Possibility of measuring the weak interaction in the HFS transitions of atoms

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An experiment to study the weak interaction in the transitions between the HFS components of atoms, which is based on the coherent oscillations of the population in a two-level system in a strong resonance field, is proposed.

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In this paper we propose an experiment to measure the effects of a weak interaction (WI) of atomic electrons with the nucleus in the transitions between the components of the hyperfine structure (HFS) of the atoms. An interest in this problem was generated by a paper[1] in which it was indicated that such experiment will make it possible to measure the heretofore unknown WI constant that depends on the nucleon spin. A direct measurement of the effect from the rotation of the polarization plane of the radio wave in the vapor of the material[1] is complicated by the small angle of rotation of the polarization plane due to both the small WI constant and the small population difference of the investigated HFS levels. We propose an experiment based on coherent oscillations of the population in a two-level system in a field of a strong resonance traveling wave.[2,3]

The experiment is shown schematically in Fig. 1. A thermostatically controlled cell 2 with Rb^{87} pairs at a temperature of 50° C is inserted into a ring-shaped microwave cavity 1. Using a pump tube 3 and a filtering cell 4, we optically pump through window 5 the upper level of the two-level system $5s_{1/2}\,F = 1, 2$ of the ground state of a Rb^{87} atom, as it was done in a rubidium frequency standard.[4] This will enable us to increase the population difference $\Delta N = N_2 - N_1$ by two orders of magnitude as compared with the equilibrium population. Using a microwave generator 6, we then excited in the ring cavity a traveling wave linearly polarized along the x axis, with the transition frequency $F = 1 \longleftrightarrow F = 2\nu_0 = 6835$ MHz (we call it the reference wave). If the wave power is such that the G probability of the induced transition is much greater than the impact width of the Γ line, then the coherent oscillations of the population, which are exponentially dampened during the time $1/\Gamma$, will occur in the two-level system at the moment the field is turned on. The linearly polarized wave is comprised of the sum of clockwise and counterclockwise-polarized waves of equal amplitude. If the gas of the atoms was unpolarized before the field was turned on, then half of the atoms will interact only with the clockwise-polarized component and the other half with the counterclockwise-polarized component of the reference wave. The oscillation frequency of the population is proportional to the matrix element of the interaction. But the WI of the electrons with the nucleus gives rise to the fact that the matrix elements of interaction of the atom with the external clockwise and counterclockwise-polarized photons differ by the amount proportional to the WI constant h^1 $M_\pm = M_0[1 \pm (P/2)]$.

