Physics Letters A 163 (1992) 309–312
North-Holland

PHYSICS LETTERS A

A vortex-force atom trap

T. Walker, D. Hoffmann, P. Feng and R.S. Williamson III
Department of Physics, University of Wisconsin – Madison, Madison, WI 53706, USA

Received 9 December 1991; revised manuscript received 20 January 1992; accepted for publication 20 January 1992
Communicated by B. Fricke

This Letter reports the invention of a new type of optical atom trap, which we call a vortex trap. The vortex-force trapping mechanism allows stable trapping with spontaneous forces required in only one or two dimensions. We achieve performance comparable to the conventional Zeeman-shift optical trap. Possible applications include the production of a spin-polarized cloud of trapped atoms and the extension of one-dimensional trapping schemes to three-dimensional traps.

1. Introduction

In recent years many advances have been made in the trapping and cooling of neutral atoms using radiation pressure (for a recent survey of the field of optical trapping and cooling, see ref. [1]). The concept of spontaneous-force trapping [2] has been particularly fruitful in the realization of the Zeeman-shift optical trap (ZOT). Several laboratories now use this type of trap to confine as many as 10^8 atoms at densities as high as 10^{11} cm^{-3}.

Although the robust characteristics of the ZOT make it attractive for a variety of experiments [3], the attainable densities and numbers of trapped atoms are limited by radiation trapping [4,5]. Therefore it is important to try new trap designs that may not be subject to this radiation trapping limit. In addition, other designs may lead to deeper or more efficient traps. Implementing new designs is complicated, however, by the necessity of providing three-dimensional cooling and confinement; often it is not obvious how to extend a one-dimensional trap design to three dimensions. In this Letter we demonstrate that vortex forces [4–6] generated by intensity imbalances allow stable trapping of atoms in three dimensions with spontaneous forces acting in only one or two dimensions.

To illustrate the vortex trapping mechanism, consider the configuration of light fields and magnetic fields shown schematically in fig. 1. The beams prop-

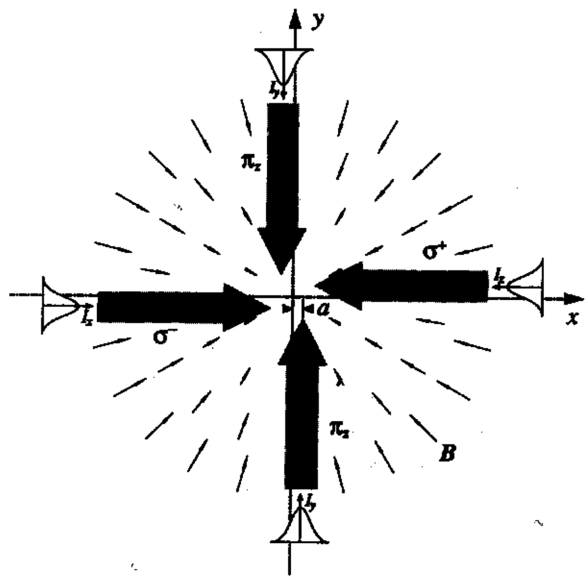

Fig. 1. Configuration (in the x–y plane) of laser beams and magnetic fields for the vortex trap. The Gaussian spatial profiles of the lasers are indicated by the shaded arrows and the small graphs. The thin arrows show the magnetic field intensities and directions. Each beam is offset a distance a from the coordinate axes. This arrangement of fields and polarizations produces a conventional spontaneous trapping force in the x-direction, no trapping force in the y-direction, and a vortex force arising from the offsets of the Gaussian beams. The coupling of the x and y motions by the vortex force results in a stable trap, even though there is no spontaneous force in the y-direction.

