Cold Atom Trap with Zero Residual Magnetic Field: The ac Magneto-Optical Trap

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A novel atom trap is described using alternating current to generate the magnetic **B** field, together with high speed polarization switching of the damping laser field. This combination produces a trap as effective as a standard magneto-optical trap (MOT), with the advantage that the average **B** field is zero. No net current is hence induced in surrounding conductive elements, and the **B** field produced by the ac MOT is found to switch off >300 times faster than a conventional MOT. New experiments can hence be performed, including charged particle probing or detection of the cold target ensemble.

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The process of atom cooling and trapping using a combination of six orthogonal damping laser fields and a spatially varying magnetic **B** field was first successfully implemented in 1987 [1] and is known as a magneto-optical trap (MOT). Since that time cold targets have been used in many atomic and condensed matter experiments, leading to new discoveries and applications [2]. Amongst these are the application of Bose-Einstein condensates produced from cold atoms held in a MOT [3], through to measurements of fundamental physical constants. The field continues to grow as new applications are found which study and manipulate these cold ensembles.

An alternative research area in atomic physics is that of collision studies, where targets are probed by charged particles (such as ions, electrons, or positrons) to ascertain the dynamics of the collision under study. Experiments include elastic scattering studies where the momentum of the charged particle varies without changing energy, through to excitation or ionization of the target [4]. In all cases, maximum information about the interaction is obtained by ensuring the momentum of the incident charged particle is well defined, and by determining the momentum and state of the outgoing products following the reaction. Detailed theories are formulated to explain the results, these models being refined as the body of experimental data increases [5]. Collision theories are now accurate at high impact energies; however, at low to intermediate energies differences between experiment and theory have yet to be satisfactorily explained. It is in this energy regime that much of the effort is now concentrated [6].

Advantages can arise if the techniques in cold atom research are combined with collision studies. As an example, efficient cooling to a Bose-Einstein condensate has resulted from detailed understanding of Feshbach resonances which arise from cold atom collisions in a magnetic **B** field. This is a direct application of methods studied in collision physics. Further, the application of charged particle detection methods in cold atom physics allows fundamental quantum effects to be studied by detecting electrons or ions that may result from experiment. For collision studies, cooling the target prior to collision increases the sensitivity of the interaction to the initial momentum of the target ensemble. This is key to experiments such as cold target recoil ion momentum spectroscopy (COLTRIMS), which have proven very successful in recent years [7]. These experiments use a supersonically cooled target beam, and the momentum of the target must be known for meaningful results to be determined. By adopting laser cooled targets, the sensitivity and accuracy of such methods could be markedly increased.

A further advantage arises using cold targets, since their very low velocity effectively eliminates Doppler effects that can reduce experimental sensitivity. This becomes particularly important when studying laser and electron interactions simultaneously (such as the superelastic scattering studies in a magnetic field recently developed by our group in Manchester [8]). For studies involving excited targets with long lifetimes, the finite Doppler profile of an effusive target beam markedly reduces the laser-excited population, making many experiments unfeasible. Cooling the atoms prior to laser preparation would effectively eliminate these constraints.

One of the main barriers to widespread adoption of cold target collision studies is that **B** fields must be reduced to less than $\sim 10^{-7}$ T before low energy studies can be performed. Larger **B** fields significantly alter the direction of electrons and ions in the experiment, and whereas a well controlled **B** field may be used [8,9], it is essential to eliminate *uncontrolled* fields before experiments can be conducted reliably. The **B** field arising from trapping cold atoms must therefore be removed before these studies are possible.

An additional complication arises since experiments must be conducted in metal chambers to eliminate charging of insulating surfaces, and any component "seen" by the charged particles must be a conductor. The **B** field from a MOT induces eddy currents in these components, and it is not possible to reduce these in the usual way (e.g., by slotting conductors to prevent current flow). Hence even for MOT currents rapidly switched to zero, the induced eddy currents continue to produce **B** fields until they too reduce to zero.

In practice the **B** field due to the MOT takes ~10 ms to reduce to $<10^{-7}$ T, this time depending on the proximity of conductors to the coils, their shape, and resistivity. During this time, a large fraction of trapped atoms escape, resulting in a cold atom density that rapidly falls to zero. Losses can be reduced by leaving the cooling lasers on to create an optical molasses (if this does not interfere with the experiment); however, the loss problems remain. The comparatively long time taken for the **B** field to decay also reduces data accumulation rates, since the repetition rate is then only ~50 Hz.

It is clearly advantageous to eliminate these constraints. Several methods have been attempted, including shaping the dc MOT driving current at switchoff to try to cancel fields due to eddy currents [10]. This technique is complicated and requires different currents when spectrometer elements move (as occurs in most collision experiments). These limitations have prevented the wider adoption of charged particle studies to cold atoms.

