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Trials and Tribulations in the First Three Years in Operation of the SSAMS for Biomedical ^{14}C -AMS at LLNL

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Abstract

We report on the first several years of operation of our recently installed 250 kV SSAMS at LLNL, purchased to replace our 1-MV AMS system for the measurement of ^{14}C from labeled biochemical samples. We have modified the ion source region to improve ion output. Additionally, the SSAMS required significant software modifications to the data acquisition system in order to accurately measure ^{14}C at the high-count rates typically encountered with labeled biochemical samples. We found that the data can be corrected assuming a nonparalyzable dead time response with a single event dead time of 6 μs . Since operation began, we have measured over 13,000 graphitic unknowns and over 1900 standards with an overall precision of 1.0%. We have optimized our system for the analysis of CO_2 gas samples. We compared aliquots of identical samples measured as solid graphite and as liquid drops. Excellent agreement was found between the two, although the average precision of the graphite targets was an order of magnitude better than the liquid drop analysis due to the much larger number of ^{14}C atoms available for measurement.

Keywords

accelerator mass spectrometry; biomedical AMS; SSAMS; gas ion source

1. INTRODUCTION

In 2014, LLNL installed a 250 kV SSAMS (S/N 015) from National Electrostatics Corporation (Middleton, WI) to replace our 1-MV AMS spectrometer for the quantification of ^{14}C for biomedical applications [1, 2]. As purchased, this instrument was configured with two 39-sample gas-accepting hybrid cesium sputter sources to which we attached a copy of our moving wire interface [3, 4]. One table was optimized for directly coupled HPLC-AMS analysis while the other was set up for the analysis of ^{14}C -labeled biochemicals from discrete liquid drops. This system has been placed in a room configured with Biosafety Level 2 controls, next to our biomedical sample preparation laboratories to better connect

the biomedical researchers to the spectrometer. Fig. 1 presents a photograph of the BioDeck instrument laboratory.

Since its installation, we have made a number of modifications of the SSAMS to improve its operation. We have previously reported on the substitution of argon for helium as the stripping gas medium [5]. Equivalent levels of molecular ion dissociation were observed with each gas; however, ion transmission is ~22% higher with helium gas than argon gas and is now the preferred medium for molecular ion dissociation.

We also modified the ion source region of each source to provide both improved pumping conductance and increased ion output. The NEC extractor electrode, with its 0.125-inch i.d. entrance aperture, was replaced with a large aperture extractor similar to the one we installed onto the hybrid source on our 1-MV AMS spectrometer [6]. This electrode, as first described by Southon and Santos [7], consists of a 3.175 cm i.d. x 5.715 cm long tube whose base is mounted to the first electrode of the ion source einzel lens. A single 9.5 mm i.d. tantalum collimator is mounted to the base of the electrode on a circular disk. Additionally, we installed a 300 l/s turbomolecular pump to improve the removal of the helium gas introduced to the ion source region from the moving wire interface. To accommodate this pump, the ion source extractor region was extended 2 inches and its upstream flange was configured with a liquid cooling channel, allowing a rubber o-ring to replace the NEC-style aluminium gasket. An electrically isolated bracket was also required to help support the new housing with its attached turbo pump. Also, vacuum controls were moved to the side for easier access. Finally, a 4-port GC valve is used to direct the CO₂ gas from the moving wire interface to either the ion source or a vacuum pump. Fig. 2 shows a picture of the modified ion source region.

2. LABELED BIOCHEMICAL ANALYSIS

As installed and accepted, the SSAMS provided equivalent ¹⁴C/C isotope ratios from graphite samples of biochemicals over three orders in dynamic range as compared to our (then) existing 1-MV AMS spectrometer. However, ion source output was approximately 3–4 times lower, potentially impacting sample throughput. To improve ion output, we increased the cathode voltage from 4 to 7 kV, with a corresponding increase in the total energy of the extracted ions to mitigate the influence of space charge effects. Operation at the higher extraction energies precludes the injection of ¹²C⁻ ions into the accelerator as the voltage required of the bouncer exceeds the upper limit of its power supply. Consequently, only ¹⁴C and ¹³C ions are measured at the high energy end. The low energy ion current integrator is used as a transient recorder of the HPLC injection signal whose purpose is to align the AMS data acquisition computer clock to the HPLC computer's clock.

