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Atomtronic Circuity

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“Atomtronics” refers to the ultracold atom analog of electronic components and circuits. This work was the first to develop and explore two key building blocks of atomtronic circuitry: a battery, which can serve to power atomtronic circuitry, and a transistor, which is the fundamental nonlinear building block that ultimately leads to the incredible breadth of the functional capability of circuits. The experimental demonstration of a battery showed that internal resistance is fundamental to battery action, and the resistance can be either positive or negative depending on the temperature of the atoms comprising the atomtronic current relative to parameters characterizing the battery’s atom-trapping potential. The results of the atomtronic battery were used to demonstrate atom-(matterwave) current flow through an atomtronic transistor comprised of a triple-well potential having “Source”, “Gate” and “Drain” regions. A semi-classical analysis shows that current gain that is greater than unity is possible. The atom-current results are measured, and are in agreement with the semi-classical models. The demonstration of gain means that it is possible to conceive of atomtronic circuits operating on matterwaves as amplifiers, oscillators,

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Atomtronic Circuitry

Final Report

Abstract

"Atomtronics" refers to the ultracold atom analog of electronic components and circuits. This work was the first to develop and explore two key building blocks of atomtronic circuitry: a battery, which can serve to power atomtronic circuitry, and a transistor, which is the fundamental nonlinear building block that ultimately leads to the incredible breadth of the functional capability of circuits. The experimental demonstration of a battery followed on the earlier theoretical work supported by AFOSR that showed that internal resistance is fundamental to battery action, and the resistance can be either positive or negative depending on the temperature of the atoms comprising the atomtronic current relative to parameters characterizing the battery's atom-trapping potential. The results of the atomtronic battery were used to demonstrate atom-(matterwave) current flow through an atomtronic transistor comprised of a triple-well potential having "Source", "Gate" and "Drain" regions. A semi-classical analysis shows that current gain that is greater than unity is possible. The atom-current results are measured, and are in agreement with the semi-classical models. The demonstration of gain means that it is possible to conceive of atomtronic circuits operating on matterwaves as amplifiers, oscillators, switches, and so on over a compete spectrum of atom-based electronic circuit analogs. This conclusion, in turn, has substantial implications for atomtronic circuitry for implementing new classes of matterwave systems for inertial sensing, time keeping, logic, and so forth.

1. Experiment Equipment and Setup

The atomtronics experiments presented in this report take place in a double-magneto-optical trap (MOT) vacuum chamber. The atom source is located in the lower chamber, in which laser cooling techniques produce a stream of cooled atoms upwards into the upper chamber. The top of the vacuum chamber is formed by an atom chip. Wires placed on both the ambient and vacuum sides of the chip allow for the creation of a 3D harmonic magnetic potential to be formed 200 μm below the chip. Additionally, the chip features a transparent window that, in conjunction with external optics, enables the projection of optical potentials onto the magnetic potential. Both the projection of the optical potentials as well as *in-situ* imaging is achieved using a high-resolution projection and imaging system (figure 2)

