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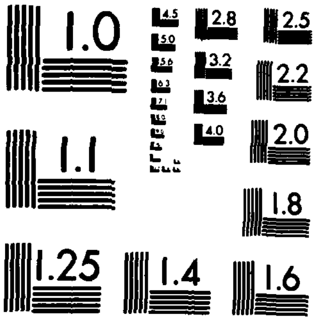
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ANNUAL SUMMARY REPORT

Forces on Neutral Atoms Due to Electromagnetic Fields

Office of Naval Research
Contract N00014-83-K-0695

covering the period
1 September 1983 - 31 August 1984

Submitted by:
David E. Pritchard

19 October 1984

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
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Annual Summary Report on ONR Contract N00014-83-K-0695

1 September 1983 - 31 August 1984

Plans for an apparatus to trap neutral atoms using conventional wire-wound magnets are described in our publication "Apparatus for Trapping Neutral Atoms". We have now gotten a sodium beam in this apparatus and are performing laser diagnostics to enable us to understand the slowing process. We hope to observe stopped atoms in a few months; then we shall look for trapped atoms.

When our DoD equipment grant arrives, we will begin construction of a trap based on superconducting technology. This will enable us to begin the research mentioned in our publication "What to Do with Trapped Atoms".

We also organized and ran a two day workshop on "Controlling Atoms" on May 28-29, 1984, just prior to the 1984 DEAP Meeting in Storrs, Connecticut. No ONR funds were expended on the organization of this meeting.

Apparatus for Trapping Neutral Atoms

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and D.E. Pritchard
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Abstract

We discuss an apparatus, currently under construction which we hope will ultimately trap neutral Na atoms. It is essentially a combination of the NBS magnetic atoms slower (PPM83) and the proposed magnetic trap of Pritchard (PRI83) in a relatively simple apparatus.

Figure 1 is a schematic diagram of the apparatus. It consists of a decelerating region and a trapping region. The spatially varying magnetic field of the slower (solenoid 1) blends smoothly into the bottle field of the trap produced by solenoid 3. The trap is a combination of this magnetic bottle field and a quadrupole field produced by Q_1 with an absolute minimum about 30 mK deep (velocities below 450 cm/sec for Na). It is capable of trapping particles in magnetic sublevels whose energy increases with the applied field. Figure 2a shows the combined longitudinal magnetic field profile as a function of z.

We intend to experiment with a laser beam near saturation ($\sim$10mW/cm^2) a diffusive sodium beam, and to detect the side fluorescence as a diagnostic. The following is an estimate of the number of trapped atoms.

1) The number of photons required to stop one sodium atom is $3\text{x}10^4$ photons. Considering -2 cm^2 as a cross sectional area, gives the number of atoms slowed down 10^{12} atoms/sec

2) Loss of atoms during the slowing occurs through optical pumping to wrong m_f, collision with the background gas, and transverse heating. The fractional number of completely decelerated atoms is roughly 0.02

3) The deceleration of the trapped atoms by the radiation force near the trap bottom (with detuning about [illegible] MHz) will maintain the atoms with velocity below 500 cm/sec for about 1 msec

4) Of the stopped atoms, only a small fraction have sufficiently small transverse velocity to be trapped. This fraction is 0.05

5) After considering these factors, the estimated number of trapped atoms is 10^6 atoms

Detection: The trapped atoms will each scatter $\sim$300 photons before recoiling out of resonance with the laser. Only $\sim$0.02 are in resonance at any one laser frequency, and $\sim$.02 of the scattered light will hit the detector. Thus one expects $\sim$0.1 photon per trapped atom. This is an easily detectable signal if the detector noise and scattered light background are low enough.

This work was supported by the Office of Naval Research.

