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Development towards ⁵³Mn Accelerator Mass Spectrometry capabilities at the University of Notre Dame

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ABSTRACT

Accelerator Mass Spectrometry (AMS) with 53 Mn has geological applications as a chronometer for exposure and burial times for discontinuously deposited sediments. It has also been used to search for evidence of recent supernovae events, and proposed as a proxy to monitor the variation in the galactic cosmic ray spectrum over time. The current sensitivity limit amongst active facilities is 53 Mn/ 55 Mn = 3×10^{-13} while a sensitivity of 53 Mn/ 55 Mn = 1×10^{-13} is necessary to fully exploit 53 Mn's capabilities. At the University of Notre Dame's Nuclear Science Laboratory (NSL), a 10 MV tandem accelerator and a Browne–Buechner Spectrograph operated as a gas-filled magnet were used to separate 53 Mn from 53 Cr. Samples covering ranges of 53 Mn/ 55 Mn = $10^{-10} - 10^{-8}$ were measured for the first time at the NSL using various settings resulting in a background level of 53 Mn/ 55 Mn = $6.2(3) \times 10^{-11}$. Analysis of the results, descriptions of experimental settings, and further explorations will be presented in this paper.

1. Introduction

Accelerator Mass Spectrometry (AMS) of ⁵³Mn is of great interest for geological applications concerning surface exposure and burial dating of iron-titaniumoxides such as magnetite and hematite. The surface exposure, burial age, and erosion rates of such minerals can be deduced by measuring concentrations of cosmogenic ⁵³Mn at the 10⁻¹² level, with AMS being the only technique capable of doing so [1,2]. Similar isochronous techniques, such as ²⁶Al/¹⁰Be dating are limited by the shorter half-life of ²⁶Al ($T_{1/2} = 0.717$ Ma) [3], whereas the longer half-life of ⁵³Mn (3.74 Ma) [4], enables burial measurements up to 25 Ma ago, covering the entire Miocene era [2,5–7].

Recently, AMS of ⁵³Mn has been used as a proxy to search for recent (<2 Ma) supernova events near Earth by measuring trace amounts of ⁵³Mn in deep sea ferromanganese crusts and on the moon [8]. Observed ⁶⁰Fe signatures found in these locations could have originated from asymptotic giant branch stars or a recent supernovae event. Elevated ⁵³Mn/⁵⁵Mn ratios found alongside ⁶⁰Fe in crust samples provide further evidence supporting the supernova origin of the iron [9]. ⁵³Mn could also be used to search for variations in the galactic cosmic ray intensity

over time by looking for muogenic 53 Mn atoms in subterranean iron ores [10].

The main challenge in AMS measurements with ⁵³Mn is in the suppression of and separation from the stable ⁵³Cr isobar. To date, the lowest limit of detection reached is 7×10^{-15} , using a 155 MeV beam, the gas-filled magnet (GFM) technique and an ionization chamber [7]. Amongst active facilities, the lowest limit of detection is 3×10^{-13} using a 181 MeV beam, the GFM technique and the FASMA ionization chamber [11], just above the ⁵³Mn/⁵⁵Mn = 1×10^{-13} sensitivity level required for the oldest burial dating measurements [1,12]. The capabilities demonstrated at ANU and Munich suggest the lowest isotopic ratio measurements require high energies obtainable at only a few AMS facilities around the world [13].

The AMS facility at the University of Notre Dame's Nuclear Science Laboratory (NSL), based around a 10 MV FN tandem accelerator, has seen major improvements in the last few years, primarily with the ion injection system and the beamline used for AMS measurements [14]. These upgrades motivated the first AMS detection of ⁵³Mn at the NSL,

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Table 1

Table of materials used in experiments. The first six entries were used to establish an initial background level, while the last two were used to study sources of chromium interference and are void of any 53 Mn. The current given in the last column refers to typical currents of MnO⁻ measured on the NEC Faraday Cup shown in Fig. 1.