agating in the $\pm\hat{x}$ directions are appropriately circularly polarized to produce a conventional ZOT trapping force in the x-direction [7]. In contrast, the beams propagating in the $\pm\hat{y}$ directions both have π_z polarizations, so there is no polarization distinction between the two beams and hence no ZOT trapping force in the y-direction. Not shown are $\pm\hat{z}$ beams which produce a ZOT trapping force in the z-direction. If the counterpropagating beams in fig. 1 were coaxial, this trap would be subject to diffusive loss of the atoms along the y-axis. However, since the antiparallel laser beams have Gaussian profiles and are offset from each other, a net scattering force (in the sense of ref. [2]) arises from the differing intensities of the antiparallel beams at different places in the trap. As illustrated, this vortex force causes atoms to circulate in a counterclockwise direction and prevents diffusive loss along the y-axis, since the scattering force always couples the y-motion to the x-motion. Thus the vortex force allows for three-dimensional trapping of the atoms even though there are spontaneous trapping forces in only two dimensions.

We have constructed the trap shown in fig. 1, and obtain performance comparable to the conventional three-dimensional ZOT.

2. Principles of vortex trapping

Vortex forces in the configuration of fig. 1 result from unbalanced scattering forces due to the offsets of the antiparallel pairs of Gaussian beams. The net scattering force $\boldsymbol{F}_s$ can be written simply as $\boldsymbol{F}_s=\sigma\boldsymbol{S}/c$, where σ is the light absorption cross-section and $\boldsymbol{S}$ the Poynting vector of the light. Due to the intensity imbalances of the identical Gaussian beams of peak intensity I_p and waist w, the scattering force becomes a vortex force $\boldsymbol{F}_v\simeq -k_{xy}y\hat{x}-k_{yx}x\hat{y}$, where

$$-k_{yx}=k_{xy}=\frac{\sigma I_p}{c}\frac{8a}{w^2}, \qquad (1)$$

in the limits a, $|\boldsymbol{r}|\ll w$.

The general equation of motion for atoms in optical traps includes damping forces and random forces due to spontaneous emission in addition to position-dependent forces. We exclude the rapidly spatially oscillating standing-wave forces from our discussion, since they average to zero on macroscopic length scales. Furthermore, since in optical traps the viscous damping force usually greatly exceeds the spatially dependent forces, we can make a drift approximation to the equation of motion and obtain $\gamma\dot{\boldsymbol{r}}=\boldsymbol{F}(\boldsymbol{r})$, where $-\gamma\dot{\boldsymbol{r}}$ is the viscous damping force and $\boldsymbol{F}$ is the position-dependent force.

The relevant position-dependent forces for the trap of fig. 1 are the trapping force and the vortex force $\boldsymbol{F}_v$. For small $\boldsymbol{r}$ their sum is $\boldsymbol{F}=-\tilde{\boldsymbol{k}}\cdot\boldsymbol{r}$. The vortex force makes the off-diagonal elements of the spring-constant tensor $\tilde{\boldsymbol{k}}$ nonzero. This coupling of the different directions causes the eigenvectors of $\tilde{\boldsymbol{k}}$ to be rotated away from $\hat{x}$ and $\hat{y}$ in fig. 1. Since the ZOT trapping force $-k_{xx}x\hat{x}-k_{zz}z\hat{z}$ has a nonzero projection along the new eigenvectors, there is a nonzero restoring force for each eigenmode of the system. Mathematically, if the real parts of the eigenvalues of $\tilde{\boldsymbol{k}}$ are positive, the motion is damped and a stable trap will be formed. For the case of fig. 1 we have $k_{yy}=0$ and so the eigenvalues are

$$\lambda_\pm=\tfrac{1}{2}k_{xx}\left(1\pm\sqrt{1+4k_{xy}k_{yx}/k_{xx}^2}\right)$$

and $\lambda_z=k_{zz}$. Thus the trap will be stable if $k_{xy}k_{yx}<0$, as is the case for the offsets shown in fig. 1 and calculated in eq. (1). For best performance, it is desirable to have $|k_{xy}|$, $|k_{yx}|\approx k_{xx}$.

Using the model of Sesko et al. [5] and the experimental parameters reported below, we estimate $k_{xx}=1.1$ K/cm^2 for a detuning of $\Delta=-13$ MHz. Likewise, for an offset of $a=2$ mm we estimate $k_{yx}=0.96$ K/cm^2. Thus it is straightforward to get vortex forces of similar strength to the trapping force.

