Test of the neoclassical theory of radiation in a weakly excited atomic system

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The neoclassical theory of radiation predicts that the decay rate of an excited atomic state depends on the population density of the lower state. Experimental evidence is presented here which shows that in the case of ^{39}K the decay rate is in agreement with the predictions of quantum electrodynamics and definitely in disagreement with the neoclassical theory.

I. INTRODUCTION

During a recent series of experiments on the optical excitation of alkali atoms in an atomic beam it became apparent that the system could be used to provide a simple test of the predictions of the neoclassical theory of radiation developed by Crisp and Jaynes[1] and Stroud and Jaynes.[2] Although there have been a number of experiments done lately to test this theory,[3-7] the present work provides a test in a regime of population density not covered in the other cases. While the neoclassical theory (NCT) has not been able to explain the previously observed results which have been explained satisfactorily by quantum electrodynamics (QED), it is still worthwhile to examine radiative processes in atoms in as many varied circumstances as possible since there are still difficulties associated with QED which prevent it from being a completely satisfactory theory.

The NCT theory avoids quantization of the electromagnetic field by treating it classically. This theory predicts, in particular, that the decay rate of the excited state of an atom depends on the population density of the lower state. An experiment by Gibbs *et al.*[5] has examined this point in a situation in which the population density of the lower state was small, and agreement was found with QED. However, in their experiment the lower-state population density was fixed by the requirements of thermal equilibrium in their sample, and this population density could not be varied as a parameter of the experiment.

In an earlier experiment, Wessner *et al.*[3] studied the decay rate of the $^2P_{1/2}$ state of atomic hydrogen as a function of the population density of this state, and again found agreement with the predictions of QED. However, there was essentially no variation of the population density of the ground state.

In the present experiment, atoms were prepared in an intermediate excited state by the action of an inhomogeneous magnetic field. The population density of the ground state could be varied as a parameter by variation of the magnitude of an rf field, causing transitions between ground-state hyperfine-structure levels. As will be discussed below, this allowed a measurement of the decay rate of an excited state as a function of ground-state population density for comparison with the predictions of NCT and QED.

II. PRINCIPLE OF THE EXPERIMENT

The apparatus used consisted of a conventional flop-in atomic-beam apparatus that has been described previously.[9] The A magnet is a hexapole and focuses atoms radially, those with $M_J=+\frac{1}{2}$ being forced towards the beam axis while those with $M_J=-\frac{1}{2}$ are removed from the beam. The magnet is equipped with a radial stop that prevents fast atoms with $M_J=-\frac{1}{2}$ from reaching the interaction region. Measurements show that when no rf resonance is being excited, less than 2% of the direct beam reaches the interaction region.

The interaction region is located in the C magnet, and consists of a hairpin which excites $\Delta F=\pm 1$, $\Delta M_F=\pm 1$ transitions between the hyperfine states of the $^2S_{1/2}$ ground state of ^{39}K. This same region is illuminated by light from a ^{39}K resonance lamp, which is chopped mechanically by means of a movable vane. The apparatus is operated by a computer, and data taken with the light on are stored in one buffer while data with the light off are stored in a second independent buffer. rf at the hyperfine frequency is scanned in amplitude by the computer first with the light on and then with it off; so each of these buffers contains data as a function of rf power. Each buffer contains about 500 words of data, and each scan lasts about 10 sec. Data are accumulated until a satisfactory signal-to-noise ratio is observed. The buffer containing the light-off data is then subtracted from that containing the light-on data so that the final buffer contains the light flop intensity as a function of rf amplitude.

The resonance lamp consists of a spherical bulb about 1 cm in diameter filled with about 10 Torr of argon or neon and containing a small amount of potassium metal. The lamp discharge is operated at 2500 MHz, and previous measurements have shown that such a lamp shows little or no self-reversal.[10] No evidence of self-reversal has been observed in the present series of experiments. All components of the resonance line are present in the radiation from the lamp, and, since no filters are used, they are present in their natural intensity.

Consider a system of three levels as shown in Fig. 1. Levels α and β are connected to γ through allowed optical transitions, while α and β are connected by an allowed magnetic dipole transition. According to the neoclassical theory of radiation, the state γ will radiate to the lower state according to[1,2]

$$\frac{d\sigma_{\gamma\gamma}}{dt} = -\left(\sum_j A_{\gamma j}\sigma_{jj}\right)\sigma_{\gamma\gamma}, \tag{1}$$

where $A_{\gamma j}$ is the Einstein A coefficient for the transition from γ to j and the atoms' population density must be unity:

$$\sum_i \sigma_{ii} = 1. \tag{2}$$

The decay rate of the state γ is, according to NCT,

$$\frac{1}{\tau_\gamma}\,(\text{NCT}) = \sum_j A_{\gamma j}\sigma_{jj}, \tag{3}$$

and according to quantum electrodynamics it is

$$\frac{1}{\tau_\gamma}\,(\text{QED}) = \sum_j A_{\gamma j}. \tag{4}$$

Observable optical transitions (light flop) may proceed through two different paths:

$$\beta \to \gamma \to \alpha, \quad \alpha \to \gamma \to \beta.$$

The first of these will result in an increase in the number of atoms in state α while the second will result in a decrease. The observed signal S will be

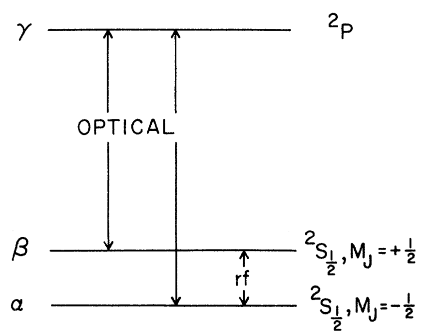

Fig. 1. Three-level model for the atomic system used in this experiment. At the right are shown the corresponding levels of ^{39}K.