Material	Description	Source	I _{NEC} (pnA)	
MnO ₂ Powder	Blank material	Alfa Aesar	300	
Standard	2.5×10^{-10} Standard	G. Herzog	21	
ANU-a	Sample 1	ANU	250	
ANU-b	Sample 2	ANU	322	
ANU-c	Sample 3	ANU	191	
ANU-d	Sample 4	ANU	265	
MnF_2	Blank material	Sigma Aldrich	339	
MnO ₂ no Ag	Blank material	Alfa Aesar	530	

the results of which and a current background level are presented in this paper.

2. Experimental setup

2.1. Description of materials

Eight different materials, a description of which can be found in Table 1, were used for these measurements. The first six materials listed were used to establish an initial background level. They consist of four samples provided by the Australian National University's (ANU) AMS laboratory, commercially available blank material of >99.99% purity, and an AMS standard (53 Mn/ 55 Mn = 2.5×10^{-10}) originally prepared by G. Herzog from meteoritic material, that has been used in other 53 Mn AMS measurements [2,7,15]. The four ANU samples cover ranges typical of meteorites (53 Mn/ 55 Mn = $10^{-8} \cdot 10^{-10}$) and were all chemically treated to reduce their chromium content at ANU. Upon reception at the NSL, all six materials were mixed with commercial silver powder with a ratio of 2:1, Ag:MnO₂, before being pressed into sample holders.

To aid with future measurements of ⁵³Mn, two more materials were prepared to study ways to limit ⁵³Cr interference. The first was commercially available MnF₂ of 98% purity. It has been demonstrated that the use of the fluoride molecule can help reduce chromium interference by a factor of three or more after chemical processing of MnO₂ materials into MnF₂ [6,7,11,16]. The second material was the same blank material used in the isotopic ratio measurements prepared without silver powder to quantify the chromium content introduced by the silver. Silver is usually added to cathodes to help with binding and conductivity, as well as provide additional volume in cases of limited materials. Together, the MnO₂ with no silver and MnF₂ materials were compared to the MnO₂+ Ag blank to quantify means of chromium suppression in material selection, as well as ion source stability and current output.

Using a re-purposed arbor press, the materials were packed into 40-Wheel MC-SNICS copper cathodes made by National Electrostatics Corp. Each cathode was packed with tools cleaned with deionized water and ethanol and then baked in a vacuum oven at 120°C to avoid any sources of cross-contamination. Due to manganese's negative electron affinity [17], it is necessary to choose a molecular injection from the ion source. Given that all six of the materials were already in the oxide form, the MnO⁻ molecule was selected for injection.

2.2. AMS system and beam development

The NSL's AMS setup, shown in Fig. 1, has seen recent upgrades, described in [14]. The ion injection system consists of an MC-SNICS ion source, a 45° electrostatic analyzer, and a 90° magnet with bouncing capabilities, followed by the 10 MV FN accelerator.

Inside the terminal of the FN, carbon foils of 3 μ g/cm² and N₂ gas was utilized to strip electrons from the incoming negative ions. For all

three tests, a combination of gas and foil stripping inside the terminal was used. The benefits of such a setup are less degradation to the foil, and a higher charge state occupancy [18]. Additionally, halfway down the high energy column, an additional $3 \mu g/cm^2$ carbon foil can be used to populate higher charge states for higher energies required for the GFM technique. Details summarizing the different accelerator settings explored in this experiment can be found in Table 2.

On the high energy side, a 90° analyzing magnet selects the charge state, followed by a switching magnet that selects the target beamline. On the AMS beamline, a Wien Filter is used to further reduce the isotopic background and a Browne–Buechner Spectrograph operated with a GFM is used for isobaric separation [19]. Here, isobars coalesce around disparate mean charge states and lose energy differently to form two separate beams [20]. A combination of position sensitive and energy loss detection is used to distinguish the nuclide of interest (53 Mn) from the isobaric interference [5,7,15,21]. The entrance to the spectrograph is a 1″ diameter, 1.5 µm mylar foil. For the spacial separation on the 193 cm mean path through the spectrograph N₂ gas was used. 2.5–4 torr of gas was used to find optimal pressure settings based on the beam energy and detector pressures.