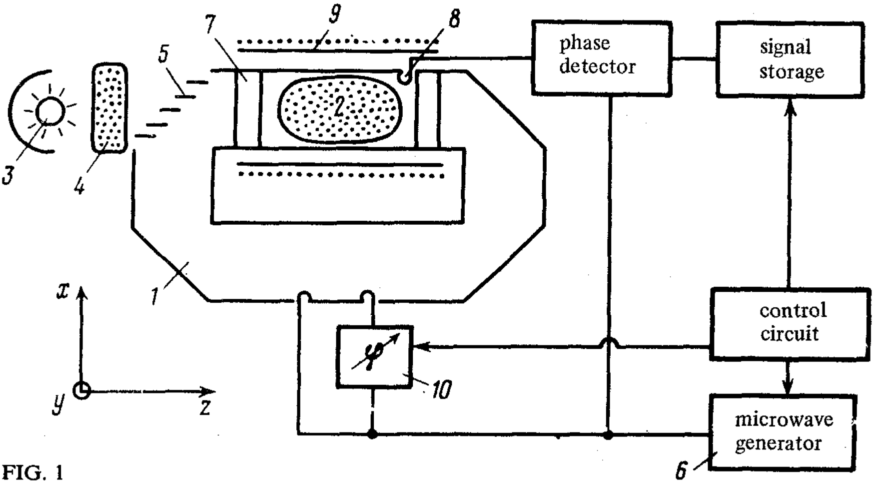

FIG. 1

(According to the results of Ref. 1, we assume that $P \approx -2\times 10^{-10}\, h$ for rubidium.) Therefore, the oscillations of the populations of one half of the atoms have the frequency Ω_+ and those of the other half have the frequency Ω_-, where $\Omega_\pm = (G_\pm^2 + \Delta^2)^{1/2}$,[3] $\Delta = \nu - \nu_0$ is the resonance detuning, $G_\pm = G_0[1 \pm (P/2)]$, $G_0 = (15/2)^{1/2}(\mu_0 H_0/h)$, and H_0 is the amplitude of the reference wave. The reference wave is partially re-emitted by the medium in the form of coherent pulses with the frequencies $(\nu_0 \pm G_0)$. If $G_+ = G_-$, then the waves that were re-emitted by the medium would produce a linearly polarized wave along the x axis, but since $G_+ = G_-$ due to the WI, the clockwise and counterclockwise-polarized waves that were re-emitted by the medium are out of phase and collectively produce a circularly polarized wave. An evaluation of the solution of the Maxwell equations for the field in a medium with an oscillating magnetic dipole moment gives a total field in the cavity: $(0 < t < 1/\Gamma)$.

$$\mathbf{H} = \mathbf{X} H_0 \cos(\omega t - kz) + \mathbf{X}\, 2\pi\left(\frac{\hbar\omega_0 \Delta N}{H_0^2}\right) H_0 \cos 2\pi G_0 t \cos(\omega t - kz) \exp(-\Gamma t)$$

$$\mathbf{Y}\, 2\pi^2\left(\frac{\hbar\omega_0 \Delta N}{H_0^2}\right) H_0 P G_0 t \sin 2\pi G_0 t \sin(\omega t - kz) \exp(-\Gamma t).$$

X and **Y** are the normal cavity modes polarized along the x and y axes.

The first term represents the field of the reference wave and the second and third terms denote the field of the wave that was re-emitted by the medium. The useful signal is the third term, which is proportional to the WI constant, whereas the first and the second term must be suppressed by taking advantage of the fact that the useful signal differs from the second term in polarization and phase, and from the reference wave in polarization, phase, and frequency. We shall denote by W_1, W_2, and W_3 the intensities of the waves corresponding to these three terms. The useful signal W_3 is isolated according to polarization in the transfer cavity 7, whose end walls are made of quarter-wave plates parallel to the y axis, through which the reference wave passes without reflection, and reflecting plates for emission with y polarization. The oscillation frequency of the populations must be the same for all the gas atoms in order to achieve coherence of the macroscopic oscillations of the populations. The size of the ring cavity with respect to x, for which the amplitude of the reference wave and hence the oscillation frequency of the population are constant in the transfer cavity $a_0 = \lambda_0/(2)^{1/2}$, can be determined easily for the H_{10}-type reference wave; if Δa represents the manufacturing flaw of the cavity, then the inhomogeneous broadening of the transition line attributable to it is $\Delta G \approx G_0(\Delta a/a_0) \equiv \Gamma$. Further, it is clear that the size of the cavity with respect to x must be $b = a_0$ in order to preserve coherence between the x and y polarized modes. The reference signal is turned on by the square pulses $1/\Gamma$ in duration. During the interval between the pulses, the pump tube restores the population difference ΔN of the levels. In the transfer cavity the W_3 signal containing the information on WI, along with the W_1 and W_2 signals whose polarization has weakened, which partially penetrate into it due to stray coupling between the x and y modes, is amplified Q_n fold due to the Q-factor of the transfer cavity. The three combined signals are then transmitted via the adjustable coupling loop 8 to the multiplier where they are multiplied with the reference signal from the generator, whose phase is shifted by $\pi/2$ relative to the reference signal in the cavity. It can easily be seen that the background of the W_1 and W_2 signals can be reduced three to four orders of magnitude by using such phase detection. The remaining reference signal W_3 is then frequency suppressed by a selective receiver. We give approximate figures for this experiment: if the power of the microwave generator is 2 W, then $G_0 \approx 10^6$ Hz; thus, for $\Delta a \approx 3\times 10^{-3}$ cm, $\Gamma \approx 10^3$ Hz (which is an order of magnitude larger than the impact width of the line[4]). The values and the Q-factors of the ring-shaped and of the transfer cavities, respectively, are