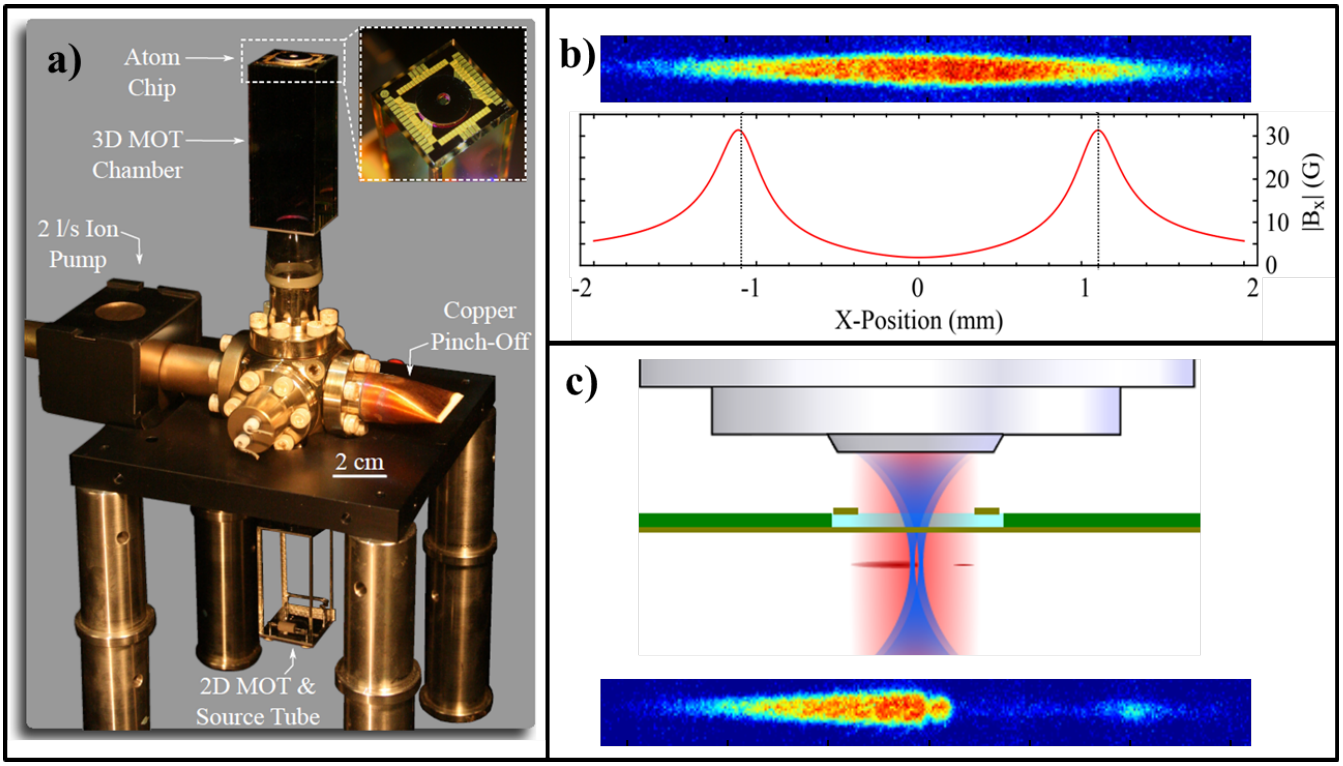

Figure 1: a) Double MOT vacuum chamber that is used to conduct the presented atomtronics experiments. The inset displays the atom chip, which forms the upper wall of the vacuum chamber and is used to form the magnetic potentials used in the presented atomtronics experiments. b) Harmonic magnetic potential formed by running current through wires on the atom chip. An in-situ absorption image of approximately 20,000 Bose-condensed atoms in the magnetic potential is also shown. c) Diagram showing how a transparent window located at the center of the atom chip allows optical access so that arbitrary optical potentials can be projected onto the harmonic magnetic potential. Accompanying this diagram is an in-situ absorption image showing atoms divided into three potential wells due to focusing two repulsive, Gaussian barriers through the chip window and onto the magnetic potential.

