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Recent developments in the AMS system at the Nuclear Science Laboratory: Impacts on radionuclide sensitivities and current capabilities

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ABSTRACT

In recent years, the AMS system at the Nuclear Science Laboratory of the University of Notre Dame has introduced a series of upgrades which have dramatically increased the capabilities for the measurement of trace radionuclides. These upgrades have solved issues with isotopic selectivity in the injection system, allowed for the measurement of heavier radionuclides, and improved the quality of both ion beams and the data obtained with them. The specifics of the installed equipment, as well as preliminary results on isotopic sensitivities for previously measured and newly-developed radionuclides, are discussed. Finally, the impacts on the development of planned radionuclide measurements in the future, including measurements of the actinides, will be mentioned.

1. Introduction

Accelerator Mass Spectrometry (AMS) is a method for particle identification based on isotopic and isobaric discrimination, using methods from nuclear and atomic physics. AMS takes the traditional elements of mass spectrometry, which is typically performed at the keV scale, and introduces an accelerator for particle analysis on the MeV scale. Because of its selectivity, AMS is used for the measurement of trace concentrations of isotopes (typically radionuclides), capable of measuring content of one part in 10^{16} [1]. The radionuclides are typically measured with respect to one or multiple stable beam current(s) to report an isotopic ratio, or with respect to a spike isotope when a stable beam is unavailable.

The AMS program of the Nuclear Science Laboratory (NSL) of the University of Notre Dame, begun in 2003, has successfully developed the capabilities for the measurement of several radionuclides with a focus towards nuclear astrophysics. The Browne–Buechner spectrograph at the NSL, initially set up for the measurement of nuclear reactions [2], was altered for the use of the Gas-Filled Magnet (GFM) technique for isobar separation. This system, both the GFM technique and the NSL AMS detection system, has been described in detail in previous literature [3]. The measurement techniques for the radionuclides ^{36}Cl, ^{44}Ti, and ^{60}Fe have been established with this system, despite some indication that the detection limits for each isotope were influenced by neighboring masses tailing through the injection system.

Along with the upgrade to the spectrograph, and the switch from a single-cathode National Electrostatics Corporation (NEC) Source of Negative Ions via Cesium Sputtering (SNICS) to a Multi-Cathode Source of Negative Ions via Cesium Sputtering (MC-SNICS), the 10 MV FN Tandem Van de Graaff accelerator facility has continued to successfully produce and accelerate the light ion beams for which it was designed for numerous experimental setups. These setups include a dedicated beamline for AMS measurements, two dedicated beamlines for studies involving nuclear structure, a dedicated beamline for production of short-lived radioactive nuclei for both nuclear structure and nuclear astrophysics, as well as several multi-purpose stations to accommodate different target or detector needs. As the trend towards the acceleration of heavier masses throughout the lab began for AMS analysis of heavier radionuclides and production of heavier short-lived radionuclides, there were signs that the MC-SNICS injection system (using a single dipole magnet) was no longer satisfactory. AMS analysis of the medium-mass radionuclide ^{36}Cl showed signs that its stable isotopes ^{35}Cl and ^{37}Cl were tailing into the injection system, and were observed in the spectra from the AMS detection system. While careful tuning of the system was able to remove these chlorine isotopes, the problem only increased with higher masses. ^{53}Mn faced issues in the previous system during preliminary measurements, suffering from contamination from tailing of ^{52}Cr and ^{54}Cr, stable isotopes of ^{53}Cr, ^{53}Mn's isobaric contaminant.

The injection of Zr^- for analysis of ^{93}Zr showed no clear separation of the zirconium isotopes as can be seen in Fig. 1. This tailing resulted in isotopic interference in the AMS detection system that produced a detection limit of $^{93}Zr/Zr \approx 1 \times 10^{-5}$, prohibiting any useful ^{93}Zr measurements (such as the measurement of nuclear fuel cladding which require a detection limit of lower than 10^{-7} [4]). Funding for an

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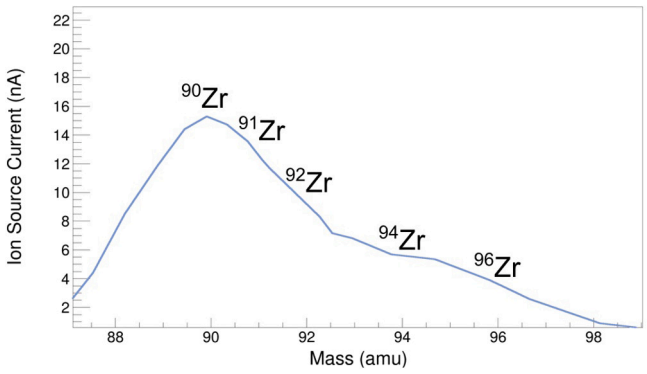

Fig. 1. Previous injection of zirconium elemental ions from a zirconium metal sample in the previous MC-SNICS setup with a very restricted horizontal image slit width of ±0.5 mm, with the current measured following the ion source injection magnet.

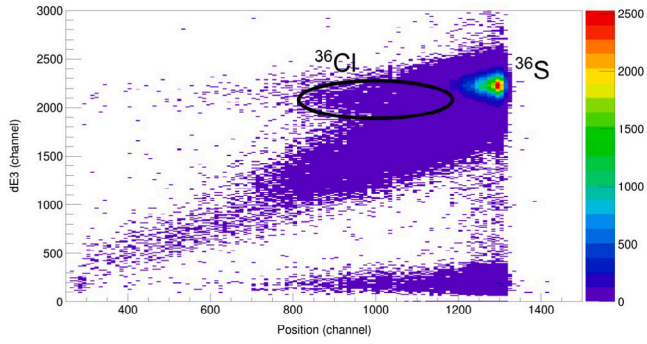

Fig. 2. Spectrum obtained from one of the anodes of the ionization chamber and position detector for ^{36}Cl, showing significant scatter of ^{36}S entering the region of interest for ^{36}Cl (black oval) using an AMS standard (^{36}Cl/Cl ≈ 4.1 × 10^{-11}).

improved injection system was applied for, and awarded through, the Major Research Instrumentation (MRI) program funded through the National Science Foundation (NSF). Although ^{93}Zr measurement was the catalyst for this upgrade, advances towards AMS analysis of heavier radionuclides (such as ^{129}I and ^{236}U) would undoubtedly benefit from this improvement.

