A high-power laser ablation ion source for Penning trap studies of nuclear reaction products

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Abstract. A state of the art Penning trap is being developed at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University to make precision mass measurements of rare isotopes. The system relies on thermalizing nuclear reaction products in a helium-filled cell and then extracting them from the gas through ion-manipulation and differential pumping. Atomic ions and clusters are needed to calibrate various aspects of the entire system such as transport efficiency and the main magnetic field. High-power laser ablation has proven to be a successful method for producing a wide range of ions under various conditions, including atmospheric pressure. We have developed a laser ablation system to explore the production of test beams using a variety of targets. Laser ablation studies of C, Al, Au, Ag, Cu, Fe, and Zn were carried out in a test chamber with the second harmonic, 532 nm, from a Q-switched Nd:YAG laser. Many studies were carried out under vacuum using an ion-drift system and mass analysis in a quadrupole mass filter. The ablation target and laser optics were moved to the gas cell used to collect the nuclear reaction products and several ablation studies were performed. An overview of the laser-ablation system as well as some of the results of this work will be presented.

1. Introduction

Laser ablation is a widespread field, with many multidisciplinary applications such as the production of gas phase ions. Many complexities are involved in understanding laser ablation, including the dynamics of the laser-produced plume, the ablation mechanism itself, and the problems of a decaying, often non-uniform target. Although the laser ablation process is not fully understood, it provides a relatively straightforward method to produce metal ions in the gas phase.

A laser ablation system has been implemented for use in the Low-Energy Beam and Ion Trap (LEBIT) project at the NSCL. The goal is to develop a new method for high-precision mass measurements of radioactive nuclei using a Penning trap [1]. These exotic nuclei, produced by fragmenting nuclear projectiles at relativistic velocities, are stopped by the gas stopping station of LEBIT in one bar of helium, followed by extraction from the gas for low energy measurements [2]. The laser ablation system is used for calibrations and test beams and to study ion collection from the gas cell. Before running the ablation system in the gas cell under atmospheric pressure, the laser ablation process was studied under vacuum. The laser ablation target is mounted on a
Figure 1. (left) Two ablation chambers: the UHV system and gas cell. (right) A mechanical drawing of the drift electrodes with the laser target, pieces of some electrodes were removed for clarity.

removable assembly on a conflat flange so that it can be transferred along with the laser optics between the two chambers. Here we discuss the laser ablation set-up and some of the results from the ablation experiments performed.

2. Experimental
The 532 nm second harmonic of a Quantel (Big Sky) Q-switched Nd:YAG laser was used for the laser ablation studies. The laser beam has an average energy of 160 mJ per 4 ns pulse and a repetition rate of 20 Hz, which was also reduced for certain measurements. The fluence was varied from 0.2 to 12 J/cm$^2$, and a Newport ESP300 raster scan system was used to minimize the unwanted effects from crater formation due to drilling.

Two stainless steel chambers of equal size were used for the ablation studies, one under high vacuum, and the other with 200 torr helium. Figure 1 illustrates the overall experimental set-up, in addition to a close-up of the target mounted on a flange inside the drift-ring structure. The ablation was studied in the chamber under high vacuum in order to eliminate the effects from background gas, including recombination, the creation of shock waves, clustering, and deceleration [3, 4]. Both chambers have a series of ring electrodes, creating a potential gradient forcing the positive ions through the chamber. The ablation target is also biased to force the ions away from the holder. In the gas cell, the ions also encounter a series of spherical electrodes that focus the ions toward the center of a supersonic exit nozzle, which also has an electrical gradient. Once the ions are within a few mm of the nozzle, movement through the nozzle is due to helium gas flow. After the ions leave the gas cell, they are both transported and selected using a series of RFQ (radiofrequency quadrupole) ion guides to the Penning trap. All of the hardware was designed and fabricated in our laboratory.

Under vacuum conditions, a Model 300 Stanford Research System Residual Gas Analyzer (RGA) was used for the detection of the ablated ions, which provided a spectrum of the mass-to-charge ratio. In the LEBIT system, the ions from the gas cell were detected in a multichannel plate. The laser pulse triggered a digital oscilloscope, which provided a time-of-flight spectrum of the ions.

Various metal targets, in addition to a Sigradur™TM glassy carbon target, were used for ablation. The target was encased in a target holder, which minimized backwards plasma ejection and scattered laser light. The target was placed on a movable bellows system in order to change
the position of the target within the chamber at a given pressure, while keeping the fluence constant. Solid metal targets studied were Al, Cu, Fe, Zn, Ag, Au, which covered a mass-to-charge ratio from 13 to 197, including doubly charged ions present at higher photon fluences. These targets contained a variety of naturally occurring isotopes, most of which were detected, except for those in abundance of less than 2 percent.

3. Results and Discussion
Various experiments were performed in the UHV ablation chamber to optimize several parameters including the lens focal length, potential gradient, position of the ablation target within the ring electrodes, bias on the target, and the laser fluence. The data was averaged over two minute runs, and the background was subtracted. Figure 2 illustrates the effect of increasing the laser fluence during the ablation of a silver target. The intensity of total $^{107}\text{Ag}^+$ and $^{109}\text{Ag}^+$ ions detected increased with laser fluence until reaching a saturation point; this behavior was also noticed with the other targets, similar to [5].

A glassy carbon target was ablated in the gas cell to study drift time and ion collection. Information obtained from the time-of-flight spectra, including the time for ions to travel through the gas cell, the ion mobility constant and the effect of the potential gradient on the ion transport compared well to calculations.

![Figure 2](image1.png)  
**Figure 2.** The effect of the fluence on the detected silver ion intensity. The ion intensity increased with the fluence until a saturation point was reached.

![Figure 3](image2.png)  
**Figure 3.** Time-of-flight spectra showing plume intensity as a function of target position within the gas cell.

When the ions were detected, a temporarily split plume was noticed, which is common in laser ablated plasmas in gas [3, 4, 6]. A region of high-pressure ionized plasma is formed on the target surface when a ns laser pulse interacts with the target. Since the 200 torr helium has a lower pressure, a pressure gradient is formed, forcing the fast ions to leave the target holder at velocities near that for propagation through vacuum. Another contributing factor to the fast component is the interaction of the initial stray laser light with the chamber surfaces. Both factors contribute to an exponentially decaying peak, to which the remaining data was normalized. The slower component results from the inner plume layers becoming thermalized and propagating through the helium with a distance-dependent peak distribution. Figure 3 illustrates the ion collection at different target positions within the gas cell showing that the time for ions to travel through the gas cell ranges from 7 ms to 106 ms, depending on the target
position. From this distribution, the ion mobility constant \( K \) can be determined, which is equal to the velocity of the ions divided by the electric field strength. For the ablation of carbon, the ion mobility constant was found to be \( 28 \text{ cm}^2/\text{Vs} \). The effect of modifying the target bias and the potential gradient was also determined. The higher the positive bias on the target, the faster the ions exited the gas cell. The results of these experiments have demonstrated the utility of using a laser ablation source not only as an ion source, but also as a method of studying the properties of the gas cell.

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