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NEAR RESONANT ABSORPTION BY ATOMS IN
INTENSE FLUCTUATING LASER FIELDS
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ABSTRACT

The objective of this program was to make quantitative measurements of the effects of higher order phase/frequency correlations in a laser beam, on non-linear optical absorption processes in atoms. The success of this program was due in large part to a unique experimental capability for modulating the extra-cavity beam of a stabilized (≤ 200 kHz) continuous-wave laser with statistically-well-characterized stochastic phase (or frequency) fluctuations, in order to synthesize laser bandwidths to ~ 20 MHz (depending on noise amplitude), with profiles variable between Gaussian and Lorentzian (depending on noise bandwidth). Laser driven processes investigated included:

- 1) the optical Autler-Towns effect in the $3S_{1/2}$ ($F=2$, $M_F=2$) $\rightarrow$ $3P_{3/2}$ ($F=3$, $M_F=3$) two-level Na resonance, using a weak probe to the $4D_{5/2}$ level;
- 2) the variance and spectra of fluorescence intensity fluctuations in the two-level Na resonance;
- 3) the Hanle effect in the 1S_0 - 3P_1 transition at $\lambda = 555.6$ nm in ^{174}Yb ;
- 4) absorption (and gain) of a weak probe, when the probe is a time-delayed replica of the resonant (with the two-level Na transition) pump laser; and
- 5) four-wave-mixing in a phase-conjugate geometry, in a sodium cell, and, finally, in a diffuse atomic sodium beam.

The experimental results from these several studies have provided important confirmation of advanced theoretical methods.

INTRODUCTION

The interaction of intense laser fields with matter is central to a large and growing body of technology. Such interactions can be quite complex, especially in view of the nature of realistic laser fields, which typically are very different in their spectral and statistical properties from the ideal laser field model involving perfect monochromaticity and coherence. Two decades ago, scientific inquiry was strongly focussed on the realization of lasers approaching this ideal, and on the interactions of such spectrally pure fields with individual atoms. The prototype application was to a new generation of atomic clocks, and interest centered on linear processes for which the interaction could be predicted solely on the basis of the lowest order correlation function (or equivalently the spectral profile of the laser field, ideally a Lorentzian). In general, descriptions of the field-atom interaction for such a system could be regarded as intuitively reasonable, a consistent extension of our academic experience with a predominately linear physical world.

With the advent of more intense lasers, the world of linear physical processes gives way to one in which nonlinear processes begin to be important or even predominate. In optics the role of higher order correlation functions in non-linear processes was implicit in the formal theory, but its implications were not developed or recognized. Thus it was a surprise to find [Phys. Rev. Letters 41, 229 (1978) see also Phys. Rev. A 24, 280 (1981)] a counter-intuitive reversal in the peak-heights ratio of the Rabi-split sodium $3P_{1/2}$ doublet in an optical double resonance experiment in this laboratory, using intense flash-lamp-pumped dye lasers with very non-ideal characteristics. P. Lambropoulos and A. T. Georges showed that the

observed reversals were probably due to the effects of fourth and higher order correlation functions of the non-ideal laser field.

This result precipitated a flurry of theoretical work aimed at elucidating the effects of higher order correlation functions in non-linear optical absorption in atoms. The theoretical methodologies were complex, and they led to detailed predictions of the behavior of atom-field interactions, but there were no experimental capabilities for quantitative study of such processes. In 1980 we proposed to the Department of Energy to develop methods for synthesizing well characterized phase (or frequency) fluctuations on the extracavity beam of an extremely well stabilized continuous-wave dye-laser operating in the visible spectrum, with the objective of carrying out fully quantitative measurements testing such theoretical predictions. The DOE awarded Contract DE-AC02-80ER10736, effective August 1, 1980. By the expiration of this contract on July 31, 1985, a method for synthesizing statistically quantified phase/frequency fluctuations on a stabilized (≤ 200 kHz) tunable dye laser had been realized, and successfully applied to the study of two-photon absorption in the $3S$ ($F=2$) $\rightarrow$ $5S$ ($F=2$) transition in atomic sodium [Phys. Rev. Letters 53, 439 (1984); and Phys. Rev. A 32, 887 (1985)], again with some intuitively surprising (yet consistent with the formal theory) results.