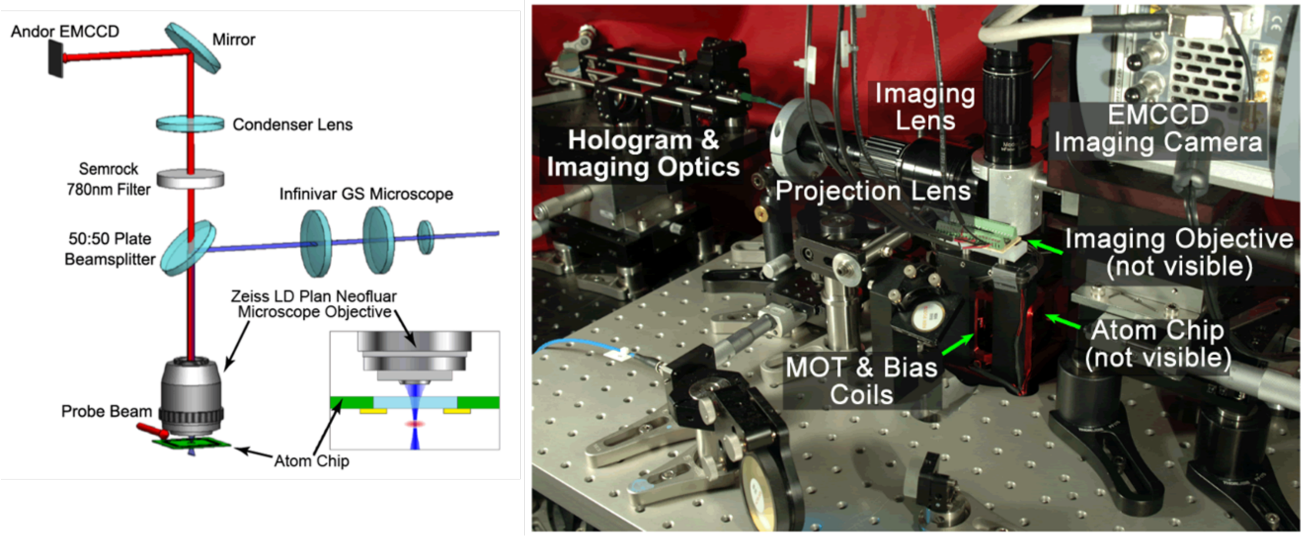

Fig 2: Left: Schematic of the high-resolution projection and imaging system for use in the atomtronics transistor experiment. The optical potentials that are projected onto the harmonic magnetic potential are shown as the blue laser beam while light imaged from the atoms in the transistor is show at the red beam. A 0.6 NA objective serves to simultaneously project the potentials and image the atoms in the transistor. Right: Photograph showing the projection and imaging system with respect to the double-MOT vacuum chamber.

2.1 Atomtronic Battery System & Experiment

The results presented in this section describe the experimental realization and characterization of an atomtronic battery that can store energy in the form of a finite-temperature Bose-Einstein condensate. The battery is capable of sourcing an atom current for an atomtronic transistor. A schematic of the atomtronic battery experimental system is shown in figure 3.

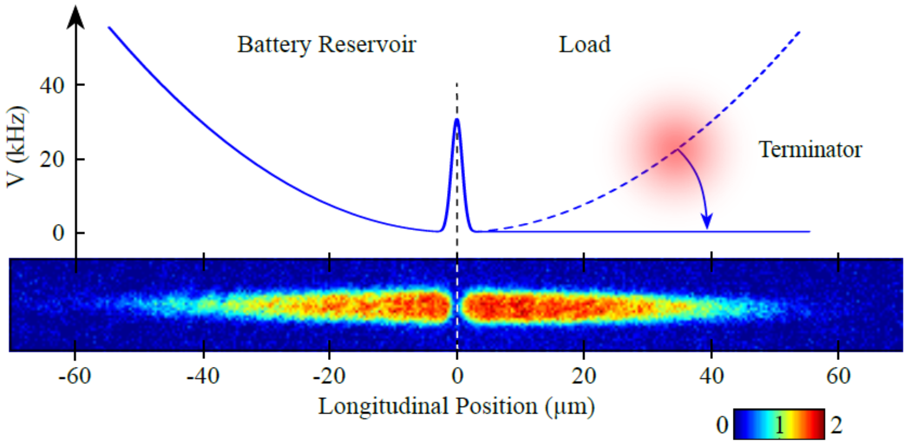

Figure 3: Schematic of the atomtronic battery potential. The top image shows the potential energy diagram (measured in units of frequency) of the hybrid magnetic and optical potential. The bottom image is an *in-situ* absorption image of atoms trapped in both wells of the potential.

The battery is initially charged by loading an ensemble of atoms into the battery reservoir well. This is accomplished by ramping on a repulsive barrier on the edge of the atom cloud and sweeping it to the center of the magnetic potential. This process is shown in figure 4. After this procedure, all of the atoms in the magnetic trap are loaded into the reservoir well and the battery is considered to be charged. The amount of energy stored by the battery is characterized by the chemical potential of the trapped atomic ensemble in the reservoir well.

Subsequent atom discharge was permitted by lowering the height of the barrier. Time evolution of the reservoir ensemble during battery discharge was observed. As the barrier height was lowered, the initial ensemble of approximately 20,000 atoms (where approximately 1,000 are condensed) begins to flow out of the source well. We additionally find that as the battery reservoir discharges, it cools. The reservoir ensemble's thermal potential energy was measured to decrease from 678 nK to 440 nK after discharging the battery for 80 ms. Lowering the barrier height was found to result in a more rapid depletion of both the reservoir atom number and its temperature. For the remainder of this report, energy is expressed in units of frequency.