We prepared graphite samples containing ¹⁴C/C concentrations between 0.1 Modern and 100 Modern representing the range of the majority of the biomedical AMS samples. Six samples at each concentration were measured at cathode voltages 4 kV, 5 kV, 6 kV and 7 kV. High energy ¹³C⁺ ion currents and ¹⁴C/¹³C concentrations were averaged for each concentration at each cathode voltage and plotted in Fig. 3. As can be seen in Fig. 3(a), analyzed ¹³C⁺ ion current increased by a factor of 5 for identical samples measured at 7 kV

over the 4 kV cathode voltage. However, as seen in Fig. 3(b), the measured $^{14}\text{C}/^{13}\text{C}$ isotope ratio decreased at the higher cathode voltage as compared to its measured ratio at the lower voltages. While the improvement observed in the former is desirable, the effect seen in the latter is calamitous.

The ^{14}C counting electronics supplied with our SSAMS uses a Pixie-4 digital pulse processor (XIA LLC, Hayward, CA) in place of a more traditional CAMAC-based ADC. The Pixie DSP was designed for fast high-precision coincidence gamma-ray spectroscopy and offers very high-speed waveform acquisition along with pulse height measurements and time stamping for event reconstruction. As such, the preferred shape of the incoming signal is what would be expected from a pre-amplifier (i.e., a sharp rise time of $<1\text{ }\mu\text{s}$, followed by a relatively long exponential tail). Noise in the ^{14}C pulse from the charge particle detector requires the use of a filter shaping amplifier, such as an Ortec 570 (Oak Ridge, TN), thereby deviating from the Pixie's preferred incoming pulse shape. Attempts to identify and mitigate this noise seen in the preamplifier output, whether electronic or mechanical, have been unsuccessful. Signals rising above a defined energy threshold are processed by the Pixie DSP for energy determination. A fast filter rapidly indicates the arrival of a peak and triggers the slow filter to begin energy measurement. Subsequent peaks arriving within a defined peak separation window are rejected as pileup and not processed, leading to the loss of potentially two valid ^{14}C events. The Pixie data acquisition identifies multiple sources of dead time associated with each pulse and attempts to account for them, assuming a paralyzable system with pileup rejection. Event rates for the samples shown in Fig. 3 ranged from approximately 5 counts/second for the 0.1 Modern samples at 4 kV cathode up to approximately 15 kHz for the 100 Modern samples measured at 7 kV cathode. These losses were initially partly due to the default setting of the PIXIE hardware to reject all pileup events with no attempt to account for them. Once this was corrected, losses were assumed to be the result of dead time common to all particle counting detector systems under conditions of high count rates. However, no attempt was made to identify the possible, specific sources.

We tested this assumption by constructing the circuit shown in Fig. 4. Under a normal data acquisition sequence, $^{14}\text{C}^+$ ions are deposited into the ^{14}C detector. Signals from the detector are initially amplified by the PreAmp before further amplification and shaping by the Amplifier. Shaped pulses are then sent to the Pixie DSP for processing and digital conversion. A timing signal, generated by the data acquisition program within the NEC AccelNET control system, is used to gate the incoming pulses such that only those pulses arriving within the ^{14}C collection time are counted.

For these tests, there were no incoming ions into the ^{14}C detector and a random pulser (DB2, Berkeley Nucleonics Corp, San Rafael, CA) generated monoenergetic pulses with a near Poisson distribution ranging from 100 Hz up to 53 kHz. These pulses were injected into a charged particle preamplifier (Model 2003BT, Canberra Industries, Meridan, CT). Signals from the PreAmp were shaped, with a $2\text{ }\mu\text{s}$ shaping time, before being sent to the Pixie-4 DSP. Trigger signals from the random pulse generator were sent to a NIM counter (Ortec 875) to record the number of pulses sent to the preamp. Both the Pixie and the counter were configured to collect only during the rare isotope gate generated by AccelNET. Additionally, the Pixie was configured to not reject pileup events and, importantly, NEC software

engineers had modified its firmware to function as a peak sensing ADC from its original total peak integration settings.

At each arbitrary random count rate setting of the pulser, the number of hardware triggers generated by the Pixie DSP, as well as the total number of data cycles was recorded by the data acquisition system. Additionally, a manual readout of the number of gated pulser triggers was also recorded. The total number of cycles varied from 15 to 491, depending on the pulser count rate, and the total number of events recorded ranged from 5,020 at 100 Hz to more than 142,000 at the highest tested rate of 53 kHz. The rare isotope collection gate was held constant at 0.100 seconds per cycle throughout these tests.

