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The Canadian Penning Trap Spectrometer at Argonne

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Abstract. The Canadian Penning Trap (CPT) mass spectrometer is a device used for high-precision mass measurements on short-lived isotopes. It is located at the ATLAS superconducting heavy-ion linac facility where a novel injection system, the RF gas cooler, allows fast reaction products to be decelerated, thermalized and bunched for rapid and efficient injection into the CPT. The CPT spectrometer and its injection system will be described in detail and its unique capabilities with respect to its initial physics program, concentrating on isotopes around the $N = Z$ line with particular emphasis on isotopes of interest to low-energy tests of the electroweak interaction and the rp-process, will be highlighted.

Key words: Penning trap, mass measurement, gas cell, RF cooler.

1. Introduction

The Canadian Penning Trap (CPT) Mass Spectrometer is a device aiming at the precise determination of the atomic masses of short-lived isotopes. It was designed for specific measurements of interest to weak interaction tests at low energy which require the ability to obtain mass measurement accuracy in the 1–10 ppb range on isotopes with half-live as short as 50 ms. The required accuracy with only a very small sample of short-lived ions available dictated the use of an ion trap system. This then required the development of a new injection technique for short-lived isotopes in ion traps, both more efficient and more universally applicable than existing systems, combined to a versatile production mechanism. Such a system is now operating at Argonne National Laboratory and its characteristics are presented in the following.

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2. Physics motivation

The physics program at the CPT mass spectrometer involves mass measurements ranging from those on heavy stable nuclides, to broad mass survey in regions far from the valley of beta stability, to high-precision measurement on specific isotopes. Mass measurements are of general interest to test nuclear model predictions in regions where little data is available but more importantly provide key input to our understanding of many physical phenomena involving isotopes far from stability. Of particular interest are explosive astrophysical processes such as the rp- and r-process but also specific decays along the $N = Z$ line which are key laboratories to test fundamental interactions at low energy. The $N = Z$ region is of particular interest because of the symmetry between the neutron and proton wave functions which often lead to simplifications that allow precise interpretation of physical processes occurring in complex systems. A particular example of this is the study of superallowed 0+ to 0+ β-decays where, because the axial-vector decay strength is zero for such decays, the measured ft values are directly related to the weak vector coupling constant through [1]:

$$Ft = ft(1 + \delta_{\mathrm{R}})(1 - \delta_{\mathrm{c}}) = \frac{K}{M_{\mathrm{F}}^2 {G'_{\mathrm{V}}}^2}, \tag{1}$$

where K is a known constant, G'_{V} is the effective vector coupling constant and M_{F} is the Fermi matrix element between analogue states. Radiative corrections, δ_{R}, modify the decay rate by about 1.5% and charge-dependent corrections, δ_{c}, modify the 'pure' Fermi matrix element by about 0.5%.

Accurate experimental data on Q_{EC}-values, half-lives and branching ratios combined with the two correction terms then permit precise tests of the Conserved Vector Current (CVC) hypothesis, via the constancy of Ft-values, irrespective of the 0+ to 0+ decay studied [1, 2]. These data also yield a value for G'_{V} which, in combination with the weak vector coupling constant for the purely leptonic muon decay, provide the most precise value for V_{ud}, the up–down quark mixing element of the Cabbibo–Kobayashi–Maskawa (CKM) matrix. Together with the smaller elements, V_{us} and V_{ub}, this matrix element provides a stringent test of the unitarity of the CKM matrix. At present V_{ud} is the most precisely known element of the CKM matrix [3] but, because of its large size, also the largest contributor of uncertainty in first row and first column CKM unitarity tests. It is therefore vital to improve the precision of this element. The existing data set of nine precisely known superallowed β-emitters can be improved and enlarged through additional, accurate Penning trap mass measurements. The most demanding such measurements will involve the extension of these cases to heavier superallowed emitters (^{62}Ga, ^{66}As, ^{70}Br, ^{74}Rb) which will provide important constraints on the isospin symmetry breaking corrections [4]. These measurements will require accuracy in excess of 10 ppb on isotopes with half-live down to about 60 ms produced in very small amounts. These requirements dictated the performance of the device.