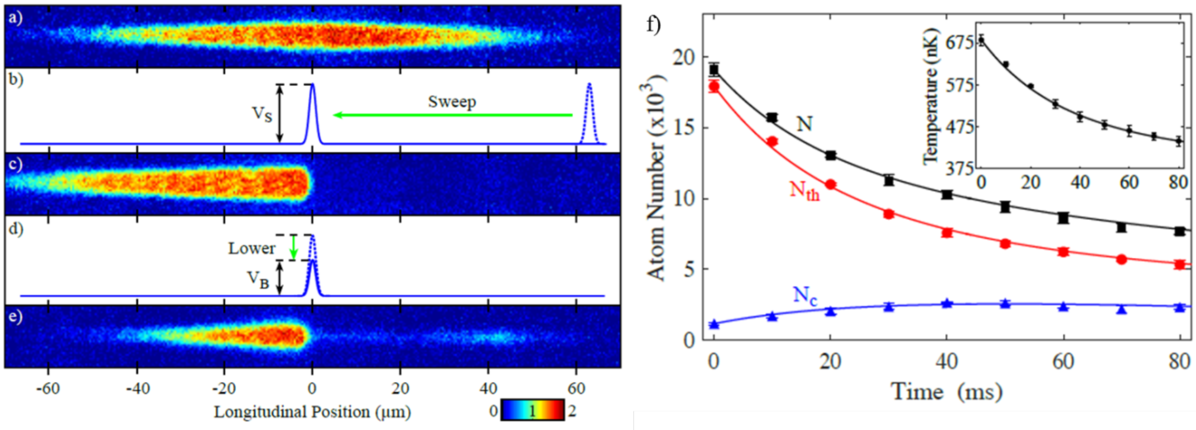

Figure 4: This figure shows the procedure and results of the atomtronic battery charging and discharging experiment. a) Atoms are loaded into a harmonic magnetic potential. b) A repulsive optical barrier at height V_S is turned on and swept from the far side of the magnetic potential to the center of the trap. c) All atoms are now trapped in battery reservoir. In this case, the battery is considered to be charged. d) The barrier height is lowered to V_B, triggering the discharge of an atom current. e) *in-situ* absorption image of atoms flowing out of the battery after 30 ms of discharge time. f) Time evolution during battery discharge of the total atom number (black squares), thermal atom number (red circles), and condensed atom numbers (blue triangles) in the battery reservoir when the battery potential is V_B=50 kHz. The inset shows the resulting temperature drop of the source well ensemble as the battery discharges.

The performance of the atomtronic battery is quantified by the current capacity, energy capacity, and the peak power output. The current capacity, defined as the total sum of the atom current as the barrier is lowered from the initial to final value, is shown in figure 5 and increases monotonically as a function of the battery discharge time. An extension to the current capacity is the energy capacity of the battery, and is shown in figure 5 to increase linearly with the increasing barrier height. Finally, the peak output power of the battery was measured experimentally and is shown in figure 5 to decrease monotonically with increasing the barrier height. From our experimental results, we find the atomtronic battery is capable of supplying a maximum peak power of 50,000 kHz^2 and occurs when the barrier height V_B satisfies $V_B/k_BT<3$ where k_B is the Boltzmann factor and T is the average temperature of the battery reservoir ensemble.

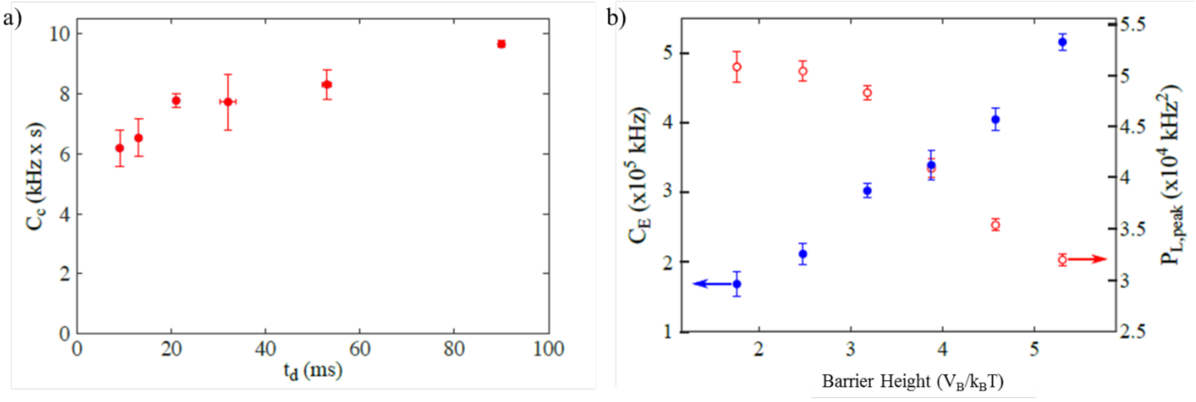

Figure 5: a) Current capacity C_c of the atomtronic battery displayed in units of kHz x s is shown to increase monotonically with the battery discharge time t_d. b) Plot showing the performance of the atomtronic battery as a function of the barrier height. The energy capacity C_E(shown in filled blue circles) is shown to increase linearly as the barrier height increases. The measured peak output power $P_{L,peak}$ (displayed in red open circles) is shown to decrease monotonically as the barrier height increases. From figure 5b, the peak output power of the atomtronic barrier was determined to be approximately 50,000 kHz^2 and occurs for scaled barrier heights $V_B/k_BT<3$.

