

A study of a  $J=1 \rightarrow J=1$  system in  
Samarium with resonant laser  
radiation at 686 nm

by

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# Abstract

An  $J=1 \rightarrow J=1$  atomic system in Samarium with incident laser resonant radiation has been investigated. A linearly polarized laser at 686nm excites atoms from the level  $4f^6 6s^2 \ ^7F_1$  to a excited level  $4f^6 6s 6p \ ^9F_1$  via the process of optical pumping. When an external magnetic field is applied to the atom-laser interaction and the decay fluorescence collected, a level-crossing profile appears. Theoretical predictions of the level-crossing profile can be made using spherically irreducible tensors to describe the density matrix which take advantage of the symmetry of the atomic system. By comparing theory with experimental data, a discussion is made of the various parameters and external factors that can affect this system, which show that Doppler broadening is the major influence. An additional investigation is made into the evolution of the  $J=1 \rightarrow J=1$  atomic system with increasing laser exposure. Comparisons of the experimental data with theoretical predictions are made by analyzing the FWHM of the overall level-crossing profile, the FWHM of the dip about  $B = 0$  and the relative depth of the dip. By charting the progress of these parameters with increasing laser exposure, it can be seen that the theory and experimental data agree qualitatively.



# Declaration

This work contains no material which has been accepted for the award of any other degree or diploma in any University or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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Supervisor: Assoc. Prof. M. Hamilton



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# List of Symbols

Throughout this thesis, several symbols will be used repeatedly to represent specific quantities or parameters, the following is a list of these symbols and short descriptions for the reader's convenience. Wherever possible standard symbols and notation have been used which appear in major references.

$J$	Angular momentum quantum number	p. 1
$m$	Magnetic quantum number	p. 2
$\Delta B$	Width of the Hanle curve at half maximum	p. 5
$\hbar$	Planck's constant	p. 5
$\tau$	Lifetime of the excited state	p. 5
$\mu_B$	Bohr Magneton	p. 5
$g_J$	Landé factor of the excited state	p. 5
$E(t)$	Electric field	p. 12
$\Gamma_J$	Relaxation rate	p. 12
$\omega_0$	Angular frequency	p. 12
$t$	Time	p. 12
$t_0$	Initial time of excitation	p. 12
$i$	Imaginary number $\sqrt{-1}$	p. 12
$\omega_{La}$	Larmor angular frequency	p. 13
$\mathbf{v}$	Velocity of electron	p. 13

<b>B</b>	Magnetic field	p. 13
$I$	Intensity of light recorded	p. 13
$\mathcal{R}$	Excitation rate of the atoms	p. 13
$\phi_p$	Angle that the electric field makes with x-axis	p. 13
$m_e$	Mass of the electron	p. 13
$e$	Charge of the electron	p. 13
$\alpha, \beta$	Index to specify atomic state	p. 15
$F, G$	Total angular momentum	p. 15
$M, N$	Projection of total angular momentum along z-axis	p. 15
$\rho$	Density operator	p. 15
$\rho_{\alpha FM, \beta GN}$	Coherence between states $ \alpha FM\rangle$ and $ \beta GN\rangle$	p. 15
$k$	Tensorial order	p. 15
$q$	$-k, -k + 1, \dots, k - 1, k$	p. 15
$\mathcal{L}$	Liouville product space	p. 15
$\mathcal{E}$	Atomic state space	p. 15
$\langle FGM - N   kq \rangle$	Clebsch-Gordon coefficient	p. 15
$T_q^{(k)}$	Irreducible spherical tensor of order k and q	p. 16
$R_{q'q}^{(k)}$	Rotation matrix	p. 16
$n_\beta$	Total population of level $\beta$	p. 16
$ \psi\rangle$	State vector for the system	p. 17
$\mathcal{H}$	Hamiltonian	p. 17
$\dot{\rho}_{\text{sp}}$	Spontaneous emission terms of the Liouville Equation	p. 18
$\dot{\rho}_{\text{rel}}$	Relaxation terms of the Liouville Equation	p. 18
$\mathcal{H}_0$	Hamiltonian describing free evolution	p. 18
$\mathcal{H}_z$	Hamiltonian describing Zeeman effect	p. 18

