivotal non-intrusive tools in environmental monitoring, offering innovative approaches to verifying nuclear activities without direct material interaction, thus preserving sample integrity and ensuring monitoring safety [11]. These detectors are particularly beneficial in scenarios where traditional methods face limitations due to accessibility or safety concerns, enabling continuous and remote nuclear activity monitoring.

Beyond basic monitoring, neutrino detectors provide insights into nuclear reactors' operational status and fuel composition. By analyzing antineutrino flux and energy spectrum, valuable information regarding the reactor's fuel cycle and burn-up processes is derived, crucial for nuclear safeguards and mitigating undetected nuclear material diversions. These analyses significantly contribute to environmental protection by ensuring nuclear energy production adheres to international non-proliferation agreements [25, 29, 70, 11, 9].

Innovative non-intrusive techniques, such as Coherent Photonuclear Isotope Transmutation (CPIT), are gaining prominence for potential applications in environmental science and nuclear medicine. CPIT offers a unique method for isotope transmutation, useful for radioactive waste remediation and medical isotope production, underscoring its relevance in environmental monitoring and management [71].

Future research should prioritize optimizing non-intrusive techniques across diverse domains, including analytical atomic spectrometry and nuclear forensics, by fully exploring their capabilities and addressing technical challenges. This includes enhancing laser-induced breakdown and laser ablation mass spectrometry for direct elemental analysis, improving fluorescence and ionization spectrometry through advanced laser technologies, and developing methodologies for standardless analysis of materials pertinent to nuclear safeguards. Efforts should focus on increasing the productivity, portability, and automation of analytical instrumentation, facilitating broader applications and advancements in nuclear science and environmental monitoring [8, 1, 50]. By advancing neutrino detectors and other non-intrusive methods, the field can enhance nuclear activity monitoring and management precision and safety, contributing to global nuclear security and environmental sustainability.

8 Conclusion

The integration of cutting-edge scientific methodologies and technologies is crucial for the effective implementation of nuclear safeguards and environmental monitoring. Techniques such as mass spectrometry and radiometric analysis are indispensable for ensuring adherence to nuclear non-proliferation agreements and for conducting precise isotopic composition studies, which are vital for characterizing and monitoring nuclear materials essential to global security and environmental protection. Nondestructive assay methods, including Passive Gamma Emission Tomography (PGET) and Muon Scattering Radiography (MSR), have significantly advanced the field by enabling the monitoring of nuclear materials without altering their state, thereby improving the precision and reliability of nuclear safeguards.

Particle analysis and the study of radioactive isotopes are fundamental in elucidating isotope distribution and behavior across various contexts, supporting both nuclear and environmental studies. The experiments conducted by the Kamiokande Collaboration underscore the necessity for refined measurement techniques and expanded datasets to enhance our understanding of spallation processes. The TRIP facility's capability to produce and trap radioactive atoms highlights the potential for precision measurements in beta-decay experiments, pointing to promising research directions.

Future research should focus on refining laser trapping techniques, expanding the range of isotopes studied, and addressing current experimental limitations to deepen our understanding of weak interactions and their potential extensions. Optimizing existing methodologies and fostering interdisciplinary collaborations are essential for developing integrated frameworks that encompass diverse analytical techniques. Moreover, enhancing databases with comprehensive information and improving criteria for isotopes with fewer detectable lines are imperative for advancing future research endeavors.

References

[1] A. C. Hayes. Applications of fission, 2023.

[2] Ming Fang, Yoann Altmann, Daniele Della Latta, Massimiliano Salvatori, and Angela Di Fulvio. Quantitative imaging and automated fuel pin identification for passive gamma emission tomography, 2020.

[3] L. Willmann, G. P. Berg, U. Dammalapati, S. De, P. Dendooven, O. Dermois, K. Jungmann, A. Mol, C. J. G. Onderwater, A. Rogachevskiy, M. Sohani, E. Traykov, and H. W. Wilschut. Aspects of cooling at the triμp facility, 2006.