Throughout the experiment, \sim 300 nA of beam was produced out of the blank material with a mass resolution of $M/\Delta M = 390$. This was achieved with the LE Entrance slits at ± 2 mm in the horizontal axis and +4,-2 mm in the vertical axis. The LE Exit slits were at +3.5,-2 mm in the horizontal axis and +1.5,-3 mm in the vertical axis. Two different beams were selected based on limitations in terminal voltage stability, charge state occupancy, and preliminary testing. The 13⁺ charge state was selected to produce a 120 MeV beam using a terminal voltage of 8.7 MV for the first test, chosen to match the beam used in preliminary tests on the MONICA detector [22]. The second and third tests selected the 9^+ charge state in the terminal, and the 18^+ charge state at the second stripper to produce a 126 MeV beam using a terminal voltage of 8.8 MV. Before and after every sample, transmission was measured by taking the 55Mn particle-current ratio of the AMS Faraday Cup and the NEC Faraday Cup. Additionally, to reduce memory effects in the ion source, a ~30 min buffer between sample changes occurred, resulting in no observable change in the blank isotopic ratios as they were measured.

2.3. Detector system

For these tests, the NSL's Parallel Grid Avalanche Counter (PGAC) followed by a four ΔE region Ionization Chamber (IC) was used. The PGAC is separated from the spectrograph by a 47 cm×11 cm window, allowing both manganese and chromium to enter the detector. In front of it, a movable aluminum shield can be used to physically block out a significant fraction of the isobaric contaminant, reducing pile-up effects and detector deadtime. Within the PGAC/IC, 2.5 µm mylar windows allow for the regions to be held at three different pressures: P_{Specr} for the spectrograph covering ~193 cm of flight path, P_{PGAC} for the PGAC covering 10.5 cm, and P_{IC} for the IC. The PGAC/IC, described in [23], was used to determine if it will be sufficient for low level ⁵³Mn measurements, or if other designs should be considered.

The combined PGAC/IC was used across three different sets of conditions, described in Table 2, that were selected based on energy loss simulations run in SRIM and Geant4 [24,25]. The first test had P_{Spect} = 3.0 torr, the same pressure used for the preliminary tests with MONICA [22]. This test, with a 120 MeV beam at the 13⁺ charge state served as a way to determine if future experiments should continue with the PGAC/IC, or if a new detector following the designs of others [11,22,26] would be necessary. The second test focused on position separation as the primary means of ⁵³Mn isolation with $P_{Spect} = P_{PGAC} = 4$ torr, using a 18⁺ 126 MeV beam. The third test, also using the 18⁺ 126 MeV beam, focused on minimizing energy lost in the spectrograph and PGAC, using $P_{Spect} = 2.5$ torr and $P_{PGAC} = 3$ torr. In this test, the pressures were chosen such that the Bragg Curves

Table 2

Table of tests, beam energies, and detector pressures. Each test used a MnO⁻ beam. The beam energy is at the entrance to the spectrograph. The terminal voltage was stable to within 0.5%. The transmission refers to the average 55 Mn particle transmission of blank cathodes measured throughout a test. When double stripping was used, the charge state is listed as terminal charge state \rightarrow second stripper charge state. The time represents total time on samples and blanks. E_{IC} corresponds to the energy available to the IC, determined using SRIM.