2.2 Semi classical Model of Atomtronic Transistor

A semi classical model has been applied to study the atomtronic transistor-like action in a triple well potential. A schematic of the triple well potential as well as the conceptualized atom and energy flow through the transistor are shown in figure 6.

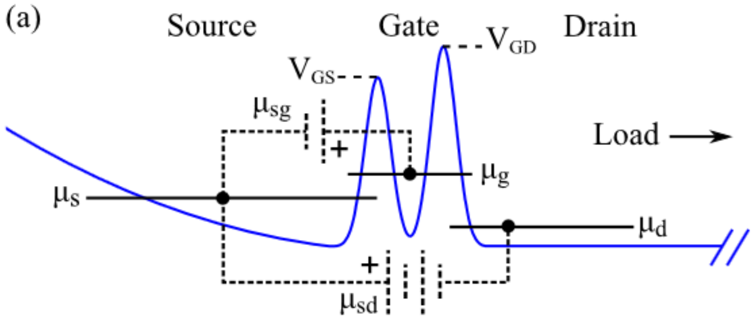

Figure 6: Triple-well potential with source, gate, and drain wells. The chemical potential in each well is shown. In this model, the atom current flowing from the source well, through the gate, and into the drain is to be controlled by adjusting the source-gate chemical potential difference.

The semi classical model shows that the chemical potential and temperature drop between the source and the gate well is determined by a feedback parameter (figure 7). This feedback parameter, defined as the ratio of the difference of barrier heights to the temperature of the source ensemble, $\upsilon=(V_{SG}-V_{GD})/T_s$, depends on the barrier heights, which is an experimentally tunable parameter.

The model shows a negative feedback parameter υ results in a negative temperature drop in the direction of net current across the source-gate barrier. This corresponds to heat transfer into the gate and thus the gate temperature T_g is greater than the source temperature T_s in steady state. Conceptually, this is analogous to a positive resistance in a classical electrical circuit. However, the model shows that if the feedback parameter is positive, then net cooling will occur and $T_g < T_s$ in steady state, thus predicting that the atoms flowing into the gate well can be cooler than the source. This behavior is analogous to a negative resistance.

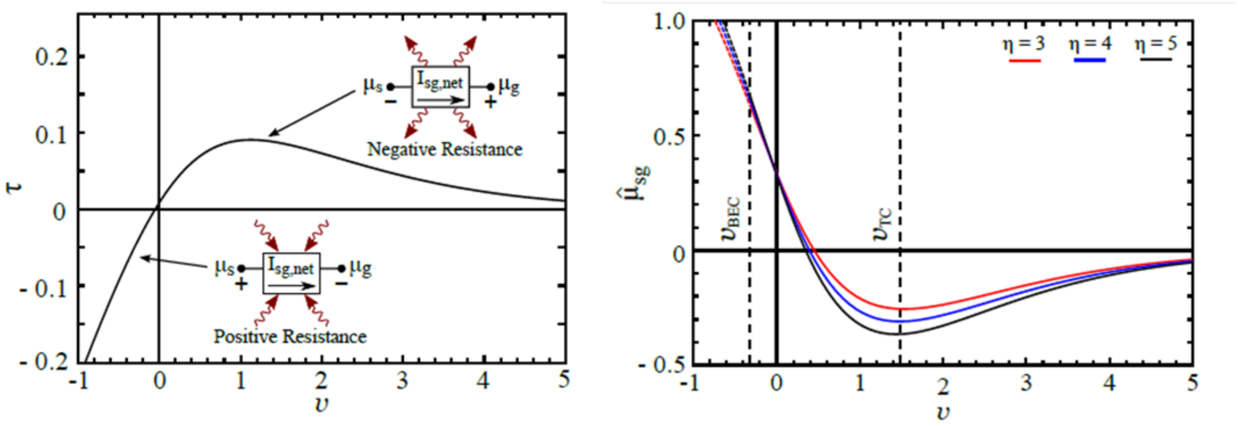

Fig 7: Left: Plot of the temperature drop τ = Ts-Tg vs. feedback parameter $\upsilon=(V_{SG}-V_{GD})/T_s$. Right: Chemical potential drop $\mu_{sg}=\mu_s-\mu_g$ between the source and gate wells as a function of the feedback parameter. In this plot, the $\eta=V/k_BT$ parameter is where V is the mean potential of both source-gate and gate-drain barriers, k_B is the Boltzmann constant, and T is atom temperature.