In this Letter we detail a novel technique which has eliminated these problems. In this method, a sinusoidally varying current is applied to the MOT coils, ensuring the current starts and ends at zero in any given trapping cycle (Fig. 1). Since the direction of the **B** field is reversed in each half-cycle, the polarization of the trapping laser beams is also switched from σ^+ to σ^- to be in phase with the current. This is facilitated using an electro-optic modulator controlled by a Behlke HTS-61-03-GSM switch [11]. In the short time the **B** field passes through zero the atoms no longer experience a restoring force; however, since the lasers remain on at this time, the molasses field prevents atoms moving from the trap. To facilitate atom trapping while minimizing extraneous **B** fields, the rms current in the ac MOT was set equal to that in the dc MOT, the laser detuning and intensity remaining unchanged. By ensuring a rapid switching frequency (up to 6 kHz has been used), the ac MOT is found to deliver the same cooling and trapping performance as when operating as a dc MOT. The trapping lifetime of the ac MOT is also found to be the same as the dc MOT for frequencies over 2 kHz.

By adopting a sinusoidal current at a *single* frequency, the inductive and resistive characteristics of the MOT coils can be determined. Precise control of the driving current (delivered by a high power audio amplifier) is then possible, since the phase shift between driving voltage and delivered current is constant at a set frequency. This contrasts with a dc MOT that is rapidly switched off, since the harmonic content of the switched current produces complex phase shifts between current and voltage as the field decays.

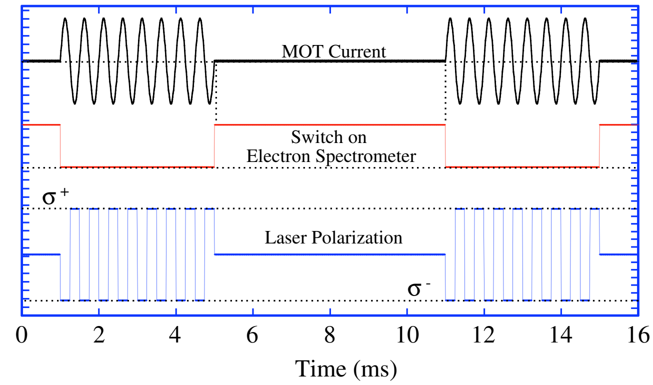

FIG. 1 (color online). The switching configuration for the ac MOT. The MOT is driven by an alternating supply, so that the net induced current in conductors surrounding the MOT coils is zero. The polarization of the six trapping laser beams is switched at the same rate as the MOT current, so as to maintain trapping. Experiments using charged particles are conducted during the time the MOT current is zero.

The main advantage the ac MOT has compared to the dc MOT is that for an appropriate choice of drive to the MOT coils, the **B** field generated by eddy currents in the surrounding conductors can be eliminated when the MOT current is switched to and from zero. This is possible since the **B** field from each half-cycle of the alternating MOT current induces currents of equal magnitude, but which are in opposite directions. Since *equal* numbers of positive and negative cycles are used, the net eddy current is then zero.

For a driving voltage from the amplifier given by $V = V_0 \sin(\omega t + \phi)$, the induced eddy currents can be estimated by modeling the conductors as an inductance L_i (which is coupled to the MOT **B** field), in series with a resistance R_i so that $\tau_i = L_i/R_i$. It is assumed that all conductors have a similar time constant in this model. Since the conductors are not close to the coils, the coupling M_i between conductors and coils is weak, so that the differential equations governing the system can be solved analytically. For coils whose transient response τ_{MOT} is much faster than that of the surrounding conductors, the induced current is then given by

$$I_{\mathrm{eddy}}^{\mathrm{ac}}(t, \phi) \propto \frac{\tau_i \omega \cos(\omega t + \phi) - \sin(\omega t + \phi) - e^{-t/\tau_i}(\tau_i \omega \cos\phi - \sin\phi)}{1 + \omega^2 \tau_i^2}, \quad (1)$$

where the constant of proportionality depends on the coupling M_i and the driving voltage V_0 [12].

By an appropriate choice of phase angle $\phi = \tan^{-1}(\tau_i \omega)$ the transient exponential term in Eq. (1) is eliminated, so that the induced current is purely sinusoidal. By choosing an integral number of half-cycles of the driving voltage, this choice of phase also eliminates transients at turn-off, so that the **B** field induced by eddy currents is zero after the MOT current is turned off.

The characteristic lifetime of eddy current decay was found to be $\tau_i \approx 1$ ms, whereas the MOT current decay was $\tau_{\mathrm{MOT}} < 20$ μs, justifying the use of Eq. (1). The phase angle ϕ was then set to minimize net eddy currents as determined by the electron beam (see below).

