Observation of Inhibited Spontaneous Emission

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The radiative decay of the cyclotron motion of a single electron is significantly inhibited when the electron is located within a microwave cavity (formed by the electrodes of a Penning trap) rather than in free space. This is the first observation of such inhibited spontaneous emission and the first use of a promising new system for radiative physics. Implications for precision measurements are mentioned.

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The fundamental interaction between matter and the vacuum is most commonly evidenced by spontaneous emission, whereby excited states are driven to their ground states. The rate Γ for spontaneous transitions from an initial state $|i\rangle$, which has no photons present, to a final state $|f\rangle$, which includes a photon, is given by the well-known "golden rule,"

$$\Gamma = \hbar^{-2}\rho(\nu_c)\,|\langle f|H|i\rangle|^2. \tag{1}$$

The interaction between the radiating system and the field is described by the Hamiltonian H, $\rho(\nu_c)$ is the density of final photon states at the transition frequency, ν_c, and the matrix element is volume normalized. For radiation to free space,

$$\rho(\nu_c) = 2(4\pi\nu_c^2/c^3). \tag{2}$$

This result is often derived with use of a cavity whose dimensions are much larger than the wavelength of the radiation, $\lambda_c = c/\nu_c$, and the factor of 2 describes the possible photon polarizations.

The radiation is significantly modified when the radiating system is located within a conducting cavity which has dimensions comparable to λ_c, rather than in free space. The language used above has been adapted to describe experimentally interesting situations with such small cavities by introducing an effective density of states which manifests the mode structure of the cavity.[1] Our one-electron oscillator is well localized in space, however, and we find it convenient to focus upon its coupling to the oscillators which represent the cavity modes. In particular, the cavity modes are standing waves which have either maxima or nodes at the center of the cavity where our electron is located. When the transition frequency ν_c is near resonance with a mode eigenfrequency, and when this mode has an electric field maxima and the appropriate electric field direction at the electron, the coupling of the two oscillators can substantially increase the spontaneous emission rate compared to that which occurs in free space.[2] Tuned cavities are often employed in lasers to take advantage of this phenomenon and such enhancement was recently observed for the first time with a sodium Rydberg atom set through a resonant, superconducting cavity.[3] Between such resonances, the spontaneous emission rate can be substantially reduced compared with free space. However, Kleppner[1] recently pointed out in this journal that such inhibited spontaneous emission had not yet been observed. He suggested using Rydberg atoms, and a number of experiments are underway.

In this Letter we report the first observation of inhibited spontaneous emission, but in a system which is quite different. We study the cyclotron motion of a single electron in a 6-T magnetic field. The cyclotron motion decays by the spontaneous emission of electric-dipole radiation. A weak electrostatic quadrupole potential is actually added to the magnetic field to form a Penning trap. The electron is in thermal equilibrium at nearly 4 K and is thus confined within a region that is small compared to λ_c. The location of the electron at the center of the trap has been checked by moving the electron slightly with small steering potentials.[4] The addition of the quadrupole potential shifts the cyclotron frequency $\nu_c \approx 164$ GHz by less than 7 parts in 10^8, indicating that the trap has negligible effect upon the cyclotron motion. The metal electrodes used to produce the quadrupole potential form the microwave cavity, with dimensions and materials as indicated in Fig. 1. The closest separation of the electrodes (nearest to the center of the trap) is 6.7 mm, compared to $\lambda_c = 2$ mm for the synchrotron radiation. All the electrodes are cooled to 4.2 K. This means that the resistivity of the copper electrodes is very low and tends to make the Q of the cavity high. On the other hand, the hole and slits in between the electrodes allow the loss of microwave power and tend to keep the Q low. We have not yet been able to measure the Q of our cavity as a result of its being submerged in liquid helium and the high frequency. On the basis of earlier measurements at room temperature,[5] however, we expect that the Q would be at least 200.

Our method for measuring the kinetic energy in the cyclotron motion is quite unusual.[6] As described by special relativity, the effective mass m of an electron

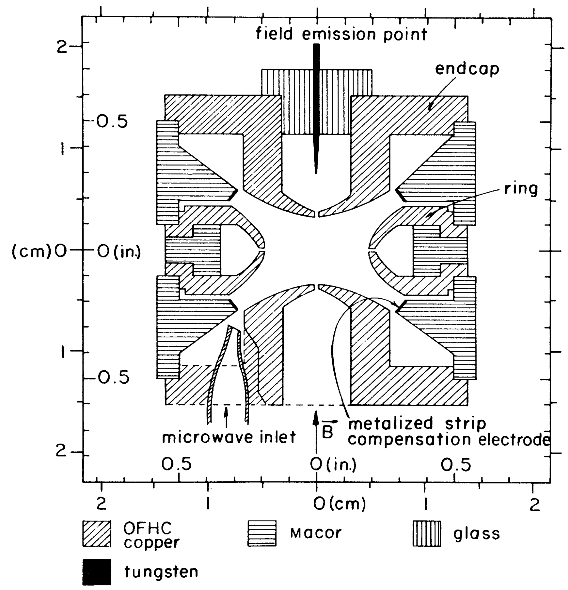

FIG. 1. Scale drawing of the electrodes of the Penning trap.