$\mathcal{H}_{\text{int}}$	Hamiltonian describing atom-laser interaction . . . . .	p. 18
$W_{\beta}$	Unperturbed energy of level $\beta$ . . . . .	p. 18
$u$	Upper level of atomic system . . . . .	p. 18
$l$	Lower level of atomic system . . . . .	p. 18
$\omega_{\beta}$	Zeeman splitting for level $\beta$ . . . . .	p. 18
$\mathbf{E}(r, t)$	Electric field of the laser . . . . .	p. 18
$\mathbf{d}$	Electric dipole operator . . . . .	p. 18
$d_x, d_y, d_z$	Cartesian components of dipole operator . . . . .	p. 19
$d_0, d_+, d_-$	Spherical components of dipole operator . . . . .	p. 19
$E_x, E_y, E_z$	Cartesian components of laser electric field . . . . .	p. 19
$E_0, E_+, E_-$	Spherical components of laser electric field . . . . .	p. 19
$d_{\alpha\beta}$	Reduced matrix element of the electric dipole operator . .	p. 19
$\mathbf{e}$	Unit vector-polarization of the laser electric field . . . . .	p. 19
$E_0$	Amplitude of the electric field . . . . .	p. 19
$\omega_L$	Laser frequency . . . . .	p. 19
$e_x, e_y, e_z$	Cartesian components of dipole operator . . . . .	p. 19
$e_0, e_+, e_-$	Spherical components of dipole operator . . . . .	p. 19
$\pi$	$\pi$ linearly polarized light . . . . .	p. 19
$\sigma$	$\sigma$ linearly polarized light . . . . .	p. 19
$\sigma^+, \sigma^-$	$\sigma$ Circularly polarized light . . . . .	p. 19
$\Gamma_{\beta}(k)$	$k$ -tensor relaxation rate . . . . .	p. 20
$\gamma_{\alpha}$	Radiative decay rate for level $\alpha$ . . . . .	p. 20
$\Gamma_{lu}(k)_{\text{coll.}}$	Rate collisional processes destroy optical coherence . . . . .	p. 20
$\Theta(u, l, k)$	Spontaneous emission factor . . . . .	p. 21
$\gamma_{ul}$	Transition probability from level $u$ to $l$ . . . . .	p. 21

$\omega_{ul}$	Atomic frequency $W_l - W_u$ ..... p. 22
${}^Q G_{q'q}^{k'k}(lu)$	Geometric factor ..... p. 22
$a(k)$	Factor for anomalous Zeeman effect ..... p. 22
$\dot{\rho}_q^{(k)}(\beta)$	Density matrix component ..... p. 22
$\tilde{\rho}_q^{(k)}(lu)$	Time independent optical coherences ..... p. 22
$\Omega$	Rabi frequency ..... p. 25
$\Delta\omega$	De-tuning between the atom and laser ..... p. 25
$L_{ul}(\lambda)$	Expectation value for the fluorescence intensity ..... p. 26
$\lambda$	Polarization vector ..... p. 26
$\theta, \phi, \alpha$	Angles defined in spherical polar coordinates ..... p. 26
$\phi_r$	Angle subtended in the x-y plane by the x-axis and lens . p. 28
$C_A, \dots, C_E$	Constants ..... p. 28
$\epsilon_0$	Vacuum permittivity ..... p. 35
$c$	Speed of light ..... p. 35
$f$	Oscillator strength ..... p. 35
$\Delta\nu_D$	Doppler spread ..... p. 43
$f_M(\nu)$	Maxwellian velocity distribution ..... p. 43
$m_S$	Mass of the samarium atom ..... p. 43
$k_B$	Boltzmann Constant ..... p. 43
$T_o$	Samarium oven temperature ..... p. 43
$\delta\omega_S$	Power broadened homogeneous width ..... p. 47
$I_S$	Saturation intensity ..... p. 47
$\gamma_i$	Relaxation rate of the absorbing level ..... p. 47
$\tau_k$	Lifetime of the level $k$ ..... p. 47
$T_F$	Transit time of the atom through the beam ..... p. 47

$f_i$	The fraction of total fluorescence intensity .....p. 47
$v_{rms}$	Root-mean-square velocity of the atoms ..... p. 60
$d_a$	The oven aperture diameter ..... p. 61
$l_o$	The distance between the oven and the interaction region p. 61
$I$	Nuclear spin quantum number ..... p. 69
$Z$	Nuclear charge ..... p. 69
$M$	Atomic weight ..... p. 69
$g_\alpha$	Landé factor of level $\alpha$ ..... p. 69
$W_{ki}$	Transition rate ..... p. 69
$\tau_k$	The lifetime of level $k$ ..... p. 72
$A$	Atomic mass number ..... p. 72
$W_I$	Interaction width ..... p. 80
$T_e$	Time that atoms travel through resonant radiation ..... p. 83
$\text{FWHM}_O$	FWHM of the overall $J=1 \rightarrow J=1$ profile ..... p. 86
$\text{FWHM}_{\text{dip}}$	FWHM of the Lorentzian function fitted to the dip ..... p. 86
$H_T$	Overall height of $J=1 \rightarrow J=1$ profile ..... p. 86
$H_{\text{dip}}$	Depth of the dip about $B=0$ ..... p. 86
$\mathcal{L}(x_{\mathcal{L}})$	Lorentzian function ..... p. 96
$x_{\mathcal{L}0}$	Centre of Lorentzian function ..... p. 96
$\Gamma_{\mathcal{L}}$	Parameter describing the width of the function ..... p. 96
$J_m(x)$	Bessel Function of order $m$ ..... p. 111