This article represents a report on a number of upgrades made to the FN accelerator facility not only to support the AMS program but also the increasing demand for heavier accelerated masses. Besides the injection upgrade, this included the use of the accelerator's gas stripping system and the design and installation of a high energy offset Faraday cup following the analyzing magnet to complement the low energy injection system. Additionally, a time-of-flight (TOF) system was integrated into the AMS beamline to allow the measurement of ^{129}I (discriminating against interfering ^{127}I) as well as the actinides. Finally, a redesign of the AMS beamline, including a series of new beamline components, was completed to improve the beam optics prior to ion analysis and to eliminate scattering in the beamline observed in previous spectra (example shown in Fig. 2). The current status of the AMS system at the NSL (shown in Fig. 3) and the impact of the recent upgrades on measurements of radionuclides will be introduced, as will the current, preliminary sensitivity levels[1]

[1] Sensitivity level is synonymous with detection limit, both meaning the lowest measurable isotopic ratio for an isotope of interest.

2. Upgrades

2.1. Injection system

Both the initial and current injection systems are shown in Fig. 4. The previous MC-SNICS injection relied solely on a 60° dipole magnet for ion selection based on magnetic rigidity, with the helium ion source (HIS) occupying the 30° port, which has been retained for use exclusively by the HIS. The new system, purchased from NEC, includes a 45° spherical electrostatic analyzer (r = 0.3 m, max voltage ±15 kV on either plate) for energy selection, which reduces the energy spread of the beam (by appropriate manipulation of downstream slits), followed by a 90° dipole magnet (r = 0.457 m) with double focusing. The image slit positions for the dipole magnet are optimized to obtain the necessary resolution for a given mass region, maintained at ±3 mm horizontal and ±5 mm vertical for medium masses (30–110 amu) and being reduced further at higher masses as required. The new injection magnet also has a higher maximum magnetic field (1.375 T) for $ME/Q^2 \approx 19$ MeV amu, which allows operation of the MC-SNICS at typical operating voltages (~60 kV) for masses up to 300 amu, whereas the previous magnet limited the full range of ion source voltages to masses less than ~100 amu.

Following the injection magnet, a chamber housing two offset Faraday cups allows for the measurement of stable beam currents while an isotope of interest is injected through the accelerator system for ion detection. There is a cup on either side of the chamber for measurement of lighter and heavier mass beams for the radioisotope being measured.

The injection system includes the ability to bias the magnet vacuum box up to 15 kV. This changes the energy of beams before and after the magnet, altering their trajectories to be directed into an offset Faraday cup on the low energy side of the accelerator, or to allow the stable beams to be sent through the accelerator system for current measurement in a downstream Faraday cup for transmission measurements. This allows for near-continuous (~10 Hz) monitoring of the ion source output, improving the accuracy of reported isotopic concentrations. The magnet bias is incorporated into the fast-switching system, which controls the magnet bias and current measurement in offset Faraday cups during a measurement sequence. During the periods in a sequence when the isotope of interest is not being injected through the system, a veto signal is sent to the data acquisition system to prevent signals from interferences from being accepted and entering detector spectra.

2.2. FN accelerator system

The FN Tandem accelerator's primary method for electron stripping are carbon foils inside the terminal, which have relatively long lives and produce excellent charge state abundances for the acceleration of light ions. In cases where this stripping method is not adequate, the FN also has two other stripping methods - a gas stripping system in the terminal as a substitute for terminal foil stripping, and a second foil stripper halfway through the high energy side of the accelerator used in combination with the terminal foil stripper. In the early years of the AMS group, neither the second foil stripper nor the gas stripper were used as the dedicated stripping method for any isotope beams.

The second stripper is located in the mid-plane of the high energy column in the FN Tandem, and allows stripping to higher charge states by making use of the additional acceleration from the terminal to the mid-plane. This can allow higher beam energies (compared to single foil stripping) to be obtained at an equal terminal voltage. The second stripper has been proven critical for providing an ion beam with enough energy and sufficient intensity in the measurement of ^{60}Fe and ^{93}Zr.

The gas stripper, the traditional stripping method for heavy ions, is not subject to the rapid degradation observed in foil strippers caused by heavy ions, and energy/angular straggling of heavy ion beams through the gas stripper is reduced compared to foil stripping. In recent years, the previous string material, used in the accelerator tank to adjust the stripper's thermomechanical leak, was replaced with a kevlar braid which has been much more resilient.

