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Neutral Atom Imaging Using a Pulsed Electromagnetic Lens

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Abstract

We present the current status of a novel technique that uses an aberration-corrected lens to focus a supersonic beam of metastable neon atoms for nanoscale microscopy. We have shown that a pulsed electromagnetic lens can significantly enhance refractive power and reduce chromatic aberrations compared to past focusing attempts. The field gradient of the pulsed hexapole lens focuses low field-seeking atoms towards a single focal spot beyond the lens. Prior to the magnetic lens, we optically pump the atoms to a low field seeking state and laser cool the atoms to further reduce the velocity dispersion. This narrow velocity dispersion ultimately optimizes our spatial resolution which we have shown to reach a 100 μm limit thus far. Using a prototype lens, we have imaged complex patterns with lower distortion and higher resolution than has been shown in any previous experiment. Comparison with simulations confirms the underlying theory and encourages further refinement. Using a focused beam of metastable atoms, we can locally probe the chemical composition of a variety of surfaces including conductors, semiconductors, and insulators with minute damage to the sample. When a metastable atom impinges upon a sample, an electron is released and its kinetic energy reflects the bound state energy of the surface atoms. The kinetic energy spectra of the released electrons indicates the chemical composition of the sample surface. Ultimately, neutral atom imaging could provide a near universal, surface-sensitive, and high-resolution tool for localized spectroscopy.

Keywords: Nanoscale Microscopy, Neutral Atom Imaging, Atom Optics

1. Introduction

Atom optics is the manipulation of the atomic trajectories of neutral atoms, often through the use of their wave properties.[1] This field has seen many developments through induced magnetic fields, laser cooling, and optical pumping. However, thus far, the combination of these techniques has not achieved high-resolution nano-scale imaging in the form of a complex atom lens. Here, we report on the developments in aberration correction to improve resolution and specific electronics involved to build a neutral atom microscope.

Neutral atom microscopy is analogous to scanning electron microscopy in that it focuses a beam that is aimed at a sample of interest and provides chemical information. Instead of a beam of electrons, neutral atom imaging uses neutral atoms to spectroscopically probe a sample. The combination of the short deBroglie wavelength of atoms and their relatively low kinetic energies could lower the spatial resolution limits seen in previous experiments[2]. Additionally, atom spectroscopy would allow for greater surface sensitivity than in traditional electron beam and optical methods.

Neutral atom imaging has the advantages of universality, surface and chemical sensitivity, minute damage to the sample, and the potential to become a high resolution tool for localized spectroscopy.[3] Neutral atom imaging provides

universality as the sample does not have to conductive, allowing the microscope to probe semiconductors, conductors, and insulators. Additionally, the microscope only minutely damages the sample, providing a means to probe biological samples without special coatings. The surface sensitivity arises from that when we aim the focused beam of neutral atoms at a sample, only surface electrons will be ejected through electron tunneling. Ultimately, a complex atom lens could pave the way towards universal, nanoscale true-atom imaging.

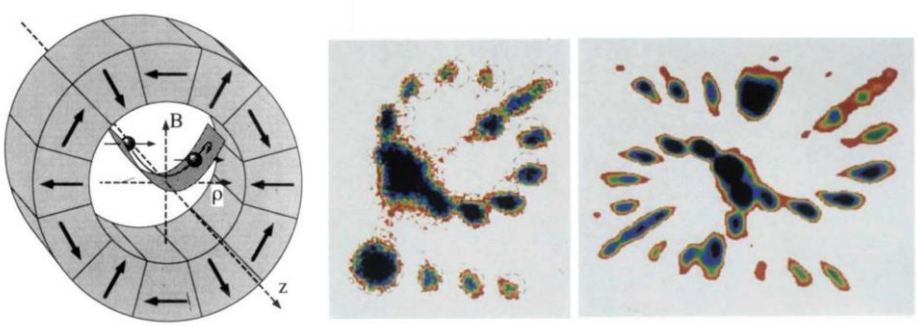

Figure 1. On the left, permanent magnetic hexapole design as used in experiment by Kaenders et al. On the right, the inverted images produced by Kaenders et al., achieving true imaging with a permanent magnetic hexapole lens.[4]

Although metastable atom spectroscopy provides a promising imaging method, there is currently not a method to create a dense, small enough beam to realize high-resolution local spectroscopy. Previous focusing attempts have used a permanent magnetic hexapole lens, a cylinder with six magnetic sections where the magnetization alternates as seen in Figure 1.[4] In this case, the atomic beam passes through the central bore where the magnitude of the magnetic field increases with the distance from the z-axis squared, yielding a hexapole field that is a harmonic function of the radius. Thereby, the field provides a force that is linearly dependent on atomic position and enables focusing of a supersonic beam of atoms. Kaenders et al. has shown that a permanent magnetic hexapole lens can focus a beam cesium atoms and achieve true imaging of a two-dimensional shape[4]. Although their experiment achieved a 200 μm resolution, their method encourages further refinement to achieve a nanoscale microscopy through aberration correction. The primary challenges posed are maximizing atomic flux, minimizing aberrations, and further developing our chemical analysis methods.