This method of synthesizing phase/frequency fluctuations on a laser beam, providing experimental realization of what is commonly called a "phase-diffusing" field, was first described in 1982 [Phys. Rev. A 26, 12 (1982)]. A more comprehensive description giving more technical detail was later published by D. S. Elliott and S. J. Smith [JOSA B5, 1927 ((1988))]. It was the basis for the series of researches for which the current grant was

awarded. In the following sections, we outline the research conducted in the period August 1, 1985 through October 31, 1993 under Grant No. DE-FG02-85ER13421.

THE OPTICAL AUTLER-TOWNES EFFECT IN ATOMIC SODIUM

The original motivation for the program of research carried out under this grant was provided by our crude early experimental work on the optical Autler-Townes process, as described in the Introduction, and a newly recognized need for fully quantitative measurements of this process for comparison with new theoretical predictions. By the methods mentioned in the Introduction, we were able to improve upon those early measurements, using a laser field with well-characterized phase/frequency fluctuations superimposed on an otherwise essentially monochromatic laser beam.

In order to further simplify and characterize the field-atom system, this work, and other experiments based on the resonance transition in atomic sodium, used a highly directional (to reduce Doppler broadening) beam of atoms, prepared by optical pumping with circularly polarized light so that essentially all atoms in the beam were in the $F=2$, $M_F=2$ magnetic substate of the $3S_{1/2}$ ground state. The measurements were then carried out using circularly polarized laser fields so that the only allowed transition in the sodium resonance line was the $3S_{1/2}$ ($F=2$, $M_F=2$) $\rightarrow$ $3P_{3/2}$ ($F=3$, $M_F=3$) transition. The system could then be described as a "two-level system", which was used wherever it facilitated direct comparison with theory.

The optical Autler-Townes process is schematically represented in Fig. 1

In this figure the strong laser field, on which the synthesized fluctuations were imposed, is detuned from the $3S_{1/2} \rightarrow 3P_{3/2}$ resonance by amount Δ , and subject to a nutation (Rabi) frequency of Ω in the intense field. The energy levels are each shifted by $\Delta/2$ and split into two levels separated by Ω , as shown in this figure. The weak probe, from an independent tunable monochromatic laser, transfers population to the $4D_{5/2}$ state, the transfer rate providing a measure of the strength of the $3S_{1/2} \rightarrow 3P_{3/2} \rightarrow 4D_{5/2}$ coupling as it is tuned over the $3P_{3/2}$ doublet. Typical scans are shown in Fig. 2, taken from Phys. Rev. A 33, 778 (1986) RC.

Fig. 2.

Here the noise-modulated laser line shape was approximately Lorentzian, the power of the laser field was such that the Rabi frequency $\Omega = 67$ MHz, and the center frequency of the laser field was detuned $\Delta = 10$ MHz below the unperturbed $3S_{1/2} \rightarrow 3P_{3/2}$ transition frequency, leading to asymmetry in the observed doublet spectrum. For Fig. 2a), the noise modulation was turned off so that the intense driving field was essentially monochromatic. For Fig. 2b) the noise modulation was turned on at a level which broadened the spectral profile of the laser field to 7 MHz half-width at half-maximum. We see a reversal of the observed asymmetry when the noise is introduced. (This is the effect which originally drew the interest of the theoretical community.) A detailed statistical theory was developed by Dziemballa and Zoller and compared with a comprehensive set of measurements of this effect [Phys. Rev. A 36, 178 (1987)]. The agreement was generally excellent.

This work demonstrated that phase fluctuations play an important role in nonlinear optical processes, typified for this set of measurements by the saturation of a transition. Over a broad range of parameters for the phase/frequency fluctuations (spectral width, spectral shape, intensity, and detuning) it proved possible to model the experiment with a theory which takes into account the finite correlation time of the fluctuations as well as other nonideal features.

