INTENSITY BEATS IN RESONANCE RADIATION ABSORBED BY A COHERENTLY EXCITED METASTABLE STATE FORMED BY ELECTRON IMPACT*

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We have observed intensity beats in the resonance absorption by coherent excitation of nondegenerate magnetic sublevels of the nonradiative $^3P_2$ metastable state of mercury. This state was formed by unidirectional low-energy electron-impact excitation in a weakly ionized plasma. This observation is an extension of the methods for detecting beats in resonance radiation arising from spontaneous decay of coherent, nondegenerate levels produced by electron impact.[1-3] The observed effect is similar to that found by Bell and Bloom[4,5] using an optical-pumping method. However, our method is not limited by the optical-pumping speed and the optical selection rule, since electron impact excites an atom in about 10^{-16} sec with less definite selection rule.

We performed this experiment (1) to find out if the effect is observable, and (2) to offer some means to overcome what we believe is an inherent limitation of the optical-pumping technique, the pumping speed. The present method may prove suitable for investigating a variety of atoms in the ground state with $J>0$ (by transmission of coherence[6] from excited states back to the ground state), and the long-lived ($J>0$) metastable state which may be coherently excited under a variety of environmental conditions for which the optical pumping method would not work. In addition, no rf perturbation is imposed on the system to observe the resonance condition by this method. Previous experiments on the metastable state $^3P_2$ of mercury[7] and neon[8] have demonstrated that the $m_J=0$ and, because of electron exchange, ±1 substates of the metastable state are preferentially populated through electron-impact excitation by a unidirectional low-energy electron beam. If one applies a magnetic field perpendicular to the direction of the electron beam, the states with $m_J=0$ and $m_J=\pm1$ transform into the coherent states

$$\mathfrak{D}(0,\pi/2,0)|^3P_2, m_J=0\rangle = \tfrac{1}{4}\times6^{1/2}|^3P_2, m_J=2\rangle - \tfrac{1}{2}|^3P_2, m_J=0\rangle + \tfrac{1}{4}\times6^{1/2}|^3P_2, m_J=-2\rangle,$$

and

$$\mathfrak{D}(0,\pi/2,0)|^3P_2, m_J=\pm1\rangle = \tfrac{1}{2}|^3P_2, m_J=2\rangle \mp \tfrac{1}{2}|^3P_2, m_J=1\rangle \mp \tfrac{1}{2}|^3P_2, m_J=-1\rangle + \tfrac{1}{2}|^3P_2, m_J=-2\rangle,$$

where $\mathfrak{D}$ is the angular-momentum rotation operator.[9] Thus one can visualize the aligned atom precessing about the magnetic field with Larmor frequency. Since the atom is aligned, not oriented, precession by 180 deg is the same as 360-deg precession about the magnetic field. Now consider an electron-beam pulse much shorter than the Larmor-precession period. This pulse aligns the ensemble of atoms, which then execute a Larmor precession about the magnetic field. Another pulse $\frac{1}{2}$ Larmor period later creates another group of aligned atoms, which precess about the field in phase with the atoms already aligned by the first pulse. Thus from this classical point of view, an aligned population will precess about the field synchronously when it is produced by short electron pulses repeated at half the Larmor period, i.e., at twice the Larmore frequency. In the experiment by Bell and Bloom, the atoms are oriented, not aligned, by a burst of circularly polarized pumping light perpendicular to the magnetic field.[4] Therefore, the oriented atoms return to the original position only after one precession. For this reason, the light is modulated at the Larmor frequency in their experiment.

We observed the precession of aligned atoms by monitoring the absorption of linearly polarized $\lambda=5461$ Å ($6\,^3P_2-7\,^3S_1$) resonance radiation propagating along the externally applied magnetic field. The wave function of the metastable state formed by the $\Delta m_J=0$ transition from the $^1S_0$ ground state to the $^3P_2$ metastable state at $t=t_0$ by a short electron pulse is

$$\Psi=\exp[-\tfrac{1}{2}\gamma(t-t_0)]\{C_2|m_J=2\rangle\exp[i\omega_2(t-t_0)]+C_0|m_J=0\rangle\exp[i\omega_0(t-t_0)]+C_{-2}|m_J=-2\rangle\exp[i\omega_{-2}(t-t_0)]\}$$

for $t > t_0$, where γ is the reciprocal spin coherence time, the C's are constants that depend on the type of excitation, and $\omega_2 = E_2/\hbar$, $\omega_0 = E_0/\hbar$, and $\omega_{-2} = E_{-2}/\hbar$ corresponding to the energy of the $m_J = 2$, 0, and -2 states, respectively. The absorption probability of the linearly polarized resonance radiation is proportional to the square of the modulus of the matrix elements $\langle\Psi(^3S_1)|d_\lambda|\Psi\rangle$, where d_λ is the electric-dipole interaction operator whose vector is parallel to the direction of polarization of the incident resonance radiation. The absorption probability is described by the damped-oscillator-type function[3,10]

$$\exp[-\gamma(t-t_0)]\{A + B\exp[-i\omega_{20}(t-t_0)] + B^*\exp[i\omega_{20}(t-t_0)]\},$$

where $\omega_{20}/2\pi$ is twice the Larmor precession frequency, i.e., due to single-pulse excitation, the absorbed linearly polarized light is modulated at twice the Larmor frequency and damped with a damping constant γ. It is interesting to note that the electron-exchange terms do not contribute to the modulation. Thus pulsing or modulating the electron beam at twice the Larmor frequency causes the damped oscillator to become undamped. If the electron beam is modulated as $(1+\cos\omega t)$, the intensity of the resonance radiation from the absorbed resonance is proportional to

