Atomic-Beam Deflection by Resonance-Radiation Pressure

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It is proposed to use the saturated value of the radiation pressure force on neutral atoms to produce a constant central force field to deflect atoms in circular orbits and make a high-resolution velocity analyzer. This is useful for studying the interaction of atoms with high-intensity monochromatic light, and to separate, velocity analyze, or trap neutral atoms of specific isotopic species or hyperfine level.

This Letter proposes a new method of studying the interaction of single atoms with intense light. It involves the use of the resonance radiation pressure of laser light[1] to give a force for deflecting neutral atoms out of an atomic beam. At high light intensity this force saturates to an essentially constant value, independent of intensity variations. If the force is always applied perpendicular to an atom's velocity, one can produce a constant central force field in which atoms follow circular orbits. An atom of specific velocity in such an orbit maintains strict resonance (Doppler effects are avoided) and we have in essence a neutral-atom velocity analyzer of high resolution. The deflection technique to be described affects the linear momentum of the atom. If circularly polarized light is used, angular momentum can simultaneously be imparted to the atom and optical orientation in the sense of Kastler[2] should also be achieved.

This Letter treats the saturation of the radiation pressure force at high light intensities phenomenologically using the Einstein A and B coefficients. The absorption cross section and linewidths used are those derived by perturbation theory[3] which is inherently a low-level theory. If modifications are needed at high values of saturation,[4] it should be possible to study them with the proposed velocity analyzer.

It has been suggested[1] that light pressure can exert on gases a sizable pressure which can be used to separate atomic or isotopic species due to the selective nature of this force. With the present technique specific isotopic species can also be selected out of an atomic beam containing many atomic species. Here the simplicity of the geometry makes the calculation of the power required to separate a given mass straightforward. The problem of trapping neutral atoms by light is also considered. We show that an extension of the velocity-analyzer technique makes it possible to trap atoms stably in circular orbits.

If we irradiate an atom with a beam of resonance radiation, connecting the ground state with an excited state, a radiation pressure force F is exerted on the atom, given by

$$F=(h/\lambda)\tau_N^{-1}f, \tag{1}$$

where τ_N is the natural lifetime of the excited state and f is the fraction of time the atom spends in the upper state. Equation (1) describes the linear momentum per second scattered isotropically out of an incident beam due to resonance fluoresence from the random spontaneous emission from the upper atomic state. To get f we compute the equilibrium population distribution of N atoms between the ground state and the excited state in the presence of resonance radiation of energy density $w(\nu)$. $(n_1+n_2=N)$. Using the well known Einstein A and B coefficients one has

$$f=\frac{n_2}{N}\frac{x}{1+Ax/BW(\nu)}, \tag{2}$$

where $x=(1+g_1/g_2)^{-1}$. Saturation occurs if the stimulated emission rate $Bw(\nu)$ is much higher than the spontaneous emission rate Ax. Then $f\cong x$. g_1 and g_2 are degeneracy factors for the lower and upper states. Absorption followed by stimulated emission, by itself, contributes negligibly to the motion of the atom. It results only in a small net drift velocity in the direction of the incident light equal, on the average, to one-half the velocity corresponding to the absorption of a single photon.

Consider an atomic beam emerging from an oven into a vacuum. If irradiated with saturating resonance radiation transverse to the initial velocity of the beam, acceleration occurs until the transverse velocity is such that atoms are Doppler shifted out of resonance. This restricts the maximum deflection angle obtainable and thus reduces the usefulness of this geometry.[5]

As an alternative to the strictly transversely directed resonance radiation we consider now a radially directed cylindric light beam as shown

