A new MOTRIMS apparatus for high resolution measurements in ion-atom collisions and trapped atoms studies

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Abstract. A new MOTRIMS (magneto-optical trap-target recoil ion momentum spectroscopy) apparatus has been built at the LPC-CAEN, and recently tested with a beam of 2 keV Na\(^+\) projectiles colliding on a trapped Rb target. In this work, we demonstrate the capability of the setup to provide, with a very high signal over background ratio, fully differential cross sections in scattering angle, initial state, and final state of the system. The fine control of the trapping lasers, the extraction of the recoil ions transverse to the ion beam axis, and the fast switching for the MOT magnetic field, are three characteristics promising for new studies including collisions with oriented targets or requiring electron detection.

1. Introduction

Two experimental techniques developed in the last decades, MOTs (magneto-optical traps), and COLTRIMS (cold target recoil ion momentum spectroscopy), have recently been merged by using trapped atoms as a cold target for the COLTRIMS methodology \([1-3]\). This new development, called MOTRIMS, added several advantages to the standard COLTRIMS technique. First, it provided an additional set of atomic species such as alkali or alkaline-earth atoms. Using such targets, measurements with different initial states, including aligned or oriented states, can now be performed. A second advantage of MOTRIMS is the very low temperature of the atomic target (of the order of 100 µK) that no longer limits the resolution in recoil momentum.

Using this novel and promising technique, various aspects of the electron capture process, MOT populations dynamic, and photoassociation in cold atoms have already been studied \([4]\). It is in this context that the LPC-CAEN and the CIMAP laboratories built jointly a new MOTRIMS set-up, devoted in a first step to ion-atom collisions study. Since its technical details have already been described \([5]\), the main section of this paper focuses only on specific instrumental aspects. The performance of the apparatus, deduced from test experiments involving Na\(^+\) projectiles at 2 keV colliding with a target of trapped \(^{87}\)Rb atoms, are then presented. Possible modifications of the set-up and future MOTRIMS experiments are discussed in the last section.

2. Experimental set-up

A simplified schematic of the experimental set-up is shown in Fig. 1. It comprises three main parts: i) the magneto-optical trap with three pairs of counter-propagating laser beams and anti-Helmholtz
magnetic coils, ii) a projectile beam-line with a charge state analyzer and, iii) the recoil ion spectrometer.

![Figure 1. Schematic view of the experimental set-up. With the combination of six laser beams (a) and the magnetic field resulting from an anti-Helmholtz pair of coils (b), the atomic target is trapped in the middle of the spectrometer (c). The beam of projectile ions is provided by an ion gun (d). After focussing (e) and collimation (f), the beam enters the collision chamber, passes through the cloud of cold trapped atoms, and is charge-state analyzed at the exit of the spectrometer. The portion of the beam having captured an electron is guided towards the projectile position sensitive detector (g), while the primary beam is collected by a Faraday-cup (h). The recoil ions resulting from charge transfer are extracted from the collision region with 100% efficiency towards the recoil ion position sensitive detector (i).]

2.1. The magneto-optical trap
The $^{87}$Rb MOT requires two laser frequencies: one tuned a few MHz below the cooling/trapping transition $^5S_{1/2}(F=2) - ^5P_{3/2}(F'=3)$ and a second tuned on the repumping transition $^5S_{1/2}(F=1) - ^5P_{3/2}(F'=2)$. We use for these transitions two external cavity diode lasers (DL), each providing an output power of 100 mW at 780 nm. A small amount of the laser power is first sent toward a frequency stabilization set-up, while the main laser beams are merged through a polarizing beam splitting cube (PBSC). The merged beams are then sent to a 110 MHz acousto-optic modulator (switch-AOM) used as a fast beam shutter. The negative first-order diffracted beam is enlarged with a two lens telescope and split into three beams of equal power with a set of half-wave plates and PBSCs. The three beams enter the trapping chamber with orthogonal directions, and are retro-reflected with gold coated mirrors on the opposite side of the chamber. Six quarter-wave plates insure adequate circular polarization for the three pairs of counter-propagating beams. The 6 laser beams have a 1.4 cm diameter and deliver to the trapping chamber a total laser power of 65 mW at the trapping frequency. When the RF power of the first AOM is switched-off, the negative first-order diffracted beam of a second 110 MHz AOM can be used to provide a polarized beam for orientation or alignment of the trapped atoms. The frequency stabilization scheme chosen for the laser diodes makes also use of an AOM [6]. The modulation for the lock-in detection is applied to the AOM radio frequency and does not affect the laser light used for the experiment. This laser control scheme provides a wide range of frequency tuning, and a very stable frequency lock with drifts below 100 kHz. This allows, for instance, to switch easily from $^{87}$Rb to $^{85}$Rb, and to vary easily and accurately the detuning of the trapping laser without affecting the laser power sent to the MOT. The magneto optical trap requires a strong inhomogeneous magnetic field (typical gradients of 10 Gauss/cm) not compatible with the recoil ion momentum spectroscopy. It is then necessary to operate the MOT in a pulsed mode where the B-field is switched off periodically for data acquisition. This B-field switch has to be fast enough to limit the cloud expansion and the trapped atoms losses. For this purpose, a fast current switch for high current and high inductance has been developed. It allows to ramp up and down the 2 A current of the coils in less than 300 µs within a simple timing sequence where the B-field is off during 3 ms and on during 9 ms. The size, the density, and the temperature of the trapped atomic cloud are measured using a fast triggered CCD-camera. The cloud size and position, and the total rate of emitted photons $\gamma_{tot}$ are monitored permanently while operating the MOT. The number of trapped atoms $N$ can
then be deduced by dividing $\gamma_{\text{tot}}$ by the scattering rate per atom $\gamma_p$, given by the spontaneous decay rate $\gamma = 38.11 \text{ MHz}$ times the excited fraction $f$ of the cloud population. The temperature measurement is performed using the ballistic expansion technique. A peak density of $1.5 \times 10^{11}$ atoms per cm$^3$ has been obtained with a cloud temperature of $\sim 200 \mu\text{K}$ and a typical cloud diameter of 0.5 mm (FWHM).