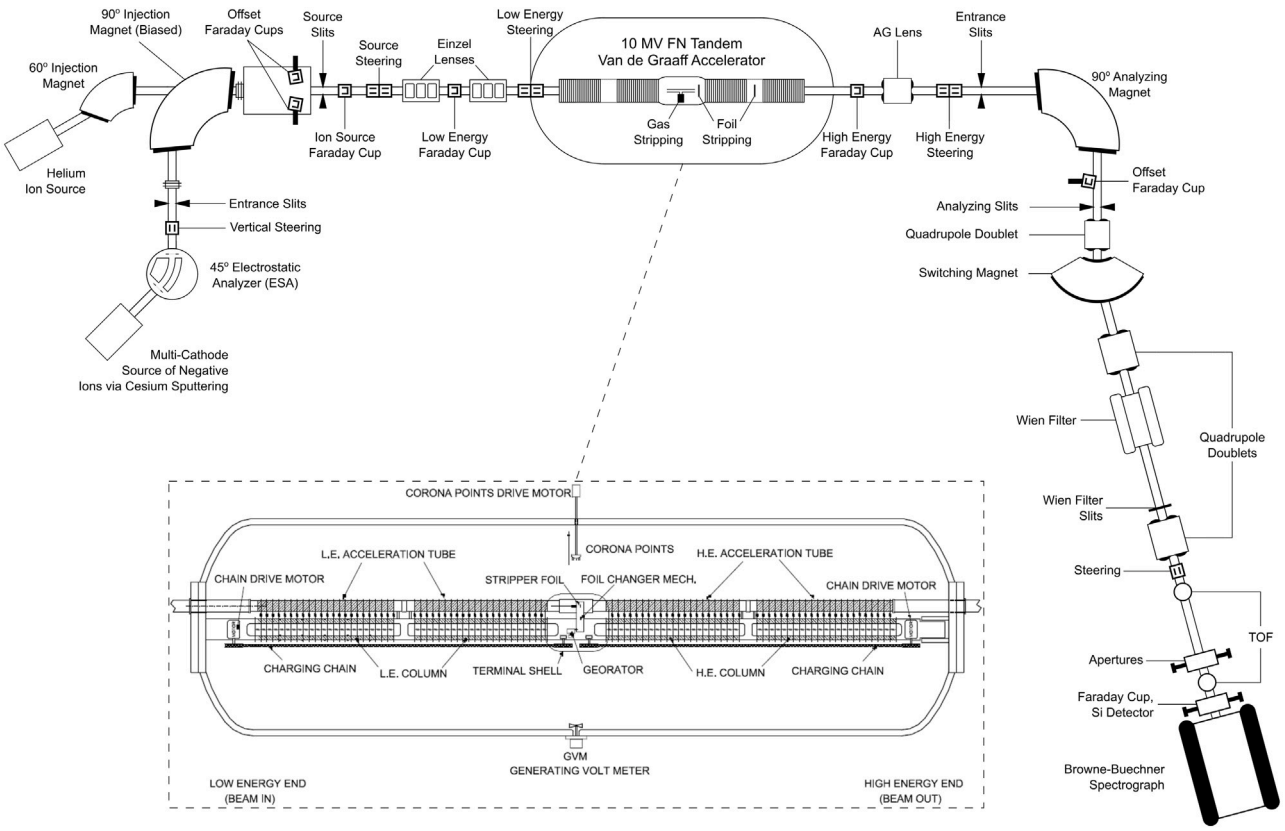

Fig. 3. Schematic drawing of the AMS system at the NSL, including the newest upgrades to the low energy injection system and the AMS beamline. Dashed region: A drawing of the FN accelerator, courtesy of Brad Mulder, Accelerator Technician.

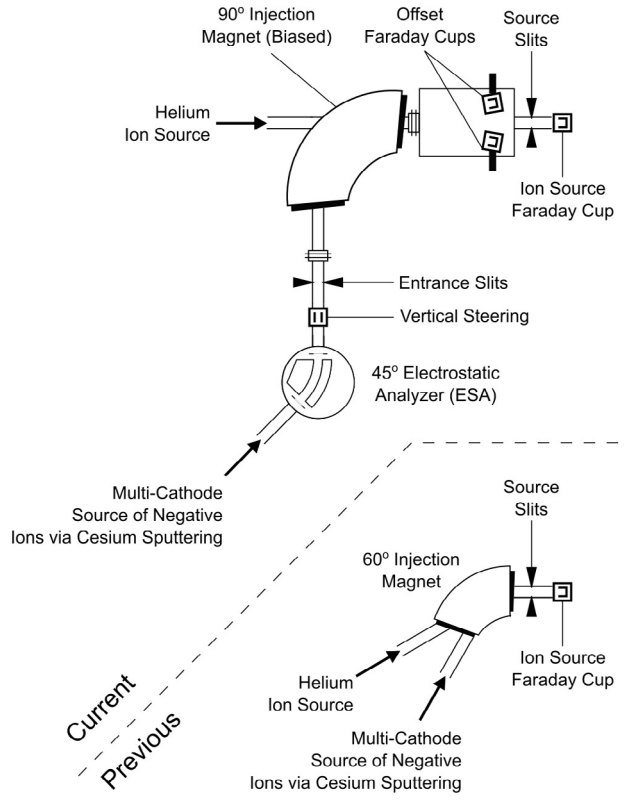

Fig. 4. Comparison of the current injection system, with improved isotopic selectivity and AMS capabilities, to the previous system with limited selectivity.

2.3. AMS system

Following the analyzing magnet on the high energy side of the accelerator, an offset Faraday cup was located based on ion optics calculations shown in Fig. 5. This cup intercepts beams injected through the accelerator as part of the fast switching system. Measurement of stable beam currents through the accelerator allows the transmission of the system to be monitored during a radionuclide measurement, necessary for achieving the required accuracy of AMS concentrations. This is particularly important when there is risk of stripper degradation, where the abundance of the selected charge state can change with changing stripper thickness. While the cup was designed specifically for the measurement of ^{127}I measured during ^{129}I AMS analysis, it is movable such that any beam with a magnetic rigidity up to ~1% less than the radionuclide of interest can be measured, with the rigidity limited only by spatial constraints in the analyzing magnet and the beamline immediately downstream.

Arguably the most significant element introduced into the beamline was the time-of-flight (TOF) region, which has enabled the AMS measurement of multiple heavy isotopes. The TOF system utilizes two microchannel plate (MCP) detectors over a ~2.5 m flight path and was initially developed for the measurement of ^{129}I, but the TOF system will be utilized for the measurement of several actinide isotopes (^{236}U, ^{237}Np) for research projects that are in development. The MCP detectors were obtained from the Racah Institute of Physics from the Hebrew University of Jerusalem, having been used previously for ^{129}I measurement [5].