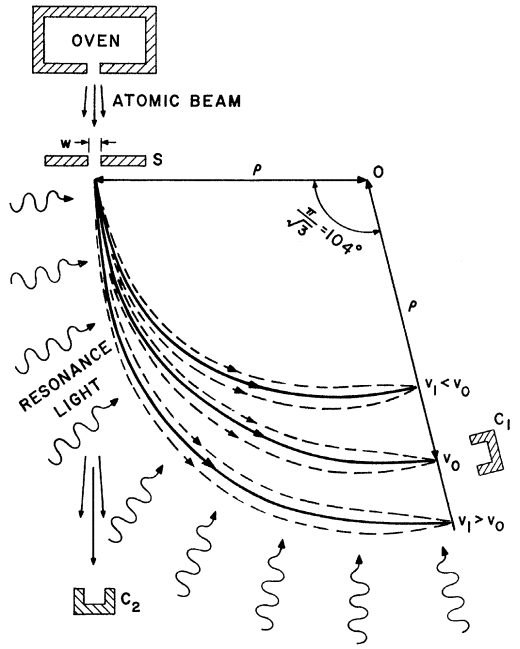

FIG. 1. The 104° atomic velocity analyzer. Resonance light directed toward the cylindric axis O is perpendicular to the equilibrium circular orbit labeled v_0. Collector C_1 detects refocused particles where atoms of different velocity arrive at different radii. Nonresonant species go to C_2. For Na atoms of velocity $v_0 = 2\times10^4$ cm/sec, deflected by Na D_2 resonance light, $\rho = 4.0$ cm.

in Fig. 1. If the light intensity is high enough a resonant atom will experience a constant radially directed central force given by (1) throughout the illuminated volume. This is true as long as the transverse component of the atom's velocity is less than the velocity required to Doppler shift out of resonance. For such a force field, atoms of velocity v_0 satisfying the equation

$$F_{\text{sat}} = (h/\lambda)x/\tau_N = mv_0^2/\rho \tag{3}$$

will follow a circular orbit of radius ρ and thus can experience large deflection from the original direction. Since v_0 is constant and perpendicular to the force no Doppler shift occurs.

This force field has focusing properties in direct analogy with other central-force fields, as for instance the cylindrical E field of electron velocity analyzers.[6,7] From the differential equation for a particle in a central force field one can derive the differential equation for δ, the departure from the equilibrium orbit of particles entering with the correct velocity v_0 but an incorrect direction (i.e., not tangential to the equilibrium circle ρ):

$$-(3v_0^2/\rho^2)\delta = d^2\delta/dt^2. \tag{4}$$

Equation (4) has solutions sin and $\cos(\sqrt{3}v_0t/\rho)$. Thus particles of the correct velocity but wrong injection angle are refocused at $r=\rho$ after transversing an angle of $\pi/\sqrt{3} = 104°$ (see Fig. 1). This is in analogy with the focusing angle of $\pi/\sqrt{2} = 127°$ for electrons in a field $\sim 1/r$ and an angle of $\pi/\sqrt{1} = 180°$ for planetary orbits where the field $\sim 1/r^2$. Particles with the correct injection angle (i.e., tangential, for which $dr/dt = 0$) but wrong velocity v_1, oscillate radially with the same period and return to $dr/dt = 0$ after $\pi/\sqrt{3}$ rad but at a new radius r_1. This radius is found from the equation for the apsides of the motion,

$$\left(\frac{dr}{dt}\right)^2 = v_1\left(1-\frac{\rho^2}{r^2}\right) + 2v_0\left(1\frac{r}{\rho}\right) = 0, \tag{5}$$

which is derived by integrating the equation of motion or simply writing the law of conservation of energy subject to the boundary condition $dr/dt = 0$ at $r=\rho$. From (5) we find that atoms with $v_1 < v_0$ arrive at the collector C_1 with $r_1 < \rho$ and those with $v_1 > v_0$ arrive with $r_1 > \rho$. For example, if $v_1 = 1.05v_0$, $r_1 = 1.07\rho$ and if $v_1 = 0.95v_0$, $r_1 = 0.93\rho$. Atoms injected with $v = v_1$ but at different angles with respect to the equilibrium orbit at the input are refocused at r_1 at the output (see Fig. 1). Thus we have a true velocity analyzer.

Consider now the power required to saturate the force. We rewrite the stimulated absorption (or emission) rate in more detail in terms of the on-resonance absorption cross section $[(\lambda_0^2/2\pi)\, g_2/g_1]$, the incident intensity $I(\nu)$ of monochromatic light, and the Lorentzian line shape $S(\nu)$[3,8]:

$$Bw(\nu) = \frac{\lambda_0^2}{2\pi}\frac{g_2}{g_1}\frac{I(\nu)}{h\nu}\frac{S(\nu)}{4\tau_N},$$

where

$$S(\nu) = \frac{\gamma_N}{2\pi[(\nu-\nu_0)^2 + \gamma_N^2/4]}; \tag{6}$$

γ_N is the natural width. ($\gamma_N = 1/2\pi\tau_N$ and $1/\tau_N = A$). Referring to (2) we define a saturation parameter $\varphi(\nu)$:

$$Bw(\nu) = \varphi(\nu)Ax \tag{7}$$

which specifies the amount of saturation at frequency ν. From $\varphi(\nu)$ we get f and also therefore the value of the saturated force F. [$F \sim (1+1/\varphi)^{-1}$ from Eq. (1)]. $\varphi(\nu)$ also gives the force on atoms entering the field at different angles with respect to the equilibrium orbit, since by virtue of the

