PREPRINT

TASCC-P-95-18

tascc

THE CANADIAN PENNING TRAP MASS SPECTROMETER

K.S. Sharma [a], R.C. Barber [a], F. Buchinger [b], J.E. Crawford [b], E. Hagberg [c], J.C. Hardy [c], V.T. Koslowsky [c], J.K.P. Lee [b], R.B. Moore [b], G. Savard [c] and M. Watson [c]

[a] Department of Physics, University of Manitoba, Winnipeg, Manitoba, R3T 2N2, Canada
[b] Foster Radiation Laboratory, McGill University, Montreal, Quebec, H3A 2B2, Canada
[c] AECL, Chalk River Laboratories, Chalk River, Ontario, K0J 1J0, Canada

Presented at
International Conference
on Exotic Nuclei and
Atomic Masses
Arles, France
1995 June 19-23

NOTICE

Physical and Environmental Sciences
Chalk River Laboratories
Chalk River, ON K0J 1J0 Canada

1995 June

THE CANADIAN PENNING TRAP MASS SPECTROMETER

K.S. Sharma[a], R.C. Barber[a], F. Buchinger[b], J.E. Crawford[b], E. Hagberg[c], J.C. Hardy[c], V.T. Koslowsky[c], J.K.P. Lee[b], R.B. Moore[b], G. Savard[c] and M. Watson[c]
[a]Department of Physics, University of Manitoba, Winnipeg, Canada, R3T 2N2
[b]Foster Radiation Laboratory, McGill University, Montreal, Canada, H3A 2B2
[c]AECL, Chalk River Laboratories, Chalk River, Canada, K0J 1J0

Abstract

A Penning trap mass spectrometer is currently under construction at the TASCC facility of the Chalk River Laboratories. When completed, the instrument will be used to conduct precise atomic mass measurements, with an accuracy of 10^{-8} to 10^{-9}, among both stable and unstable isotopes of a wide variety of elements. The unstable isotopes, produced in heavy-ion reactions with beams from the TASCC facility, will be collected with a He-jet gas-transport system. After transport to a background free area, the nuclides of interest will be laser desorbed and resonantly ionized. They will then be accumulated and cooled in a Paul trap prior to injection into a precision Penning trap for mass analysis. The instrument will also provide opportunities for other precision experiments on unstable nuclei such as studies of hyperfine anomalies or of parity non-conservation in atomic systems.

1. Introduction

The mass is one of the basic macroscopic properties of the nucleus along with its charge, size and electromagnetic moments. The mass of a nucleus contains information about the constituents of the nucleus and the forces that bind them together, and provides a means to study the fundamental nucleon-nucleon interaction. Such information, when combined with data on nuclear shapes, sizes and spins, provides a basis on which the theories of nuclear physics are developed. It is therefore essential that such data be available for as large a fraction as possible of the (approximately 6000) nuclei expected to be bound.

There exists a large body of measurements that form a backbone of well known masses [1] near the region of β-stability. The masses of nuclei removed from this region are usually determined via chains of α or β decay measurements connecting them to the backbone. Unfortunately, uncertainties and errors may accumulate across the chain so that this information is often unreliable.

The direct measurement of the masses of unstable nuclei is the best way to obtain such basic information about them. Experiments at ISOLDE (CERN) [2] have determined the masses of the atoms in several chains of alkali and alkaline-earth elements to a modest precision with a deflection-type mass spectrometer. The Chalk River On-line Isotope Separator has been used to determine the masses of some isotopes [3] near the N=Z=50 doubly magic region. Recent measurements at CERN have improved the accuracy by using the ISOLTRAP spectrometer at ISOLDE [4]. This new spectrometer used Penning traps, for the first time, to capture, cool and carry out mass measurements on short-lived nuclides with unprecedented resolution and accuracy. For technical reasons, the instrument is currently limited to alkali-like elements.

Mass measurements made in Penning traps are based on a determination of the cyclotron frequency of a group of ions and may be carried out with great resolution and precision. The resolution obtained is dependent on the observation time and requires only a small number of ions (approximately 10) in the trap. This combination of sensitivity, resolution and precision is hard to achieve with deflection type instruments where, as a rule, higher resolution and precision is achieved at the expense of sensitivity. Penning trap mass spectrometers therefore provide an exciting opportunity for carrying out precise mass-spectrometric studies, particularly on rare species of ions. They are ideally suited for the study of nuclei far from stability which are produced in reactions with small cross sections. Their high resolution allows one to resolve contributions from low-lying isomeric states [4] and allows the unambiguous determination of ground-state masses for any species with lifetimes longer than a second with a precision that approaches 10^{-9}. The technique has already been applied to stable isotopes [5] where results ranging in precision from 10^{-9} to 10^{-11} have been reported (for light isotopes).