Test number	Beam energy (MeV)	Charge state	Terminal voltage (MV)	Stripping mechanisms	Transmission (%)	Time (min)	P _{Spect} (torr)	P _{PGAC} (torr)	P_{IC} (torr)	E _{IC} (MeV)
1	120	13+	8.72	Gas & Terminal Foil	.0141(4)	720	3.0	3.0	15.0	44.6
2	126	$9^+ \rightarrow 18^+$	8.82	Gas & Both Foils	.023(3)	488	4.0	4.0	10.0	38.6
3	126	$9^+ \rightarrow 18^+$	8.81	Gas & Both Foils	.0249(3)	966	2.5	3.0	14.0	56.4



Fig. 1. Full system used for AMS at the NSL. The main upgrades on the low energy side are the electrostatic analyzer and bouncing magnet. After a switching magnet, the beam is directed down the main AMS beamline with a Wien Filter, ToF region, and Browne–Buechner Spectrograph, as well as various focusing elements all of which are magnetic. When making transmission measurements, the NEC Faraday Cup and the AMS Faraday Cup are used and the beam energy is adjusted such that ⁵⁵Mn has the same magnetic rigidity, eliminating any issues with hysteresis effects.



Fig. 2. Bragg Curve simulations of ⁵³Mn and ⁵³Cr in the IC done in SRIM. Both ⁵³Mn and ⁵³Cr beams of 126 MeV are sent through the spectrograph, PGAC, and the three mylar windows before entering the IC. For this simulation, the pressures used match those of test three in Table 2. The vertical black lines represent the boundaries between the ΔE regions within the IC.

corresponding to 53 Mn and 53 Cr crossed over early in anode 3, as shown in Fig. 2. During each test the shield was moved to block out as much of the chromium coming in on the higher energy side as possible, while not affecting the manganese region.

2.4. Data analysis

Each test was broken into 30 min runs with 1-2 h on each sample. For each test, software cuts were used to define the ⁵³Mn regions of

interest, as shown in Fig. 3. The figure shows two different cuts made on the region, one fully encompassing the manganese peak (N_{ROI}) and the other slightly offset (N_{Off}). The selection of this offset region selectively removed ~ 15% of the manganese data, while in return suppressed the background level by a factor of ~ 30. The other region, N_{ROI} is used on the highest sample to accurately quantify the amount of ⁵³Mn lost.

The isotopic ratio of a given sample in each 30 min run is determined as

$$C_{Sample} = \frac{(N_{off} - f \cdot N_{Cr}) \times S.F.}{I_{NEC} \times t \times \epsilon_{55}}$$
(1)

 $N_{Off} - f \cdot N_{Cr}$ is a background subtraction with $f \cdot N_{Cr}$ representing the fraction of total chromium counts that appear in the region defined for N_{Off} . Using the blank runs, f is determined as the ratio of counts in the offset cut region to total counts of chromium. *S*.*F*. is a scale factor to account for the ⁵³Mn counts not appearing in the offset region. This scale factor is based on the ratio of counts N_{ROI}/N_{Off} for the highest sample, an example of which is shown in Fig. 3. I_{NEC} , t, and ϵ_{55}_{Mn} refer to the ion source current for ⁵⁵Mn in pnA, counting time in seconds, and transmission for each sample, respectively and give the total number of ⁵⁵Mn counts that would have reached the detector in the same amount of time.

As mentioned in Section 2.2, the ion source current was measured before and after each 30 min run changing the bias on the 90° bouncing magnet to inject 55 MnO⁻ on the NEC Faraday Cup. Transmission measurements were made before and after each cathode was measured by adjusting a bias on the 90° bouncing magnet, the terminal voltage, and Wien Filter bias to produce a 55 Mn beam with the same magnetic rigidity of 53 Mn. The transmission through the spectrograph is taken to be 100%, verified by comparing count rates on a Si detector placed at the AMS Faraday Cup's location, and the PGAC/IC without the shield.



Fig. 3. Example of cuts used for the 126 MeV beam with more optimal settings on sample 1 (above) and a blank (below). The regions are drawn around spectra for the highest sample and then applied to all others. One cut around the region of interest, ROI, determines the total number of 53 Mn counts in the region (black). The other cut eliminates the 53 Mn counts by ~ 15%, but in the process reduces the background by a factor of 30. The spectra shown here correspond to the Bragg Curve region (Fig. 2) where 53 Mn is losing more energy than 53 Cr, so the low energy tail from the 53 Cr peak does not contribute to background. Discrepancies in the number of counts appearing in the chromium regions are attributed to the chemical treatment done on the samples to lower their chromium concentrations.