[4] J Matthew Durham, D Poulson, J Bacon, DL Chichester, Elena Guardincerri, CL Morris, Kenie Plaud-Ramos, Wyn Schwendiman, JD Tolman, and Philip Winston. Verification of spent nuclear fuel in sealed dry storage casks via measurements of cosmic-ray muon scattering. *Physical Review Applied*, 9(4):044013, 2018.

[5] K. J. Dong. Measurement of trace i-129 concentrations in csi powder and organic liquid scintillator with accelerator mass spectrometry, 2005.

[6] Kamiokande Collaboration. First measurement of radioactive isotope production through cosmic-ray muon spallation in super-kamiokande iv, 2015.

[7] Amanda D. French, Sonia Alcantar Anguiano, Mary Bliss, Josef Christ, Maria Laura di Vacri, Rebecca Erikson, Khadouja Harouaka, Eric W. Hoppe, Jay W. Grate, and Isaac J. Arnquist. Mass spectrometric investigations into 3d printed parts to assess radiopurity as ultralow background materials for rare event physics detectors, 2022.

[8] Zsolt Varga, Judit Krajkó, Maxim Peńkin, Márton Novák, Zsuzsanna Eke, Maria Wallenius, and Klaus Mayer. Identification of uranium signatures relevant for nuclear safeguards and forensics. *Journal of radioanalytical and nuclear chemistry*, 312:639–654, 2017.

[9] BM Van der Ende, L Li, D Godin, and B Sur. Stand-off nuclear reactor monitoring with neutron detectors for safeguards and non-proliferation applications. *Nature communications*, 10(1):1959, 2019.

[10] P. Collon, W. Kutschera, and Z. T. Lu. Tracing noble gas radionuclides in the environment, 2004.

[11] Adam Bernstein, Nathaniel Bowden, Bethany L Goldblum, Patrick Huber, Igor Jovanovic, and John Mattingly. Colloquium: Neutrino detectors as tools for nuclear security. *Reviews of Modern Physics*, 92(1):011003, 2020.

[12] A. Jaries, S. Nikas, A. Kankainen, T. Eronen, O. Beliuskina, T. Dickel, M. Flayol, Z. Ge, M. Hukkanen, M. Mougeot, I. Pohjalainen, A. Raggio, M. Reponen, J. Ruotsalainen, M. Stryjczyk, and V. Virtanen. Probing the n=104 midshell region for the r process via precision mass spectrometry of neutron-rich rare-earth isotopes with the jyfltrap double penning trap, 2024.

[13] A. Dobi, C. Hall, S. Slutsky, Y. R. Yen, B. Aharmin, M. Auger, P. S. Barbeau, C. Benitez-Medina, M. Breidenbach, B. Cleveland, R. Conley, J. Cook, S. Cook, I. Counts, W. Craddock, T. Daniels, C. G. Davis, J. Davis, R. deVoe, M. Dixit, M. J. Dolinski, K. Donato, W. Fairbank Jr. au2, J. Farine, P. Fierlinger, D. Franco, G. Giroux, R. Gornea, K. Graham, G. Gratta, C. Green, C. Hagemann, K. Hall, D. Hallman, C. Hargrove, S. Herrin, M. Hughes, J. Hodgson, F. Juget, A. Karelin, L. J. Kaufman, A. Kuchenkov, K. Kumar, D. S. Leonard, G. Lutter, D. Mackay, R. MacLellan, M. Marino, B. Mong, M. Montero Díez, P. Morgan, A. R. Müller, R. Neilson, A. Odian, K. O'Sullivan, A. Piepke, A. Pocar, C. Y. Prescott, K. Pushkin, A. Rivas, E. Rollin, P. C. Rowson, A. Sabourov, D. Sinclair, K. Skarpaas, V. Stekhanov, V. Strickland, M. Swift, K. Twelker, J. L. Vuilleumier, J. M. Vuilleumier, M. Weber, U. Wichoski, J. Wodin, J. D. Wright, and L. Yang. Xenon purity analysis for exo-200 via mass spectrometry, 2011.

[14] James O. F. Thompson, S. Tahereh Alavi, Justin R. Walensky, and Arthur G. Suits. Time of flight mass spectrometry with direct extraction of a uranium plasma, 2020.