1. William D. Phillips, John V. Prodan, and Harold J. Metcalf, Nat. Bur. Stand. (N.S.) Spec. Publ. 653, 1 (1983).

2. David E. Pritchard, Phys. Rev. Lett. 51, 1336 (1983).

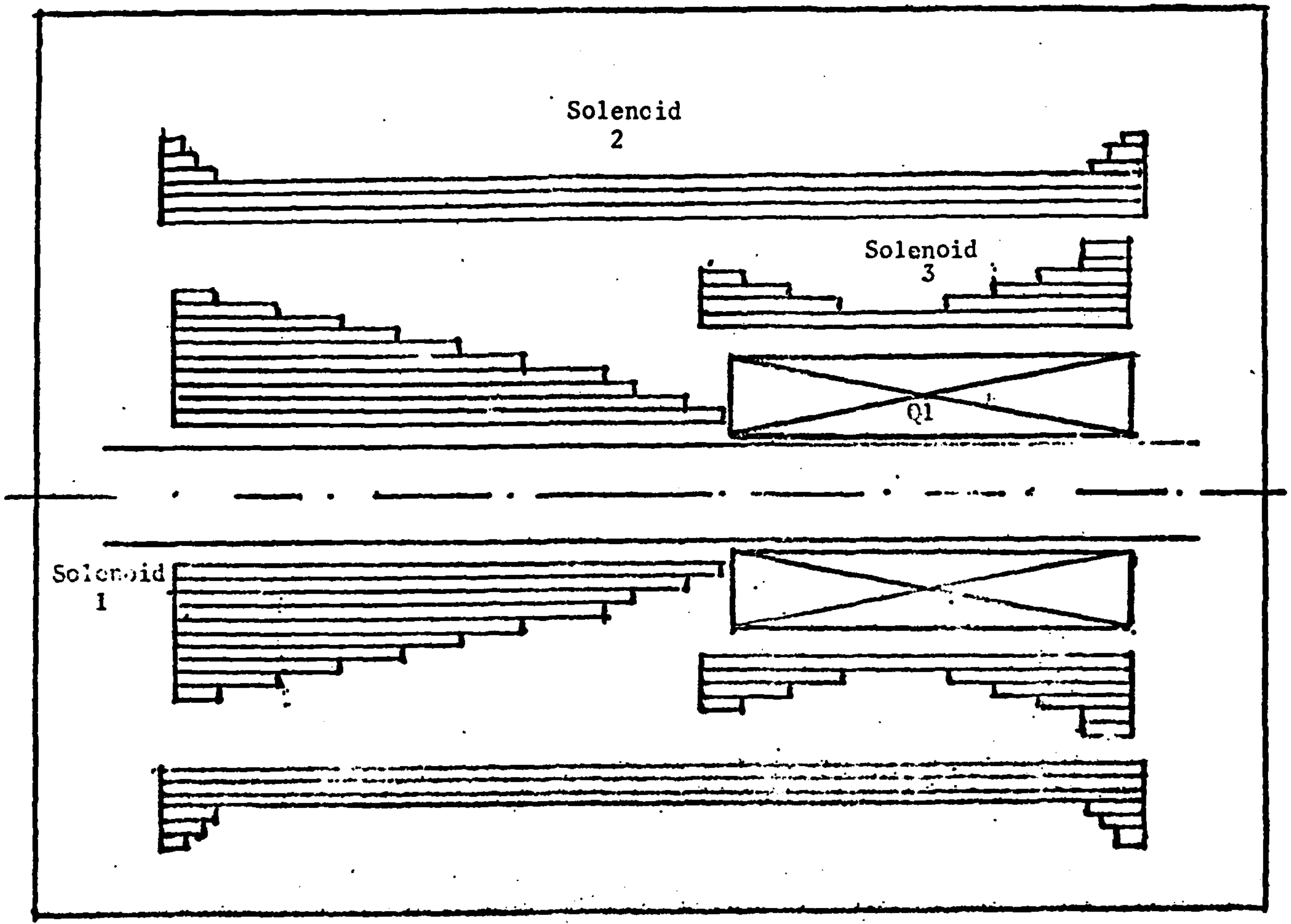

Figure 1

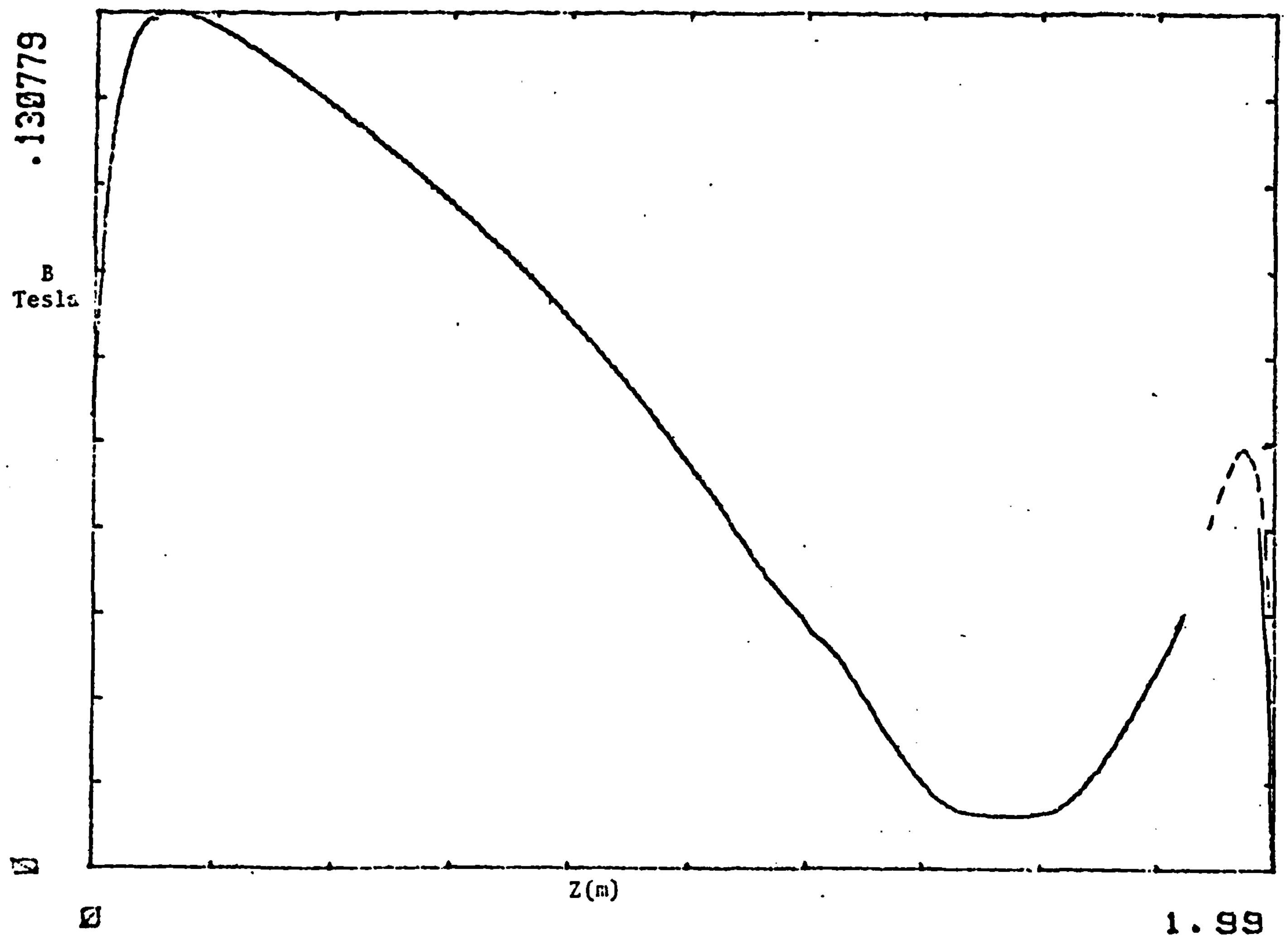

Figure 2

What to Do with Trapped Atoms

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Abstract

One watt of yellow light has enough photons to stop 10^{14} Na atoms per second using the relatively inefficient spontaneous light force (see Phillips and Hall abstracts). Let us now consider some of the scientific payoffs (and problems) raised by the possibility of trapping one second's flux (i.e. 10^{14} atoms) in a magnetic trap such as the one we have proposed (PRI83). It seems barely possible to construct such a trap with stiffness ~ 1 Kelvin (1.6 Tesla) per cm^2 using superconducting magnet technology.

Cooling

The first thing to do is to consider how cold it may be possible to get the atoms, since this is of paramount importance in many applications. The three most useful types of cooling appear to be

Doppler Cooling (WII79) Limit $\lesssim h\Gamma_N \sim 10^{-3}$K for Na D lines.