Due to low current outputs with the standard material, a standard correction was unable to be performed. Because of this, uncorrected isotopic ratios are reported. Instead of a reference standard, the blank ratios are compared to each other using the measured values of Sample 1 as a normalization. This sample is chosen since it has the highest 53 Mn/ 55 Mn ratio. For any given test *i*, a correction factor, n_i can be applied to the measured ratio for Sample 1, C_{S1_i} , such that $C_{S1_i} \cdot n_i = C_{nominal} = C_{S1_3}$.

Values for the ⁵³Cr/⁵⁵Mn isotopic ratios, $C_{CrSample}$, $C_{CrBlank}$, were also calculated to quantify the suppression factor that chemical treatment on the samples had relative to the untreated blanks. The ratio is determined in a manner similar to Eq. (1), with $(N_{off} - f \cdot N_{Cr}) \times$ *S.F.* replaced by the number of chromium counts in each run. The suppression factor $C_{CrBlank}/C_{CrSample}$ quantifies how much chromium had been chemically removed from each sample relative to the blank material.

3. Results

3.1. Isotopic ratio measurements

The measured samples are shown in Table 3. The run time, ⁵³Mn counts, final isotopic ratio, and beam current are presented for each sample across each run. For sample 1, the results are consistent across all tests, while, for the other three samples, minor discrepancies are present. For the 120 MeV test (Test 1) and 126 MeV test with $P_{Spect} = 4$ torr (Test 2), the energy separation was smaller, causing ⁵³Cr to fall in the ⁵³Mn region, skewing the isotopic ratios higher. Additionally, the

Table 3

Counting times, ⁵³Mn counts, and final isotopic ratios for each sample over each test. For test 2, separation of the two peaks was less resolvable and samples 3 and 4 were not measured in order to focus on development for test 3. *C* refers to absolute isotopic ratio measurements, as no standard correction was able to be done. ⁵⁵I refers to the average ⁵⁵Mn current measured at the AMS Faraday Cup when measuring the transmission. Uncertainties listed include both statistical and systematic sources with the dominant contribution being uncertainty in the AMS Faraday Cup measurement.

Test	Sample	Time (min)	Counts ${}^{53}Mn$ (N_{Off})	Counts ${}^{53}Cr$ ($f \cdot N_{Cr}$)	⁵³ Mn⁄ ⁵⁵ Mn (10 ⁻⁹)	⁵⁵ I (enA)
1	1	60	86727	727	38(3)	0.51
	2	120	2448	62	.40(3)	0.60
	3	60	22079	229	10.9(7)	0.44
	4	60	6486	99	3.1(2)	0.35
	Blank	420	1763	-	.25(2)	0.21
2	1	60	123 509	3843	36(2)	1.0
	2	120	3508	331	.38(2)	1.1
	Blank	308	23605	-	1.7(3)	1.1
3	1	30	51 039	28	35(2)	0.89
	2	126	4724	30	.53(3)	1.1
	3	120	59 090	41	8.2(4)	1.0
	4	120	30651	54	6.1(3)	0.74
	Blank	570	1558	-	.062(3)	0.87

shield for test 1 was far enough into the beam path to affect the 53 Mn region, therefore skewing the isotopic ratios lower. It is suspected that a combination of both issues led to the lower isotopic ratio samples not being in close agreement.

For Test 2, with $P_{Spect} = 4$ torr, the separation was quickly found to be worse than Test 1, leading to only the first two samples being measured at those settings, while the other two tests measured all four samples. Test 3, whose settings maximized energy delivered to the IC, yielded the lowest measured background of $C_{Blank} = 6.2(3) \times 10^{-11}$. When compared to Test 1, the correction factor, $n_1 = 0.92$, gives a background reduction factor of 3.71. The same process applied to Test 2 gives a correction factor of $n_2 = 0.97$ and a reduction factor of 27.1. This shows that higher beam energy is not enough to get better separation, but work should be done in the future to continue finding optimal pressures.