Along with the implementation of the TOF system, several components on the AMS beamline (beamline following the switching magnet in Fig. 3) were installed, shown in Fig. 6. These pieces of equipment were used to replace identical components in the scattering chamber that served as the optical focus before the Browne–Buechner

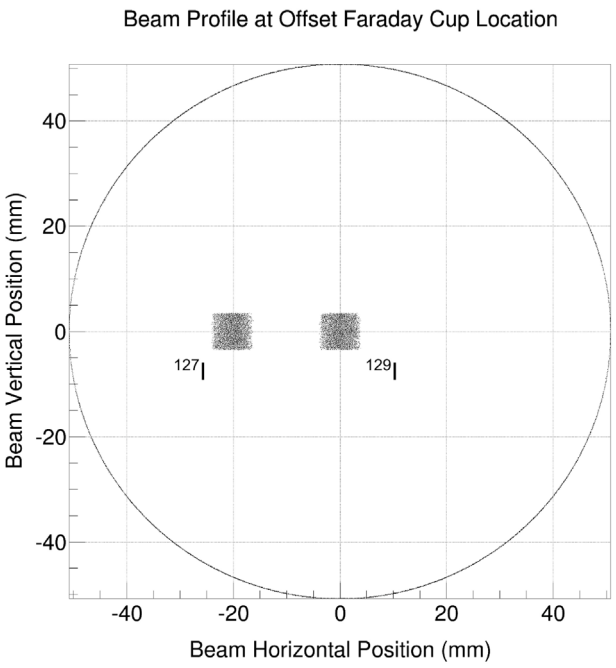

Fig. 5. A Monte Carlo calculation of ^{127}I and ^{129}I performed following an ion optics calculation using the code COSY Infinity with beam parameters (energy spread, beam width, beam angular spread) typical of the FN Tandem.

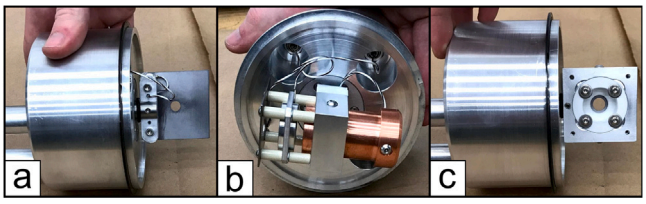

Fig. 6. Devices installed on the AMS beamline for resolving beam transport issues. A set of two different apertures (a) of 7.5 mm and 10 mm diameter, a Faraday cup (b), and a silicon detector holder (c), used to replace the components in the previous scattering chamber.

spectrograph, which has been uninstalled from the beamline for the present time, but can be reinstalled if desired. The constriction into the scattering chamber had been known to cause regions of bad vacuum and ion scattering that led to energy tailing in detector spectra (see Fig. 2). The pieces include two retractable apertures for focusing, a retractable Faraday cup for stable current measurement during tuning, and a retractable silicon detector at the same position as the Faraday cup for energy measurement (specifically for use along with the TOF system).

3. Results

3.1. Impacts on injection selectivity

Following the installation of the upgrade to the low-energy injection system, the injection of ^{93}Zr and several higher-mass isotope beams were studied to evaluate the improvement that was obtained. For all mass resolution studies, the bias applied to the magnet vacuum chamber is used to change the injected mass at a constant magnetic field to avoid hysteresis in the magnet.

As can be seen from the upgraded injection of zirconium elemental ions in Fig. 7a and zirconium oxide ions in Fig. 7b, the zirconium isotopes can be easily resolved, presenting a dramatic improvement over the previous system. This greatly expanded the capabilities for ^{93}Zr AMS measurements by essentially eliminating isotopic interference as well as increasing the signal intensity.

Progressing to even heavier nuclides, the injection of $^{127}I^-$ (for the measurement of the radionuclide ^{129}I) was investigated utilizing the commonly-used sample material of silver iodide mixed with niobium powder packed into a copper sample holder. The magnet bias range corresponding to ^{129}I is clear of any interference, shown in Fig. 7c.

Exploration to further mass regions, including lead dioxide (Fig. 7d) and uranium oxide (Fig. 7e), have produced initial results that demonstrate partial isotopic separation. The ultimate limitation has been in deciding the operating position of the injection slits, which requires a compromise between the reduction of ion beam intensity and increased mass resolution.

3.2. Impacts on radioisotope sensitivities

Following the installation of the upgrade components, several radionuclides that were previously measured, and several additional radioisotopes, were studied to establish new sensitivity levels for the AMS system. Table 1 shows the list of radioisotopes measured, along with the corresponding measurement parameters and the resulting sensitivities. Each isotope is discussed further in the following paragraphs.

^{14}C ($t_{1/2} = 5.7 \times 10^3$ yr), arguably the most well-known and widely-applicable isotope measured using AMS (primarily for radiocarbon dating), has been in routine measurement. While the focus of AMS applications has primarily been nuclear astrophysics, the ^{14}C program has been a strong, undergraduate-driven project that serves as an excellent opportunity for undergraduate training in accelerator operation, data acquisition, and data analysis. ^{14}C solely requires energy measurement, as interfering isotopes are easily separable through magnetic rigidity and velocity selection. The isobar, ^{14}N, is suppressed by using a negative ion source as nitrogen does not form a negative ion. Both the measurement technique, as well as the chemistry procedure used to produce sample graphite, have been explored alongside undergraduates for the purposes of supporting departments such as Art and Biology at the University of Notre Dame. The system has been used to measure samples (at a beam energy of 10.0 MeV) with a ^{14}C/C isotopic ratio of 1×10^{-12}, consistent with ^{14}C/C values both modern to pre-nuclear. Measurement of "blank" material ("dead carbon" originating from coal from a mine in Virginia) suggests a background level of 5×10^{-15}, similarly obtained for both raw coal and graphitized coal.