At the Chalk River Laboratories (CRL) of the Atomic Energy of Canada Ltd (AECL), we are constructing a Penning trap mass spectrometer which will be on-line to the heavy-ion accelerators of the Tandem Accelerator SuperConducting Cyclotron (TASCC). A He-jet gas transfer system will be used to transfer the wide range of unstable nuclei produced in the heavy-ion reactions to the spectrometer. The nuclides of interest will be laser desorbed and resonantly ionized with pulsed lasers. The ions produced will be accumulated in a Paul trap and cooled by collisions with the helium buffer gas. They will then be transferred from the Paul trap to the Penning trap where the precise mass measurements will be carried out.

2. Description of the Spectrometer

A schematic view of the Canadian Penning Trap (CPT) Mass Spectrometer is shown in figure 1. A detailed description of the main components of the instrument system under construction is presented below.

i) The target and He-jet transfer system: A wide variety of beams ranging from protons to uranium with energies ranging from 1 to 50 MeV per nucleon are available at TASCC. With these projectiles fusion-evaporation, light-ion induced fission or fragmentation reactions can employed making it possible to produce a wide range of both neutron deficient and neutron rich nuclides that span the entire chart of the nuclides.

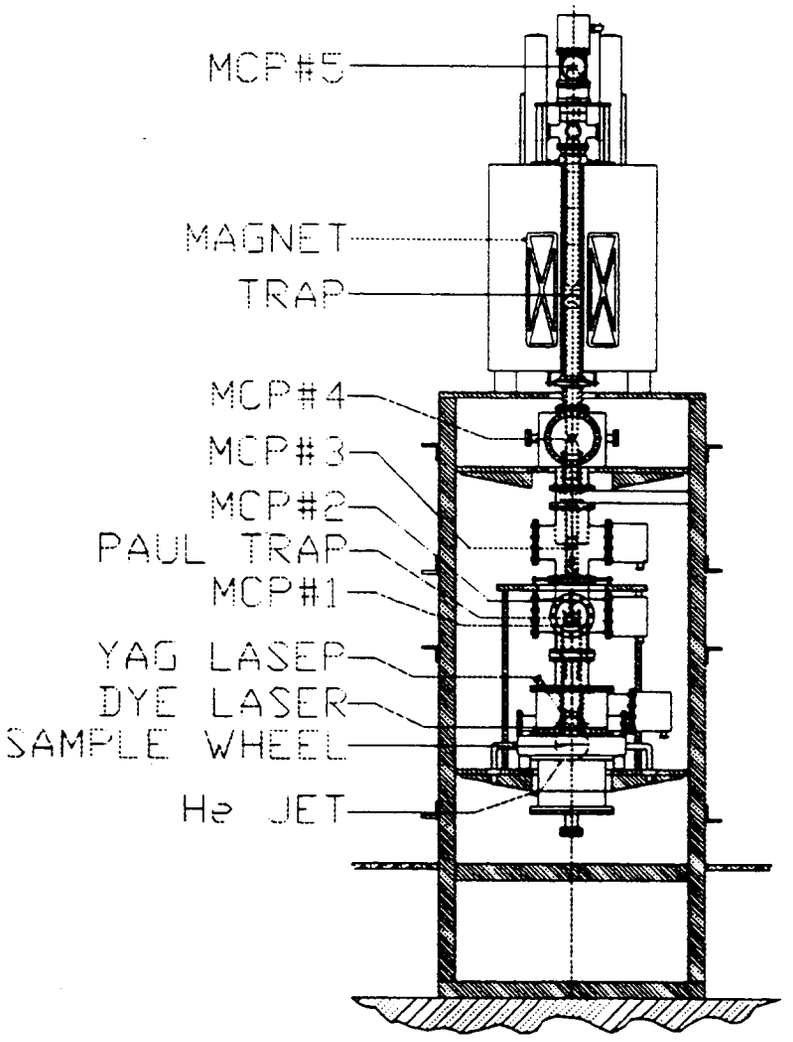

Figure 1. The Canadian Penning trap mass spectrometer.