In Fig. 5(a), we plot the ratio of measured hardware triggers (CntTotS, in AccelNET parlance) with respect to the number of expected events as measured by the NIM counter as a function of the average random pulser rate over the data collection period (“Uncorrected”). The tailing off at the higher count rates is indicative of a nonparalyzable dead time response [8]. The number of measured events were corrected with the following formula:

$$Events_{corrected} = \frac{Events_{measured}}{1 - (Count\ Rate * single\ event\ dead\ time)} \quad (1)$$

where, the Count Rate was determined from the measured hardware triggers. A single event dead time of 6 μ s was found to give the best fit of the data for $Events_{measured} = Events_{expected}$. The corrected events are plotted in Fig. 5(a) with open circles. A nearly straight line averaging 1.000 with a 1-sigma standard deviation of 0.18% over the event rate range from 100 Hz to 50 kHz shows the accuracy of the correction over the typical count rate range of bioAMS samples.

We remeasured our suite of samples, ranging from nominal 1 Modern up to 100 Modern (the 0.1 Modern samples had been consumed during earlier evaluations), over different cathode voltages and applied this correction to the ^{14}C counts. The results are presented in Fig. 5(b) where the $^{14}\text{C}/^{13}\text{C}$ isotope ratio of each sample at the different cathode voltages are normalized to its ratio as measured at 4 kV. Only slight deviations from unity are observed indicating we have significantly improved the accuracy in the ^{14}C analysis of high-count rate samples. The correction factor, determined to the nearest microsecond, is periodically remeasured and has not drifted or changed over time. This includes a detector replacement following the failure of a power supply that led to the deposition of a stable ion beam onto it. However, we have not had the need to replace any of the detector electronics (HV power supply, pulse shaping amplifier and preamplifier), and therefore, cannot comment on the reproducibility of the correction following such hardware replacement.

An illustration of our gating methods is shown in Fig. 6, for a 50 Modern sample with a ^{14}C count rate of approximately 12 kHz. To accurately account for ^{14}C pileup events, two software gates are used, the first, CntTotGT, is established from the low energy side of the ^{14}C peak to the end of the spectrum and contains 42,132 events. The second gate, CntTotBG, drawn to measure the pileup signal, starts at the high energy side of the ^{14}C peak and

extends to the end of the spectrum and contains 639 events. The total number of measured ^{14}C events is determined by the sum of the number of counts within each gate, or 42,771 counts in this example. The number of events is then corrected to 46,002 ^{14}C counts using Eqn. 1 above assuming a 6 μsec single event dead time with the average count rate as measured by the total number of hardware triggers with respect to the rare isotope collection time.

3. SOLID SAMPLE ANALYSIS

Since we completed the transition from our 1-MV AMS system in 2014, over 11,000 analytical unknowns have been measured on the SSAMS. Nearly 900 swipes have been measured to determine ^{14}C contamination on laboratory surfaces and equipment [9]. Additionally, we have measured a number of standards and labelled stock solutions to be used in support of a number of other projects. Presented in Fig. 7 are histogram distributions of (a) 1924 unique measurements of an IAEA C-6 ANU sucrose standard and (b) measurements of 262 unique graphite samples of a secondary oxalic acid standard with a nominal Fraction Modern of 12.3. The measured averages, along with the results of a fit to a Gaussian distribution are presented in Table 1. For both secondary standards the measured average and Gauss fit agree with their accepted or previously determined values.

Typically, samples are measured to 3% precision about the average $^{14}\text{C}/^{13}\text{C}$ ratio, with a minimum of 5 measurements up to a total of 10 repeats. Each measurement is configured to record 10,000 gated ^{14}C events or to collect for 1500 cycles, whichever occurs first. A full wheel of samples will contain 33 unknowns, four ANU sucrose standards, one 12 Modern target for tuning purposes and one graphite target for ion source warmup. A full wheel can take between 2 and 8 hours to measure, depending on the level of activity of the samples. Although in the event of excessively high $^{14}\text{C}/\text{C}$ ratios (>400 Modern), a wheel may be rerun at a lower cathode voltage to reduce ion output and ^{14}C count rates. Typically, 2 wheels per day can be measured with the first wheel loaded with “hot” samples, if possible, to measure during the work day; while the second wheel is started towards the end of the day to run unattended into the night.