[15] Jay W. Grate, Isaac J. Arnquist, Eric W. Hoppe, Mary Bliss, Khadouja Harouaka, Maria Laura di Vacri, and Sonia Alcantar Anguiano. Mass spectrometric analyses of high performance polymers to assess radiopurity as ultra low background materials for rare event physics detectors, 2020.

[16] G. Audi. The history of nuclidic masses and of their evaluation, 2006.

[17] C. Izzo, G. Bollen, M. Brodeur, M. Eibach, K. Gulyuz, J. D. Holt, J. M. Kelly, M. Redshaw, R. Ringle, R. Sandler, S. Schwarz, S. R. Stroberg, C. S. Sumithrarachchi, A. A. Valverde, and A. C. C. Villari. Precision mass measurements of neutron-rich co isotopes beyond n=40, 2017.

[18] J. R. Angevaare, P. Barrow, L. Baudis, P. A. Breur, A. Brown, A. P. Colijn, G. Cox, M. Gienal, F. Gjaltema, A. Helmling-Cornell, M. Jones, A. Kish, M. Kurz, T. Kubley, R. F. Lang, A. Massafferri, R. Perci, C. Reuter, D. Schenk, M. Schumann, and S. Towers. A precision experiment to investigate long-lived radioactive decays, 2018.

[19] Tyana Stiegler, Kareem Kazkaz, Erik Swanberg, and Vladimir Mozin. Replacement of a photomultiplier tube with silicon photomultipliers for use in safeguards applications, 2020.

[20] R. Reifarth, R. C. Haight, M. Heil, F. Kaeppeler, and D. J. Vieira. Neutron capture measurements at a ria-type facility, 2004.

[21] R. C. Ogliore, G. R. Huss, and K. Nagashima. Ratio estimation in sims analysis, 2014.

[22] K. Ichimura, K. Chiba, Y. Gando, H. Ikeda, Y. Kishimoto, M. Kurasawa, K. Nemoto, A. Sakaguchi, Y. Takaku, and Y. Sakakieda. Development of a method to measure trace level of uranium and thorium in scintillation films, 2024.

[23] T. Niwase, M. Wada, P. Schury, H. Haba, S. Ishizawa, Y. Ito, D. Kaji, S. Kimura, H. Miyatake, K. Morimoto, K. Morita, M. Rosenbusch, H. Wollnik, T. Shanley, and Y. Benari. Development of an "α-tof" detector for correlated measurement of atomic masses and decay properties, 2019.

[24] B. P. Datta. Pros and cons of the technique of processing irms data as desired-delta values: uncertainty and comparability in results, a case study for determining carbon and oxygen isotopic abundance ratios as co_2^+, 2013.

[25] Christopher Stewart, Abdalla Abou-Jaoude, and Anna Erickson. Employing antineutrino detectors to safeguard future nuclear reactors from diversions. *Nature communications*, 10(1):3527, 2019.

[26] Mark Croce, Daniel Becker, Katrina E. Koehler, and Joel Ullom. Improved nondestructive isotopic analysis with practical microcalorimeter gamma spectrometers, 2021.

[27] Zhuang Ge. Development of a large-area timing and position-sensitive foil-mcp detector for mass measurements at the rare-ri ring in riken, 2024.

[28] R. J. Chen, X. L. Yan, W. W. Ge, Y. J. Yuan, M. Wang, M. Z. Sun, Y. M. Xing, P. Zhang, C. Y. Fu, P. Shuai, X. Xu, Y. H. Zhang, T. Bao, X. C. Chen, X. J. Hu, W. J. Huang, H. F. Li, J. H. Liu, Yu. A. Litvinov, S. A. Litvinov, L. J. Mao, B. Wu, H. S. Xu, J. C. Yang, D. Y. Yin, Q. Zeng, X. H. Zhang, W. H. Zheng, X. H. Zhou, and X. Zhou. A method to measure the transition energy γ_t of the isochronously tuned storage ring, 2018.

[29] Carlos Paradela, Jan Heyse, Stefan Kopecky, Peter Schillebeeckx, Hideo Harada, Fumito Kitatani, Mitsuo Koizumi, and Harufumi Tsuchiya. Neutron resonance analysis for nuclear safeguards and security applications. In *EPJ Web of Conferences*, volume 146, page 09002. EDP Sciences, 2017.