3. Experimental set-up

The CPT mass spectrometer uses a combination of two ion traps, a radio-frequency quadrupole (RFQ) trap and a precision Penning trap, to capture and accumulate short-lived isotopes and confine them at rest in vacuum. This then enables properties of these isotopes to be precisely determined using sample size as small as a few ions injected in the measurement trap. The CPT is located on-line at the ATLAS superconducting accelerator of Argonne National Laboratory. Radioactive ions created by heavy-ion reactions are injected in the CPT after preparation in a novel device, the RF gas cooler, which is used to stop fast reaction recoils and efficiently cool and accumulate them. The main components of the CPT mass spectrometer and its injection system are depicted in Figure 1. They will be described briefly below in the order in which the beam and reaction products go through them.

3.1. PRODUCTION AND PRESEPARATION OF RADIOACTIVE ISOTOPES

The unstable isotopes are produced at the target location of the Enge split-pole magnet by fusion-evaporation reaction of the heavy ion beams from the ATLAS superconducting linac on thin targets. The ATLAS linac is capable of producing very high intensity beams of stable ions at Coulomb barrier energy allowing significant production of unstable isotopes. The targets and thin windows used in the production of unstable isotopes are all cooled by gas to better sustain the intense beam heating.

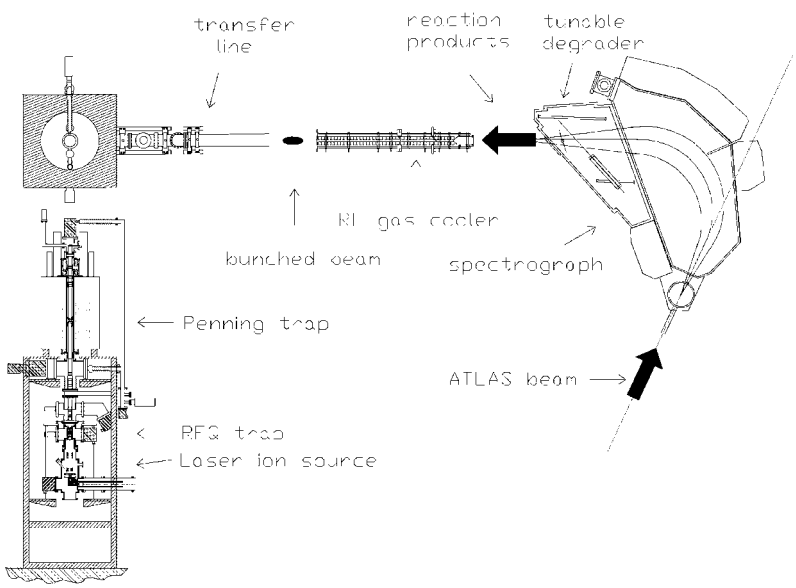

Figure 1. Schematic layout of the CPT mass spectrometer and its injection system at ATLAS.

The kinematics of the reaction carries the reaction products forward and into the spectrograph. The Enge split-pole spectrograph, operating in the gas-filled mode, is used to separate the reaction products from the primary beam. The spectrograph is used at zero degrees to maximize the collection efficiency and a mini Faraday cup (made of tantalum) also located at zero degrees removes the bulk of the primary beam. A transmission type parallel-plate avalanche counter is used to locate the reaction products in the spectrograph and tune the magnetic field. A tunable degrader made of a series of thin aluminum foils on a rotating stage is then used to decelerate the fast reaction products to an energy of roughly 15–30 MeV before they reach the focal plane of the spectrograph.

This initial production and preseparation is performed with an efficiency varying between 10% and 100% depending on the kinematics of the reaction and limited mostly by the acceptance of the spectrograph. The time involved in this part of the process is of the order of 0.5 μs.

3.2. RECOILS DECELERATION, COOLING AND BUNCHING

The reaction products must then be transformed from a fast continuous beam of enormous longitudinal and transverse emittance to a bunched cooled beam suitable for efficient injection into ion traps. A new device, the RF gas cooler, was developed for this task (see Figure 2). The reaction products are stopped in a large volume gas cell filled with high-purity helium at a pressure of about 150 Torr. In the slowing down process the reaction products recapture charge with the vast majority of them ending up in the singly-charged state where they remain since further neutralization on the helium is forbidden by its high ionization potential. The singly-charged reaction products are then extracted from the gas cell by a combination of DC and RF fields (in the high pressure gas cell) which bring the