Cyclic Cooling: A combined RF-laser optical pumping scheme has been proposed (PRI83) which appears capable of cooling to an energy of a few $*(\hbar k)^2/2M$, the kinetic energy due to the recoil of a single photon.

Adiabatic Cooling: If the inhomogeneous trapping fields are slowly relaxed, the trapped particles will cool adiabatically. A 10^4 reduction of trap stiffness increases the deBroglie wavelength by 10 and decreases the temperature by 10^2.

Other promising methods of cooling include collisional exchange with a heavy cyclically cooled atom and evaporative cooling.

Cooling schemes which do not weaken the trap result in an increase in particle density $n \propto T^{-3/2}$ because the cooled atoms cluster closer to the bottom of the trap.

Type of Cooling	T_L Kelvin	n cm^{-3}	ℓ cm	v cm/s	λ_d cm	$V(\ell)$ Kelvin	Q cm^2	Γ_c .
Doppler	$<10^{-3}$	10^{17}	2×10^{-6}	105	1.7×10^{-6}	10^{-7}	8×10^{-13}	8×10^{6}
Cyclic	10^{-5}	10^{20}	2×10^{-7}	10	1.7×10^{-5}	0.1	2×10^{-12}	2×10^{9}
Adiabatic	10^{-7}	10^{17}	2×10^{-6}	1	1.7×10^{-4}	10^{-7}	5×10^{-12}	5×10^{5}

This table summarizes anticipated conditions in a superconducting trap with 10^{14} atoms using the cooling schemes outlined above (and assuming the clever experimentalist can figure out a way to utilize the basically single particle cooling schemes at these projected densities). ℓ is the average interatom separation, λ_d is the deBroglie wavelength, $V(\ell)$ is the van der Waals interaction at ℓ, Q is the cross section, and

$\Gamma_c \equiv vQ$ is the collision rate.

The collision cross section is based on standard quantal results for scattering by long range potentials. Below $T \sim 10^{-3}$K, the scattering becomes predominately s-wave and, although this is still the most probable value, the cross section can be anything up to $4\pi ƛ d^{2}\ 9\text{Å}^{2}/T$(Kelvin) if there is an s-wave resonance. Three body s-wave collisions may lead to the formation of bound (and also trapped) triplet state diatomics (KVS81).

Collective phenomena will obviously be very important under the projected conditions. Bose condensation occurs when $\lambda_{d} \geq \ell$, a condition which would obtain even if the number of trapped atoms decreases by 10^{6}! It will be observable as a sharp spike in the NMR spectrum, even for a transition which is broadened by the magnetic field inhomogeneities necessary to trap the atoms. This spike is probably not useful as a frequency reference because the Bose condensation enhances the interparticle interactions, shifting the resonance. A degenerate Fermi gas might be a preferable frequency standard since the density of filled states near the bottom of the Fermi sea is nearly independent of the temperature and number of trapped atoms - moreover fermions have no s-wave scattering, so interparticle interactions would be strongly suppressed.

One particularly intriguing possibility for new coherent behavior arises in atom-radiation field coherence. In contrast to the phenomena of superradiance in extended samples and phase matching in general, where the wavelength of the radiation is the dominant long range interaction, the de Broglie wavelength now has the longest range. For two particle systems this means that the atoms closer than a light wavelength are in a free molecular state with zero rotational angular momentum. Since the energy spread is $\sim kT$, it will be possible to do high resolution free-bound spectroscopy (eg. of pure long range molecules, STW81). I do not know the implications of $\lambda d > \lambda$ light in multi-atom systems, however.

This work was supported by the Office of Naval Research.

KVS81 Yu Kagan, I.A. Vartanyantz, G.V. Shlyapnikov, Zh. Eksp & Teor. Fiz (USSR) 1113 (1981); JETP Sept. '81.

PRI83 David E. Pritchard, Phys. Rev. Lett. 51, 1336 (1983).

STW81 Bill Stwalley's idea - I lost the reference.

WII79 D.J. Wineland and W.M. Itano, Phys. Rev. A20, 1521 (1979).

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