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cw Self-Focusing and Self-Trapping of Light in Sodium Vapor

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We report steady-state self-focusing, self-trapping, and self-defocusing of a cw dye laser beam in sodium vapor for frequencies within several Doppler widths of the D-line resonance transitions. We measured the variation of the beam profile as the light propagates through the vapor. We observed a 20-mW beam self-trapped in a 12-cm-long filament having a half-power diameter of 70 μm.

We report steady-state self-focusing,[1] self-trapping,[2] and self-defocusing of a tunable cw dye laser beam in sodium vapor. These strong effects occur at power levels of tens of milliwatts when the laser frequency is fine tuned within several Doppler widths of either of the D-line resonance transitions. Because the effects are cw, we were able to measure directly for the first time the variation of the beam profile as the light propagates through the self-focusing medium. Previously the behavior of self-focused beams could only be inferred from indirect measurements. Also, we have unequivocally observed propagation of light in a filament of constant small diameter, without spreading. In analogy with Chiao, Garmire, and Townes[2] we term this self-trapping of light. It is current opinion that self-trapping has not previously been observed,[3] except possibly for the case of thermal self-trapping.[4]

Heretofore only thermal self-focusing effects had been observed on a cw basis.[4] All other previous self-focusing work was done with pulsed lasers which complicates interpretation of time-integrated observations such as photographs. For instance, observations made with nanosecond pulses of filaments in Kerr liquids which were originally thought to demonstrate self-trapping are presently being described in terms of the "moving focus" model.[3] Prior observations of self-focusing effects in atomic vapors[5-7] have used multikilowatt lasers tuned many Doppler widths off resonance, and the results were consistent with the moving-focus model.[5]

We believe the effects we observe are basically due to intensity-dependent saturation of the anomalous dispersion which makes the vapor lenslike for spatially nonuniform light beams.[8] As expected for such a mechanism, we observe self-focusing for tuning on the high-frequency side of a transition and self-defocusing on the low-frequency side.

Light from a cw dye laser was passed through a 20.3-cm-long, 2.5-cm-i.d. Pyrex cell containing sodium vapor in a vacuum. The linearly polarized, TEM_{00}-mode light was focused at the entrance face of the cell with an input half-power diameter of 69 μm.[9] The sodium cell was held in a Pyrex oven. Temperature along the length of the cell was uniform within 2°C. Purified sodium metal was contained in a side arm of the cell at a temperature 20°C lower than that of the main cell body. Use of transparent materials allowed us to observe the beam size along the length of the cell via resonance fluorescence (see Fig. 1). The rhodamine 6G cw dye laser cavity[10]

FIG. 1. Resonance fluorescence along the last 13 cm of the cell for (a) normal divergence (tuning far off resonance) and (b) self-trapping. The beam propagates from left to right and the gaps are due to the heating cord.

included an uncoated 2-mm-thick glass etalon to restrict the number of axial modes. Single-mode operation was possible, but only with erratic tunability. Instead the laser was operated on two axial modes of approximately equal amplitude, separated in frequency by about 1.85 GHz, which could be tuned continuously. Frequency stability was ±20 MHz for 30 sec.

The focusing effects are strongest for tuning to the D_2 line at 5890 Å ($^2S_{1/2}$-$^2P_{3/2}$ transition), and the results we present are for this case. The $F=2$ and 1 levels of the $^2S_{1/2}$ ground state are hyperfine split by 1.77 GHz with the $F=1$ level having lower energy. This splitting is slightly larger than the Doppler width of ~1.7 GHz and cannot be ignored. However the small splitting of the $^2P_{3/2}$ levels are negligible. In effect we have a three-level system.

Self-action effects are easily observed in the far-field pattern of the light passing through the cell as the laser is tuned through resonance. Figure 2 shows photographs of such patterns at a distance of 200 cm from the exit face of the cell. Figure 2(b) shows the beam for tuning far off resonance, corresponding to normal diffraction. In Fig. 2(a) the laser was tuned for strong self-focusing by observation of the beam in the vapor via fluorescence. For this case self-focusing reduces the divergence of the laser beam. The high-frequency laser mode was 1.8 GHz to the *high-frequency side* of the $F=1$ transition while the low-frequency mode was resonant with

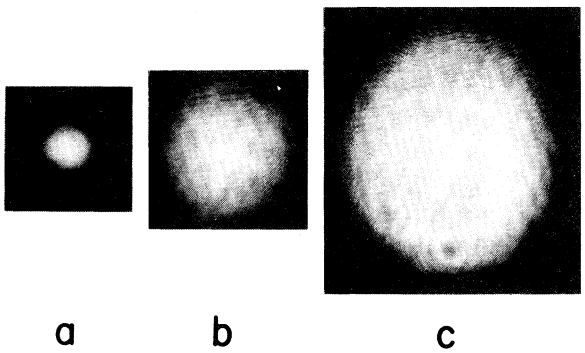

FIG. 2. Far-field patterns of the laser beam after passing through the sodium cell for (a) self-focusing, (b) normal divergence, and (c) self-defocusing.