OBSERVATION OF POPULATION FLUCTUATIONS IN TWO-LEVEL ATOMS DRIVEN BY A PHASE-DIFFUSING FIELD

In the work described in the previous section, and represented schematically in Fig. 1, the weak probe provided a physical observable reflecting the behavior of the two-level system

in the intense fluctuating field. Another important observable to which information from the fluctuating driving field is transferred, is the resonance fluorescence. Motivation for investigation of this parameter actually came from colleagues working on precision measurements where the observed quantity is the fluorescence from an atomic transition. It was noticed [C. W. Weiman, C. Tanner, and L. Hollberg, private communication] that the spectral distribution of fluctuations in the fluorescence did not conform to expectations based on usual statistical arguments and residual background noise. For example, under certain circumstances, the "grass" on the near wings of an observed line was larger than around the peak of the line. Clearly, such behavior may compromise the designed experimental resolution of a precision measurement, so a detailed understanding of the effect is essential. Haslwanter, Ritsch, Cooper, and Zoller [Phys. Rev. A 38, 5652 (1988); and Phys. Rev. A 41, 2653 (1990)] showed that such fluorescence fluctuations may derive from phase and/or amplitude fluctuations of the driving laser field. In a subsequent experimental investigation supported by this grant, the transformation of phase fluctuations from the driving field to fluorescence was studied in detail using a field with Lorentzian and Gaussian spectral profiles, as a function of laser field bandwidth and intensity [Phys. Rev. Letters 64, 1346 (1990); and Phys. Rev. A 42, 6690 (1990)]. Since it was necessary to carry out the work in a regime where the fluorescence fluctuations ($\propto n$) derived from the field fluctuations completely dominated the shot noise ($\propto \sqrt{n}$), a high flux, n , of fluorescent photons was a requirement. In this regime the instantaneous fluorescence intensity follows the upper state population. Figure 3 shows typical results obtained using the two-line level system in atomic sodium.

FIG. 3.

The solid lines show the measured fluorescence intensity and the dashed lines show the fluorescence intensity fluctuations (variances). Open circles show the corresponding theoretical predictions. The figure is arranged with columns from left to right corresponding to increasing laser power levels ($\Omega \cong 1, 12$, and 25 MHz, respectively) and the rows, from top to bottom, to increasing laser bandwidths ($2, 5$, and 8 MHz, respectively). The agreement with theory is quite good, with small discrepancies at high power presumed due to spatial variation of laser intensity. The double-peak in the variance is typical for the phase diffusion field. Other noise models (ie. amplitude fluctuations) lead to variance curves with different characteristics.

THE HANLE EFFECT IN SPECTRALLY BROADENED LIGHT

Another investigation of significance for an important body of precision measurement work, was a collaboration initiated by Prof. Harold Metcalf and others at SUNY-Stony Brook, and joined by M. W. Hamilton, Strathclyde University and J. R. Brandenburger, Lawrence University. This was a comprehensive investigation of the dependence of the so-called Hanle Effect signal on the intensity and statistical parameters of a well-characterized phase-diffusing optical field. The work was carried out at JILA, with the beam apparatus and Hanle detection equipment provided by Stony Brook and Lawrence Universities. The project also constituted the thesis project for graduate student K. Arnett.

The Hanle effect has been extensively used for the determination of natural lifetimes of atomic levels, the accuracy of such measurements typically involving limitations due to power broadening effects, and the effects of finite bandwidths of the optical field. These were usually dealt with on a semi-empirical basis.

The Hanle technique involves observation of fluorescence, from an optically driven $J=0 \leftrightarrow J=1$ transition in a uniform magnetic field, H . The latter determines a quantization axis, so that the $J=1$ level may be treated as a superposition of $M_J = \pm 1$ states if the driving field is linearly polarized on a transverse axis. Detection is usually along the third orthogonal axis, a null in the dipole distribution of fluorescence for $H=0$. For $H \neq 0$ the otherwise degenerate $M_J = \pm 1$ states are separated in energy, resulting in quantum mechanical interference which spatially modulates the fluorescence pattern. In essence, this provides a time frame against which the spontaneous decay rate of the $J=1$ level can be determined. This work was carried out on the $^1S_0 \rightarrow ^3P_1$ transition at $\lambda = 555.6$ nm in ^{174}Yb [Phys. Rev.

A 41, 2580 (1990)]. The work demonstrated strong dependences of the fluorescence signal on the power and on the statistical properties of the driving field, and provided a quantitative test of the capability of theoretical methodology [Phys. Rev. A 43, 6142 (1991)] for predicting the behavior of this type of atom-field interaction.