[30] Dina Chernikova, Syed F. Naeem, Nermin Trnjanin, Kåre Axell, and Anders Nordlund. Gamma rossi-alpha, feynman-alpha and gamma differential die-away concepts as a potential alternative/complement to the traditional thermal neutron based analysis in safeguards, 2015.

[31] J. M. Durham, D. Poulson, J. Bacon, D. L. Chichester, E. Guardincerri, C. L. Morris, K. Plaud-Ramos, W. Schwendiman, J. D. Tolman, and P. Winston. Verification of spent nuclear fuel in sealed dry storage casks via measurements of cosmic ray muon scattering, 2018.

[32] Craig E. Aalseth, Paul H. Humble, Emily K. Mace, John L. Orrell, Allen Seifert, and Richard M. Williams. Shielding concepts for low-background proportional counter arrays in surface laboratories, 2015.

[33] A. Jacobs, C. Andreoiu, J. Bergmann, T. Brunner, T. Dickel, I. Dillmann, E. Dunling, J. Flowerdew, L. Graham, G. Gwinner, Z. Hockenbery, B. Kootte, Y. Lan, K. G. Leach, E. Leistenschneider, E. M. Lykiardopoulou, V. Monier, I. Mukul, S. F. Paul, W. R. Plaß, M. P. Reiter, C. Scheidenberger, R. Thompson, J. L Tracy, C. Will, M. E. Wieser, M. Yavor, J. Dilling, and A. A. Kwiatkowski. Collision-induced dissociation at triumf's ion trap for atomic and nuclear science, 2022.

[34] Ammon N Williams and Supathorn Phongikaroon. Laser-induced breakdown spectroscopy (libs) in a novel molten salt aerosol system. *Applied spectroscopy*, 71(4):744–749, 2017.

[35] Deseada Díaz Barrero, Thanh-Long Le, Simon Niemes, Stefan Welte, Magnus Schlösser, Beate Bornschein, and Helmut H. Telle. The generation and analysis of tritium-substituted methane, 2023.

[36] J. Amare, S. Cebrian, C. Cuesta, E. Garcia, C. Ginestra, M. Martinez, M. A. Olivan, Y. Ortigoza, A. Ortiz de Solorzano, C. Pobes, J. Puimedon, M. L. Sarsa, J. A. Villar, and P. Villar. Production and relevance of cosmogenic radionuclides in nai(tl) crystals, 2015.

[37] R. Saldanha, W. G. Thompson, Y. Y. Zhong, L. J. Bignell, R. H. M. Tsang, S. J. Hollick, S. R. Elliott, G. J. Lane, R. H. Maruyama, and L. Yang. Cosmogenic activation of sodium iodide, 2022.

[38] K. J. Dong. Measurement of ultra-low potassium contaminations with accelerator mass spectrometry, 2007.

[39] G. B. Kim, A. R. L. Kavner, T. Parsons-Davis, S. Friedrich, O. B. Drury, D. Lee, X. Zhang, N. Hines, S. T. P. Boyd, S. Weidenbenner, K. Schreiber, S. Martinson, C. Smith, D. McNeel, S. Salazar, K. Koehler, M. Carpenter, M. Croce, D. Schmidt, and J. Ullom. Decay energy spectrometry for improved nuclear material analysis at the iaea nml, 2024.

[40] Alexis Aguilar-Arevalo, Xavier Bertou, Carles Canet, Miguel A. Cruz-Pérez, Alexander Deisting, Adriana Dias, Juan Carlos D'Olivo, J. Francisco Favela-Pérez, Estela A. Garcés, Adiv González Muñoz, Jaime Octavio Guerra-Pulido, Javier Mancera-Alejandrez, Daniel José Marín-Lámbarri, Mauricio Martínez-Montero, Jocelyn Monroe, Sean Paling, Simon Peeters, Paul R. Scovell, Cenk Türkoglu, Eric Vázquez-Jáuregui, and Joseph Walding. Contextual isotope ranking criteria for peak identification in gamma spectroscopy using a large database, 2022.

