Resolving power of the SHIPTRAP Preparation Trap

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A study of the experimental parameters of the SHIPTRAP preparation Penning trap was conducted to improve its mass resolving power and the subsequent accuracy of the measurement trap using singly charged ^{133}Cs ions from a surface ion source. Whilst certain trends of improvement were identified, more research is required for the individual ion species during online experiments.

1 Introduction

Measuring the masses of superheavy nuclei gives insight into their nuclear structure as a function of properties like the binding energy [1]. In a uniform magnetic field, ions spin on the plane orthogonal to the magnetic field with their intrinsic cyclotron frequency. From the latter, the ion mass-to-charge ratio can be calculated; with a known charge, the mass is easily determined. In a Penning trap, a quadrupolar electric field is superimposed with the magnetic field, resulting in a "modified" cyclotron and slow magnetron motion of the ion. These may also be accompanied by an axial motion, shown in Fig. 1.

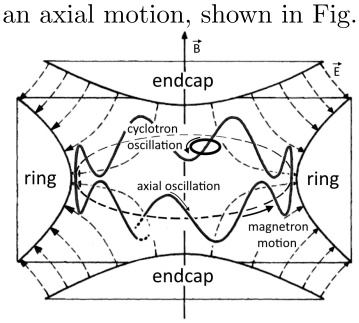

Fig. 1: *The three types of intrinsic components of charged particle motion in a Penning trap: cyclotron, axial, and magnetron motion [2].*

The "reduced" cyclotron frequency of the modified cyclotron motion is denoted as ν_+, and is related to the true cyclotron frequency, ν_c, the magnetron frequency, ν_-, and the axial frequency, ν_z by [3]:

$$\nu_c = \sqrt{\nu_+^2 + \nu_-^2 + \nu_z^2} \approx \nu_+ + \nu_-. \qquad (1)$$

The SHIPTRAP mass spectrometer is dedicated to the mass measurements of superheavy ions; it has two Penning traps in succession (the preparation trap (PT) and the measurement trap (MT)), embedded in a 7 T superconducting magnet. The PT is used to cool the ions under study and remove possible contaminants from the ion bunch (as mass measurements in the MT require the electron of a pure sample of ions of the same species i.e. mass and atomic numbers), providing repeatable initial conditions for the MT, which measures the cyclotron frequency (ν_c) of the selected ions using the PI-ICR method. This report focuses on the PT; the measurement method of the MT and associated details are further discussed in [3].

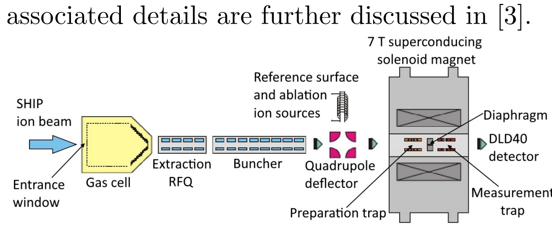

Fig. 2: *A schematic of the SHIPTRAP mass spectrometer set-up [4].*

In the PT, RF fields oscillating at linear combinations of the motional frequencies are used to manipulate the ions. In particular, the buffer gas cooling technique [5] uses a dipolar pulse at ν_- (mass-independent), to drive all ions to an increased magnetron radius. A quadrupolar pulse at ν_c of the ion of interest couples its magnetron and modified cyclotron motions. In the presence of buffer gas, the modified cyclotron motion is quickly damped, thus achieving mass-selective cooling and centering. The trajectories of the ions under these effects are shown in Fig. 3. The centered ions pass through a small aperture, referred to as a diaphragm, before they are captured by the MT in which the PI-ICR process is implemented. They are then ejected towards a position-sensitive Roent-Dek DLD40 detector. This path can be seen in Fig. 2. With a known charge, the mass selectivity is characterized through the mass resolving power (MRP), defined as $m/\Delta m$ for a mass number m and mass difference Δm. A high PT MRP allows the removal of isobaric contaminants such that only one species passes to the MT. For example, ^{207}Pb and ^{207}Tl have a mass difference of $(1522 \pm 6) \cdot 10^{-6}$ u. To distinguish them in the PT, the MRP should exceed:

$$\mathrm{MRP} = \frac{207\ \mathrm{u}}{1522 \cdot 10^{-6}\ \mathrm{u}} \approx 140\,000.$$