it and was totally absorbed in the cell. The input power at the high frequency was 16 mW and its transmission was 63%. For much less intense beams at the same frequency the cell was opaque ($\alpha \approx 8.5$ cm^{-1} on resonance). The side-arm temperature was $T=180$°C, giving an atomic density $N \approx 8.7\times10^{11}$ cm^{-3}. In Fig. 2(c) the laser was tuned for strong defocusing by observing the beam in the vapor. The low-frequency laser mode was 900 MHz to the *low-frequency side* of the $F=2$ transition and the high-frequency mode was totally absorbed. The input power at the low frequency was 17 mW and its transmission was 37%. Here $T=200$°C, $N \approx 2.7\times10^{12}$ cm^{-3}, and $\alpha \approx 26$ cm^{-1}. Stronger defocusing was observed for tuning closer to resonance, except the transmitted beam pattern became more complex, exhibiting nulls in the central region. For slightly higher sodium densities complex patterns reminiscent of higher-order spatial modes[11] were observed for self-focusing.

To study the evolution of the beam size as the light propagates through the vapor we visually observed or took photographs of the resonance fluorescence from the atoms *within* the laser beam (see Fig. 1). This fluorescence intensity is very nearly linearly proportional to the laser-beam intensity even for intensity levels typical of our experiments, which were thousands of times the saturation intensity $I_s=77$ mW/cm^2.[12] This is due to optical pumping, which will be described later. The bright streak of light from atoms *within* the laser beam is superimposed upon a more or less uniform background of light given off by atoms *outside* the laser beam as a result of radiation trapping. For small beams the contrast between the streak and the background is large. However, as the beam expands the contrast is greatly reduced, limiting quantitative analysis of the photographs to self-focusing. The photographs were taken with Polaroid type-55 positive/negative film, samples of which had been calibrated. The negatives were scanned with a microdensitometer.

The self-action effects are *not* due to the two-mode spectrum of the laser and the same effects occur for monochromatic light. We verified this

by placing another sodium cell in front of the lens to absorb selectively one of the two laser frequencies. Nonetheless, there is an interaction between the two modes in the usual case of equal power in each mode. For example, the focusing of a mode 0.9 GHz above the $F=1$ transition is stronger if the other mode is in the resonance than if it is 2.7 GHz above the $F=1$ transition. However, this coupling affects only the exact details of the focusing, not the basic effect. Most data were taken with two modes because higher power per mode could be obtained.

Detailed quantitative measurements for three cases, all with approximately the same tuning, are shown in Fig. 3. The high-frequency laser mode was 0.9 GHz to the high-frequency side of the $F=1$ transition. The light beams at the two frequencies diverged differently and it was possible to distinguish between them except for the first few centimeters. The curves depict the focusing behavior of the high-frequency light only. The low-frequency light experienced little focusing and was totally absorbed. Cases *a* and *b* demonstrate that the focusing effects increase with increasing input power. The side-arm temperature was 180°C. For case *a* the input power in the focused mode was 15 mW and for case *b* it was 23 mW. In both cases the transmission was about 50%. Case *c* [same as Fig. 1(b)] is for a side-arm temperature of 200°C, and it shows that the effects also increase as N increases. The input power in the focused mode was 23 mW and its transmission was 40%. The low-frequency mode was totally absorbed in the first half of the cell.

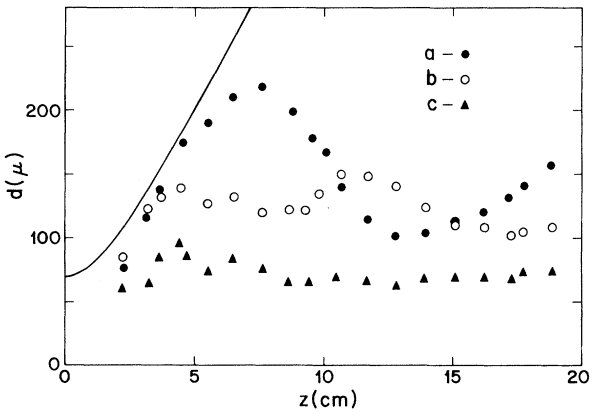

FIG. 3. Half-power diameter of the laser beam along the length of the cell for three cases. Each point is the average of several measurements showing small scatter. The solid curve shows the free-space propagation of the beam.