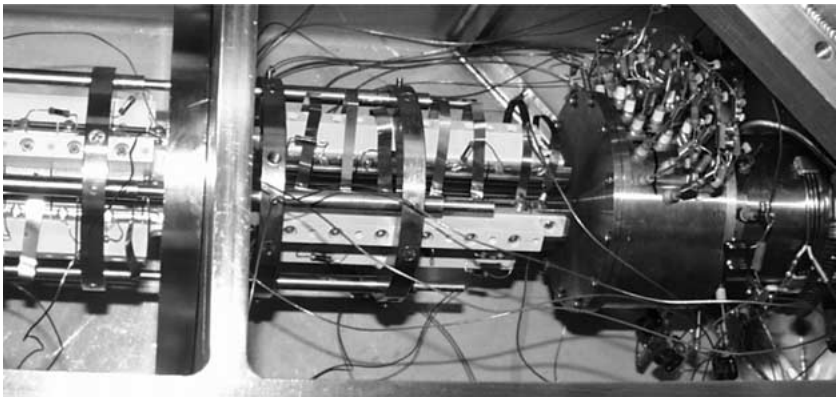

Figure 2. Extraction end of the gas cell system leading to the first two sections of the RF gas cooler. The gas cell and the RF gas cooler are segmented to apply guiding electrical fields while applied RF signals provide radial confinement of the ions.

ions towards an exit nozzle where the flow carries them out. The ions are pushed by the flow into a segmented linear RF structure which pulls the ions through two differential pumping apertures while the gas is pumped away by large root blowers. The final section of the linear RF structure is a linear RF trap where the ions are accumulated and cooled. The bunched ions are then ejected every 50 ms and transported through a shielding wall by a low energy electrostatic transport line to the CPT mass spectrometer located in an adjacent room. The transfer line is equipped with movable microchannelplate and Si detectors to provide diagnostics for both stable and low-intensity pulsed radioactive ions.

The RF gas cooler compresses the longitudinal phase-space of the reaction products by over 10 orders of magnitude with a total efficiency of about 20%. This technological breakthrough now forms the basis of a new approach for the production of radioactive beams which has been adopted for the next generation large scale radioactive beam facility, RIA [5], in preparation in the US. The delay time introduced in the extraction out of the gas cell is about 7 ms with the maximum extraction fields usable at this time and a new cell currently under construction should allow this delay to be reduced to a ms or less. The total delay time introduced in this part of the cycle can be as low as 10–20 ms.

3.3. MASS MEASUREMENT SYSTEM

The mass measurements take place in the CPT mass spectrometer which consists of a radio-frequency quadrupole (RFQ) trap, used for accumulation and preparation of the ion sample, and a precision machined Penning trap located inside the highly homogeneous 5.9 T field of a superconducting solenoid.

The RFQ trap can receive ions from two sources: (1) the laser ion source provides the CPT with ions of stable isotopes either for calibration of the device or actual precision measurements, and (2) the RF gas cooler provides unstable isotopes gathered in the Enge split-pole spectrograph. Both sources are synchronized to inject ions into the RFQ trap at a specific RF phase to maximize capture efficiency. The RFQ trap is operated with a helium buffer gas pressure of 10^{-5}–10^{-6} Torr to cool the ions before the capture of the next ion bunch. This part is also essential to remove any 'memory' effect due to the use of different sources for calibration and measurement. After accumulation of a sufficient number of ions, the ions are extracted from the RFQ trap and transfered to the Penning trap via a ramped cavity which matches the phase-space of the extracted beam to the acceptance of the Penning trap.

Capture efficiency in the RFQ trap is about 50% from the laser ion source and 5–10 times less from the RF gas cooler. The minimum cycle time is of the order of 10 ms, limited by the cooling time in the RFQ trap. A second ramp cavity is being added to the transfer line to better match the phase-space of the ions extracted from the RF gas cooler to the acceptance of the RFQ trap. This should raise the capture efficiency for ions from the RF gas cooler by a factor of 5.

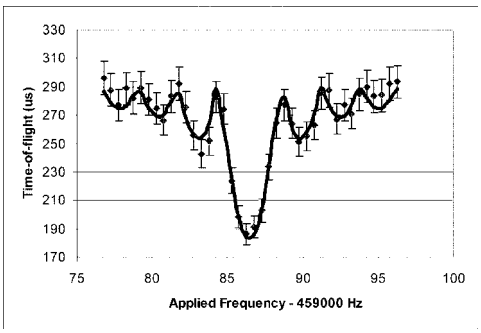

Figure 3. Cyclotron resonance obtained in 10 min of data taking on stable ^{197}Au with a 0.5 s interaction time in the 5.9 T of the superconducting magnet.