In this paper, we will focus on the optical pumping stage of the beamline and the electron analyzer controller. The optical pumping ensures the neon atoms are in a low-field seeking state and the controller provides chemical information across the sample of interest.

2. Optical Pumping Of Neon

Metastable atom microscopy requires a cold beam of any atom that has an easily attainable paramagnetic metastable state. Generally, noble gases meet these requirements and the lighter gases also have the advantage of becoming a colder beam during supersonic expansion. The ability of an atom to be magnetically focused depends on its magnetic moment to mass ratio. Both neon and helium would be ideal candidates, but our laser was set to the frequency necessary for neon.

In the ground state, the electrons in neon are all paired and its orbital shells are filled, providing no net orbital angular momentum. However, through optical pumping we can excite some of these electrons to a higher energy metastable state which can remain in that state throughout the duration of our experiment. Optically pumping allows the experiment to access the $^3P_2$ and $^2D_3$ states of metastable neon as seen in Figure 2. The $^3P_2$ state is a long lived easily accessible state with a lifetime of τ = 14.73, over 1,000 longer than the lifetime of the experiment. Within these metastable states, there exist a number of substates that are indistinct without the presence of a bias magnetic field.

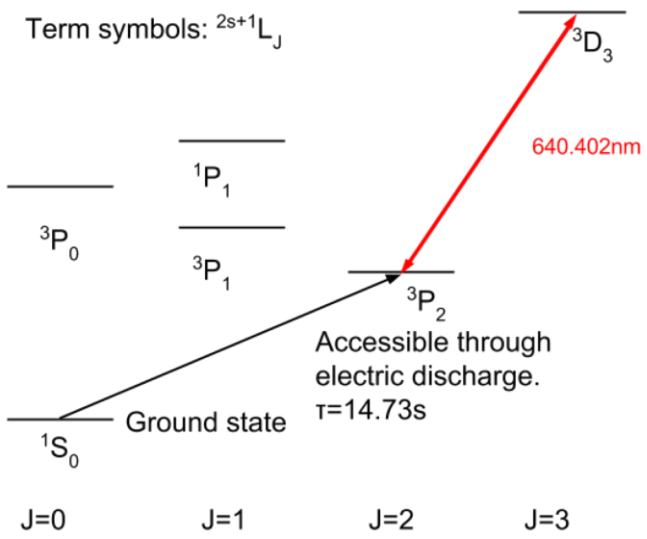

Figure 2. Atomic transition to create metastable $^3P_2$ Neon with a magnetic dipole moment. Schematic created by Dr. Anciaux.[2]

This uniform bias magnetic field has to be strong enough to lift the degeneracy of the substates, inducing Zeeman splitting of the substates where the shift in energy is proportional to $\Delta E = B\mu_B m_j g_j$. This splitting of the substates allows access to the low-field seeking state $m_j = 2$ that will be focused most strongly by a magnetic hexapole lens. The uniform bias magnetic field was induced by a pair of Helmholtz coils with tunable currents. Helmholtz coils consist of two circular electromagnets with their radius equal to the distance between them.

$$B_z = \frac{\mu_0 I r^2}{2(z^2+r^2)^{3/2}} \tag{1}$$

$$B_z = \frac{\mu_0 I r^2}{2}\left(\frac{1}{((z+\frac{a}{2})^2+r^2)^{\frac{3}{2}}} + \frac{1}{((z-\frac{a}{2})^2+r^2)^{\frac{3}{2}}}\right) \tag{2}$$

The magnetic field of a single coil in the axial direction where z = 0 is equal to equation 1. In the case of two coils, placed at $\pm\frac{a}{2}$, the sum of the magnetic fields will equal equation 2. Upon taking the series expansion and realizing that the geometry is symmetric about the z = 0 axis, only even powers of z will be nonzero. Since for Helmholtz coils, a = r, the z^2 term vanishes and only z^0 and z^4 remain. In Figure 3, the uniform magnetic field produced by the coils along the z-axis is clearly visible.