with kinetic energy K is related to its rest mass m_0 by

$$m = \gamma m_0 = (1 + K/mc^2) m_0. \quad (3)$$

The quadrupole potential makes the electron oscillate harmonically along the direction of the magnetic field. This axial oscillation is perpendicular to the cyclotron motion and its frequency, $\nu_z = 62$ MHz, is inversely proportional to the square root of the mass. The relativistic mass increase thus shifts the axial frequency

$$\nu_z = \nu_{z0}(1 - K/2mc^2) \quad (4)$$

in proportion to the kinetic energy K in the cyclotron motion. The axial frequency shift is monitored continuously with a sensitivity better than 1 Hz and thus kinetic energies larger than 16 meV can be measured.

A 16-meV cyclotron energy corresponds to an average quantum number $n = 24$ so that a classical description of the radiation is appropriate. It is thus very easy to calculate the damping time for a cyclotron motion in free space. The radiated power in the dipole radiation (to free space) is given by the Larmor formula,

$$P = \tfrac{2}{3}(e^2/c^3)\ddot{\mathbf{r}}^2. \quad (5)$$

For a circular cyclotron orbit, $\ddot{\mathbf{r}}^2 = (2\pi\nu_c)^4\rho^2$ and the kinetic energy is $E = \frac{1}{2}m(2\pi\nu_c)^2\rho^2$, where ρ is the cyclotron radius. The cyclotron decay time in free space τ_c is the ratio of E and P so that

$$\tau_c = \tfrac{3}{4}mc^3/e^2(2\pi\nu_c)^2 = 0.075 \text{ sec}. \quad (6)$$

This familiar result could be derived (with somewhat more effort) by our taking the appropriate classical limit, using the "golden rule" in Eq. (1).

Our first observation of inhibited spontaneous emission took place over a year ago.[7] The classical cyclotron motion was excited with a microwave driving field at approximately 164 GHz. The frequency of this drive was chirped down in frequency through cyclotron resonance in the same way that accelerations are accomplished in a synchrocyclotron. The chirping compensates for the downward shift in the cyclotron frequency brought about by the relativistic mass shift [Eq. (3)] as the kinetic energy in this motion is increased. The excitation typically took place as quickly as 1 msec. Details, however, are unimportant as long as a reproducible cyclotron excitation was produced. The microwave drive was then turned off. After a brief delay time, the detection electronics was switched on for a time comparable to the measured damping constant. During this observation window, the average cyclotron excitation energy was measured. The average excitation energy decreased exponentially as a function of the delay time with a time constant of 0.27 ± 0.04 sec, which is approximately 3 times longer than the calculated free-space value in Eq. (6). Several months later a confirming measurement was done in a completely different apparatus with a different detection technique and also indicated inhibited spontaneous emission.[7,8]

After these initial reports, we delayed this Letter until we had demonstrated the dependence of the damping time on the frequency of the radiation. We exploited an important feature of the cyclotron oscillator which is very useful for radiative studies. The frequency of the radiator can be tuned by changing the magnetic field without disturbing the cavity. Figure 2 shows the measured average cyclotron excitation energy as a function of time for two different magnetic fields which differ by 0.5%. Nothing else is changed. Both damping times are larger than the value calculated in Eq. (6) for free space. The measured damping times as a function of the cyclotron frequency are plotted in Fig. 3. The solid line indicates the free-space damping time. The points on the left-hand side illustrate the inhibition of spontaneous emission and the damping rate is clearly increasing with increasing cyclotron frequency. Once the damping time gets much shorter than the free-space value, however, it rapidly becomes comparable to the damping constant of the axial motion that we use for detection, which is about 30 msec. With our present techniques we can only set a lower limit to the damping time in this situation but we are developing a new technique which should change this. It will also eventually be possible to extend the range of frequencies over which we can sweep the microwave drive so that we can probe the cavity structure over a wider range of frequencies than is indicated in Fig. 3. We point out that the stability of the magnetic field required to measure a damping time is

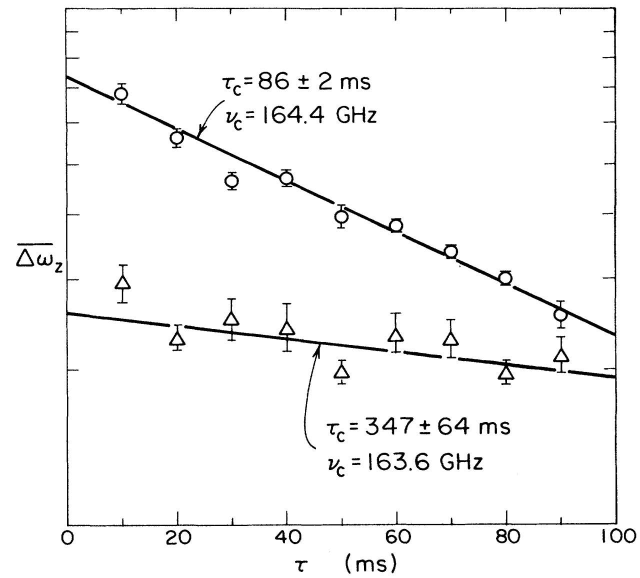

FIG. 2. The measured value of the axial frequency shift, averaged over a detection window which is 0.13 sec long, as a function of the time lapsed after the microwave power is turned off until the observation window begins. Each of the curves is normalized separately. The error bars indicate the reproducibility of the points and depend upon the stability of the magnetic field.