OBSERVATION OF MODULATED HANLE RESONANCES

In 1968 Corney [J. Phys. B2, 458 (1968)] improvised on the standard Hanle detection scheme by weakly amplitude modulating (approximately 1%) the driving field, causing an intensity modulation of the fluorescence. This is used for phase sensitive detection of the fluorescence signal as a function of the magnetic field. Corney found resonances in the in-phase and in-quadrature components of the signal, where the Zeeman splitting equalled half the modulation frequency. The work, carried out with a broad band discharge lamp, provided important new insight on the Hanle process. Subsequently, Saxena and Agarwal [Phys. Rev. A 25, 2123 (1982)] developed a full theoretical framework for studying phase-sensitive modulated Hanle signals, including the effects of fluctuating fields of arbitrary bandwidths. G. Vemuri, a Research Associate supported by the grant and former Agarwal student, designed and helped develop an experimental test of the theory in the $^1S_0 \rightarrow ^3P_1$ ($J = 0$ to $J = 1$) transition at 553.5 nm in ^{138}Ba , using an electro-optic crystal to achieve 10% modulation at 100 MHz [Phys. Rev. A 44, 7635 (1991)].

This study revealed that there are resonances in the in-phase and in-quadrature parts whose positions, shapes, and strength are sensitive to laser bandwidth. These resonances, which are Lorentzian or dispersion shaped, or a combination of the two, occur where the

Zeeman splitting of the $M_J = \pm 1$ sublevels equals the modulation frequency for the case of monochromatic light, and for a splitting equal to half the modulation frequency for broadband light (as for the Corney experiment). The experimental results were in good agreement with the theoretical predictions.

FOUR-WAVE MIXING WITH TIME DELAYED CORRELATED PHASE-DIFFUSING FIELDS: THEORY AND CALCULATIONS

Following the studies of the role of fluctuations in the two-level resonance transition in atomic sodium, and of the Hanle resonance process in ytterbium and barium, attention was directed to processes involving the coherent interaction of more than one laser beam in a diffuse medium, notably to four-wave-mixing. The objective, again, was to characterize the influence of phase fluctuations, over a range of statistical parameters, on the observables in such processes.

Four-wave mixing interactions in atomic and molecular media have become a very important spectroscopic tool. The role of laser fluctuations in four-wave mixing interactions with time-delayed fields has recently become of interest because of the discovery that incoherent or partially-coherent broadband laser pulses of nanosecond duration can be used to great advantage for measurement of femtosecond relaxation times in atomic or molecular vapors, liquid phase solutions, or solid state media. In effect, the high temporal resolution of these measurements is made possible by the extremely short correlation times of these broadband pulses. Typically these measurements are made using a strong pump laser beam and a probe laser beam, both derived from the same laser source, with the probe time

delayed with respect to the pump. The coherent interaction of these beams with the medium is responsible for the generation of a new beam, either in the forward direction, or in the backward direction, depending on the experimental configuration. Since the pump and probe laser fields have a common source, their fluctuations are identical, up to a time delay, and the net field in the nonlinear medium, where these two beams are overlapped, has "memory". The field consisting of the pump field and the time-delayed probe is known as non-Markovian. Theoretical calculation of the four-wave mixing interaction is extremely difficult for intense, non-Markovian laser fields.

As a step in the extension of theoretical predictions to the parameter space accessible for experimental work using the phase-noise modulation technique, Vemuri and JILA colleagues, in collaboration with G. S. Agarwal at the University of Hyderabad and R. Roy at Georgia Institute of Technology, considered the generation of four-wave-mixing signals by an ensemble of two-level atoms interacting with broadband, correlated, pump and probe fields [Phys. Rev. A 44, 6009 (1991)]. The dependence on time delay between the correlated pump and probe fields was of particular interest. By reducing the calculation to the solution of six Langevin equations, which were integrated using Monte Carlo methods, valid predictions of the signal behavior over a wide range of experimentally accessible intensities and noise bandwidths were obtained.

A further study, in collaboration with Agarwal, extended these results for phase diffusion fields and compared them with predictions of the effects of a different field-fluctuation model, the "chaotic" field.