When compared to those of untreated blanks, the chromium counts in the chemically treated samples, showed a suppression factor of 7.4 for samples 1 and 4, 25 for sample 2, and 9.3 for sample 3. This suggests that chemically treating blank material, following a process such as the one described in [27], could further improve the background level by another order of magnitude.

3.2. Further explorations

Based on the results, a number of improvements are needed to increase ion source output, and further suppress the chromium contaminant to lower the background level.

3.2.1. Chromium in alternative samples

A blank cathode without any silver showed an increase to over 0.5 μ A of 55 MnO⁻ produced, a factor of 2 more than the silver-packed cathodes, and a transmission of 0.023%. This resulted in an isotopic ratio of 53 Cr/ 55 Mn= 1.34(7) × 10⁻⁶ as opposed to 1.49(7) × 10⁻⁶ for the blank material mixed with silver. This increased current suggests that cathodes packed without any silver powder could be used to get better statistics and less chromium interference, especially when trying to measure lower isotopic ratios, assuming adequate amount of material is available.

The MnF₂ material yielded a 53 Cr/ 55 Mn ratio of $1.05(5) \times 10^{-7}$ with an overall transmission of .020%, resulting in a reduction factor of 12.7 when compared to the MnO₂ prepared without silver. This factor is in reasonable agreement with other groups [6,7,11], and suggests using a chemical procedure to transform terrestrial and meteoritic manganese



Fig. 4. Sample spectra from initial test with the MONICA detector for Sample 1 (above) and a blank (below). This figure shows one of the split anode sets where both position and energy loss are used to distinguish the two isobars.

oxide materials into fluorides in future experiments. Use of the fluoride also introduced an additional contaminant that is believed to be 56 Fe injected as an oxide and stripped in the same manner as 53 MnF.

3.2.2. MONICA results

A single test of ⁵³Mn was performed using the 120 MeV beam at the 13⁺ charge state with the MONICA detector. MONICA is an eight ΔE region ionization chamber with two sets of split anodes to give position measurements, described in [22]. The benefits of such a system are the concurrent position and ΔE measurements, which maximize the energy deposited in the IC by not having an additional mylar foil and gaseous region to travel through as with PGAC/IC. A sample spectra from the initial test is shown in Fig. 4. Despite the ⁵³Cr scattering on the side of MONICA, limited time to optimize settings, and lower ion source output, the ⁵³Mn is still easily resolvable and the blank isotopic ratio is similar to that of the 120 MeV test using PGAC/IC. Combined with the observation that more energy delivered to the IC when using PGAC/IC yielded better separation for the measurements discussed in Section 3.1, this suggests that designing a new split-anode IC for use at the NSL will help push the detection limit of medium mass isotopes like ⁵³Mn lower.

4. Conclusions and future work

The first ever 53 Mn/ 55 Mn measurements were made at the NSL. Three different sets of measurements were made on the existing PGAC/IC detector and display capabilities based on different beam and detector settings. Maximizing energy delivered to the final IC yielded the best suppression of chromium and resulted in a background level of $C_{Blank} = 6.2(3) \times 10^{-11}$. Other observations included a reduction in current when using silver as a binder, when compared to no added binder, in MnO⁻ beams and a further suppression of chromium background when using a MnF⁻ beam.

Moving forward, future measurements should focus on increasing energy delivered to the detector. This can be done in one of two ways: limit losses before detection (e.g. lowering GFM operating pressure), or increasing beam energy. With an upgrade to full SF_6 insulation in the FN underway, it is expected that stability at higher terminal voltages will be obtainable. Secondary stripping in the high energy column can also be used to occupy higher charge states, however more work needs to be done to better understand the potential contaminants it can introduce into spectra.

Finally, with detection of 53 Mn at the 10^{-11} isotopic ratio level possible, procuring more AMS standards and samples covering a wider range of isotopic ratios should be done to confirm the current background level, and further develop the NSL's AMS program for 53 Mn, ultimately trying to push down to the 10^{-13} isotopic ratio level.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Thomas Bailey reports financial support was provided by National Science Foundation. Adam Clark reports financial support was provided by US Nuclear Regulatory Commission. Michael Paul reports financial support was provided by Israel Science Foundation.