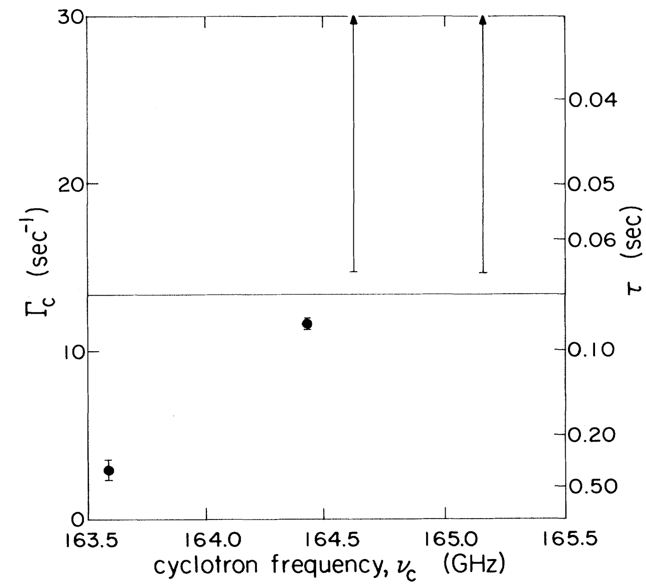

FIG. 3. Measured cyclotron damping time for cyclotron frequencies which are presently accessible.

such that it is often necessary to wait for more than a week after adjusting the field in the superconducting magnet. Longer times are required to achieve stabilities exceeding 1 part in 10^9 per hour which are required for the precision measurements done in this apparatus. These long settling down times are the reason for the long separation between the initial observations of inhibited spontaneous emission and the recent shifts of the magnetic field to change the radiation frequency.

The hyperbolic shape of the trap electrodes which make up the microwave cavity (Fig. 1), along with the holes and slits in these electrodes, make it difficult to calculate the mode structure in our trap. We therefore cannot present exact theoretical comparisons. The mode structure of a cylindrical cavity, however, is very well known. With this in mind, the possibility of producing an electrostatic quadrupole potential with cylindrical electrodes, which is of high enough quality to allow trapping and monitoring of a single particle, was investigated earlier.[9] Such a trap is now being assembled[10] and a detailed calculation of the radiation rate and the cyclotron frequency shifts of a one-electron cyclotron oscillator in this cavity is nearly finished.[11] The calculation should give a qualitative indication of the properties of our hyperbolic cavity as well. The average spacing of the eigenfrequencies of the cavity modes which are in our frequency range and which couple to the cyclotron motion is approximately 3 GHz. This means that for cavity Q values greater than 60 the modes would be resolved. We would thus expect that three times out of four an observable cavity resonance would occur within a range of cyclotron frequencies of the size plotted in Fig. 3. The calculation also suggests that a Q greater than several hundred is required to produce an inhibition of the spontaneous rate by the maximum value observed.

The observations of inhibited spontaneous emission have both favorable and unfavorable consequences for the precision measurements of a cyclotron frequency within a Penning trap. The inhibition is good insofar as the cyclotron linewidth is thereby reduced, allowing additional precision in the measurement of the cyclotron frequency. The larger the Q of the cavity, the larger the possible reduction in the cyclotron linewidth. The danger, however, is that systematic shifts in the cyclotron frequency will occur as well. The larger the Q of the cavity, the larger the possible shifts in the cyclotron frequency. The measurement accuracies are now approaching 1 part in 10^{12} so that very small shifts are important. While we cannot yet establish experimentally the size of these shifts, an approximate analysis[12] and the detailed calculation with a cylindrical cavity[11] both suggest that the shifts could be large enough to be of concern at the precisions now being achieved, depending upon the Q of the cavity. A technique to minimize the shifts has been proposed.[12]

In conclusion, we have demonstrated the usefulness of the one-electron cyclotron oscillator for the study of the interaction of a radiating system with a surrounding microwave cavity by presenting the first observation of inhibited spontaneous emission. This system shows promise for further radiation studies because of several properties. The electron is essentially stationary in the center of the cavity, it occupies a region small compared to a wavelength, and its location can be shifted slightly. The transition frequency of the radiating oscillator can be shifted without disturbing the cavity, by simply shifting the magnetic field. The initial analysis of this system requires only classical arguments. With improved sensitivity, it will be possible to investigate the quantum limit as well. A more detailed study of possible shifts in the cyclotron frequency due to the interaction with the cavity is clearly desirable for precision measurements of the cyclotron frequency. The cylindrical Penning trap is a promising tool for these studies, because the mode structure of a cylindrical cavity is well known.

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