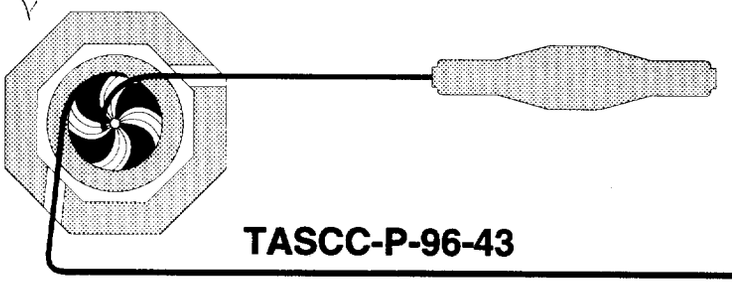

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THE CANADIAN PENNING TRAP MASS SPECTROMETER

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The Canadian Penning trap mass spectrometer

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A Penning trap mass spectrometer is currently being commissioned at the TASCC facility in Chalk River. This versatile on-line apparatus uses a new helium-jet-coupled laser ion source to load ions into a system composed of a Paul trap and a precision Penning trap. This system is intended for high-precision mass measurements on stable and unstable isotopes, but will also offer many new possibilities for precise measurement of the properties of unstable isotopes.

1. INTRODUCTION

The Penning trap offers an ideal environment for high-precision measurements. Charged particles can be stored for extended periods of time in a well controlled and stable environment, free from outside perturbations. These devices are particularly well suited to mass measurements since the cyclotron frequency (ω_c) of charged particles in the magnetic field of a Penning trap can be measured very precisely yielding an accurate mass determination from the simple relationship $\omega_c = \frac{qB}{m}$. This method forms the basis of most new high-accuracy mass measurements [1–4]. Extension of this technique to radioactive ions requires the development of fast and reliable methods for injecting unstable isotopes into the trap. The ISOLTRAP spectrometer [3] was developed for this task and is now operating at the ISOLDE/BOOSTER mass separator of CERN. It is a tandem Penning trap system where the first trap collects and prepares the ions and the second trap is used for the actual mass measurement. While the high accuracy achievable with such a system has been demonstrated, it is so far limited to surface ionizable elements.

The Canadian Penning trap mass spectrometer, which uses a new more versatile injection system, is presented in this paper. It makes use of a helium-jet-coupled laser ion source system for injection into a Penning trap system designed for high-accuracy mass measurements.

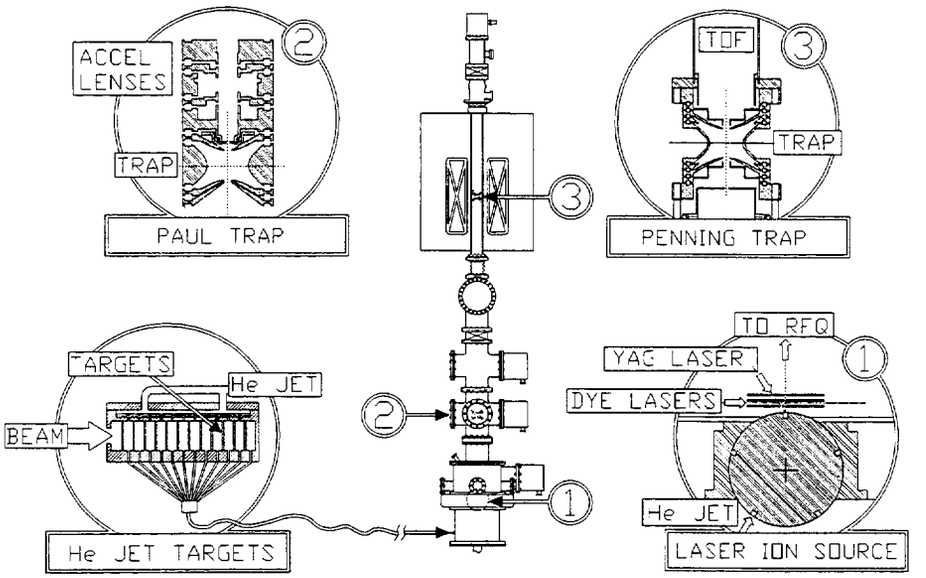

Figure 1. Schematic layout of the Canadian Penning trap mass spectrometer

2. GENERAL LAYOUT OF THE SYSTEM

A schematic layout of the system is shown in figure 1. The heavy-ion beam from the TASCC facility impinges on a stack of thin targets. The reaction products recoil out of the targets, are thermalized in helium gas and are transported by an aerosol-loaded helium jet system to a collection spot where micrograms of aerosol with traces of radioactive isotopes accumulate. A typical transport efficiency is of the order of 50% over distances of tens of meters with transport times of 100-1000 ms. A transport system moves the collection spot to a laser interaction chamber through a differential pumping section. A pulsed Nd:Yag laser deposits a short burst of heat on the surface, vaporising part of the collection spot and creating a plume of neutral atoms expanding from the surface. This plume is illuminated by two excimer-pumped dye laser beams tuned to resonantly excite and ionize the isotope of interest. The clean ion bunch created in this fashion can now be accelerated and transported to the rest of the system. This method of creating the ions is particularly advantageous since a pulsed ion beam is easily captured into ion traps.