[41] Klaus Blaum, Jens Dilling, and Wilfried Nörtershäuser. Precision atomic physics techniques for nuclear physics with radioactive beams, 2012.

[42] Colin M. Weber, Dwaipayan Ray, Adrian A. Valverde, Jason A. Clark, and Kumar S. Sharma. Gaussian mixture model clustering algorithms for the analysis of high-precision mass measurements, 2021.

[43] Xing Xu, Meng Wang, Peng Shuai, Rui-Jiu Chen, Xin-Liang Yan, Yu-Hu Zhang, You-Jin Yuan, Hu-Shan Xu, Xiao-Hong Zhou, Yuri A. Litvinov, Sergey Litvinov, Xiao-Lin Tu, Xiang-Cheng Chen, Chao-Yi Fu, Wen-Wen Ge, Zhuang Ge, Xue-Jing Hu, Wen-Jia Huang, Da-Wei Liu, Yuan-Ming Xing, Qi Zeng, and Wei Zhang. A data analysis method for isochronous mass spectrometry using two time-of-flight detectors at csre, 2016.

[44] Susana Cebrian. Cosmogenic activation of materials, 2017.

[45] J. L. Erchinger, C. E. Aalseth, B. E. Bernacki, M. Douglas, E. S. Fuller, M. E. Keillor, S. M. Morley, C. A. Mullen, J. L. Orrell, M. E. Panisko, G. A. Warren, R. O. Williams, and M. E. Wright. Development of a low background liquid scintillation counter for a shallow underground laboratory, 2015.

[46] Adam J. Mayer, Michael Wieser, William Matthews, and Robert Ian Thompson. Measuring the isotopic composition of trace elements in zircon: application to radiogenic molybdenum, 2018.

[47] Goutam Hatra. Radioactive pollution: An overview. *The holistic approach to environment*, 8(2):48–65, 2018.

[48] Matthew Redshaw, Richard A. Bryce, Paul Hawks, Nadeesha D. Gamage, Curtis Hunt, Rathnayake M. E. B. Kandegedara, Ishara S. Ratnayake, and Lance Sharp. Status and outlook of chip-trap: the central michigan university high precision penning trap, 2015.

[49] G. Eitel, M. Block, A. Czasch, M. Dworschak, S. George, O. Jagutzki, J. Ketelaer, J. Ketter, Sz. Nagy, D. Rodriguez, C. Smorra, and K. Blaum. Position-sensitive ion detection in precision penning trap mass spectrometry, 2009.

[50] A. A. Bol'shakov, A. A. Ganeev, and V. M. Nemets. Prospects in analytical atomic spectrometry, 2006.

[51] Evan E. Groopman, David G. Willingham, Albert J. Fahey, and Kenneth S. Grabowski. An overview of nrl's nautilus: A combination sims-ams for spatially resolved trace isotope analysis, 2019.

[52] Jonas Karthein, Dinko Atanasov, Klaus Blaum, David Lunney, Vladimir Manea, and Maxime Mougeot. Analysis methods and code for very high-precision mass measurements of unstable isotopes, 2021.

[53] M. Zhang, X. Zhou, M. Wang, Y. H. Zhang, Yu. A. Litvinov, H. S. Xu, R. J. Chen, H. Y. Deng, C. Y. Fu, W. W. Ge, H. F. Li, T. Liao, S. A. Litvinov, P. Shuai, J. Y. Shi, R. S. Sidhu, Y. N. Song, M. Z. Sun, S. Suzuki, Q. Wang, Y. M. Xing, X. Xu, T. Yamaguchi, X. L. Yan, J. C. Yang, Y. J. Yuan, Q. Zeng, and X. H. Zhou. $b\rho$-defined isochronous mass spectrometry and mass measurements of ^{58}ni fragments, 2022.