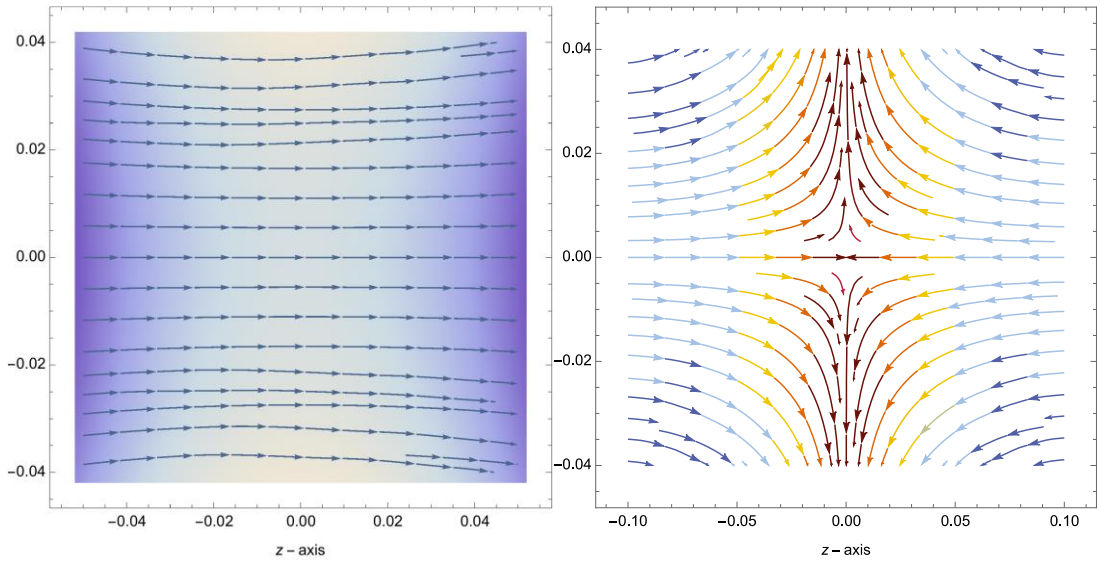

Figure 3. On the left, magnetic field of radial and z components along z-axis induced by Helmholtz coils. On the right, force field induced by radial and z-components of Helmholtz coils.

The force field on the right in Figure 3 was calculated by taking the gradient of the magnetic field in accordance with $F = \Delta(m \cdot B)$ where m is the magnetic moment and B the magnetic field. The simulation of the force field implies that the beam would feel a force that compresses the size of the beam slightly. Further experimentation would be required to confirm this slight effect. More importantly, the bias magnetic field of the Helmholtz coils allows the Zeeman splitting of the metastable substates. Lifting the degeneracy, the Helmholtz coils enable circularly polarized light to excite the neon atoms, ultimately reaching the metastable $^3P_2$ state. Nearly all atoms end up in the $m_j = 2$ state that is most strongly focused by the hexapole lens. In Figure 4, the implemented Helmholtz coils in the beamline are illustrated and their observed effect on atom intensity is seen in 4b. Optical pumping doubles the atom intensity as it changes from 6000 to 12000 AU. In Figure 4b, a narrowing of the atomic beam is already noticeable, but this becomes even more evident in Figure 5. The 18 mm width marks the size of the CCD detector. As we enable optical pumping, we qualitatively observe the focusing of our atomic beam of metastable neon atoms. This is merely one part of the beamline in our neutral atom imaging device, but we can see that the optical pumping phase significantly contributes to the focusing of our beam.