The apparatus used for these studies is shown in Fig. 2. A well collimated beam of ^{39}K atoms produced from a recirculating oven in the source chamber enters a Zeeman slower which cools and compresses the atomic beam to a velocity $\sim 40 \pm 1$ ms^{-1}. These atoms enter the ac MOT coils located centrally in the trapping chamber. Six orthogonal red-detuned circularly polarized laser beams operating at 766.7 nm illuminate the MOT after passing through CF70 windows. The MOT coils are constructed from 184 turns of Kapton coated wire wound on split copper formers which produce a **B** field gradient of $\sim$1.5 mT/cm in the trapping region. The system operates with a base pressure in the trapping chamber $\sim 8 \times 10^{-11}$ torr. The combination of oven, Zeeman slower, and MOT produces a high density trap ($\sim 10^{11}$ atoms/cm^3) which fills in $<$1 s, atoms remaining in the trap for $>$400 s. The temperature of atoms in the trap has been estimated as $\sim$300 μK using ballistic time-of-flight techniques. A set of Helmholtz coils surround the trapping chamber to eliminate external magnetic fields. Full details of the apparatus will be given in a future publication [12].

To test the viability of charged particle experiments with cold atoms, an electron gun is installed in the trapping chamber. This produces an electron beam with energy from 2 to 100 eV, and beam currents up to 12 μA. For the present measurements the electron current was on for 800 ns, this time being accurately controlled using custom-built delay generators [13]. In this way the effects of the **B** field due to the MOT coils were determined by monitoring the electron beam that passed through the interaction region in the center of the MOT coils, on a Faraday cup located 450 mm from the gun. Any deflection of the electron beam by the **B** field was seen as a reduction in beam current, providing a sensitive probe of the effects of this field.

Figure 3 shows results for (a) the dc MOT and (b) the ac MOT operating at 5 kHz, with an electron beam energy of 50 eV. The Zeeman slower was also operating, so that all **B** fields to cool and trap atoms were present when data were obtained. Decay of the **B** field from the dc MOT is seen to take $\sim$6000 μs before reaching an acceptable level, whereas the field from the ac MOT only takes $\sim$18 μs to reach the same condition. These results clearly demonstrate the striking advantages accrued by operating the atom trap as an ac MOT.

The results agree well with predictions of the above model. Differences from an exponential decay for the dc MOT are due to the 20 mm entrance diameter of the Faraday cup, which could measure currents for the electron beam deflected by $\sim 5°$. The decay for the ac MOT field matches the slew rate of the 2 kW audio amplifier used to drive current through the coils, and is due to the driving voltage rapidly switching to zero after the 5 kHz alternating current reaches zero at $t_{\mathrm{off}} = 0$ μs [Fig. 3(b)].

To test the electron spectrometer, a pulsed time-of-flight ion detector was installed to detect K$^+$ ions created by electron impact with cold atoms. The spectrometer was initially commissioned using an atomic beam source in place of the MOT, so as to characterize the system. The Zeeman slower and ac MOT were then adjusted to produce cold potassium atoms, and the experiment repeated. The ac MOT was driven with two complete sine waves (400 μs duration) and then switched off for 200 μs in each cycle (efficient trapping has been demonstrated with only a single sine wave of 200 μs duration, with an off time of 100 μs). The ionizing electron beam was switched on 50 μs after the ac MOT field turned off, to ensure zero **B** field from the coils (since atoms move $<$25 μm in this time, this does not significantly affect trapping). Ions produced from the collision were then extracted and accelerated to a channeltron detector using a pulsed electrode located 40 mm from the interaction region. The resulting ion signal was displayed on an Ortec 914 Turbo-MCS multichannel scalar.

As a rigorous test of the ac MOT performance, time-of-flight spectra were collected for incident electron energies from $\sim$2 to 70 eV. These data are presented in Fig. 4 as a 3D spectrum. The ionization cross section for ^{39}K$^+$ atoms is clearly seen from low energies (the ^{39}K$^+$ ionization

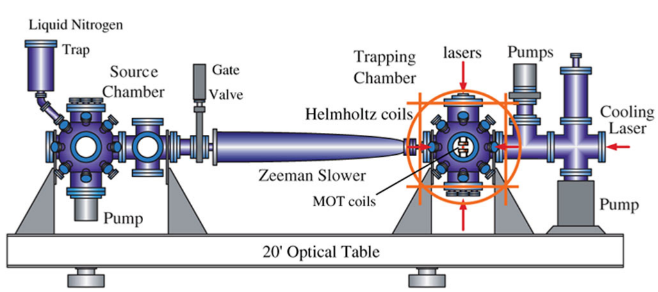

FIG. 2 (color online). The experimental apparatus, showing the source chamber, Zeeman slower, and trapping chamber.