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References

- [1] M. Schiffer, A. Stolz, D.A. López, R. Spanier, S. Herb, C. Müller-Gatermann, S. Heinze, S. Binnie, J. Melchert, N. Kivel, D. Schumann, et al., Method developments for accelerator mass spectrometry at CologneAMS, ⁵³Mn/³He burial dating and ultra-small ¹⁴CO₂ samples, Glob. Planet. Change 184 (2020) 103053.
- [2] L.G. Gladkis, L.K. Fifield, C.R. Morton, T.T. Barrows, S.G. Tims, Manganese-53: Development of the AMS technique for exposure-age dating applications, Nucl. Instrum. Methods Phys. Res. B 259 (2007) 236–240.
- [3] M.S. Basunia, A.M. Hurst, Nuclear data sheets for A=26, Nucl. Data Sheets 134 (2016) 1–148.
- [4] M. Honda, M. Imamura, Half-life of Mn53, Phys. Rev. C 4 (4) (1971) 1182–1188.
- [5] M. Schiffer, R. Spanier, C. Müller-Gatermann, S. Herb, C. Feuerstein, G. Hackenberg, M. Marock, S. Heinze, A. Stolz, A. Dewald, et al., The first (⁵³Mn/⁵⁵Mn) isotopic ratio measurements at the Cologne FN-Tandem Accelerator, Nucl. Instrum. Methods Phys. Res., B 437 (2018) 87–92.
- [6] K. Dong, H. Hu, X. Wang, C. Li, M. He, Z. Li, S. Wu, J. Liu, G. Zheng, H. Li, et al., Further study on highly sensitive AMS measurement of ⁵³Mn, Nucl. Instrum. Methods Phys. Res., B 285 (2012) 57–60.
- [7] M. Poutivtsev, I. Dillmann, T. Faestermann, K. Knie, G. Korschinek, J. Lachner, A. Meier, G. Rugel, A. Wallner, Highly sensitive AMS measurements of ⁵³Mn, Nucl. Instrum. Methods Phys. Res. B 268 (2010) 756–758.
- [8] J. Feige, A. Wallner, L.K. Fifield, G. Korschinek, S. Merchel, G. Rugel, P. Steier, S.R. Winkler, R. Golser, AMS measurements of cosmogenic and supernova-ejected radionuclides in deep-sea sediment cores, EPJ Web Conf. 63 (2013) 03003.
- [9] G. Korschinek, T. Faestermann, M. Poutivtsev, A. Arazi, K. Knie, G. Rugel, A. Wallner, Supernova-produced ⁵³Mn on earth, Phys. Rev. Lett. 125 (3) (2020) 031101.
- [10] D. Eichler, R. Kumar, M. Pohl, Is the galactic cosmic-ray spectrum constant in time? Agron. J. 769 (2013) 138.
- [11] 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. B 438 (2019) 141–147.
- [12] J.M. Schaefer, T. Faestermann, G.F. Herzog, K. Knie, G. Korschinek, J. Masarik, A. Meier, M. Poutivtsev, G. Rugel, C. Schlüchter, et al., Terrestrial manganese-53 — A new monitor of Earth surface processes, Earth Planet. Sci. Lett. 251 (3) (2006) 334–345.