4. GAS SAMPLE ANALYSIS

Each ion source is configured to accept CO_2 gas samples for analysis generated using our moving wire interface [3, 4]. Briefly, liquid samples containing microgram, or less, quantities of non-volatile carbonaceous material are deposited onto a moving wire, either as a discrete microliter-sized drop or from the continuous output of an HPLC. The sample passes through a drying oven, then enters a high-temperature combustion tube furnace, where the sample is combusted in a helium/oxygen atmosphere to CO_2 . The CO_2 gas, along with carrier helium and any residual oxygen gas are transported along a $180\text{ }\mu\text{m}$ i.d. x 5 m long fused silica capillary to the ion source for subsequent ionization and ^{14}C -AMS analysis.

We found that by adjusting the cathode in/out position, we could maximize ion yield from gas samples with the cathode voltage and immersion lens voltage both set to 7 kV. We found it advantageous to run with these equal voltages as breakdown between these two elements

was our leading cause of ion source failure. We also examined the effects of the cesium reservoir temperature and ionizer power on ion yield. The highest yield of measured ^{14}C counts at the detector and integrated ^{13}C ion current at the high energy ^{13}C Faraday cup from gas samples was obtained with the cesium temperature at 102°C and 150 Watts of ionizer power.

Table 2 summarizes the operation parameters and typical performance of the ion source. In general, the ion source operating parameters are identical for both gas and graphite samples, although we see no significant increase in ion source output from graphite samples above 140 Watts ionizer power. The operating pressure is measured at the exit of the high voltage gap, outside the ion source high voltage safety cage and is most likely significantly lower than the pressure near the surface of the cathode. The $^{14}\text{C}/\text{C}$ background for gas samples arises from residual carbon in and on the wire, as well as from any ambient CO_2 that may be adsorbed onto the titanium surface of the cathode prior to its introduction to the cesium sputter beam. The machine background for graphite samples was determined from the measurement of unprocessed Ultracarbon (Alfa-Aesar) graphite and does not include any background carbon introduced into the sample during processing. A processed blank value of $8 \times 10^{-15} \text{ }^{14}\text{C}/\text{C}$ was measured from a graphitized sample of hexamethylnonane, an aliphatic hydrocarbon which is derived from fossil fuels and hence, ^{14}C -free.

An example of a typical ion peak, recorded from a single discrete liquid drop is presented in Fig. 8(a). Peak shapes are the result of a number of contributing factors, such as wire speed, transfer capillary i.d. and length, as well as the ion source geometry [3]. However, in general, single drop peak shapes from the NEC MCGSNICS hybrid source exhibit a sharp rise time, with a reasonably narrow full width at half maximum (FWHM), followed by a relatively longer tail. The example peak shown in Fig. 8(a) is from a $2.5 \mu\text{l}$ drop of an aqueous sucrose solution containing $0.5 \mu\text{g}$ carbon and $73 \text{ zmol } ^{14}\text{C}$. The rise time, defined here as the amount of time it takes to go from 10% to 90% of the maximum value, is 2.2 sec. The FWHM of this peak is 4.7 sec. Evidence of tailing is observed as the fall time (the amount of time it takes for the signal to drop from 90% to 10% of its maximum value) is 6.5 sec, almost three times longer than its rise time. Typical ion source efficiency for gas samples is approximately 1%.

Multiple drops from the same sample are often deposited onto the wire to improve the counting statistics of the ^{14}C measurement, thereby improving the precision of the isotope ratio. Fig. 8(b) shows a plot of measured ^{14}C and ^{13}C ion traces from a series of drops placed onto the wire, approximately 8 seconds apart, containing a total of $9 \mu\text{g}$ carbon. The separation is required to prevent overwhelming the front surface of the titanium insert on the gas target cathode with an excess of CO_2 . In this case, the total trace from the start of the first peak through to the point at which the ^{13}C signal has dropped to 2.5 times the background level (as determined by the level of the ^{13}C signal at the beginning of the trace) is summed to determine the isotope ratio of the sample.

Absolute quantitation of the ^{13}C and ^{14}C isotopes, as well as the $^{14}\text{C}/^{13}\text{C}$ ratio of the CO_2 gas sample is obtained by accounting for the fraction of time spent measuring each isotope including time spent on data transfer. For each data grab, a timestamp, in Unix time, of the

cycle is generated and included in an additional file. The time fraction of each isotope is calculated by comparing the time between each data cycle with the isotope's data collection time and folded into its measured value. Knowing the absolute time of the data cycle and correcting the data is necessary for aligning the AMS data to the HPLC data and for determining the absolute value of the measured isotope. Note that, in general, the ^{14}C count rate from gas samples is low, so the correction for live time, as described above, is minimal.