The heavy-ion reaction products recoil out of the targets and are thermalized in He-gas (approximately 1 atm) loaded with NaCl aerosols. The recoils attach themselves to these aerosols and are then pumped, along with the helium, through a capillary tube to a low-background area where the spectrometer is located. At the spectrometer, the aerosols are deposited on the rim of stainless-steel wheel while the helium is pumped away by a large mechanical pump. The "salt spot" on the rim of the wheel consists of a milligram quantity of NaCl containing about 10^6 atoms of the desired species. The wheel is then rotated, carrying the sample through a set of differentially pumped vacuum baffles into a high vacuum chamber (10^{-6} torr) where the atoms are ionized.

ii) The laser desorption and resonant ionization ion-source: The ionization technique must be efficient as well as selective in order to provide sensitivity while at the same time discriminating against the salt and other impurities that constitute the major portion of the sample. The sample is first desorbed by a pulse of light from a Nd-Yag laser. After a short delay a sweep potential is applied to remove any ions created during this process. The desorbed atoms are then illuminated by pulses from two, tunable, dye lasers pumped by a

(600 mJ per pulse) excimer laser. The lasers run at a frequency of 20 Hz. The beams from the dye lasers cross at 90° so that the beams overlap in a small, well defined volume of space. The wavelengths may be chosen to produce either one- or two-step resonant ionization of the nuclides of interest [6]. Only those isotopes that have the right configuration of atomic energy levels and are located in the illuminated volume are ionized. This makes it possible to extract the ions in a pulse with a well defined phase space volume. Each pulse of ions is guided to the entrance aperture of the Paul trap by a set of einzel lenses and steerers. A channel plate detector (MCP1) can be introduced into the space between the transfer system and the Paul trap to monitor the ionization process. The time of flight of the ions provides further discrimination against any remaining unwanted species.

Laser desorption can evaporate even the most refractory species and such resonant ionization techniques have been successfully applied to nearly all the elements in the periodic table. Therefore, our ion-source will be highly effective in producing ions of essentially all elements. Additionally, by scanning the wavelength of the dye lasers and monitoring the ion current produced it will be possible to perform optical spectroscopy on the sample atoms as well. In this manner one can study the atomic level schemes of the transuranic atoms or the hyperfine structure of radioactive atoms in a manner similar to experiments at ISOCELE [7] and ISOLDE [8]

iii) The Paul trap: The Paul trap (or radio-frequency quadrupole trap) consists of a hyperbolic ring and two endcap electrodes (top and bottom). A radio-frequency excitation is applied between the ring and endcap electrodes. If the laser pulses are appropriately synchronized to the RF then the ion pulses produced will arrive at the correct time to enter the trap [6] through the entrance aperture. Once inside, they lose their energy because of collisions with the He buffer gas (10^{-3} torr) and become trapped. Subsequent bunches of ions can then be trapped without danger of loosing the ions already accumulated. In order to effectively couple the ion source (producing pulses at a frequency of 20 Hz) with the cycle time of the Penning trap (1 Hz), approximately 20 ion pulses will be collected and cooled in the Paul trap before transfer to the precision Penning trap. The averaging of the production rate for the ions will ensure that similar numbers of ions are available for measurement each time.

iv) Transfer of ions to the Penning trap: The ions accumulated in the Paul trap must be transferred to the Penning trap which is located inside the bore of a 5.9 T superconducting magnet. The ions are ejected from the Paul trap by the application of a high-voltage pulse to the endcaps of the trap. Another channel plate detector (MCP2) can be inserted above the Paul trap to monitor the ions as they are ejected. The ions pass through a bunching cavity, which optimizes their time and energy distributions for capture [9] in the Penning trap. A second set of einzel lens and deflectors provides the focussing and steering necessary to guide the ions through a pair of 3 mm diameter apertures which serve to isolate the Paul trap

vacuum chamber from the ultra-high vacuum chamber (10^{-9} torr) of the Penning trap. A third set of lenses guides the ions through the fringe field of the magnet to the entrance aperture of the precision Penning trap. Great care must be taken to ensure that the ions are injected tangentially to the magnetic field lines so that the cyclotron motion of the ions is minimized.

v) The Penning trap: The design of the Penning trap and the mass measurement technique used here is similar to that used by the ISOLTRAP group [4] but with some exceptions. The inner surfaces of the ring and endcaps are hyperboloids of revolution as required to produce a harmonic electric potential. The ring electrode is split into quarters to allow dipole and quadrupole excitations to be applied to the trapped ions. All parts are carefully machined and mounted so as to minimize any radial asymmetries that might otherwise contribute to systematic effects. The introduction of materials into the bore of the magnet degrades the magnetic field uniformity and introduces temperature-dependent fluctuations in the magnetic field because of the magnetic susceptibility of the materials used. Therefore, all parts in the magnetic field should be made out of materials that have as low a susceptibility as possible. Despite its low susceptibility, OFHC copper, a common choice for trap electrodes, appreciably distorts the magnet field seen by the trapped ions. A unique aspect of our design is that the shape of the outer surfaces of the OFHC copper electrodes are chosen so that the magnetic field uniformity in the centre of the trap is left unperturbed by the trap elements. The vacuum tube that houses the trap inside the bore of the magnet also has a large effect on the magnetic field. Because of its softness OFHC, copper is unsuitable for use in this application. We have fabricated this tube from molybdenum, which has a much lower magnetic susceptibility than the commonly used non-magnetic stainless-steel tubes. We expect that the design and choice of materials for our trap elements and vacuum tube will significantly enhance the performance of our spectrometer. In addition, the 5.9 T, superconducting magnet is equipped with a passive superconducting shield to reduce the effects of changes in the ambient magnetic field (present in the laboratory) by a factor of 10^2.