^{36}Cl ($t_{1/2} = 3.01 \times 10^5$ yr) has primarily geological and astrophysical applications, though the measurements of ^{36}Cl have focused on the astrophysical, measuring cross sections for its production in the Early Solar System (ESS) [6–9]. The current limit of the ^{36}Cl/Cl isotopic ratios measurable using a beam energy of 74.7 MeV is 5×10^{-14}, partially owed to the residual ^{36}S interfering in the regions of interest of ^{36}Cl, with spectra shown in Fig. 8. It is possible that sulfur reduction chemistry can be used to improve this sensitivity, and will be a subject of active exploration for future ^{36}Cl measurements. At greater sensitivity levels, reactions with lower cross sections, and lower energies for those reactions already studied, will become feasible.

^{41}Ca ($t_{1/2} = 9.94 \times 10^4$ yr) has geological and astrophysical applications, similar to ^{36}Cl, but also has potential biomedical applications. Like ^{36}Cl, the measurements of ^{41}Ca are focused towards its astrophysical production in the ESS. While the method and system settings are still under development, preliminary measurements of ^{41}Ca using GFM at 87.2 MeV have been promising, with a sensitivity level of ^{41}Ca/Ca of 1×10^{-13}. The CaF^- molecule is currently injected because of its relative production compared to CaF_3^- in the ion source, but using CaF_3^- has been reported to partially suppress the production of the isobar ^{41}K and will be examined [10]. The current detection limit is well below the levels predicted to be produced for planned cross sections studies ($10^{-10} - 10^{-12}$), and thus is not expected to prohibit any measurements in the immediate future.

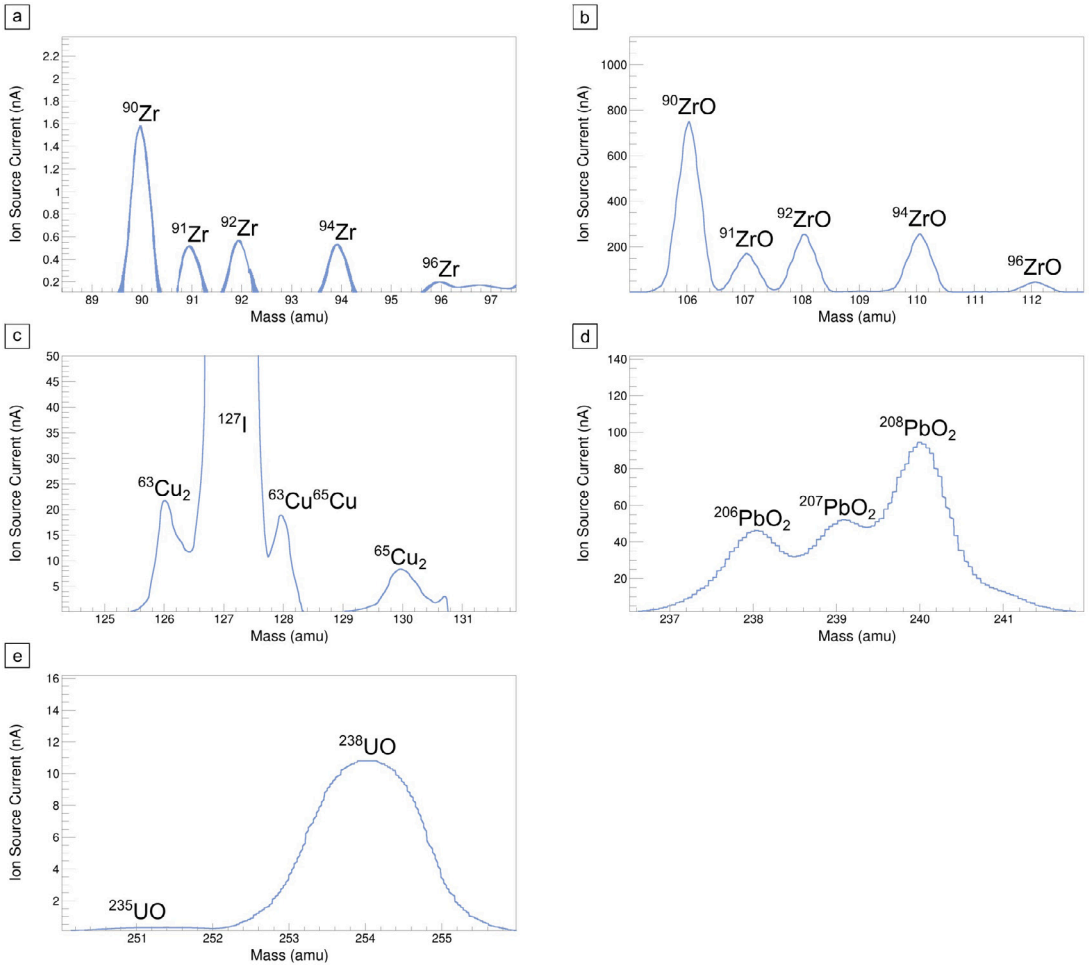

Fig. 7. Injection profiles from the updated injection system, using the ion beam current measured following the injection magnet. The zirconium isotopes in the elemental (a) and oxide forms (b) from a zirconium oxide sample show dramatic improvement from the previous system. ^{127}I is easily separated from the expected injection region for ^{129}I with this system as well (c), with minor production of copper diatomic molecules compared to the ~6 μA of ^{127}I. Heavier mass regions lead oxide (d) and uranium oxide (e) show partial separation, and are currently in development.

Table 1
Summary of measurement parameters and sensitivity levels for radionuclides measured by AMS in the NSL. Transmission is defined as the ratio of the particle current measured in the Faraday cup at the end of the AMS beamline to the Faraday cup following the ion source injection system. Sensitivity refers to the concentration of a radioisotope measured in a "blank" sample; samples above this concentration can be measured above background in the NSL's AMS system.

