Induction of collective phase coherence in a quantum system without a resonant phasing field

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The induction of a collective phase coherence is analyzed in terms of a phasing of dipole moments in a momentum phase subspace. The coherence is assumed to be induced by a δ-function video pulse of a magnetic field $\vec{H}_{xy,\delta}$ (or of an electric field $\vec{E}_{xy,\delta}$). The length of this pulse, τ_δ, is substantially shorter than the period (T_0) of the quantum transition: $\tau_\delta \ll T_0$. Experimental results are reported. They demonstrate microscopic structure in the onset of a coherence signal $S_{y,\delta}$ at the frequency $\langle f_0 \rangle$ of a Zeeman transition in the spin system of ^{133}Cs atoms. It is suggested that quantum transitions could be induced at 10^{10} Hz, in the microwave range, by this method. This approach opens up the possibility of developing, in particular, highly stable atomic frequency standards in which a continuous free-oscillation signal would be induced without a Ramsey resonator and without a system for synthesizing the frequency of the resonant microwave field.

We consider a quantum system with a population inversion involving the levels $|1\rangle$ and $|2\rangle$. We know that collective coherent transitions between these levels can always be induced by an agent associated with energy conservation, $\Delta E_{2,1} = \hbar\omega_0$, either directly, by means of a resonant field, or indirectly, by means of (for example) a variation of a suitable parameter of the system at a frequency ω near the resonance. A phasing field can be introduced in the system either adiabatically or nonadiabatically, by means of short pulses with a modulated frequency ω_0 in the rf, microwave, or optical range. The transitions induced by a resonant interaction $\mathscr{H}_{2,1}$ occur with a probability $W_{2,1} \sim 2\pi\hbar^1 |\mathscr{H}_{2,1}|^2 \delta(E_2 - E_1 - \hbar\omega)$.

In Ref. 1, I departed from tradition and took up another limiting case (for the first time): the possibility of inducing collective transitions without employing a resonant phasing field to act on a transition. I proposed a specific realization of this idea. The proposal was to apply a δ-function video pulse of a field $\vec{H}$ or $\vec{E}$ to a quantum system. The pulse would have a length τ_δ much shorter than the period (T_0) of the quantum transition: $\tau_\delta \ll T_0$. The effect was called "shock excitation of a collective phase coherence." Suggestions regarding the use of this effect to construct an absolute quantum magnetometer[2] and to measure the components of an ultraweak magnetic field[3] were subsequently studied. Nevertheless, some key factors pertinent to the mechanism for the shock excitation of a collective phase coherence were not revealed.

This letter is an analysis of studies of various spin systems. The results of this analysis are used to discuss a simple and graphic model for the mechanism for this effect. This model explains the results which have already been achieved, and it also suggests several elegant experiments. For example, one might carry out an experiment to separate one group of spin packets from another such group when the two lie within the same envelope. We formulate the basic ideas of the phenomenon. In confirmation of these arguments, we describe an experiment which demonstrates a microscopic structure in the onset of a coherent signal $S_{y,\delta}(t)$ for a given type of excitation. We propose various quantum systems in which a collective phase coherence might be realized by means of a δ-function video pulse of a field $\vec{H}$ or $\vec{E}$.

We consider the mechanism for the excitation of a collective phase coherence by a δ-function video pulse of a magnetic field $\vec{H}_{x,\delta}$ in the example of a two-level Zeeman spin system consisting of an ensemble of k spins of the $|1\rangle$ state and l spins of the $|2\rangle$ state, with a larger population. The spin system is in a constant magnetic field $\vec{H}_0(z)$. It has a resultant magnetic moment $\vec{M}_{2,1}(z) = \Sigma_l \vec{\mu}_2^{(l)}(z) - \Sigma_k \vec{\mu}_1^{(k)}(z) \equiv \vec{M}_z$ along the z axis. The projections of the moments of the individual spins, $\vec{\mu}_1^{(k)}(x,y,t) = \vec{\mu}_\perp^{(k)}$ and $\vec{\mu}_2^{(l)}(x,y,t) = \vec{\mu}_\perp^{(l)}$, which oscillate in the XY plane, have phases $\phi_1^{(k)} = E_1 t/\hbar - \varphi_1^{(k)}$ and $\phi_2^{(l)} = E_2 t/\hbar - \varphi_2^{(l)}$. The initial phases of the spins, $\varphi_1^{(k)}$ and $\varphi_2^{(l)}$ are distributed isotropically in the XY plane, so there is no oscillatory transverse moment $\vec{M}_{2,1}(x,y,t)$. A video pulse $\vec{H}_{x,\delta}$ of length τ_δ is applied to the system along the X axis at the time t'. This pulse can be described by

$$\vec{H}_{x,\delta} = H_{1,\delta}\vec{e}_x\delta(t-t'), \tag{1}$$

where $H_{1,\delta}$ is the amplitude of the δ-function pulse, and $\vec{e}_x$ is a unit vector.