The preceding analysis assumes that the antiparallel x- and y-beams have identical, smoothly varying spatial profiles. If this is not the case, radically different motions can be obtained. The vortex-force trap is much more sensitive to differing intensities of the antiparallel beams than the ZOT because the vortex force results from differences of intensities, whereas the ZOT force results from sums of intensities. To illustrate, consider the y-direction of fig. 1: the atoms will come to rest where $F_y=0$, or, equivalently, where the two y-beams are equal in intensity. If R is the ratio of the peak intensities of the beams, we find $x_{eq}=-(w^2/8a)\ln R$ for the equilibrium x-coordinate of the trap. For small a this can be very large. For a typical value $R=0.84$ arising from four glass–air interfaces (such as would result from retroreflection of the antiparallel beams through an uncoated window) a value $a/w=0.2$ gives rise to a displacement of $x_{eq}=0.44w$. A similar sensitivity is obtained for the x-beams. This effect is easily eliminated by using asymmetrical offsets or by balancing the beam intensities. The vortex force is also sensitive to high spatial-frequency structures on the spatial profiles of the laser beams, as might result from diffraction from apertures.

The vortex-force trap presented here is very different from previous discussions of such forces in optical traps. Walker et al. [4] showed that vortex forces play an integral role in the collective behavior observed in traps, but the spontaneous trapping force was three-dimensional for that work. Kazantsev and Krasnov [6] showed that rectification forces that arise from interferences between nearly co-propagating plane waves can have a vortex structure. They predicted localization of atoms in the multiple cells of the force field. In contrast, he vortex force described here arises from intensity imbalances and allows stable trapping of atoms without the need for spontaneous restoring forces in all three dimensions.

Although for simplicity we have emphasized the layout of fig. 1, which has spontaneous forces in two dimensions, the vortex mechanism also will work for a one-dimensional spontaneous force. The optical Earnshaw theorem [8] prohibits a three-dimensional trap based on vortex forces alone.

3. Observations of the vortex trap

We have demonstrated a trap based on the alignment and polarizations shown in fig. 1. The trapping cell is an ion-pumped stainless-steel vacuum chamber with uncoated windows. A small vapor pressure of Rb is maintained within. The loading of the trap is directly from the low-velocity tail of the Maxwellian distribution of the Rb vapor [9]. The trapping lasers are semiconductor lasers stabilized by optical feedback from gratings in the Littrow configuration [10], and locked to Rb saturation spectroscopy resonances. The Rb vapor pressure ($<6\times10^{-11}$ Torr) is much lower than the vacuum chamber pressure of $\sim10^{-9}$ Torr (for convenience of other experiments [11]) so the number of trapped atoms, estimated from fluorescence to be $\sim3\times10^{6}$, is smaller than obtained in other cell traps [9]. In order to minimize the effects of unequal powers in the antiparallel beams, each of the four beams ($\pm\hat{x}$, $\pm\hat{y}$) that produce the vortex force are derived from separate beamsplitters. The powers in each pair of beams can be balanced to better than 2%, if desired. The beams are spatially filtered, with a Gaussian waist $w=0.7$ cm. The powers in the $\hat{x}$, $\hat{y}$, and $\hat{z}$ beams were 0.52, 0.71, and 0.39 mW, respectively. The spatial profile of the trapped atom cloud is observed using a CCD camera and the total fluorescence from the trapped atoms is measured with a photodiode. The magnetic field gradient was $\partial B_z/\partial_z=28$ gauss/cm.