Over the last 12.5 cm of the cell the beam half-power diameter remains essentially constant at ~70 μm. The free-space divergence for a beam this size is shown by the solid curve and is very large by comparison. This is the first clear-cut observation of self-trapping caused by other than thermal means. Since the beam suffers absorption it is important to differentiate our operational definition of self-trapping from the original notion[2] which described a lossless and unstable[4] case. Over the last 11.5 cm of the cell the peak beam intensity falls off with distance at a rate of ~6.8 W/cm^3, implying that the density of atoms in the $^2P_{3/2}$ excited state was $0.12N$. This agrees with an approximate rate-equation analysis for the saturation of the three-level system which includes power-broadened holes burned in the inhomogeneous lines. It indicates that 2.5% of the atoms are in the three degenerate $F=1$ levels of the ground state, that 84.5% are in the five $F=2$ levels, and that 13% are in the sixteen $^2P_{3/2}$ levels. Thus the $F=2$ level was optically pumped, greatly reducing the excited-state population and the light absorption. Applying electromagnetic fields at 1.77 GHz to destroy the optical pumping should change the self-focusing.

The behavior of the curves in Fig. 3 is suggestive of the oscillations in beam size that a Gaussian beam undergoes when propagating in a lossless focusing medium.[13] Thus self-trapping might also be obtained for cases *a* and *b* if the correct (larger) input-spot sizes are used.

We have also observed "beam-breakup" with an input power of 35 mW. The single input beam was observed to break up into three separate self-trapped filaments which started about 5 cm from the input face and propagated distinctly apart from one another through the rest of the cell. Presumably breakup occurs because of inhomogeneities in the input beam. Upon reducing the input power, the three separate beams collapsed into a single self-trapped filament.

The effects, we believe are due mainly to *steady-state* saturation of the anomalous dispersion of the D_2-resonance transition. This is to be distinguished from the focusing effects that have been observed for *dynamic* saturation of dispersion.[5] In our experiments saturation of the absorption plays a role as well as saturation of the anomalous dispersion. Clearly, its effects are not dominant since absorption saturation alone would produce a focusinglike beam distortion on *both* sides of the resonance line. For tuning close to resonance the sodium vapor must be treated

as a three-level system. Calculation of the refractive index must consider optical pumping of inhomogeneous lines in the presence of strong hole burning. Such a theory is difficult and has not previously been worked out. Also the nonlinearity is not strictly local since the time constant for optical pumping is comparable to the excited-state lifetime and thermal atoms move tens of micrometers during this time. For tuning many Doppler widths off resonance the calculation is simplified since the sodium vapor may then be treated as an inhomogeneously broadened two-level system. For this case we have shown that the refractive index is of the form $n(\nu) - 1 = -\delta n \times \mathrm{Im}[w(\Delta + iy)]$,[14] where w is the error function for complex arguments,[15] Δ is a normalized detuning, and y is the normalized width of the power-broadened hole burned in the line. For sodium, $\delta n = 2.7 \times 10^{-17} N$, which is more than enough to account for the observed focal-spot diameters.[8] The above result can be used to estimate the maximum detuning for self-focusing to occur at a given intensity. For $I/I_s \approx 10^4$ this estimate agrees with our observation of strong self-focusing as far as 3 GHz above the $F = 1$ transition. The allowed detuning increases for larger N and increased input power.

Detailed comparison of accurate cw experiments like ours with a complete theory would be worthwhile. Understanding of self-action effects in simple atomic vapors may be applicable to similar effects in more complicated media such as Kerr liquids. Our demonstration of self-trapping should stimulate further work to elucidate the general conditions under which self-trapping can occur.

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Atomic Capture of Negative Mesons*

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The atomic capture of negative mesons is examined in detail, using the model of Fermi and Teller. We calculate the initial distribution in angular momentum of the mesons upon capture and that after de-exciting through the electron cloud. The mesonic x-ray intensities are computed from a quantum-mechanical cascade and compared with experiment for K^- mesons. Our results agree fairly well with the average (over Z) of the experimental data.

The physics involved in the precise calculation of the *energy shifts* and *widths* of mesonic x-ray lines has received considerable attention.[1] In contrast, the physics that determines the *intensities* of these lines has been comparatively neglected.[2] The usual procedure for calculating

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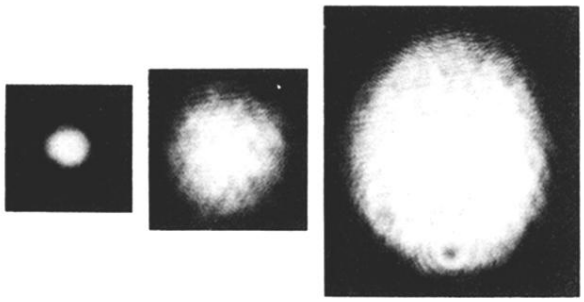

FIG. 2. Far-field patterns of the laser beam after passing through the sodium cell for (a) self-focusing, (b) normal divergence, and (c) self-defocusing.