MEASURED ABSORPTION AND GAIN BY TWO-LEVEL ATOMS IN A TIME-DELAYED NON-MARKOVIAN FIELD

As a step preliminary to the investigation of four-wave mixing, we measured the absorption from a weak time-delayed probe by a two-level atomic system, $3S_{1/2}$ ($F = 2$, $M_F = 2$) $\rightarrow$ $3P_{3/2}$ ($F = 3$, $M_F = 3$) in an atomic sodium beam, saturated by a phase-diffusing pump field [Phys. Rev. A 47, 3202 (1993)]. In this work the probe was a time-delayed, attenuated replica of the pump, being derived from the same artificially-noise-modulated phase-diffusing laser beam. They were then frequency degenerate, and were resonant with the atomic transition. Figure 4 shows the measured absorption when the synthesized phase fluctuations provide a nearly Lorentzian laser field spectral profile of half-width ~ 8 MHz, with a Rabi frequency of about 26 MHz. The natural linewidth of the atomic transition is ~ 10 MHz. Measurements are shown as points, and the solid line represents a calculation by Gheri, Marte, and Zoller [J. Opt. Soc. Am. B5, 1559 (1991)], modified to account for Doppler broadening and beam overlap factors.

Fig. 4

Negative absorption represents probe gain, which is significant for small time delays. An oscillatory behavior is evident, with a period closely associated with the time period of a Rabi oscillation. This has a simple physical explanation on the basis of transients induced in the population difference (and coherence) between the two states, initiated by phase noise on the pump. These transients oscillate at the Rabi frequency and damp out with the spontaneous decay of the upper level. Amplification occurs if the fluctuations of the probe arrive just as the pump induced population has inverted in the course of the first Rabi oscillation. (The atom is not undergoing free-precession, but is being continuously driven by the noise-modulated pump field.)

FOUR-WAVE-MIXING WITH TIME-DELAYED CORRELATED

PHASE DIFFUSING FIELDS: EXPERIMENT

The final goal of the program supported by this grant has been an experimental study of the role of phase/frequency fluctuations in four-wave-mixing in a low-density ensemble of two-level atomic systems. As mentioned previously, four-wave-mixing with time-delayed correlated stochastic fields is already recognized as a powerful tool for high-resolution spectroscopy and measurement of fast dephasing times in atomic media. Early experiments were restricted to four-wave-mixing in broadband fields below saturation while some later experiments also explored the regime in which pump fields saturated the two-level transition [P. Tchenio, A. Debarre, J. -C. Keller & J. -L. Le Gouet, Phys. Rev. Lett. 62, 415 (1989); Phys. Rev. A 39, 1970 (1989); J. Opt. Soc. Am. B 5, 1292 (1988)]. These experiments were performed in Doppler broadening media using pulsed lasers for which the statistics are

neither well-defined nor variable in a controlled manner. The results of such measurements, particularly with Doppler broadening, do not provide strict tests of theory.

In order to realize conditions of a collision-free, nearly Doppler free environment, in addition to other conditions which would facilitate a result as directly comparable to theoretical predictions as possible, we undertook to carry out the four-wave-mixing experiment in an atomic sodium beam. We found no precedent for this in the literature.

Our initial efforts failed. We could obtain good signals in vapor cells, but our initial attempts using a beam produced signal-to-noise ratios at the one-to-one level, due to scattered light from the pump beams. The difficulty was overcome by chopping the probe beam at 50 kHz and using phase sensitive detection to provide subtraction of the main component of background scattered light. The signal was also enhanced by raising the oven temperature to increase the atom beam density.

The measurement was carried out with counter-propagating pump beams in a phase conjugate geometry obtained by reflection. The time delay between the pump and probe was imposed by passing the probe beam through one of a set of calibrated optical fibers. Servo loops were used to reduce intensity noise on the pump and probe beams. An additional servo loop controlled the detuning of the laser frequency from the sodium resonance frequency. The signal beam was spatially filtered to reduce noise and directed to a photomultiplier. Spectra were measured by tuning the pump and probe frequency through the sodium resonance, and recording the intensity of the phase conjugate beam as a function of detuning.

Fig. 5

Sample spectra of the four-wave-mixing interaction. Curves (a) and (b) correspond to the frequency/phase fluctuations of the pump and probe beams turned off and on, respectively.