We first aligned the beams with $a=0$ and optimized the usual ZOT. We then removed the $\lambda/4$ plates from the $\pm\hat{y}$ beams and observed the diffusive loss mentioned in the introduction. Next we offset the four vortex-producing beams by about $a=1.5$ mm, and the trapped atom cloud reappeared. Adjusting the laser beams by small amounts maximized the number of trapped atoms. Depending on the exact adjustments of the beams, faint fluorescence extending from the main cloud sometimes was observed. The total number of atoms trapped by the vortex trap was 1.5×10^{6}, one-half that of the original ZOT. The trapped atom cloud was also less dense (1×10^{10} cm^{-3} versus 4×10^{10} cm^{-3}) than the ZOT, and resembled an ellipsoid as opposed to the spherical shape of the ZOT cloud. This shape is expected since the effective spring constants for the two eigenmodes of the vortex trap are different. The loss rates of the ZOT and vortex traps were the same to within 15%, and were about 0.15/s.

Although the vortex force is sensitive to peak intensity imbalances, these can be compensated for by using asymmetric offsets of the antiparallel beams. In this way we were able to operate the vortex trap with R as low as 0.75.

To summarize our observations, the vortex trap has many of the same characteristics as the conventional ZOT: the number of atoms trapped and the trap loss rates are comparable. However, the vortex trap is more sensitive to intensity imbalances and the profiles of the laser beams than the ZOT.

4. Conclusions

We have demonstrated that vortex forces can be used to provide stable trapping of atoms without need for a spontaneous trapping force in every direction. The resulting trap is robust and stores a number of atoms comparable to the three-dimensional ZOT. These results have several implications for the development of spontaneous-force traps.

The vortex force is a substantial conceptual simplification for the design of new types of spontaneous-force traps, since the spontaneous force need now provide stable trapping in only one of the three dimensions. This is important since other types of traps may have very different radiation trapping properties or may be deeper than the ZOT. In particular, if some new trap had slightly weaker radiation trapping than the ZOT, the forces arising from optical thickness of the clouds might become attractive instead of repulsive, allowing much higher densities to be obtained. Likewise, a trap that is deeper than the ZOT or that loads atoms more efficiently may trap a larger number of atoms.

The vortex force mechanism allows the ZOT to be used with a variety of light polarizations, which may be useful for various experiments. For example, by making a ZOT in the x–y plane and using vortex forces for trapping in the z-direction, it should be possible to optically pump the atoms by making the $\pm\hat{z}$ beams much more intense than the others. In particular, a high degree of spin-polarization could be produced by using the same sense of circular polarization for the $\pm\hat{z}$ beams. Potential applications include experiments involving nuclear targets, nuclear beta decay, and spin-dependent atomic collisions.

Acknowledgement

We appreciate the financial support of the University of Wisconsin Research Committee. T.W. is an Alfred P. Sloan Research Fellow.

References

[1] S. Chu and C. Wieman, eds. Special issue of J. Opt. Soc. Am. B 6 (1989).
[2] D. Pritchard, E. Raab, V. Bagnato, C. Wieman and R.N. Watts, Phys. Rev. Lett. 57 (1986) 310.
[3] J. Tabosa et al., Phys. Rev. Lett. 66 (1991) 3245; D. Grison et al., Europhys. Lett. 15 (1991) 149; M. Kasevich et al., Phys. Rev. Lett. 66 (1991) 2297; F. Shimizu et al., Opt. Lett. 16 (1991) 339.
[4] T. Walker, D. Sesko and C. Wieman, Phys. Rev. Lett. 64 (1990) 408.
[5] D. Sesko, T. Walker and C. Wieman, J. Opt. Soc. Am. B 8 (1991) 946.
[6] A. Kazantsev and I. Krasnov, J. Opt. Soc. Am. B 6 (1989) 2140.
[7] E. Raab, M. Prentiss, A. Cable, S. Chu and D. Pritchard, Phys. Rev. Lett. 59 (1987) 2631.
[8] A. Ashkin and J. Gordon, Opt. Lett. 8 (1983) 511.
[9] C. Monroe, W. Swann, H. Robinson and C. Wieman, Phys. Rev. Lett. 65 (1990) 1571.
[10] C. Wieman and L. Hollberg, Rev. Sci. Instrum. 62 (1991) 1.
[11] D. Hoffmann, P. Feng, R. Williamson and T. Walker, University of Wisconsin preprint.