	^{14}C	^{36}Cl	^{41}Ca	^{60}Fe	^{93}Zr	^{129}I
Injection form	C^-	Cl^-	CaF^-	FeO^-	ZrO^-	I^-
Stable isotopes	^{12,13}C	^{35,37}Cl	^{40,42,43,44,46}Ca	^{54,56,57,58}Fe	^{90,91,92,94,96}Zr	^{127}I
Interference	–	^{36}S	^{41}K	^{60}Ni	^{93}Nb	^{127}I
Technique	Si	GFM	GFM	GFM	IC	TOF
Terminal voltage (MV)	2.5	8.3	9.0	8.5	8.9	7.9
Charge state (+e)	3	8	9	9→16	14	9
Energy (MeV)	10.0	74.7	87.2	113.0	132.4	79.0
Transmission (%)	3.2	4.2	2.2	0.9	9.0×10^{-2}	7.0×10^{-2}
Sensitivity	5×10^{-15}	5×10^{-14}	1×10^{-13}	1×10^{-12}	1×10^{-10}	6×10^{-14}

^{60}Fe ($t_{1/2} = 2.62 \times 10^6$ yr) is exclusively of astrophysical importance, and was initially measured [11] for verification of its half-life [12]. At 113.0 MeV, obtained using the second foil stripper, the sensitivity level that is currently obtained is ^{60}Fe/Fe = 1×10^{-12}. This is a result of the isobaric contaminant ^{60}Ni (^{60}Co is not present in sufficient quantities unless artificially introduced). For measurements of ^{60}Fe in ferromanganese ocean crusts and ocean sediments, the most common use of measuring ^{60}Fe, a background of 1×10^{-16} should be obtained. ^{60}Fe was the first isotope to employ the second foil stripper for AMS measurements, and future measurements will explore higher energy to further separate ^{60}Ni.

^{93}Zr ($t_{1/2} = 1.61 \times 10^6$ yr) is a radionuclide produced astrophysically in s-process nucleosynthesis as well as in nuclear fuel through neutron captures on fuel rod cladding. The measurement of ^{93}Zr is difficult due to the presence of the isobar ^{93}Nb, and typically requires the use of larger accelerator facilities. The measurements at the NSL have utilized the existing GFM detection system, a Bragg curve detector [13], and an alternate ionization chamber after [14], with the latter two operated outside of GFM. The lowest detection level obtained using a beam energy of 132.4 MeV with the Browne–Buechner spectrograph's detection system (operated without using the GFM) is estimated to be ^{93}Zr/Zr = 1×10^{-10} using a niobium-reduced zirconium oxide

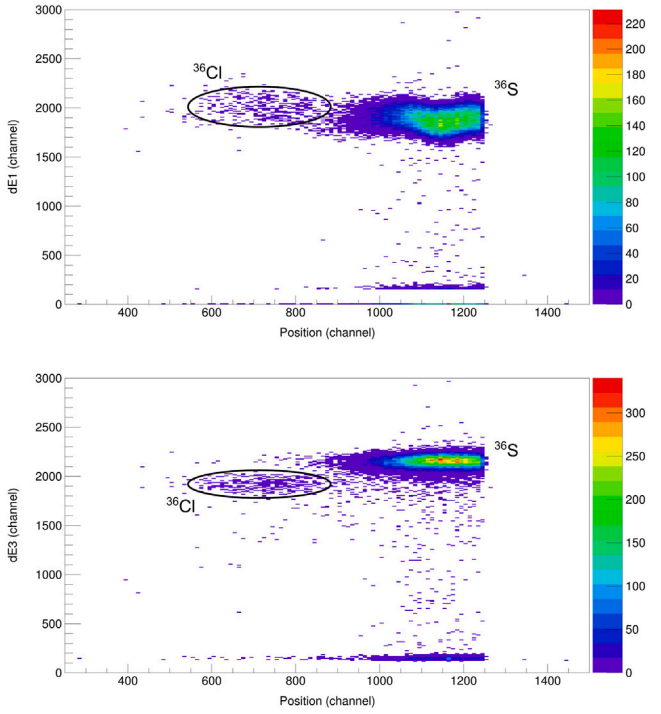

Fig. 8. Spectra obtained from the first and third anodes of the ionization chamber versus the position obtained from the position detector during the use of the GFM on a ^{36}Cl standard. Compared to Fig. 2, there has been an almost complete reduction of scatter in the beamline. The regions of interest for ^{36}Cl are shown in the black ovals, and are used to gate on signals to obtain true ^{36}Cl counts, shown using an AMS standard (^{36}Cl/Cl $\approx 4.1 \times 10^{-11}$).

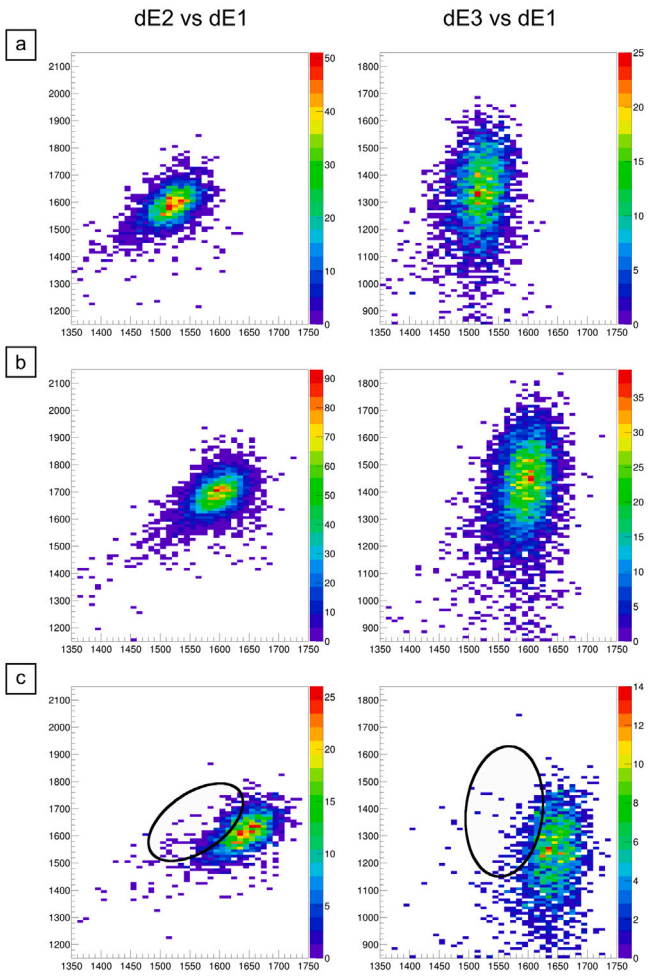

Fig. 9. Spectra obtained using 3 anodes of the ionization chamber for ^{92}Zr (a), ^{94}Zr (b), and ^{93}Nb (c), with the expected regions for ^{93}Zr (the black ovals) inferred from the regions occupied by ^{92}Zr and ^{94}Zr. ^{92}Zr (a) and ^{94}Zr (b) are attenuated beams, and ^{93}Nb (c) is unattenuated and shown using a sample devoid of ^{93}Zr.