On the lower end, separation of a hypothetical contamination of ^{257}Db with ^{257}Rf requires an MRP of $\sim 56\,000$. Several parameters can be varied to increase the MRP.

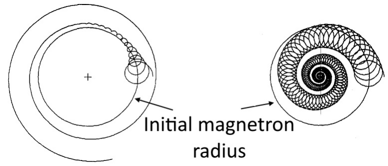

Fig. 3: *Left: only buffer gas - energy is lost to the buffer gas, the cyclotron radius vanishes and the magnetron radius slowly increases. Right: a combination of buffer gas and RF fields - a decrease of cyclotron and magnetron radii [5].*

The effect of each parameter is discussed in Section 2; the results of the different parameter settings are explored in Section 3, with possible improvements and areas of further investigation.

2 Method

In this section, the resulting variables, the parameters, and the optimization procedure are discussed. All measurements were conducted using singly charged ^{133}Cs.

2.1 Variables

After many ion hits on the detector, the resulting distribution resembles a spot, as shown in Fig. 4, where the spread is mostly due to residual motional amplitudes. The observable used for comparing spot sizes is defined as:

$$r = \sqrt{x^2_{\mathrm{FWHM}} + y^2_{\mathrm{FWHM}}}, \tag{2}$$

where x_{FWHM} and y_{FWHM} are the full-width half-maxima of the count distribution on each detector axis. A small spot size is required for the best possible performance of the PI-ICR technique in the MT [3]. The MRP is evaluated using a frequency scan; the frequency of the quadrupolar pulse is varied in a range around ν_c and the count of ions that are sufficiently centered (ions that exit the PT through the diaphragm and hit the detector), is recorded. The MRP is experimentally defined as ν_c /FWHM, where "FWHM" refers to the full-width half-maximum of the Gaussian distribution formed by the ion count as a function of frequency, shown in Fig. 5.

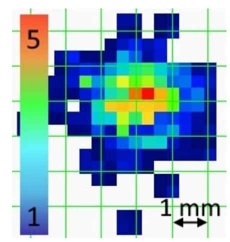

Fig. 4: *Detector hits forming a "spot", where the colors are indicative of the counts per bin.*

2.2 Parameters

Several parameters were studied to improve the MRP and spot size: helium gas pressure, axial cooling time, dipolar magnetron pulse, and quadrupolar pulse. Each is discussed below.

Helium is used as a buffer gas with which the ions interact mainly via elastic scattering. Kinetic energy is lost and the ions are quickly thermalized. If the pressure is too low, the ions will not lose enough energy to be sufficiently centered. If it is too high, the surplus of collisions between the helium atoms and the ions may result in a large spot size and a small MRP. The gas flow supplied to the PT was varied from $10^{-5} - 10^{-3}$ mbar Ls^{-1}.

If the initial axial amplitude is large, the ions spend a short time in the RF fields in the trap center. Larger centering amplitudes are then required for centering, which produces a smaller MRP. Allowing the ions to interact with the buffer gas for a specified "axial cooling time" before applying the RF fields reduces the axial amplitude by allowing kinetic energy to be dissipated. The initial axial motion was measured after 1 ms, then longer axial cooling times, up to 200 ms, were trialed to investigate changes to the spot size and MRP.