Finally, the semi classical model shows the triple-well transistor potential exhibits regions of both positive and negative current gain, depending on the feedback parameter (figure 8). Additionally, this current gain value can exceed unity. The magnitude of the gain depends on the mean trap frequency of the gate well, and thus shows an important results that the gain of the transistor is a tunable parameter.

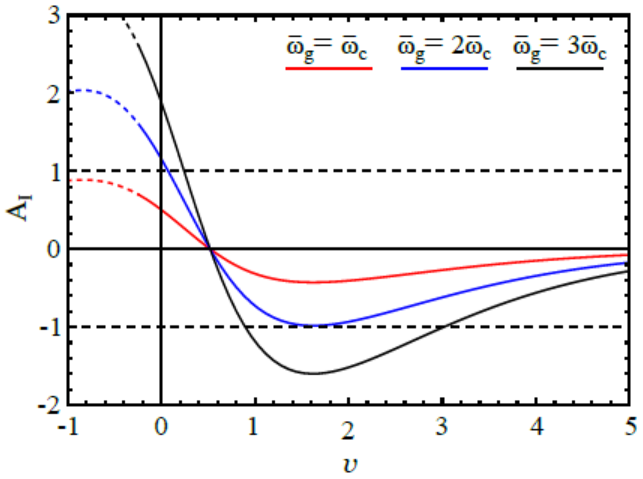

Figure 8: Plot of current gain of the atomtronic transistor. The three curves are illustrating that the increase in current gain magnitude is due to an increase in the mean trap frequency of the gate well. The results of this plot show that the gain of the transistor is a tunable parameter.

2.2 Observed Transport Dynamics in the Atomtronic Transistor

The atomtronic transistor potential is formed from the overlap of a harmonic, magnetic potential with two repulsive Gaussian barriers. The resulting trap geometry is a triple-well potential, with the three potential energy wells labeled as the source, gate, and drain wells (figure 9).

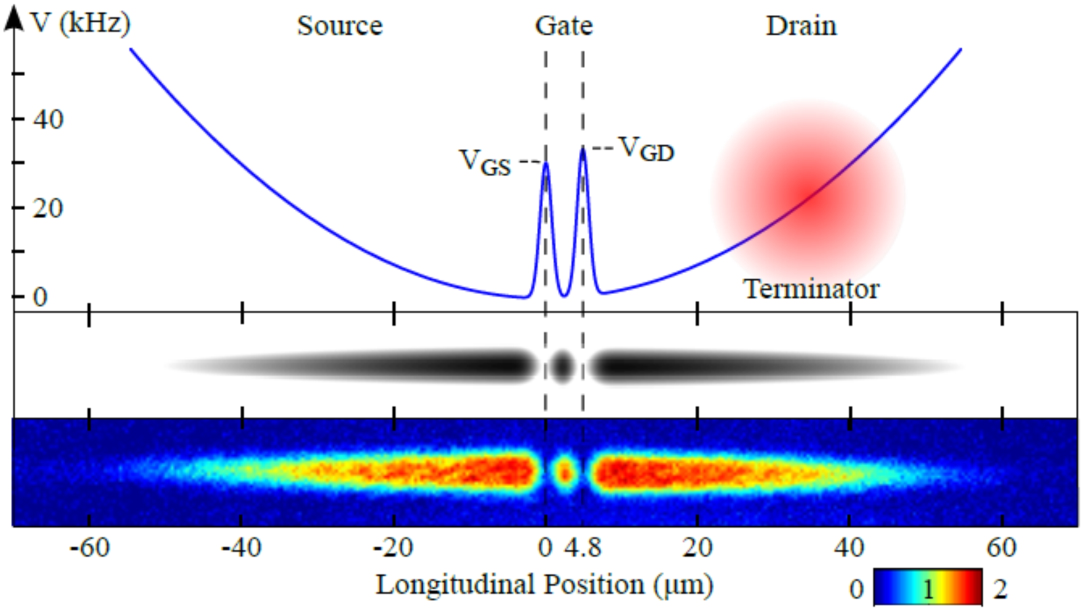

Figure 9: Potential energy profile of the triple-well transistor potential. The potential is created by overlapping two repulsive, Gaussian barriers over a harmonic, magnetic potential. The two repulsive barriers are at heights labeled V_{GS} and V_{GD} and divide the potential into three wells labeled the source, gate, and drain well. The bottom images show the calculated 2D energy contour of this potential and an *in-situ* absorption image of 45,000 atoms trapped in the potential, with the three regions distinctly observed.