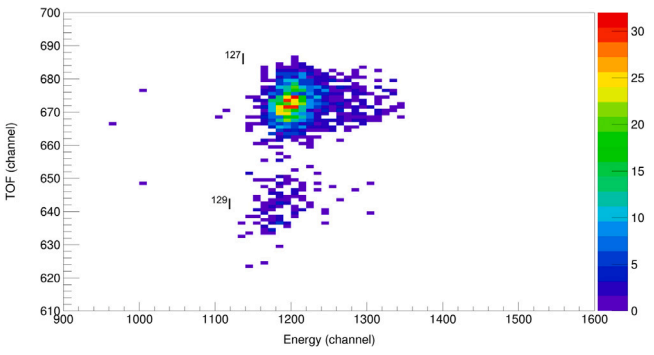

Fig. 10. Time-of-flight versus energy spectra obtained during the measurement of ^{129}I using an ^{129}I standard (^{129}I/I $\approx 6.6 \times 10^{-11}$), showing separation from interfering ^{127}I.

sample (zirconium oxide processed via ion-exchange chromatography for niobium removal), though the alternate ionization chamber may be able to improve this and will be explored in the future. The sensitivity level is estimated by extrapolating the region of interest for ^{93}Zr from ^{92}Zr and ^{94}Zr, shown in Fig. 9. The low energy injection upgrade has succeeded in removing other zirconium isotopes from entering the spectra, so future attempts at separation will focus on experimental methods and beam settings for removal of ^{93}Nb, including additional niobium reduction chemistry for a potential improvement in sensitivity.

^{129}I ($t_{1/2} = 1.57 \times 10^7$ yr) is produced naturally in the atmosphere through cosmic-ray-induced reactions with xenon isotopes. However, its largest contribution on Earth comes from neutron-induced fission of common nuclear fuels ^{235}U and ^{239}Pu, and its subsequent release from fuel reprocessing centers. Measurements of ^{129}I have focused on measuring the impact of these ^{129}I releases in the Great Lakes region. The interference for ^{129}I measurements comes not from the isobar ^{129}Xe, which is suppressed by using a negative ion source, but from the isotope ^{127}I. ^{129}I is separated from ^{127}I using the time-of-flight method, along with energy measurement, as shown in Fig. 10. The current detection limit is ^{129}I/I $= 6 \times 10^{-14}$ at 79.0 MeV, which is only slightly higher than the 3×10^{-14} of the iodine carrier solution used in sample preparation (from Woodward Iodine Corporation, Woodward, OK) [5,15], which is the elemental iodine with the lowest ^{129}I/I that is currently known to be commercially available.

4. Future work

At present, the measurement capabilities for several new radionuclides are being developed, as are methods for improving those already being measured. A new split-anode ionization chamber is being designed following [16] for use with GFM, specifically for the measurement of ^{53}Mn. ^{53}Mn ($t_{1/2} = 3.74 \times 10^6$ yr) is produced in explosive silicon burning, but is a valuable isotope in a geological context, where the measurement of ^{53}Mn produced through spallation of the Earth's surface is used in erosion studies. While the injection upgrade prohibits tailing from neighboring chromium isotopes through the AMS system, the ^{53}Cr isobaric interference cannot be removed this way. Separation from ^{53}Cr presents a significant challenge, and the use of the split-anode ionization chamber that is under development to measure position as well as energy loss, compared to the distinct detectors

used to measure these beam characteristics currently, should prove invaluable for successful particle identification.

Additionally, the TOF system will be used for measurement of several of the actinides along with the implementation of the compact ionization chamber inspired by [16–18]. The samples for the actinides originate from the MANTRA collaboration [19], having been irradiated by reactor neutrons at Idaho National Laboratory under several neutron filters for determining integrated neutron capture yields over specific energy ranges. Isotopically-purified samples will be measured for single, double, and possibly triple neutron capture cross-sections. This is in no way the extent of the applications of the actinides, but will serve as an initial project for the actinide program's development.

Two accelerator developments are also being installed, of benefit to all users of the FN Tandem. An upgrade to 100% SF_6 as the insulating gas will soon be complete, allowing higher maximum terminal voltages (up to 10 MV without alteration of charging components) to be explored and described in future publications. This will allow for higher energies for several AMS radioisotopes, in particular ^{60}Fe and ^{93}Zr, which have been energy-limited by the accelerator. Secondly, the gas stripping system is planned to be improved through the installation of a turbo pump for recirculating the stripping gas. Not only does this reduce the use of gas in the system, but it also helps confine the stripping region to the stripping canal instead of extending into the accelerator tubes.

5. Conclusion

The AMS system at the NSL has increased its capabilities for the measurement of several radionuclides thanks to an upgraded low-energy injection system. Several other improvements including the design and implementation of a high energy offset Faraday cup and a time-of-flight system have further improved the capabilities of the AMS system not only in terms of the measurable radionuclides, but also the repeatability of the system. Several more radionuclides are planned for measurement in the near future, pending the implementation of two new detectors that will work within the existing system but greatly enhance the capabilities for the measurement of more challenging radionuclides.