The Penning trap is fed by the RFQ trap and is used to determine accurately the mass of the stored ions by measuring their cyclotron frequency

$$\omega_c = \omega_+ + \omega_- = \frac{qB}{m} \tag{2}$$

in the field B of the superconducting solenoid. The cyclotron resonance is observed by the time-of-flight method [6]. Great care was taken to insure that Equation (2) was valid at the ppb level over the volume occupied by the ions inside the trap. The superconducting magnet has self-shielding coils to minimize field fluctuations due to the proximity of large spectrometer and beam line magnets. The material inside the warm bore of the superconducting solenoid was also selected to minimize field drifts due to thermal effects. No systematic shifts of cyclotron resonances are observed at the 10^{-8} level over periods of a day. A typical calibration measurement can be performed in 10 minutes yielding a cyclotron resonance as shown in Figure 3.

4. Performance

The CPT mass spectrometer and its injection system are operating on-line at ATLAS with a total efficiency, from isotope production to measurement in the Penning trap, of the order of 10^{-3}. The demonstrated capabilities of the machine with radioactive isotopes are 1 ppm mass precision for isotopes produced with cross-section at the fraction of a mb level and 100 ppb mass precision for isotopes produced at the 1–10 mb level. Both are demonstrated in Figure 4. The left panel of Figure 4 shows resonances at the modified cyclotron frequency where two species (^{120}Cs and ^{120}Xe) produced on-line are simultaneously loaded into the trap and selectively removed via a mass selective resonant excitation. This approach yields mass accuracy at the ppm level. The right panel of Figure 4 shows a cyclotron resonance obtained on ^{120}Cs after the ^{120}Xe is selectively removed from the trap. The cyclotron resonance yields more accurate mass values, below the 100 ppb level

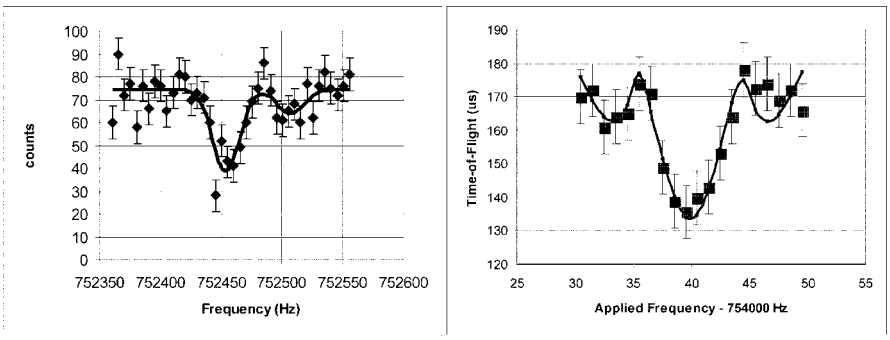

Figure 4. Left panel: Modified cyclotron resonance for ^{120}Cs and ^{120}Xe loaded simultaneously in the Penning trap. Right panel: Cyclotron resonance on ^{120}Cs after the ^{120}Xe ions are removed from the trap.

in this case, but requires a production cross-section at the mb level or larger to be presently applicable. The system is still undergoing continuous improvements, in particular in the phase-space matching in the transfers between the different components and the tuning, and we expect an order of magnitude improvement in the total efficiency with modifications currently in progress. These include not only improvement in efficiency but also increasing the automation of various tasks on a system which has grown to be very complex. A first measurement at the 10 ppb level of the mass of a short-lived isotope will follow the round of current efficiency improvements.

5. Conclusion

The CPT mass spectrometer and its novel injection system are now operating on-line at the ATLAS accelerator in Argonne. They now provide the capabilities for mass measurement accuracy at the 100 ppb level for short-lived isotopes produced by fusion-evaporation reaction, independently of their chemical properties. This allows precision measurements on short-lived isotopes not normally available at ISOL facilities because of the limitations of the extraction out of thick targets. These capabilities will soon be extended to the 10 ppb level of accuracy.

Acknowledgements

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