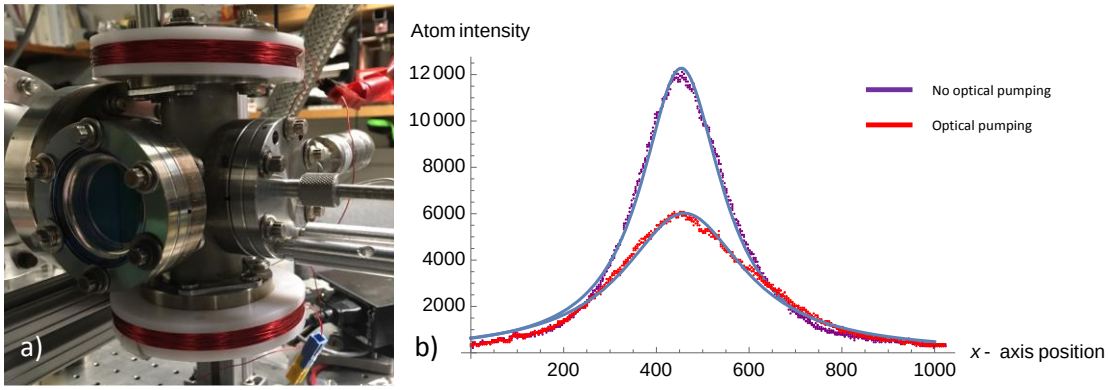

Figure 4. a) Helmholtz coils built and implemented in neutral atom lens system. b) Atom intensity at CCD with and without optical pumping fitted to Lorentzian curves.

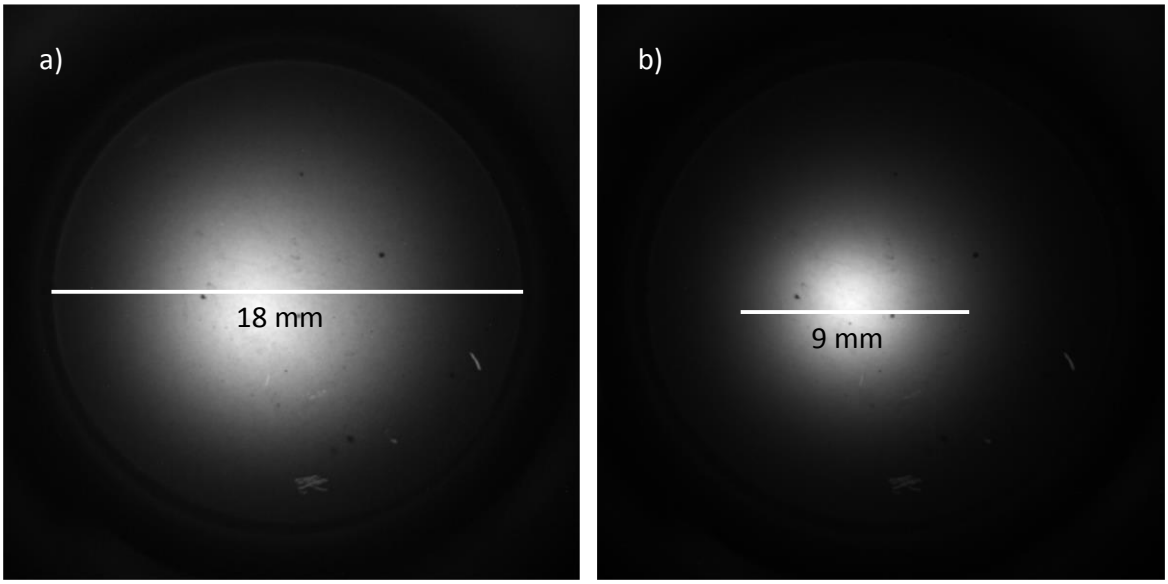

Figure 5. a) A CCD image of atomic beam as it reaches the detector. In this image the lasers are off and the beam is at room temperature. b) A CCD image of an atomic beam that is optically pumped to the $^3P_2$ state with $m_j = 2$ and at room temperature.

After the optical pumping phase, our beam passes through our pulsed magnetic hexapole lens that significantly reduces chromatic and geometric aberrations. As our beam of neon atoms impinges on a surface, an electron from the surface will fill the unfilled inner electronic state of the metastable neon. Then, two processes can occur: a) penning ionization or b) Auger neutralization and resonance ionization. The process that occurs does not directly depend on the material of the sample. However, penning ionization occurs in insulators, conductors and semiconductors while Auger neutralization does not occur in insulators.

$$KE = E_{excitation} - E_{binding\ energy} \quad (3)$$

If penning ionization occurs, an electron will be ejected from the metastable and reach the electron analyzer. Alternatively, in Auger neutralization and resonance ionization, an electron from the metastable is ejected and trigger the ejection of an electron from the sample. In this case, the electron from the sample will reach the analyzer. The electron analyzer then provides the kinetic energy of the emitted electrons. Since the kinetic energy of this electron equals equation 3, this kinetic energy provides us the binding energy to the surface. Equation 3 holds due to conservation of energy, enabling metastable atom electron spectroscopy to provide a density of energy states across the surface of a sample. This electron tunneling events give rise to the chemical and surface sensitivity of neutral atom spectroscopy.