[54] J. H. Liu, X. Xu, P. Zhang, P. Shuai, X. L. Yan, Y. H. Zhang, M. Wang, Yu. A. Litvinov, H. S. Xu, K. Blaum, T. Bao, H. Chen, X. C. Chen, R. J. Chen, C. Y. Fu, D. W. Liu, W. W. Ge, R. S. Mao, X. W. Ma, M. Z. Sun, X. L. Tu, Y. M. Xing, J. C. Yang, Y. J. Yuan, Q. Zeng, X. Zhou, X. H. Zhou, W. L. Zhan, S. Litvinov, T. Uesaka, Y. Yamaguchi, T. Yamaguchi, A. Ozawa, and B. H. Sun. Improving the resolving power of isochronous mass spectrometry by employing an in-ring mechanical slit, 2019.

[55] M. Wang, M. Zhang, X. Zhou, Y. H. Zhang, Yu. A. Litvinov, H. S. Xu, R. J. Chen, H. Y. Deng, C. Y. Fu, W. W. Ge, H. F. Li, T. Liao, S. A. Litvinov, P. Shuai, J. Y. Shi, M. Si, R. S. Sidhu, Y. N. Song, M. Z. Sun, S. Suzuki, Q. Wang, Y. M. Xing, X. Xu, T. Yamaguchi, X. L. Yan, J. C. Yang, Y. J. Yuan, Q. Zeng, and X. H. Zhou. $b\rho$-defined isochronous mass spectrometry: a new approach for high-precision mass measurements of short-lived nuclei, 2022.

[56] P. Shuai, X. Xu, Y. H. Zhang, H. S. Xu, Yu. A. Litvinov, M. Wang, X. L. Tu, K. Blaum, X. H. Zhou, Y. J. Yuan, X. L. Yan, X. C. Chen, R. J. Chen, C. Y. Fu, Z. Ge, W. J. Huang, Y. M. Xing, and Q. Zeng. An improvement of isochronous mass spectrometry: Velocity measurements using two time-of-flight detectors, 2016.

[57] B Russell, SL Goddard, H Mohamud, O Pearson, Y Zhang, H Thompkins, and RJC Brown. Applications of hydrogen as a collision and reaction cell gas for enhanced measurement capability applied to low level stable and radioactive isotope detection using icp-ms/ms. *Journal of Analytical Atomic Spectrometry*, 36(12):2704–2714, 2021.

[58] D. A. Nesterenko, R. P. de Groote, T. Eronen, Z. Ge, M. Hukkanen, A. Jokinen, and A. Kankainen. High-precision mass measurement of ^{168}yb for verification of nonlinear isotope shift, 2020.

[59] M. Sohani. Trimp - a new facility to produce and trap radioactive isotopes, 2006.

[60] L. B. Wang, P. Mueller, R. J. Holt, Z. T. Lu, T. P. O'Connor, Y. Sano, and N. C. Sturchio. Laser spectroscopic measurement of helium isotope ratios, 2003.

[61] The KamLAND Collaboration. Production of radioactive isotopes through cosmic muon spallation in kamland, 2010.

[62] Ghulam Hussain, Zhi Zeng, Chunfa Yao, Mohan Li, Ziyi Guo, Lei Guo, Zhe Wang, and Shaomin Chen. Assay of low-background stainless steel by smelting for the neutrino experiment at jinping, 2017.

[63] V. Alvarez, I. Bandac, A. Bettini, F. I. G. M. Borges, S. Carcel, J. Castel, S. Cebrian, A. Cervera, C. A. N. Conde, T. Dafni, T. H. V. T. Dias, J. Diaz, M. Egorov, R. Esteve, P. Evtoukhovitch, L. M. P. Fernandes, P. Ferrario, A. L. Ferreira, E. D. C. Freitas, V. M. Gehman, A. Gil, A. Goldschmidt, H. Gomez, J. J. Gomez-Cadenas, D. Gonzalez-Diaz, R. M. Gutierrez, J. Hauptman, J. A. Hernando Morata, D. C. Herrera, F. J. Iguaz, I. G. Irastorza, M. A. Jinete, L. Labarga, A. Laing, I. Liubarsky, J. A. M. Lopes, D. Lorca, M. Losada, G. Luzon, A. Mari, J. Martin-Albo, A. Martinez, T. Miller, A. Moiseenko, F. Monrabal, C. M. B. Monteiro, F. J. Mora, L. M. Moutinho, J. Munoz Vidal, H. Natal da Luz, G. Navarro, M. Nebot, D. Nygren, C. A. B. Oliveira, A. Ortiz de Solorzano, R. Palma, J. Perez, J. L. Perez Aparicio, J. Renner, L. Ripoll, A. Rodriguez, J. Rodriguez, F. P. Santos, J. M. F. dos Santos, L. Segui, L. Serra, D. Shuman, A. Simon, C. Sofka, M. Sorel, J. F. Toledo, A. Tomas, J. Torrent, Z. Tsamalaidze, D. Vazquez, J. F. C. A. Veloso, J. A. Villar, R. C. Webb, J. T. White, and N. Yahlali. Radiopurity control in the next-100 double beta decay experiment: procedures and initial measurements, 2013.