This cloud temperature of $200 \mu\text{K}$ corresponds to a standard deviation $\sigma_p = 0.01 \text{ a.u.}$ for the three components of the target atoms momentum.

2.2. The recoil ion spectrometer

The recoil ion spectrometer is made of three main elements: a stack of electrodes providing an extraction field transverse to the projectile beam axis, a field free flight tube, and a 2-dimensional position sensitive detector (2D-PSD). We use for the recoil ion detection a commercial 83 mm MCP 2D-PSD from Roentdek. A post-acceleration region is defined by an 85 % transmission grid placed 3 mm upstream from the MCPs. The grid is at the same potential as the field free region and the front area of the detector is typically at -4 kV. This provides the additional acceleration eventually needed to ensure maximum detection efficiency. To maximize the recoil momentum resolution, the spectrometer extraction field is shaped to achieve the three dimensional focusing (3D-focussing) of the collision region in the detection plane. The inhomogeneous extraction field ensuring this focusing, generated by the simple succession of a weak field region with a strong field region, was designed with SIMION. The polarization scheme of the spectrometer was chosen so that the potential of the collision region is set to the ground. This requires a polarized field free region, defined by a stainless steel tube connecting the last ring electrode to the 2D-PSD post acceleration grid. That way, the access holes needed for the trapping lasers have negligible effect on the 3D-focusing properties. In addition, this polarization scheme is well adapted to collisions involving very low energy projectile ions. The focusing properties of the spectrometer reduce by a factor of 5 the effect of the collision region size.

3. Sample results

To test the apparatus, we chose the 2 keV Na$^+$ + $^{87}\text{Rb}(5s, 5p)$ collision system, which has already been studied using the MOTRIMS technique [7]. For each detected event, the full momentum of the recoil ions could be reconstructed, and the event flagged with both the status of the switch-AOM and the status of the B-field. Doubly differential cross sections in $P_{//}$ and $P_{\perp}$ for the laser on and laser off cases are displayed in Fig. 2. The relative cross sections of the different capture channels can thus be extracted along with their associated scattering angle distributions. It is to be noticed that due to the transverse extraction geometry and to simple filters applied to the data (on the projectile position and recoil ion time of flight), the signal over background ratio obtained here is excellent and allows the observation of very weak electron capture channels.

![Figure 2](image_url). Doubly differential cross sections in $P_{//}$ and $P_{\perp}$ (upper panels) and differential cross sections in $P_{//}$ (lower panels) for the laser on and laser off cases. The different electron capture channels are labelled by the final state of the Na projectile. An asterisk is added for the capture from the Rb(5p) excited state of the target.
With the ability to switch the MOT B-field combined with 3-D focusing, the resolution on the recoil ion momentum measurement is currently $\sigma_p = 0.07$ a.u., and was found to be only limited by the use of a post-acceleration grid in front of the recoil detector. Using the results from both cases laser on / off and the methodology described in [4], the excited fraction of the atomic target $f = 0.30(3)$ could also be deduced from the data. This gives direct access to the cross section ratios from the two possible initial states.

4. Future applications
In this work, a direct measurement of the excited fraction of the atomic cloud has been performed using charge exchange as a probe. The laser lock system of our apparatus is particularly well adapted for a systematic study of excited fractions as a function of the MOT parameters, like laser detuning and intensity. This study would provide a test of the simple models commonly used to determine the number of trapped atoms in a MOT.

The laser system was also designed to easily “prepare” the target in an anisotropic excited state. With the high resolution of MOTRIMS, the study of charge transfer with such oriented targets looks very promising. Similar experiments have been performed using energy gain spectroscopy, but not using the RIMS technique, which gives access to much smaller scattering angles.

To study ionization processes, future developments should include the detection of electrons with an additional detector. This is here made possible by the use of transverse extraction geometry combined with the ability to switch off the MOT B-field. This improvement would not require a large modification of the experimental set-up.

Last, the capability to control accurately the position of the atomic cloud, with a set of correction coils for the B-field and a CCD-camera, can give access to absolute cross sections measurements. Such measurements are usually limited by an insufficient knowledge of the target and ion beam densities in the interaction region. With our apparatus, the target density profile can be permanently monitored with the CCD-camera, while the correction coils are used to scan the interaction region by moving the atomic cloud through the projectile ion beam.

5. Conclusion
A new MOTRIMS apparatus using transverse extraction geometry has been designed and tested for the 2 keV Na$^+$ + $^8$Rb ($5s$, $5p$) collision system. Its capability to provide fully differential cross sections in scattering angle, initial state, and final state of the system has been demonstrated. Compared to previous experiments using longitudinal extraction, a very good signal over background ratio has been obtained. The resolution of the recoil ion momentum is currently limited by the use of a post-acceleration grid in front of the recoil detector. Regarding this point, the apparatus will be improved by combining several grids. Specific features such as the transverse extraction geometry, the ability to switch off the MOT B-field, and the fine control of the target using our laser system, will allow a large variety of studies involving ion-atom collisions.

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