Examples of spectra are shown in Figure 5. All data with broadband fields to this point have been recorded using a laser field with a nearly Lorentzian power spectrum, of width about 10.5 MHz. We have varied the Rabi frequency of the interaction from ~ 7 MHz

to ~ 28 MHz, thus spanning the range about the natural linewidth (10 MHz) of the sodium transition. For each intensity, we have recorded the four-wave mixing spectrum also as a function of probe delay. The spectra in Figures. 5(a) and 5(b) correspond to the frequency/phase fluctuations turned off and on, respectively, and with Rabi frequency of ~ 28 MHz. The widths of the spectra corresponding to the laser noise off are determined by the natural linewidth of the sodium, residual Doppler broadening (~ 5 MHz) and power broadening.

The dependence of the peak four-wave mixing signal as a function of a delay for two intensities is shown in Figure 6. Each curve is normalized to the intensity of the four-wave-mixing signal generated with fully coherent light. For low Rabi frequencies, the four-wave mixing signal shows only a slight dependence on delay time, decreasing monotonically from ~ 0.6 for zero delay to ~ 0.4 for long delays. At large Rabi frequency, however, the dependence of the four-wave mixing intensity on delay is very strong, decreasing sharply with increasing delay for short delays, but then partially recovering for large delays. The slope of the initial plunge depends strongly on the intensity of the pump laser. These results are in qualitative agreement with recent Monte Carlo simulations of G. Vermuri [Phys. Rev. A 48, 3256 (1993)].

Fig. 6

Peak four-wave-mixing intensity as a function of delay time between the pump and probe beams for Rabi frequencies of 7 MHz and 28 MHz.

In a general sense, we have achieved our goals for studying four-wave mixing in an atomic beam. We have carried out measurements using continuous-wave laser fields undergoing frequency and phase fluctuations characteristic of the phase-diffusion model. Our results have shown a strong dependence of the phase-conjugate signal on delay time, and a rapid variation with changes in the Rabi oscillation frequency of the interaction.

There are some loose ends which will require further attention elsewhere. In Figure 5 a prominent dip in the four-wave mixing spectrum is seen for detunings to the blue side of the resonance. The depth of this dip increases with increasing pump intensities, and is significant only for narrowband laser spectra. This feature maybe due to a laser heating effect, as follows: The atomic beam produced by the effusive oven has a finite divergence, determined by the diameters of the two apertures which define the atomic beam, and by their separation. As the atoms pass into the volume of the counterpropagating pump beams, their transverse velocity results in a Doppler shift of the optical frequency. In the rest frame of the atom, one pump beam appears shifted up in frequency, the other down. Thus the atom is more likely to absorb from one pump beam than the other. Momentum transfer through photoabsorption tends to increase the atom's transverse velocity when the pump beam is tuned to the blue side of the resonance. This decreases the four-wave mixing interaction as atoms are Doppler tuned out of resonance. One test of this hypothesis would be the introduction of transverse cooling of the atom beam, to see if this modifies the anomalous shape.

While making the measurements of the phase conjugate four-wave mixing signal, we observed an intensity-dependent phase shift for which we as yet have no explanation. This shift is a phase difference between the modulation of the probe beam and that of the phase

conjugate signal, which has displayed a dependence on the intensity of the pump beam. Especially puzzling is the time scale of this effect. The modulation frequency (or chopping frequency) of the probe beam was 37 kHz, so that a phase shift of, say, 15° represents a time delay of 1 μ sec. The lifetime of the Na 3P state is only 16 nsec, and any transit times which one might imagine to be important are also of the nanosecond time scale. Further work will be necessary to trace the origins of this effect.

PhD THESIS PROGRAMS

Kenneth Edmund Arnett "Hanle Effect Between the 1S_0 - 3P_1 Levels of Ytterbium With a Phase Diffusing Laser Field", 1988.

B.S. University of Missouri - Rolla, 1980

M.S. University of Colorado - Boulder, 1983

PhD. University of Colorado - Boulder, 1988

Dr. Arnett was supported by this grant from August 1982 until January 1988.