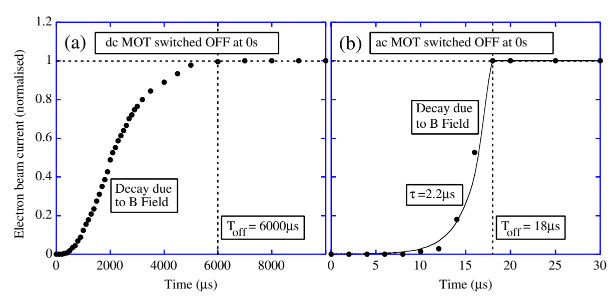

FIG. 3 (color online). Measurement of the electron beam current as a function of time after switching off the MOT. (a) The **B** field from the dc MOT is seen to switch to $<10^{-7}$ T (where electrons are detected without loss) in $\sim$6000 μs. (b) By contrast, the ac MOT is seen to switch off in $\sim$18 μs, more than 300 times faster.

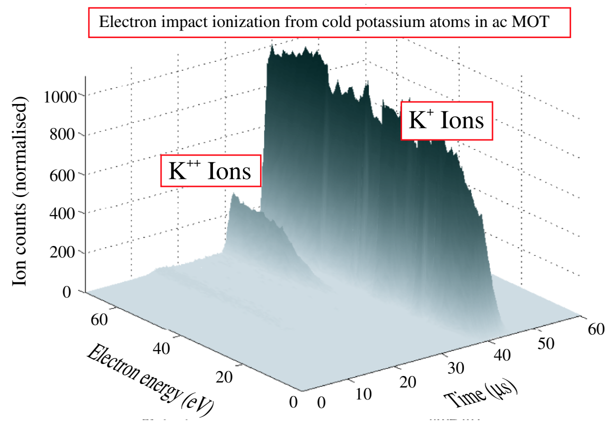

FIG. 4 (color online). Time-of-flight spectra from cold atoms held in the ac MOT as a function of incident electron energy, showing the development of the first and second ionization states of the target as a function of electron impact energy.

potential is 4.34 eV), whereas at energies above 31.6 eV the second ionization cross section for $^{39}K^{2+}$ is also observed. No evidence of $^{39}K^{3+}$ ions was seen (the ionization potential of this state is 45.7 eV), which we attribute to a low cross section for electron impact ionization to this state.

The experiments performed here used an electron gun of relatively low resolution (~0.8 eV), and the uncertainty in the electron beam energy was ~1 eV. The ac MOT cooling laser beams remained on during ionization, and so the measured cross sections include a contribution from laser-excited atoms. At present we do not have the facilities to rapidly switch off the laser beams; however, additional information on the ionization of laser-excited targets could be obtained by adopting such techniques.

In this Letter we have demonstrated the considerable advantages that accrue by trapping atoms with an ac MOT, rather than using a conventional dc MOT. The technique is simple to instigate, and produces a trap equivalent to that of a conventional MOT. We have shown the trapping fields can be accurately controlled, and that experiments can be cycled more than 300 times faster than was possible previously. These methods should be equally effective for Zeeman slowers, by switching the polarization of the cooling laser beam in synchronicity with driving alternating sinusoidal current through the coils. It should then be possible to switch off the Zeeman-slower **B** field as rapidly as for the ac MOT. Although the currents required for Zeeman slowers are higher than for the ac MOT, these can easily be delivered by high power sound reinforcement amplifiers at low cost. We are at present setting up experiments to investigate this.

These ac techniques open up the possibility of performing new experiments using cold atoms. In particular, it now becomes possible to routinely combine the fields of cold atom physics and charged particle collision physics, which will add significant advantages to each. Further, existing experiments that suffer from eddy currents within their apparatus can adopt this new approach to eliminate these problems.

Finally, it should be possible to extend these ideas to switch the **B** field generated by magnetic traps more rapidly than is presently possible. This would require the trapping fields to be controlled by fast alternating currents, to ensure losses due to Majorana spin flips were minimized as the field direction reversed. We have not yet attempted this; however, since magnetic traps are inherently symmetric, this should be possible [e.g., by combining the techniques used in time-orbiting potential (TOP) traps [14] with an ac-driven quadrupole and Ioffe configuration (QUIC) trap [15]]. ac-driven magnetic traps have been realized previously for trapping high-field seeking atoms [16]; however, they have not been used for the applications considered here. Such an ac-driven magnetic trap would allow ultracold physics to explore new directions including studies using charged particles, an area ripe for future theoretical and experimental study.

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