3. Electron Analyzer Controller

The electron analyzer controller consists of six electromagnetic lenses with adjustable voltages. Through simulations on SIMION, ion simulator software, set voltages that only allow electrons of 5 eV, 10 eV, 15 eV, 20 eV, and 25 eV to reach the detector were found. If the voltage of each lens is set to only allow 10 eV electrons to reach the detector, the count of electrons at the detector corresponds to the number of electrons with those energies across the surface of the sample.

To control and adjust the voltage of these six lenses, a circuit was designed with an operational amplifier, OPA454, and several potentiometers, BOURNS_3296, as illustrated in the simplified schematic in Figure 6. The Printed Circuit Board (PCB) in Figure 7 is the full design that still requires further testing before full implementation.

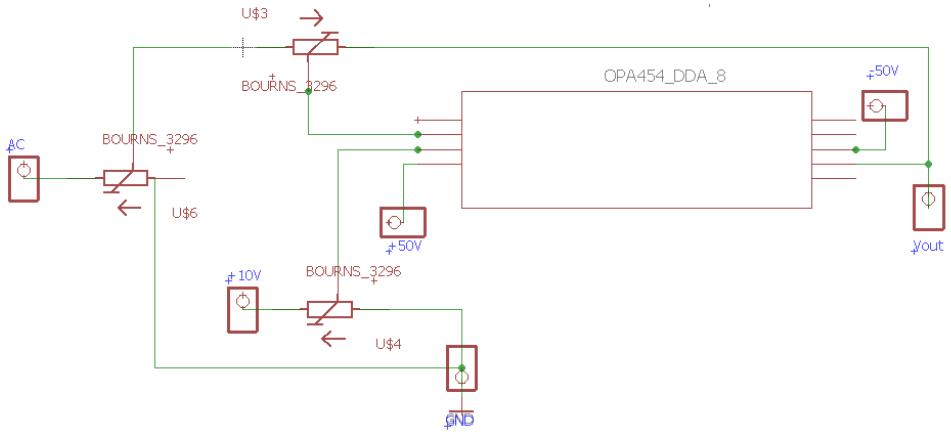

Figure 6. Simplified circuit diagram for electron analyzer controller designed in Eagle.

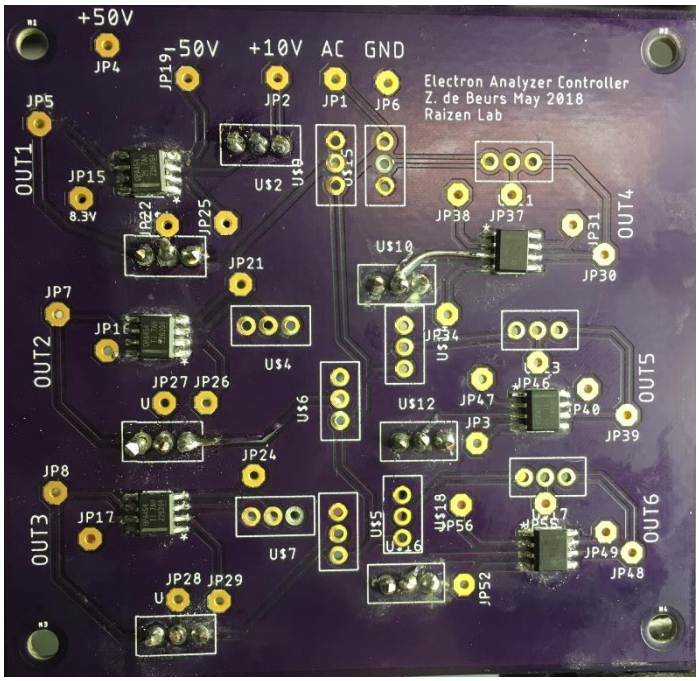

Figure 7. PCB design implemented as electron analyzer controller

4. Conclusion

In this experiment, the combination of optical pumping with a pulsed hexapole lens to create a high-flux, focused atomic beam for atom imaging advances techniques of aberration correction in atom lenses. We have shown that a pulsed electromagnetic lens can significantly enhance refractive power and reduce chromatic aberrations compared to past focusing attempts. The close agreement of simulations and experimental results also supports further refinement of this technique. Through its universality and chemical sensitivity, neutral atom imaging has the potential to become

a high-resolution tool for localized spectroscopy. Ultimately, further refinement could pave the way toward true atom nanoscale imaging.

5. Acknowledgements

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6. Citations

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