When the Penning trap is ready to receive an ion pulse, the trapping potential on the lower endcap is removed. When the ejected ions from the Paul trap are at the centre of the Penning trap the potential is restored, thereby trapping the ions. The motion of the trapped ions can be expressed as the superposition of three different motions. First the ions oscillate along the axis of the trap in the harmonic electric potential of the endcaps. The presence of this electric field splits the radial motion into two orbital components with different frequencies: ω_- and ω_+. The lower frequency (ω_-) motion is only weakly mass-dependent. The higher one (ω_+) is much closer to the cyclotron frequency (ω_c) and is strongly mass-dependent. The trapped ions are "cleaned" by the application of a large amplitude dipole excitation at the, ω_+, frequencies corresponding to any unwanted species that may be

present. These unwanted ions are excited to larger orbits and are lost through collisions with the walls of the trap. The remaining "pure" sample is then excited by a dipole excitation at the magnetron frequency (ω_-) to an orbit of a preset radius. This ω_- motion can be converted to ω_+ motion of the same radius by the application of a quadrupole excitation at ω_c for a prescribed time. This energy gain by the ions in the trap is detected by ejecting the trapped ions and monitoring their time of flight as they drift through the fringe field of the magnet. A sharp decrease in the time-of-flight signals the presence of a resonance and allows the determination of ω_c and therefore the mass of the ions.

3. Conclusion

At present the gas jet transport system and resonance ionization ion-source have been completed. On-line tests of the apparatus are scheduled for July 1995. The magnet is expected to be delivered in July 1995 and we expect that the instrument will be completed and available for first tests in early 1996.

The CPT mass spectrometer will provide a versatile tool for the study of nuclei far from stability. It will allow high-accuracy mass measurements to be made on any nuclide of interest that can be produced at the TASCC facility. Mass measurements with and accuracy of 10^{-9} may also be carried out on stable isotopes. Additionally, the ionization technique employed may be used to obtain information about the atomic structure of the isotopes studied such as isotopic shifts and the hyperfine structure for heavy elements.

This work has been supported in part by grants from the Natural Sciences and Engineering Research Council of Canada.

4. References

[1] A.H. Wapstra, G. Audi and R. Hoekstra, Nucl. Phys. A565 (1993) 1.
[2] M. Epherre, G. Audi, C. Thibault, R. Klapish, G. Huber, F. Touchard and H. Wollnik, Phys. Rev., C19 (1979) 1504.
[3] K.S. Sharma, P.P. Unger, G.R. Dyck, R.C. Barber,E. Hagberg, J.G. Hykaway, V.T. Koslowsky, J.C. Hardy, H. Schmeing, G. Savard, W. Perry and M. Watson, Proc. AMCO-9/NFFS-6 Int. Conf., Bernkastel-Kues, 1992, eds. R. Neugart and A. Woehr (IOP Publishing Ltd., 1993) 25.
[4] H-J. Kluge and G. Bollen, Hyperfine Interactions, 81 (1993) 15.
[5] V. Natarajan, K.R. Boyce, F. DiFilipo and D.R. Pritchard, Proc. AMCO-9/NFFS-6 Int. Conf., Bernkastel-Kues, 1992, eds. R. Neugart and A. Woehr (IOP Publishing Ltd., 1993) 13.
[6] J.E. Crawford, F. Buchinger, L.Davey, Y. Li, J.K.P. Lee, J. Pinard, J.L. Vialle and W.Z. Zhao, Hyperfine Interactions, 81 (1993) 143.
[7] J.K.P. Lee, G. Savard, J.E. Crawford, G. Thekkadath, H.T. Duong, J. Pinard, S. Libermann, F. Leblanc, P. Kilcher, J. Obert, J. Oms, J.C. Putaux, B. Roussiere and J. Sauvage, Phys. Rev., C38 (1988) 2985.
[8] K. Wallmeroth, G. Bollen, A. Dohn, P. Egelhof, J. Gruener, F. Lindenlauf, U. Kroenert, J. Campos, A.R. Yunta, M.J.G. Borge, A. Venugopalan, J.L. Wood, R.B.Mooreand H-J. Kluge, Phys. Rev. Lett., 58 (1987) 1516.
[9] R.B. Moore, Hyperfine Interactions, 81 (1993) 143.