The flow of atoms through the atomtronic transistor potential was observed by first loading atoms into the harmonic magnetic potential (figure 1b). The source-gate barrier (shown in figure 9) at an initial height of V_{SG}=100 kHz is swept across the potential to compress all atoms into the source well. This operation is equivalent to charging an atomtronic battery and it prepares the atoms for transport through the transistor potential. Immediately after loading all atoms into the source, the gate-drain barrier (shown in figure 9) is turned on, establishing the complete atomtronic transistor potential shown in figure 9.

Each run of this experiment begins with approximately 20,000 atoms in the source well at some initial chemical potential. Initially, the source well atoms are not necessarily condensed. The source-gate and gate-drain barrier heights are then set to their desired energies, which in this experiment correspond to 30 kHz and 33 kHz, respectively (shown in figure 9). The system is then allowed to evolve freely in time and the evolution of the atoms through the transistor system is observed with *in-situ* time-of-flight imaging. The evolution of this system as a function of time is shown in figure 10.

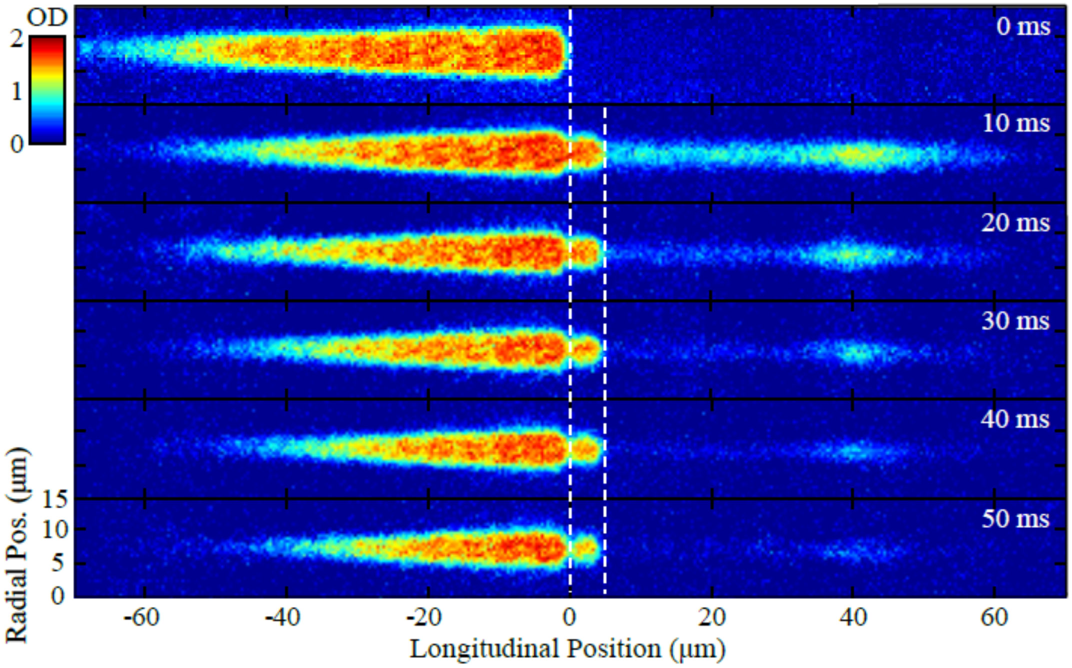

Figure 10: *in-situ* absorption images arranged to show a time series of the atomtronic transistor as atom current flows from the source well, through the gate, and into the drain. In the images, the vertical dashed lines indicate the spatial location of the source-gate and gate-drain repulsive Gaussian barriers.

The results of this experiment clearly show that within the first few milliseconds, there exists a rapid rise in the gate population. Shown in figure 11, the population of the gate well spontaneously increases from zero to approximately 1380 atoms within the first 20 ms of evolution time, which corresponds to the semi classically calculated equilibrium value. The gate well is spontaneously occupied with atoms due to the existence of a substantial population inversion as energy states lying below the height of the barriers are initially unpopulated. This is explained by the source well holding atoms at a higher chemical potential than the gate well chemical potential.