The typical procedure for the measurement of gas samples is to insert a fresh target and allow surface contamination to sputter off. This typically takes a couple of minutes and is monitored by displaying running plots of the ^{14}C and ^{13}C signals. The target surface is sufficiently prepared when these signals have stabilized to approximately <1 ^{14}C count/sec and <1 nA ^{13}C ion current. A known amount of IAEA C-6 ("ANU sucrose") aqueous solution is deposited onto the wire with the use of a PHD-2000 infusion pump (Harvard Apparatus, Holliston, MA). For discrete drop analysis, the measured ratio of the standard is compared to the measured ratio of the unknown to obtain the absolute isotope quantitation. For HPLC injections of ^{14}C -labeled mixtures, the analysis is a bit more complicated. Often the amount of material injected into the HPLC for analysis is very small and while a ^{14}C peak may be seen, the stable carbon content of a separated peak can be below our level of detection. In this case, absolute normalization of each isotope is determined based on its measured value from the standard and the AMS functions not as an IRMS, but as an absolute ^{14}C detector.

We compared $^{14}\text{C}/\text{C}$ isotope ratio results from prepared aqueous glucose solutions measured as solid graphite samples and as CO_2 gas generated from discrete liquid drops placed onto the moving wire interface. Glucose solutions with $^{14}\text{C}/\text{C}$ isotope ratios ranging from 1 Modern (unlabelled) up to approximately 200 Modern were prepared by isotope dilution of labelled glucose into unlabelled aqueous glucose solutions to a nominal concentration of 50 mg C/ml. Aliquots containing approximately 1 mg carbon were prepared in duplicate and converted to graphite using our standard solid graphite methods [10] Liquid samples were prepared by a 1:100 dilution of the "graphite solutions" in Barnstead™ GenPure™ (ThermoFisher Scientific, Waltham, MA) water to 0.5 mg C/ml. Liquid drops, containing between 0.6 and 3 μg carbon, were hand pipetted onto the moving wire for eventual analysis as CO_2 gas. Each solution was measured a minimum of 3 times. Results, presented in Fig. 9, show an excellent agreement between the two sample types. A least squares fit to the data between 1 and 80 Modern yields a line with a slope of 1.00 ± 0.01 , an intercept 0.16 ± 0.35 and correlation coefficient $r^2 = 0.9998$. Typical errors for the graphite measurements were 0.5%, while typical errors of the individual CO_2 gas measurements were 5%, indicative of the different levels of ^{14}C available within each sample. While the liquid sample AMS measurements obtained equivalent results as graphite with significantly less material, the graphite measurements were an order in magnitude more precise. Precision can be improved with the liquid samples by increasing the amount of measured material, if available.

5. FUTURE DIRECTIONS

Our development efforts will focus on increasing capabilities around the use of the gas ion source. To that end, we have installed a Xevo G2-XS QTOF mass spectrometer (Waters

Corp., Milford, MA). Output from the HPLC is split, using a quantitative flow splitter, with a portion going to the moving wire and AMS for quantitation and the rest going to the MS for structural information, provided sufficient material for analysis. Examples of this Parallel Accelerator Mass Spectrometry-Molecular Mass Spectrometry (PAMMS) capability include the identification of novel metabolites following exposure to pesticides or other toxicants, and the measurement of metabolite exchange in microbial communities. Additionally, we have installed a NIMBUS (Hamilton Robotics, Reno NV) liquid handling robot to automate the dispensing of discrete liquid samples onto the moving wire, thereby eliminating the tedious task of hand pipetting. Work is ongoing to fully incorporate it into our moving wire interface and SSAMS operation.

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Fig. 1.
Photo of the LLNL 250 kV SSAMS spectrometer for biomedical ^{14}C measurements. The moving wire interface benches, with their associated equipment, are shown in the foreground.

Fig. 2.