The suggestion to experimentally investigate the Hanle resonance with the phase diffusing laser, which Kenn helped in a major way to develop, was made by Drs. Harold Metcalf and Tom Bergeman from the State University of New York, Stony Brook. The work was carried out, primarily by Dr. Arnett, at JILA. He benefitted from advice and

guidance from Dr. John Brandenberger, Lawrence University, and Dr. Murray Hamilton, then at Strathclyde, Scotland.

Dr. Arnett has been employed at Display-Tech, in Boulder, Colorado, since 1988. He has been engaged in technology transfer projects, typically involving the application of lasers to non-linear optical processes.

Mike Howard Anderson "Studies of Atomic Response to Phase-Diffusing Laser Fields", 1992.

B.A. University of Minnesota, 1982

PhD. University of Colorado, 1992

Dr. Anderson was supported by this grant from May 1988 through November 1992.

His thesis was in two parts, each demanding an understanding of the physics of the atom-field interaction at a very sophisticated level, and the experimental skill and patience to carry out difficult state-of-the-art measurements. The first part was the study of fluorescence fluctuations, and the second part was the study of absorption and gain by two-level atoms in a time delayed non-Markovian optical field.

Dr. Anderson is presently a Postdoctoral Research Associate at JILA, working with Dr. Eric Cornell in an attempt to use laser cooling to achieve conditions for Bose condensation.

POSTDOCTORAL RESEARCH ASSOCIATES

Daniel S. Elliott February 1981 to November 1982; August 1983 to June 1984

Professor of Electrical Engineering, Purdue University

Rajarshi Roy April 1981 to August 1982

Professor of Physics, Georgia Institute of Technology

Murray W. Hamilton April 1983 to March 1985

Professor of Physics, Adelaide, Australia

Lynn Westling April 1986 to March 1988

Professor of Physics, Bryn Mawr

Richard D. Jones September 1987 to September 1990

Staff Scientist, National Institute for Standards and Technology, Boulder, Colorado

Gautam Vemuri July 1990 to September 1992

Professor of Physics, Indiana University - Purdue University at Indianapolis (IUPUI)

MAJOR CONTRIBUTORS AND CONSULTANTS

The program has benefitted immensely from the contributions and interest of a number of JILA colleagues, visitors, and former associates.

Prof. John Cooper, JILA, has participated from the beginning of the program as an invaluable consultant on theoretical and experimental issues. His participation has been extraordinarily dedicated and valuable during several extended absences of the Principal Investigator. On those occasions he has consulted with graduate students and postdoctoral research associates on a daily basis, has convened and led group meetings, and has taken care of many administrative responsibilities.

Dr. John L. Hall, JILA, has taken an interest in critical technical issues from the beginning of the project. His input to the understanding of noise generation, signal processing, laser beam modulation, and laser stabilization were absolutely essential to the success of the project. This program would have realized a much more limited success without the unique highly stabilized JILA ring dye laser which Dr. Hall designed and which was implemented under his direction.

Prof. Daniel S. Elliott's initial contribution as a postdoctoral research associate, the recognition that there is a theoretical basis for describing the spectral characteristics of phase-diffusion in terms of the bandwidth and amplitude of Gaussian noise which lends itself to implementation in the laboratory, was a real breakthrough. Dr. Elliott has continued to make important contributions to the project, and, following termination of the program at JILA, has transferred essential components of the apparatus to his laboratory at Purdue, where he hopes to address the unresolved questions in the study of four-wave mixing in a diffuse beam.

We benefited from encouragement by several theoreticians interested in this work, notably by Prof. Peter Lambropoulos, USC, and by Prof. Joseph Eberley, Rochester, in the very early stages; and during the course of the program we enjoyed an essentially collaborative relationship with Prof. Peter Zoller, JILA. The calculations carried out by Zoller and his associates were closely coordinated with the experimental plan, and greatly enhanced the value of and interest in the experimental results. The later stages of the program were strongly influenced by the work of Prof. G. S. Agarwal, Hyderabad, India. From the beginning he encouraged us to address multi-beam phenomena, notably four-wave-mixing, and he developed some important theoretical predictions which greatly enhanced interest in the experimental program.

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"Experimental synthesis of phase-diffusing optical fields," D. S. Elliott and S. J. Smith, *J. Opt. Soc. Am. B* **5**, 1927-1939 (1988).

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