$$\left[\frac{A}{\gamma} + 2|B|\frac{\gamma\cos x + \omega_{20}\sin x}{\gamma^2 + \omega_{20}^2}\right]$$

$$+ |B|\left[\frac{\gamma\cos(\omega t - x) + (\omega - \omega_{20})\sin(\omega t - x)}{\gamma^2 + (\omega - \omega_{20})^2} + \frac{\gamma\cos(\omega t + x) + (\omega + \omega_{20})\sin(\omega t + x)}{\gamma^2 + (\omega + \omega_{20})^2} + \frac{A}{|B|}\,\frac{\gamma\cos\omega t + \omega\sin\omega t}{\gamma^2 + \omega^2}\right].$$

The first term corresponds to the Hanle depolarization in a magnetic field. The second term represents the beat at twice the Larmor frequency. The above equation is derived in a manner similar to that used by Aleksandrov and Kozlov.[10]

A large quantity of $^3P_2$ metastable-state atoms was produced in a gap of a planar diode with an indirectly heated Phillips cathode containing mercury vapor at room temperature. This diode, which was the same type used in our previous experiment,[8] was operated under the space-charge-neutralization condition at about 15 V.[7,8,11] The electron beam was modulated by varying the applied voltage between the cathode and the anode. The typical electron current we used was about 400 mA peak at 3 MHz with about 100% modulation. To eliminate the stray magnetic field produced by the indirect cathode heater, observations were made only during periods when the heater current was switched off (every 1/50 sec). To estimate the magnetic field width associated with the beat experiment, we first observed the coherence lifetime, using the Hanle effect since this signal was very large. For observing an intensity beat, the electron beam was modulated at 2.89 MHz, and the absorbed light

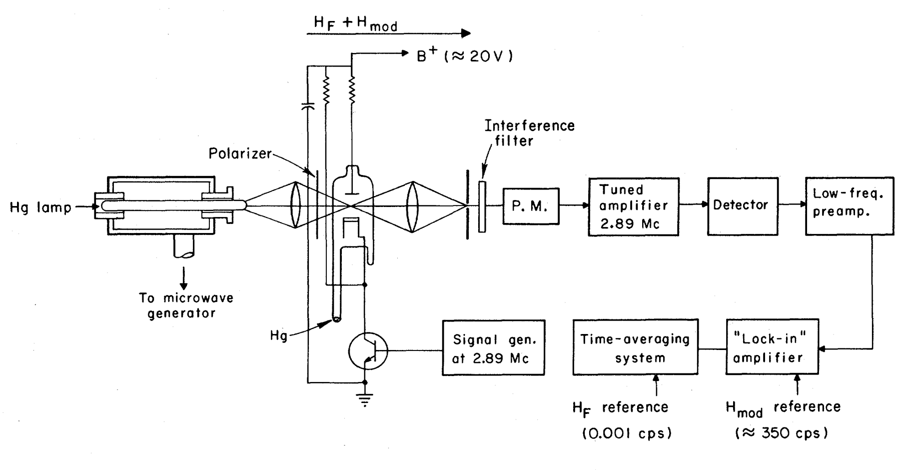

FIG. 1. Schematic of the apparatus. For the Hanle-effect measurement, the signal was fed directly into the low-frequency preamplifier either with or without rf modulation.

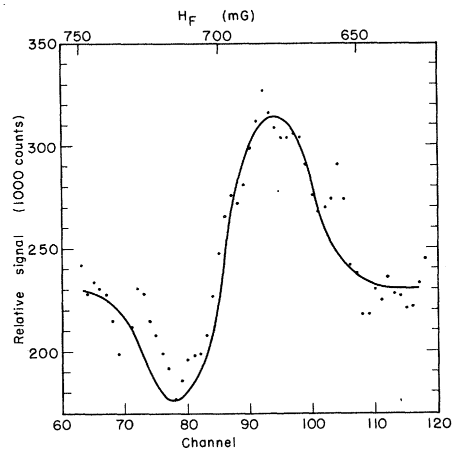

FIG. 2. Resonance-absorption beat signal with electron beam modulated at 2.89 MHz.

was detected by a 2.89-MHz tuned amplifier. This signal was traced as a function of the externally applied magnetic field. In addition to phase-sensitive detection, we used digital integration employing a 400-channel multiscalar, as in our previous work.[8] The schematic of the experiment is shown in Fig. 1. Figure 2 shows the 2.89-MHz component of the optical absorption as a function of the applied magnetic field. The peak absorption corresponds to a magnetic field of $H = 688 \pm 10$ mG, at $\nu_L = 1.445$ MHz. The Hanle effect was quite strong and had a magnetic field width the same as that of the absorption signal. To make certain that the signals were real, we shifted the modulating frequency to 2.72 MHz and observed the proper shift of the beat signal. We also observed an absorption signal at $H = 1376 \pm 15$ mG, corresponding to a Larmor frequency $\nu_L = 2.89$ MHz. This signal had $\frac{2}{3}$ the width and $\frac{1}{2}$ the amplitude of the signal seen at $H = 688 \pm 10$ mG. We have not yet fully explained this effect.

We have observed a considerable broadening of the magnetic field width as the plasma ionization increases, indicating a decrease in the coherence time due probably to perturbations arising from the plasma fields. We are currently investigating this effect in detail to study the mechanisms of the perturbation.

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