Photo of modified ion source region of the LLNL SSAMS. Changes to the original design of the ion source include the replacement of the extractor/einzel lens housing (1) with a liquid-cooled entrance flange (2) that can accommodate a 400 l/s turbomolecular vacuum pump (3). The heavier mass of the pump necessitated the addition of an electrically-isolated support bracket (4). A 4-port GC valve (5) was mounted above the ion source to direct the incoming CO₂ gas from a fused silica capillary (6) to either the ion source or to a vacuum pump (7), enabling fast switching between gas and solid samples. To accommodate the gas feed line, the focus electrode power supply was moved up and mounted with 29.2 cm long aluminum brackets (8). Finally, vacuum controls (9) were moved from the backside of the

ion source stand to the side to provide easier access during wheel changes and source maintenance.

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Fig. 3.

Average $^{13}\text{C}^+$ ion currents as measured at the high energy off-axis Faraday cup (a) and $^{14}\text{C}/^{13}\text{C}$ isotope ratios (b) for replicate samples at nominal $^{14}\text{C}/^{13}\text{C}$ concentrations between 0.1 Modern and 100 Modern at different cathode voltages. In (b), the isotope ratios for each concentration is normalized to its average value as measured at 4 kV cathode voltage.

Fig. 4. Schematic of the setup used to measure counting electronics response to random pulses to determine dead time. See text for details. Where appropriate, typical signal shapes are depicted.

Fig. 5.

Measurement and correction of dead time. (a) Ratio of measured hardware triggers as recorded by the Pixie DSP (“measured”) to the number recorded by the Ortec NIM 875 counter (“expected”) at average random pulser trigger rates. The data plotted with closed circles is the uncorrected data while the open circles is the same data corrected using Eqn. 1 using a single event dead time of 6 μ sec. (b) Isotope ratio data corrected using Eqn. 1, with the ratio for each concentration normalized to its corrected value as measured at 4 kV cathode voltage.

Fig. 6.
 ^{14}C gating example. The total ^{14}C counts is determined by the number of counts in the software gate marked CntTotGT (solid line) and in the gate marked CntTotBG (dashed line). In this scheme, each pileup event is counted twice; once by CntTotGT and again by CntTotBG.

Fig. 7.

Histogram distributions of (a) 1924 measured graphite samples of ANU sucrose standard and (b) 262 graphite samples of our 12 Modern oxalic acid tuning standard. Both histograms were fitted with a Gaussian distribution, which is plotted as a solid line in each plot. Data averages and the fitting results are summarized in Table 1.

Fig. 8.

Recorded spectra of discrete drops placed onto the moving wire and measured with the SSAMS. (a) A single 2.5 μl ANU sucrose drop. (b) A series of nine 2.5 μl drops, spaced 8 seconds apart.

Fig. 9.

Comparison of measured Fraction Modern data for graphite (“solid”) and CO₂ (“liquid”) samples prepared from aqueous glucose solutions of identical ¹⁴C/C concentrations. Data between 1 and 80 Modern were fitted with a straight line with slope 1.00 ± 0.01 , intercept 0.16 ± 0.35 and correlation coefficient $r^2 = 0.9998$ and extrapolated up to the highest level of approximately 170 Fraction Modern.

Table 1.

Measured Fraction Modern values along with fitted values, assuming a Gaussian distribution, of secondary standards measured on the SSAMS as presented in Figure 7.

Standard	N	Average $\pm 1\sigma$	Gauss Fit	χ^2	Accepted value
IAEA C-6 (ANU sucrose)	1924	1.506 ± 0.011	1.510 ± 0.011	0.0599	1.508[11]
12 Mod OX (tuning)	262	12.25 ± 0.20	12.32 ± 0.19	0.092	$12.31 \pm 0.30^*$

* Archival data of 110 measurements made on the 1 MV AMS system.

Table 2.

Operation parameters of the ion source for both solid and gas samples.

Source operating parameters		Performance	
Cathode voltage	7 kV	Extracted ion energy	47 keV
Immersion lens voltage	7 kV	Operating pressure	5.4×10^{-7} Torr (gas) 2.0×10^{-7} Torr (graphite)
Reservoir temperature	102 °C	$^{14}\text{C}/\text{C}$ background	10^{-13} (gas) 4×10^{-15} (graphite) [*]
Ionizer power	150 W	Typical $^{13}\text{C}^+$ currents	35 nA (gas) [†] 500 nA (graphite)
Focus electrode	0 kV	Efficiency	1% (gas) [°]

^{*} Ultracarbon (Alfa-Aesar); pressed into cathodes without any processing

[†] typical ion current at its peak from a single drop containing 0.5 µg carbon

[°] estimated, assuming 43% transmission through the accelerator and ion optics.