- [13] K. Knie, T. Faestermann, G. Korschinek, G. Rugel, W. Rühm, C. Wallner, Highsensitivity AMS for heavy nuclides at the Munich Tandem accelerator, Nucl. Instrum. Methods Phys. Res. B 172 (1) (2000) 717–720, 8th International Conference on Accelerator Mass Spectrometry.
- [14] M. Skulski, T. Anderson, L. Callahan, A.M. Clark, A.D. Nelson, D. Robertson, E. Stech, P. Collon, Recent developments in the AMS system at the Nuclear Science Laboratory: Impacts on radionuclide sensitivities and current capabilities, Nucl. Instrum. Methods Phys. Res. B 488 (2021) 30–36.
- [15] T. Fujioka, L.K. Fifield, J.O. Stone, P.M. Vasconcelos, S.G. Tims, J. Chappell, In situ cosmogenic ⁵³Mn production rate from ancient low-denudation surface in tropic Brazil, Nucl. Instrum. Methods Phys. Res., B 268 (2010) 1209–1213.
- [16] K. Dong, D. Zhou, Y. Xu, M. He, G. Liu, H. Hu, L. Dou, J. Liu, S. Wu, X. Wang, et al., AMS measurement of ⁵³Mn and its initial application at CIAE, Nucl. Instrum. Methods Phys. Res., B 361 (2015) 58–62.
- [17] R. Middleton, A Negative-Ion Cookbook, Department of Physics, University of Pennsylvania, 1989.
- [18] P. Thieberger, H.E. Wegner, Test of heavy-ion gas-foil stripping for improved foil lifetime in Tandem Van de Graaff accelerators, Nucl. Instrum. Methods 126 (2) (1975) 231-233.
- [19] D. Robertson, C. Schmitt, P. Collon, D. Henderson, B. Shumard, L. Lamm, E. Stech, T. Butterfield, P. Engel, G. Hsu, et al., A new AMS setup for nuclear astrophysics experiments, Nucl. Instrum. Methods Phys. Res. B 259 (2007) 669–672.

- [20] M. Paul, B.G. Glagola, W. Henning, J.G. Keller, W. Kutschera, Z. Liu, K.E. Rehm, B. Schneck, R.H. Siemssen, Heavy ion separation with a gas-filled magnetic spectrograph, Nucl. Instrum. Methods Phys. Res. A 277 (2) (1989) 418–430.
- [21] A. Wallner, K. Buczak, C. Lederer, H. Vonach, T. Faestermann, G. Korschinek, M. Poutivtsev, G. Rugel, A. Klix, K. Seidel, et al., Production of long-lived radionuclides ¹⁰Be, ¹⁴C, ⁵³Mn, ⁵⁵Fe, ⁵⁹Ni and ^{202g}Pb in a fusion environment, J. Korean Phys. Soc. 59 (2011) 1378–1381.
- [22] L.K. Callahan, P. Collon, M. Paul, M. Avila, B. Back, T. Bailey, A. Clark, C. Dickerson, J. Greene, H. Jayatissa, et al., Initial tests of Accelerator Mass Spectrometry with the Argonne Gas-Filled Analyzer and the commissioning of the MONICA detector, Nucl. Instrum. Methods Phys. Res. B 532 (2022) 7–12.
- [23] D. Robertson, P. Collon, D. Henderson, S. Kurtz, L. Lamm, C. Schmitt, B. Shumard, J. Webb, First results from the nuclear astrophysics AMS program at the NSL using the MANTIS system in gas-filled mode, Nucl. Instrum. Methods Phys. Res. B 266 (2008) 3481–3486.
- [24] J.F. Ziegler, M.D. Ziegler, J.P. Biersack, SRIM The stopping and range of ions in matter (2010), Nucl. Instrum. Methods Phys. Res. B 268 (11–12) (2010) 1818–1823.
- [25] S. Agostinelli, et al., GEANT4: A simulation toolkit, Nucl. Instrum. Meth. A506 (2003) 250–303.
- [26] K. Knie, T. Faestermann, G. Korschinek, AMS at the Munich gas-filled analyzing magnet system GAMS, Nucl. Instrum. Methods Phys. Res. B 123 (1) (1997) 128–131, Accelerator Mass Spectrometry.
- [27] I. Leya, J.C. David, T. Faestermann, M. Froehlich, N. Kivel, D. Koll, G. Korschinek, S. McIntyre, S. Merchel, S. Pavetich, et al., 53Mn and 60Fe in iron meteorites—New data, model calculations, Meteorit. Planet. Sci. 55 (4) (2020) 818–831.