[64] S. G. Lebedev and V. E. Yants. Gaseous radiochemical method for registration of ionizing radiation and its possible applications in science and industry, 2005.

[65] Valentin Niess, Kinson Vernet, and Luca Terray. Goupil: A monte carlo engine for the backward transport of low-energy gamma-rays, 2024.

[66] B. P. Datta. Prospects of ratio and differential $(\delta) ratiobasedmeasurement - models : acasestudyforirmsevaluation$, 2015.

[67] Li Zhang and Yun-Chong Fu. Preliminary study of 10be/7be in rainwater from xi'an by accelerator mass spectrometry, 2016.

[68] Przemysław Sękowski, Izabela Skwira-Chalot, and Tomasz Matulewicz. Measurement of proton-induced radiation in animal tissue, 2018.

[69] J. Matthew Durham. Cosmic ray muon radiography applications in safeguards and arms control, 2018.

[70] S. Oguri, Y. Kuroda, Y. Kato, R. Nakata, Y. Inoue, C. Ito, and M. Minowa. Reactor antineutrino monitoring with a plastic scintillator array as a new safeguards method, 2014.

[71] H. Ejiri and S. Date. Coherent photonuclear reactions for isotope transmutation, 2011.

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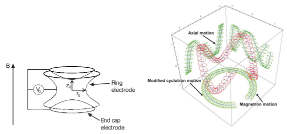
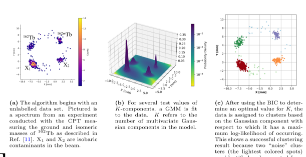
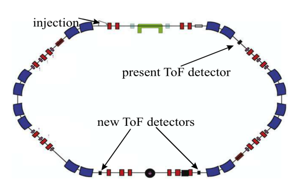


(a) Electron Motion in a Ring-End Cap Electrode System[41]

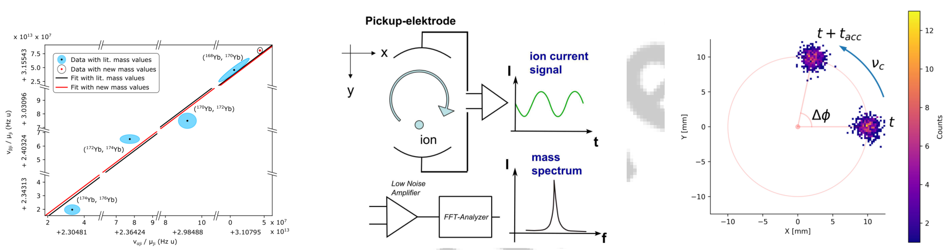


(b) The algorithm begins with an unlabelled data set. Pictured is a spectrum from an experiment conducted with the CPT measuring the ground and isomeric masses of 162Tb as described in Ref. [11 .X1 and X2 are isobaric contaminants in the beam.[42]]



(c) The image depicts a schematic of a particle detector system, highlighting the presence and placement of new and existing ToF (Time-of-Flight) detectors.[43]

Figure 4: Examples of Particle Analysis Techniques



(a) The image shows a scatter plot comparing the vibrational frequencies of ytterbium isotopes with their corresponding masses.[58]

(b) Mass Spectrometry System[41]

(c) Particle Tracking in a Circular Orbit[42]

Figure 5: Examples of Advanced Techniques for High-Precision Measurements