The dipolar magnetron pulse increases the radius of the magnetron motion of all ions in the PT. This means only the selected mass-to-charge ratios of the ions in the PT are recentered by the applied RF field at ν_c, after being driven out by the magnetron pulse. All off-resonance ions remain at larger radii and cannot pass through the diaphragm. If the magnetron pulse amplitude is too high, the ions are driven out too far. A larger centering amplitude is required to recenter the selected ions. The driving amplitude was trialed at 0.5, 1.0, and 2.0 V.

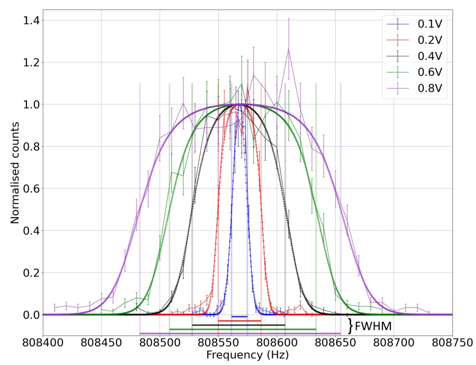

Fig. 5: *Determination of the MRP for different quadrupolar pulse amplitudes at 4.5 mbar* Ls^{-1} *of gas flow, 450 ms of cyclotron cooling time, 10 ms of axial cooling time, and 2.0 V of magnetron driving.*

With a high amplitude of the quadrupolar pulse, the selected ions are centered, producing a smaller spot size, but off-resonant ions are also centered. This is also shown by the distributions of counts measured in the frequency scans for different amplitudes in Fig. 5; the saturation occurs at non-resonant frequencies where all ions are centered enough to pass through the diaphragm, increasing the FWHM, and therefore decreasing the MRP. Insufficient centering occurs with a lower quadrupolar amplitude, resulting in a large spot size. Increasing the time spent in the quadrupolar RF field and buffer gas, known as the "cyclotron cooling time", implies increased centering and more energy lost to the gas. However, a shorter cooling time is necessary for the mass measurements of short-lived particles. The cooling time was varied between 100 ms and 450 ms and the spot size was measured for different quadrupolar amplitudes. These amplitudes were varied from 0.1 to 2.0 V, but only the lowest values which resulted in the convergence of the spot size per cooling time were used. For example, 0.3 - 0.4 V was chosen for 250 ms, and 0.2 - 0.3 V for 450 ms.

3 Results and Discussion

In this section, the results of varying the different parameters described in Section 2 are discussed, and possible areas of further investigation are suggested.

Varying the axial cooling time, with 350 ms of cyclotron cooling, 2.0 V of magnetron driving, and 0.3 V of the quadrupolar centering, there appeared no correlation between the initial axial motion and the resulting MRP, nor the spot size. This is likely because the axial motion was damped enough during the cooling time, making its effects negligible. Regarding the magnetron driving amplitude, a value of 0.5 V was not high enough to drive all the ions out, as ion hits were still registered. However, 2.0 V resulted in a lower MRP. An amplitude of 1.0 V was a suitable compromise, but more testing is required to find the lowest feasible amplitude without allowing the MRP to drop. This should also be measured and optimized for each ion source. The remaining parameters are discussed in the order in which they were tested.

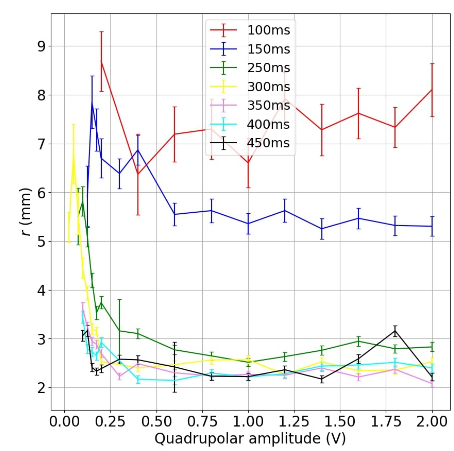

Fig. 6: *Spot size as a function of the quadrupolar pulse amplitude at* $5 \cdot 10^{-5}$ *mbar* Ls^{-1} *of gas pressure, 10 ms of axial cooling, and 2.0 V of magnetron driving. The colors indicate the cyclotron cooling time setting.*

In Fig. 6, the spot size generally decreases with higher quadrupolar amplitude and longer cooling time. Beyond 0.5 V, with a long cooling time, the spot size converges. To maintain a high MRP, amplitudes below 0.5 V should be used, ensuring the spot size remains small.