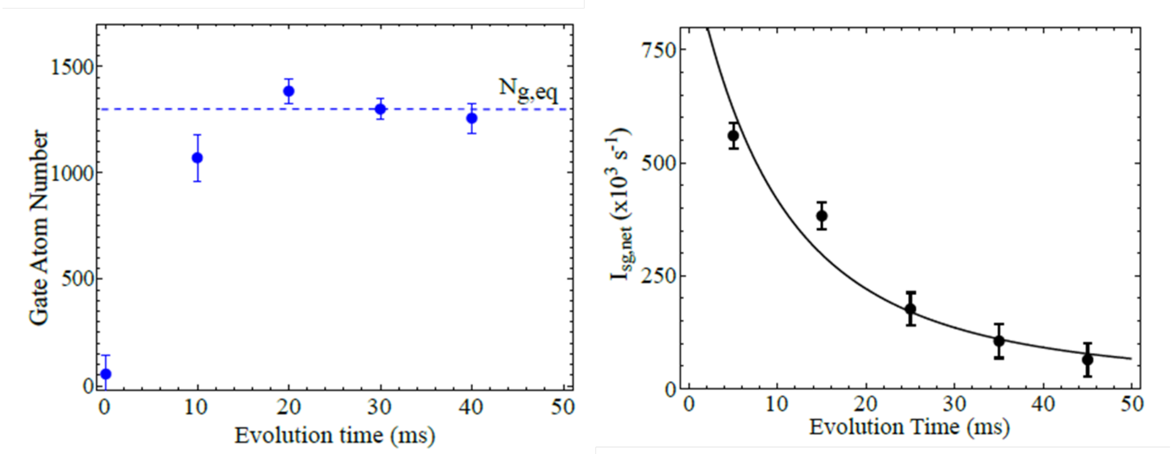

Fig 11: Left: Plot showing the gate well population as a function of evolution time. The gate well was observed to rapidly fill with atoms and quickly approaches the calculated equilibrium value. Right: Plot showing the measured net source-gate atom current as a function of the evolution time.

Finally, the atoms spontaneously filling the gate well are found to be cooler than the source well and furthermore, can undergo spontaneous Bose-Einstein condensation in the gate well (figure 12). A critical feedback parameter defined as the ratio of the difference of barrier heights to the temperature of the source ensemble, $\upsilon=(V_{SG}-V_{GD})/T_s$ governs the spontaneous occupation of a Bose-Einstein condensate in the gate well. The experiment shows that for critical feedback parameters above υ= -0.24, a condensate forms in the gate well in steady state.

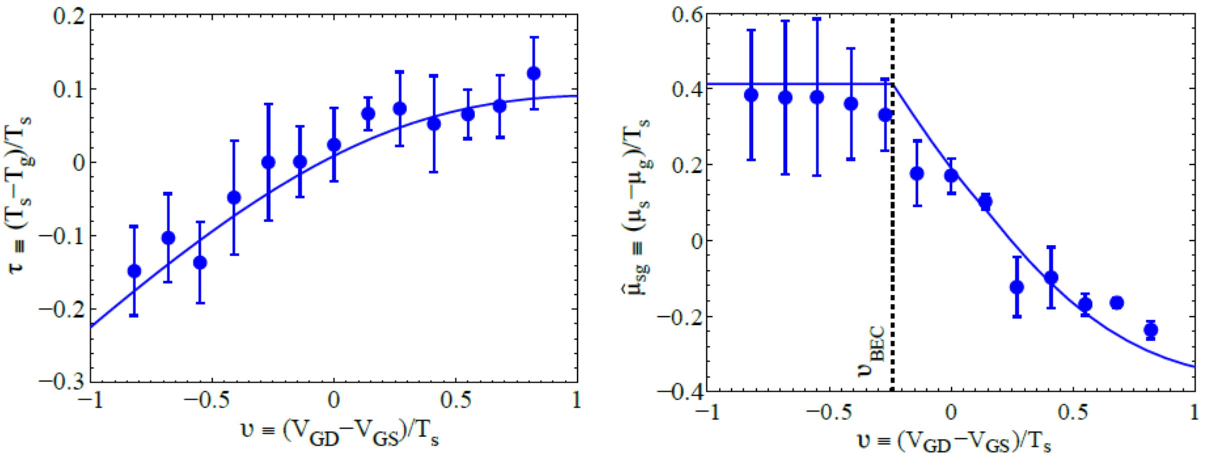

Figure 12: Left: Temperature drop between source and gate wells (at T_s and T_g, respectively) of the atomtronic transistor as a function of the feedback parameter after an evolution time of 30 ms. Right: Chemical potential drop between the source and gate wells of the atomtronic transistor as a function of the feedback parameter after an evolution time of 30 ms. The critical parameter of υ= -0.24 is shown. For chemical potential drops above this value, a condensate spontaneously forms in the gate well.