A Paul trap is inserted as a buncher between the laser ion source and the Penning trap. It is used to match the 20 Hz repetition rate of the laser ion source with the approximately 1 Hz loading cycle of the Penning trap. An ion bunch created by the laser ion source is transported to the Paul trap, captured by applying a slowing down pulse on the upper endcap and then cooled by buffer gas collisions. Subsequent ion bunches are captured in the same fashion, the process repeating until a sufficient number of ions has been accumulated. The amplitude of the capture pulse (150 Volts for 500 ns duration) is selected to allow high capture efficiency (a 50% capture efficiency has been obtained with

this system [5]) while not disturbing ions already stored in the trap. The accumulation has been observed to be 100% efficient. The cooled ion cloud can then be extracted and transferred to the Penning trap. A ramped cavity situated above the Paul trap is included to match the phase-space of the ion bunch extracted from the Paul trap to the acceptance of the Penning trap.

The ions of the isotope of interest are now stored in the Penning trap which is located in the 5.9 Tesla magnetic field of a superconducting solenoid. High-magnetic field homogeneity is obtained in the trap region by careful selection of the materials inside the magnet bore and by the design of the trap electrodes so that their respective field perturbations cancel. The magnetic field at the trap location must be highly stable since it will ultimately limit the accuracy of the mass measurements. This stability is ensured by control of the parameters which affect the field locally, such as the temperature of materials in the magnet bore and the helium recovery pressure in the magnet cryostat, and the self-shielding design of the superconducting solenoid which attenuates external field fluctuations by roughly a factor of 100.

In the Penning trap section, a vacuum of lower than 10^{-9} Torr is obtained by differential pumping in the transfer section between the two ion traps. The main electrodes of the Penning trap consist of two endcaps and a ring electrode with inner surfaces shaped like hyperboloids of revolution. Correction electrodes are added to compensate for the finite size of the main electrodes and for the presence of apertures in the endcaps for injection and ejection of the ions. The ring electrode is split in quarters to allow dipolar and quadrupolar azimuthal excitations of the ion motions.

In a Penning trap, ions are confined by the combined effects of an axial quadrupolar electrostatic field and an axial magnetic field. The ions have three basic motions inside the trap, the axial oscillation ω_z, the reduced cyclotron motion ω_+ and the magnetron motion ω_-. These frequencies are affected by the electrostatic field and only the true cyclotron frequency $\omega_c = \frac{qB}{m}$ can be related to the mass independently of the electrostatic field. This true cyclotron frequency is related to the eigenfrequencies of the ions in the trap by $\omega_c^2 = \omega_z^2 + \omega_-^2 + \omega_+^2$ and $\omega_c = \omega_- + \omega_+$. The second relationship is used in the excitation scheme under consideration. The cyclotron frequency is determined by excitation of the ions at the sum frequency $\omega_+ + \omega_-$ $(=\omega_c)$ with the ion excitation detected by a time-of-flight technique[6].

3. NEW POSSIBILITIES

The present system will offer many new possibilities for mass measurements. First, the versatility of the injection system will allow the spectrometer to be used to study a wide range of stable and unstable isotopes. In particular, the isotopes of very refractory elements will become available since the difficulty of getting them out of the target/ion source is solved by the helium-jet coupled laser ion source. The number of ions required in a trap is small (about 10) so that a yield of the order of 10^3 per second should be sufficient to perform the mass measurement of isotopes with an half-life of 1 second or more. Many new isotopes will therefore become available for study, even for elements accessible with standard ion sources. The present system could also accept isotopes produced by reactions with accelerated radioactive ion beams in cases where this would be more advantageous.

With the technique described above, an accuracy of $\frac{\delta m}{m} \simeq 10^{-7} - 10^{-8}$ will be available for short-lived isotopes and of up to 10^{-9} for stable and long-lived isotopes. This should allow critical mass measurements to be performed in such areas as double beta-decay and the superallowed $0^+ \rightarrow 0^+$ decays, where these high accuracies are required.

The instrument also opens up many new possibilities beyond those of mass measurement. The helium-jet coupled laser ion source will provide pulsed radioactive ion beams of high purity. It is applicable to elements that are not amenable to on-line extraction from conventional ion sources. The laser resonant ionization process could be used to make isotope shift measurements on heavy elements where the resolution achievable by this technique is sufficient to obtain valuable information. The traps connected to this unique ion source will enable the storage of radioactive ions of a selected isotope in a well controlled environment. Properties of these radioactive ions which are not amenable to observation under normal conditions might then become apparent. For example, high-precision experiments to measure the hyperfine anomaly on chains of isotopes could be carried out in this system with the nuclear magnetic moments measured in the strong magnetic field of the Penning trap and the hyperfine structure (HFS) splitting factors measured in the Paul trap. The extremely low uncertainties (10^{-11}) demonstrated in HFS splitting-factor measurements in Paul traps [7] could also be used to search for higher moments in nuclei. It will also open up new possibilities for the study of fundamental phenomena. For example, an essentially 100% polarized radioactive source at rest in a vacuum would be an asset to the field of β-decay asymmetry studies. In all these cases, the possibility of storing different species of radioactive ions allows the experimenter to select the nucleus best suited to isolate the specific effect under investigation.

4. CONCLUSION

A Penning trap mass spectrometer with a novel injection system has been described. It combines a helium-jet system collecting the reaction products obtained from a heavy-ion beam bombarding thin targets with a resonant-ionization laser ion source to load efficiently a system of two ion traps. This system offers many new mass-measurement possibilities because of its universal injection system and the high accuracy that it provides for measurements of stable and unstable isotopes. In addition, this system will allow the storage of unstable isotopes at rest in a well-controlled environment opening many new possibilities for precision measurements in atomic, nuclear and fundamental physics.

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