proportional to the rate of change of atoms in state α,

$$S \propto B_{\beta\gamma}\sigma_{\beta\beta}\frac{1/\tau_{\gamma\alpha}}{1/\tau_\gamma} - B_{\alpha\gamma}\sigma_{\alpha\alpha}\frac{1/\tau_{\gamma\beta}}{1/\tau_\gamma}, \tag{5}$$

where B is the Einstein B coefficient between the two states and $1/\tau_{\gamma j}$ is the partial decay rate to the state j, i.e.,

$$1/\tau_\gamma = 1/\tau_{\gamma\alpha} + 1/\tau_{\gamma\beta}. \tag{6}$$

According to QED Eq. (5) becomes

$$S(\text{QED}) \propto B_{\beta\gamma}\sigma_{\beta\beta}\frac{A_{\gamma\alpha}}{A_{\gamma\alpha}+A_{\gamma\beta}} - B_{\alpha\gamma}\sigma_{\alpha\alpha}\frac{A_{\gamma\beta}}{A_{\gamma\alpha}+A_{\gamma\beta}}. \tag{7}$$

If the model is now applied to ^{39}K, γ corresponds to the ^2P states, β to $^2S_{1/2}$, $M_J = +\frac{1}{2}$, and α to the $^2S_{1/2}$, $M_J = -\frac{1}{2}$ states. It can be easily shown by direct calculation that $A_{\gamma\alpha} = A_{\gamma\beta}$. Also, if the intensity of the exciting light is weak $\sigma_{\alpha\alpha} + \alpha_{\beta\beta} \approx 1$, and Eq. (7) becomes

$$S(\text{QED}) \propto \tfrac{1}{2}[B_{\beta\gamma} - (B_{\beta\gamma} + B_{\alpha\gamma})\sigma_{\alpha\alpha}]. \tag{8}$$

Similarly,

$$S(\text{NCT}) \propto (B_{\beta\gamma} - B_{\alpha\gamma})\sigma_{\alpha\alpha}(1-\sigma_{\alpha\alpha}). \tag{9}$$

Thus NCT predicts that no net change in the population of state α can occur by means of the transitions discussed above when $\sigma_{\alpha\alpha} = 0$. The signal should therefore approach zero as $\sigma_{\alpha\alpha}$ approaches zero. Also the dependence of the signal on $\sigma_{\alpha\alpha}$ should be linear for QED and nonlinear for NCT.

Assume now that a resonance magnetic dipole transition is excited between states α and β at the same time and same point in space that the optical transitions are being excited. According to the Rabi two-level formula[11] evaluated at resonance, if $\sigma_{\beta\beta} = 1$ at $t = 0$, $\sigma_{\alpha\alpha} = b^2t^2$, where b is the amplitude of the rf perturbation and t is the time that the atom spends in the interaction region. Assuming that this time is the same for all atoms of interest and the atoms are initially all in state β, $\sigma_{\alpha\alpha}$ is proportional to the square of the amplitude of excitation of the magnetic dipole transition. Thus $\sigma_{\alpha\alpha}$ can be varied by changing the amplitude of this excitation. In the case of ^{39}K, the levels α and β are separated by the hyperfine structure in the $^2S_{1/2}$ state, and transitions can be excited between them by rf at a frequency of 461.720 MHz.

III. RESULTS

Results of the experiment are shown in Fig. 2, where the light flop intensity is plotted against $\sigma_{\alpha\alpha}$. The data are observed to fall off linearly with increasing $\sigma_{\alpha\alpha}$, and a fit can be made to Eq. (8) as shown by the straight line. The data do not

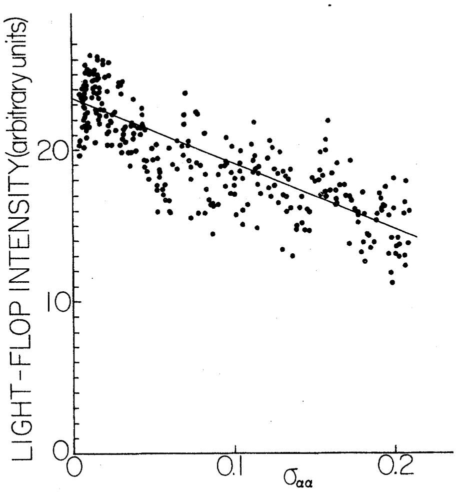

Fig. 2. Observed light flop intensity vs rf power or $\sigma_{\alpha\alpha}$. Straight line, fit to the data using the predictions of QED, Eq. (8).

agree with NCT, Eq. (9), which predicts that there should be no observable effect for $\sigma_{\alpha\alpha}=0$. There does not seem to be any way that the data could agree with NCT while there is agreement with QED. Therefore it must be concluded that the neoclassical theory fails to describe the radiative process under the conditions of this experiment. It should be noted that the occurrence of a "light flop" signal in the early work of Perl, Rabi, and Senitzky[8] is an indication of the failure of the NCT theory.

The experiment can be criticized on one point. Because of the state selection by the A magnet, the state $^2S_{1/2}$, $F=2$, $M_F=-2$ will be included in state α. The other states in α are separated from state β by the hyperfine interval which is large compared to h/τ, where τ is the lifetime of state γ. At the weak magnetic fields used in the interaction region, the $F=2$, $M_F=-2$ state does not meet this condition which is assumed in the derivation Eq. (1).[12] These considerations do not change the fact that the data agree with QED, and it is difficult to see how taking proper account of the $F=2$, $M_F=-2$ state could result in agreement with NCT.

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[12]See Appendix A of Ref. 1.