CRediT authorship contribution statement

M. Skulski: Formal analysis, Validation, Investigation, Writing - original draft, Visualization. **T. Anderson:** Formal analysis, Investigation, Writing - review & editing. **L. Callahan:** Investigation, Writing - review & editing. **A.M. Clark:** Formal analysis, Investigation, Writing - review & editing. **A.D. Nelson:** Formal analysis, Investigation, Writing - review & editing. **D. Robertson:** Writing - review & editing, Supervision, Project administration. **E. Stech:** Writing - review & editing, Supervision, Project administration, Funding acquisition. **P. Collon:** Conceptualization, Methodology, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] R. Hellborg, G. Skog, Accelerator mass spectrometry, Mass Spectrom. Rev. 27 (2008).
[2] J.D. Goss, A.A. Rollefson, C.P. Browne, Design and performance of a new magnetic spectrograph for accurate energy measurements, Nucl. Instrum. Methods 109 (1973).
[3] D. Robertson, C. Schmitt, P. Collon, D. Henderson, B. Shumard, L. Lamm, E. Stech, T. Butterfield, P. Engel, G. Hsu, G. Konecki, S. Kurtz, R. Meharchand, A. Signoracci, J. Wittenbach, A new ams setup for nuclear astrophysics experiments, Nucl. Instrum. Methods Phys. Res. 259 (2007).
[4] F. Chartier, H. Isnard, J.P. Degros, A.L. Faure, C. Fréchou, Application of the isotope dilution technique for ^{93}Zr determination in an irradiated cladding material by multiple collector-inductively coupled plasma mass spectrometry, Int. J. Mass Spectrom. 270 (2008).
[5] E. Boaretto, D. Berkovits, G. Hollos, M. Paul, Measurement of natural concentrations of ^{129}I in uranium ores by accelerator mass spectrometry, Nucl. Instrum. Methods Phys. Res. 50 (1990).
[6] M. Bowers, P. Collon, Y. Kashiv, W. Bauder, K. Chamberlin, W. Lu, D. Robertson, C. Schmitt, First experimental results of the ^{33}S(α, p)^{36}Cl cross section for production in the early solar system, Nucl. Instrum. Methods Phys. Res. 294 (2013).
[7] M. Bowers, Y. Kashiv, W. Bauder, M. Beard, P. Collon, W. Lu, K. Ostdiek, D. Robertson, Measurement of the ^{33}S(α, p)^{36}Cl cross section: Implications for production of ^{36}Cl in the early solar system, Phys. Rev. C 88 (2013).
[8] T. Anderson, M. Skulski, A. Clark, A. Nelson, K. Ostdiek, P. Collon, G. Chmiel, T. Woodruff, M. Caffee, Re-measurement of the ^{33}S(α, p)^{36}Cl cross section for early solar system nuclide enrichment, Phys. Rev. C 96 (2017).
[9] T. Anderson, M. Skulski, L. Callahan, A. Clark, A. Nelson, P. Collon, G. Chmiel, T. Woodruff, M. Caffee, Measurement of ^{34}S(^{3}He, p)^{36}Cl cross sections for nuclide enrichment in the early solar system, Phys. Rev. C 101 (2020).
[10] P.W. Kubik, D. Elmore, AMS of ^{41}Ca using the CaF_3 Negative Ion, Radiocarbon 31 (1989).
[11] K. Ostdiek, T. Anderson, W. Bauder, M. Bowers, A. Clark, P. Collon, W. Lu, D. Nelson, D. Robertson, M. Skulski, Activity measurement of ^{60}Fe through the decay of ^{60m}Co and confirmation of its half-life, Phys. Rev. C 95 (2017).
[12] G. Rugel, T. Faestermann, K. Knie, G. Korschinek, M. Poutivtsev, D. Schumann, N. Kivel, I. Günther-Leopold, R. Weinreich, M. Wohlmuther, New measurement of the ^{60}Fe half-life, Phys. Rev. Lett. 103 (2009).
[13] C. Schiessl, W. Wagner, K. Hartel, P. Kienle, H.J. Körner, W. Mayer, K.E. Rehm, A bragg-curve spectroscopy detector, Nucl. Instrum. Methods 192 (1982).
[14] J. Buchriegler, Construction of a Multi-anode Ionization Chamber for AMS at VERA (Ph.D. thesis), Universität Wien, 2013.
[15] C. Vockenhuber, N. Casacuberta, M. Christl, H. Synal, Accelerator mass spectrometry of ^{129}I towards its lower limits, Nucl. Instrum. Methods Phys. Res. 361 (2015).
[16] M. Martschini, L.K. Fifield, M.B. Froehlich, G. Leckenby, S. Pavetich, S.G. Tims, B. Tranter, A. Wallner, New and upgraded ionization chambers for AMS at the Australian national university, Nucl. Instrum. Methods Phys. Res. 438 (2019).
[17] M. Stocker, M. Döbeli, M. Grajcar, M. Suter, H.-A. Synal, L. Wacker, A universal and competitive compact AMS facility, Nucl. Instrum. Methods Phys. Res. 240 (2005).
[18] O. Forstner, L. Michlmayr, M. Auer, R. Golser, W. Kutscher, A. Priller, P. Steier, A. Wallner, Applications of a compact ionization chamber in AMS at energies below 1 MeV/amu, Nucl. Instrum. Methods Phys. Res. 266 (2008).
[19] G. Youinou, R. Vondrasek, H. Veselka, M. Salvatores, M. Paul, R. Pardo, G. Palmiotti, T. Palchan, O. Nusair, J. Nimmagadda, C. Nair, P. Murray, T. Maddock, S. Kondrashev, F.G. Kondev, W. Jones, G. Imel, C. Glass, J. Fonnesbeck, J. Berg, W. Bauder, MANTRA: An integral reactor physics experiment to infer the neutron capture cross sections of actinides and fission products in fast and epithermal spectra, Nucl. Data Sheets 119 (2014).