$$V_\kappa \approx 5\times 10^2\ \text{cm}^3,\ Q_\kappa \approx 10^3,\ V_n \approx 10^2\ \text{cm}^3,\ Q_n \approx 10^3,\ \Delta N \approx 2\times 10^{10}\ \text{cm}^{3},$$

$$W_1 \approx \frac{H_0^2 V_\kappa \nu_0}{4\pi} \approx 2\times 10^3\ \text{W},\quad W_2 \approx \pi^2\left(\frac{\hbar\omega_0\,\Delta N}{H_0^2}\right)^2\left(\frac{V_n}{V_\kappa}\right)W_1 \approx 5.8\times 10^{-7}\ \text{W},$$

$$W_3 \approx \pi^4\left(\frac{\hbar\omega_0\,\Delta N}{H_0^2}\right)^2\left(\frac{PG_0}{\Gamma}\right)^2\left(\frac{V_n}{V_\kappa}\right)W_1 \approx 2.2\times 10^{-19}\,h^2\ \text{W}.$$

If the receiver's band is 10^4 Hz, the power of the reference signal from the generator must be stabilized with an accuracy of 10^{-2}. We can see that $W_3 Q_n \approx 2\times 10^{-16}\,h^2$ W must be recorded against a 2×10^3 W background of the reference signal; however, a frequency, polarization, and phase decoupling allows us, in principle, to suppress the background of the W_1 and W_2 signals. The ring cavity is placed inside a magnetic shield which reduces the external magnetic field to $H_{\text{res}} \sim 10^{-4}$ G. The cell with the gas is inserted into the coil 9; by passing a current through it, we can produce a weak longitudinal magnetic field inside the shield. The action of the magnetic field H on the gas atoms is equivalent to the WI, where the parameter P should be replaced by the parameter $P_H \approx (\mu_0 H/3\hbar\omega_0)$.[1] If the direction of propagation of the reference wave is periodically reversed by using a phase inverter

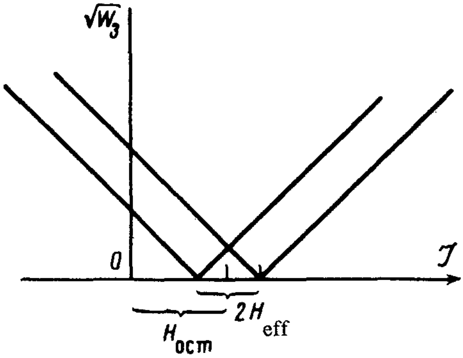

FIG. 2.

10, then the amplitude of the W_3 signal, which is proportional to the WI constant, will be constant and the amplitude of the W_3 signal, which is proportional to the magnetic field H, will change its sign. By storing the signals separately for the two different directions of propagation of the reference wave, we obtain two curves for the dependence of the amplitude of the W_3 signal on the current in the coil (Fig. 2).

Thus, by passing the current through the coil, we can measure the sign of the WI constant and calibrate the WI according to the magnetic field, if WI is represented as the action of the effective magnetic field $H_{\text{eff}} \approx (3\hbar\omega_0/2\mu_0)P$. We note that the circular polarization of light of the pump tube, which can be produced by the magnetic field and by the strain in the glass of the cell and the tube, must be eliminated. Additional control of the accuracy of the experiment–coincidence of the shape of the W_3 signal with the expected shape, the results of studies on polarization suppression of signals,[5] and also the sensitivity of modern receivers and techniques of separating signals from the noise by storage–are at a sufficiently high level for conducting the experiment. If the sensitivity obtained in Ref. 6 can be reached and the background is suppressed to a sufficient level with use of the stored signal, then we will be able to observe a nonvanishing WI constant equal to 10^{-2}.

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