Doppler shift such atoms absorb at a shifted frequency. Explicitly,

$$\varphi(\nu)=\frac{\lambda_0^2(1+g_2/g_1)I(\nu)S(\nu)}{8\pi h\nu}=\varphi(0)\frac{S(\nu)}{4\tau_N}, \quad (8)$$

where $\varphi(0)$ is the degree of saturation achieved with intensity $I(\nu)=I_0$ at line center.

As an example, consider Na atoms irradiated with Na D_2 resonance light with $\lambda_0=5890$ Å and $\gamma_N=10.7$ MHz. Due to the nuclear spin of Na^{23} ($I=\frac{3}{2}$), the $^2S_{1/2}$ ground level is actually split into two levels with $F=1, 2$ whereas the $^2P_{3/2}$ level is split into four closely spaced hyperfine levels with $F=0, 1, 2, 3$. The selection rule $\Delta F=\pm1, 0$ permits one, in principle, to interact with either level of the split ground state without coupling to the other. However, to avoid the possibility of cross coupling due to the close spacing of the upper F levels, it is advantageous to use light with circular polarization (σ^+) connecting the degenerate magnetic sublevel $m_F=2$ of the $F=2$ ground state with the $m_F=3$ magnetic sublevel of the $F=3$ upper level. Decay from the $m_F=3$ excited sublevel to any other degenerate sublevels of either $F=2$ or $F=1$ is prohibited by the $\Delta m_F=\pm1$ selection rule for σ components. Statistically one-eighth of all ground-state atoms emerging from the source will be in the $F=2$, $m_F=2$ magnetic sublevel. This fraction will be increased by the σ^+ optical pumping[2,9] from the other m_F sublevels of $F=2$. We have thus, in effect, achieved an ideal two-level system of the type considered above in which, in addition, all the deflected atoms have completely oriented spins. For the case considered $g_2/g_1=1$. This example suggests that the deflection technique can be used to supplement existing atomic beam techniques for studying hyperfine structure, nuclear mangetic moments, and atomic orientation by optical pumping.

Applying Eq. (8) to the Na D_2 line, one finds

$$\varphi(0)=\frac{I_0(\mathrm{W/cm^2})}{2.1\times10^{-2}}. \quad (9)$$

If incoming atoms are restricted by slits of width w and height h parallel to the cylindric axis of the analyzer, then we must provide the saturating light intensity I_0 over an area of $\pi\rho h/\sqrt{3}$. If the source temperature is $T=510°$, then the Na pressure $=10^{-3}$ Torr, the density $n_0=3.4\times10^{13}$ atoms/cm^3, the mean free path $L=30$ cm, and the average atomic velocity $v_{av}=(2kT/m)^{1/2}=6.1\times10^4$ cm/sec. If we consider atoms with velocity $v_0=v_{av}/3\cong2\times10^4$ cm/sec, then from Eq. (3) the equilibrium orbit radius $\rho=4.0$ cm. Taking $h=0.1$ cm, and $\varphi(0)=10^2$, we must therefore have a total power of $2.1\times10^{-2}\times10^2\times\pi(4)(0.1)/\sqrt{3}=1.5$ W of resonance power in the incident beam. This situation is appropriate for a cw experiment. To calculate an acceptance angle for incoming particles we specify that $\varphi(\nu)$ vary from a minimum of 10 to a maximum of 10^2 within the acceptance angle. This yields a range of ±2.6°. An atom making an angle of 2.6° with respect to the equilibrium orbit is absorbing at a Doppler-shifted frequency of $(\nu-\nu_0)=1.5\gamma_N$ with $\varphi(\nu)=10$. The number of atoms emerging from the source within this angular tolerance with velocity $v=v_{av}/3\pm\frac{1}{2}\%$ is $\sim2.2\times10^{11}$ atoms/cm^2 sec. If we use slits of width $w=\rho/100=0.04$ cm and $h=0.1$ we have a flux of $\sim10^8$ atoms/sec which is adequate for most experiments.