The effect of the gas pressure on the MRP can be seen in Fig. 7. Higher amplitudes result in a lower MRP, as shown previously in Fig. 5. Lower gas flows, e.g. 10^{-5} mbar Ls^{-1}, result in a higher MRP. This is indicative of sufficient energy loss before the ion passes to the MT. However, the increase in MRP for 0.4 V is not as large as that for 0.2 V. It appears that for lower amplitudes the increase in MRP is higher than that for higher amplitudes as the gas pressure decreases. Varying the quadrupolar amplitude seems to have more impact than varying the gas pressure, but more measurements should be made for each amplitude and pressure to draw a more significant conclusion. Additionally, there was no correlation between the spot size and the gas pressure.

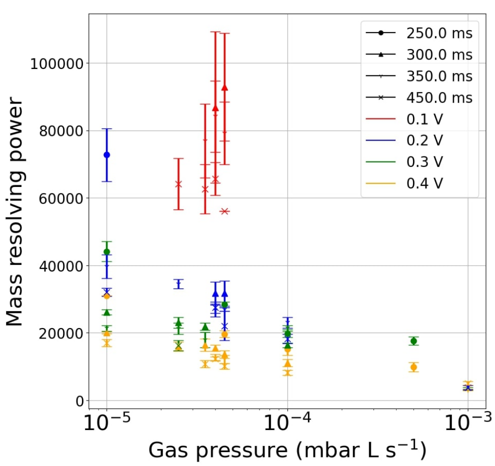

Fig. 7: *MRP as a function of gas flow for different cyclotron cooling times and quadrupolar amplitudes, with 10 ms of axial cooling and 2.0 V of magnetron driving.*

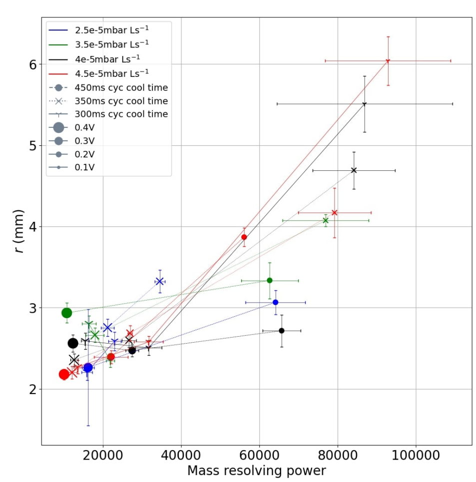

Fig. 8: *MRP vs. spot size for different gas pressures, cyclotron cooling times, and quadrupolar amplitudes.*

The final results are graphed in Fig. 8. The trend of the amplitudes confirms that lower values result in a higher MRP. This is improved with a longer cyclotron cooling time, which decreases the spot size. The range of gas flows in Fig. 8 is likely too small to show a correlation; the outcome of larger gas flows was a high MRP but a large spot size, and a small spot size but low MRP for much smaller gas flows. A mid-range gas flow is therefore preferred for the PT. More research should be conducted to determine the impact of the resulting pressures on the MT.

4 Conclusion

As can be seen in Fig. 8, compromise is necessary when both good centering and high MRP are required. The lowest quadrupolar amplitude, while still producing a small spot size, should be used to obtain a high MRP, and where possible, the longest cyclotron cooling time. A gas flow of the order 10^{-5} mbar Ls^{-1} allows for sufficient cooling. Whilst the axial cooling time does not appear to have an effect on the MRP or spot size, the impacts on the individual ion species should be investigated, as well as from the magnetron driving amplitude.

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