Since the transit time for an atom through the analyzer is $\sim4\times10^{-4}$ sec, a pulsed experiment is possible with much higher peak power and higher saturation. Thus, if the peak power is 10^4 W, then $\varphi(0)\cong7\times10^5$. The angular tolerance based on Doppler shift is so large that other considerations dictate the acceptance angle. The main advantage of high power is the relaxation of the requirement on the frequency control of the laser. Thus one can scatter power with $\varphi(\nu)=10^2$ or larger within the band $(\nu-\nu_0)=\pm42\gamma_N=\pm450$ MHz as seen from (8). In some cases one might take advantage of the wide bandwidth of a mode-locked laser to ease the frequency control problem, provided the power per mode is enough to saturate the force.

A useful feature of the analyzer is its insensitivity to light intensity variations when strongly saturated [$\varphi(\nu)\geq10$]. Thus the incoming light could be part of a TEM_{00} Gaussian-mode beam, with the atoms following a phase front. Since a far-field diffraction angle of $\pi/\sqrt{3}$ represents rather tight focusing one could break the incoming beam into separate beams without much difficulty. Although the total optical power required is fairly modest, it can be further reduced by using a scheme where the unscattered light is recirculated through the analyzer. A further modification of interest is to depart from strict cylindric geometry and use spherical beams in analogy to the Purcell velocity analyzer for electrons.[10] This would give vertical focusing as well as radial focusing and one could in principle trap atoms in a stable circular orbit in a geometry in which the flux is incident over 2π rad. Figure 2 shows such a trapping apparatus

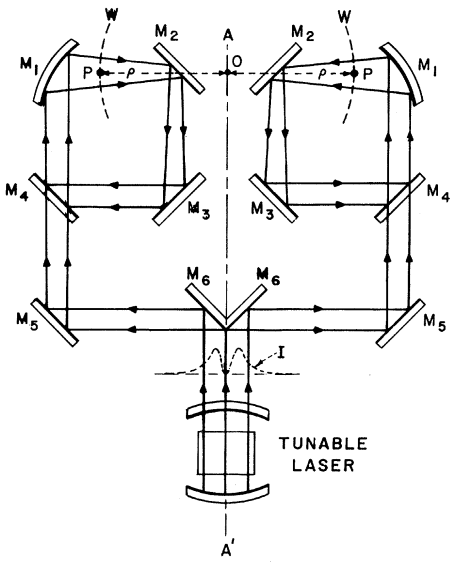

FIG. 2. Apparatus for trapping atoms in a circular orbit. AA' is the axis of a figure of revolution. Mirrors M_1, M_2, M_3, and M_4 recirculate light converging with spherical wavefronts w on the circular orbit P of radius ρ centered at O. A tunable laser with an intensity profile I (i.e., a "do-nut" or TEM_{01}* mode) feeds the recirculating resonator M_1, M_2, M_3, M_4 via M_5 and M_6.

including means for recirculating the light.

The analyzer can also serve as an isotope selector. Only resonant atoms are deflected to collector C_1 in Fig. 1. Nonresonant species proceed undeflected to C_2. For particle selectors of this type it is simple to calculate the optical power needed to separate atoms. An atom of velocity v_0 spends a time $=(\pi/\sqrt{3})\rho/v_0$ in the light field and scatters $2t_N^{-1}(\pi/\sqrt{3})\rho/v_0)$ photons which by (1) and (2) equals $(\pi/\sqrt{3})mv_0(h/\lambda)^{-1}$. If we use $qP \times 10^7/h\nu$ photons/sec, where qP is the fraction of the incident power in watts scattered, the number of atoms/sec N we collect is

$$N = \frac{\sqrt{3}}{\pi}\frac{qP\times 10^7}{mv_0 c}. \tag{9}$$

Equation (9) shows that the number of atoms/sec collected depends on P and the incident velocity v_0 but not on the force F_{sat}. F_{sat} and v_0 do, however, determine the size of the orbit radius as seen in (3). Using $v_0 = 2\times 10^4$ cm/sec one finds that it takes 1.2×10^4 photons per atom collected. Assuming $q \sim 1$, $N = 2.4\times 10^{14}$ atoms/sec W collected. With the expenditure of 1 kW h we can collect a mass of 30 mg.

In conclusion this Letter points out the use of resonance radiation pressure to separate, trap, and velocity analyze neutral atoms. It should also prove useful in studying the details of the basic interaction of atoms with high-intensity monochromatic light.

It has come to the author's attention that Frisch,[11] in the last paper of the thirty "Untersuchungen zur Molekular Strahlmethode," has observed the recoil of sodium atoms on emitting a single photon of resonance radiation.

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