The experiment shows that the application of a video pulse $\vec{H}_{x,\delta}$ to a spin system along the X axis creates a macroscopic moment $\vec{M}_x(t'+\tau_\delta) = \vec{M}_{x,\delta}$, which then, at $t > t' + \tau_\delta$, oscillates at the resonant frequency $\langle\omega_0\rangle = \gamma H_0$. One might attempt to explain the appearance of the transverse moment $\vec{M}_{x,\delta}$ in the traditional way, in terms of a rotation of the vector $\vec{M}_z$ in the XY plane in the resultant field $\vec{H}_\Sigma = \vec{H}_x + \vec{H}_0(z)$. This approach was taken in Ref. 4, where a study was made of the case of a nonadiabatic application of a strong pulse ($|\vec{H}_x| \gg H_0$) and long pulse ($\tau \ll \tau_2$, where τ_2 is the relaxation time) with the shape of a unit step function $\theta(\tau)$. During the application of this pulse, the energy of the system changes. In our experiments, however, the transverse moment $\vec{M}_{x,\delta}$ is induced under the opposite conditions: ($|\vec{H}_{x,\delta}| < H_0(z)$ and $\tau_\delta \ll T_0$. The rate at which $\vec{M}_{x,\delta}$ arises exhibits an essentially instantaneous reaction of the transverse projections $\vec{\mu}_\perp^{(k)}$ and $\vec{\mu}_\perp^{(l)}$ to a change in the magnetic field in the XY plane. Because of all these factors, one can think of the induction of the collective phasing of the spins as the result of a direct (orienting) application of a δ-function pulse of a magnetic field $\vec{H}_{x,\delta}$ to the transverse magnetic projections $\vec{\mu}_\perp^{(k)}$ and $\vec{\mu}_\perp^{(l)}$. The interaction energy is correspondingly

$$\mathcal{H}_{1,\delta}^{(k)} = -(\vec{\mu}_\perp^{(k)}\vec{H}_{x,\delta}), \quad \mathcal{H}_{2,\delta}^{(l)} = -(\vec{\mu}_\perp^{(l)}\vec{H}_{x,\delta}). \tag{2}$$

Over the ultrashort time τ_δ, the video pulse $\vec{H}_{x,\delta}$ ties the projections $\vec{\mu}_\perp^{(k)}$ and $\vec{\mu}_\perp^{(l)}$ to itself according to (2), simultaneously in the two sublevels and in the direction along the X axis. It thereby synchronizes the instantaneous phases $\phi_1^{(k)}$ and $\phi_2^{(l)}$ of the spins. Later, after a time τ_δ, macroscopic parallel projections $\vec{M}_1(x,t'+\tau_\delta)$ and $\vec{M}_2(x,t'+\tau_\delta)$ [and corresponding pulses $\vec{P}_1(x,t'+\tau_\delta)$ and $\vec{P}_2(x,t'+\tau_\delta)$] are formed along the X axis. They have identical macroscopic initial phases: $\varphi_1(x,t'+\tau_\delta)=\varphi_2(x,t'+\tau_\delta)$. It follows that a coherent superposition of Zeeman sublevels $|1\rangle$ and $|2\rangle$ arises when there is a zero difference between the initial phases: $\Delta\varphi_{2,1}(x,t'+\tau_\delta)=0$.

After the application of $\vec{H}_{x,\delta}$, at $t>t'+\tau_\delta$, an interference between the components $\vec{M}_1(x,t)$ and $\vec{M}_2(x,t)$ starts with an instantaneous phase $\Phi_{2,1}=(E_2-E_1)t/\hbar=\langle\omega_0\rangle t$. An observable coherence component $\vec{M}_{2,1}(x,t)\equiv\vec{M}_{x,\delta}(t)$ is formed. It has a shape similar to that of a Green's function in the momentum-energy representation:

$$\vec{M}_{x,\delta}(t)=\vec{M}_{x,\delta}\vec{e}_x\cos<\omega_0>t\exp(-\Gamma t), \tag{3}$$

where Γ is the width of a Zeeman sublevel.

On the other hand, an examination of the phase $(\Phi_{2,1})$ of the interference state and of the probability $(W_{2,1})$ for transitions resulting from the application of $\vec{H}_{x,\delta}$ to the momentum subspace reveals certain characteristic properties of this type of collective phasing of dipole moments. Here is the complete expression for $\Phi_{2,1}$ in terms of the phase of the wave function:

$$\Phi_{2,1}=\hbar^{-1}[(E_2-E_1)t-(\vec{P}_2-\vec{P}_1)\vec{X}]. \tag{4}$$

Transforming $W_{2,1}$, making use of the properties of the δ-function, and using (4), we find

$$\vec{P}_2=\vec{P}_1,\quad \vec{M}_2(x,t'+\tau_\delta)=\vec{M}_1(x,t'+\tau_\delta),\quad \varphi_2=\varphi_1\,. \tag{5}$$

We also find an expression for the probability $(W_{2,1})$ that transitions will be induced by a δ-function video pulse:

$$W_{2,1}\sim 4\pi m\hbar^{-1}|\mathcal{H}_{2,1}|^2\delta(P_2^2-P_1^2)\delta(\varphi_2-\varphi_1). \tag{6}$$

It follows from (5) and (6) that the transverse moments which are produced take part in an interference with equal values $|\vec{M}_2|=|\vec{M}_1|$ and with initial phases $\varphi_2=\varphi_1$.

The phase $(\Phi_{2,1})$ of the macroscopic interference of sublevels $|1\rangle$ and $|2\rangle$ reflects the common coherent phase space of (4), which consists of two continuously linked subspaces: an energy subspace $\hbar^{-1}(E_2=E_1)t$ with a discrete spectrum and a momentum subspace $\hbar^{-1}(\vec{P}_2-\vec{P}_1)\vec{X}$ with a continuous spectrum. Accordingly, a coherence can be induced in the quantum system by acting on the phase state of one of the subspaces or on the phase of the two subspaces simultaneously. Let us generalize these arguments.

1. A collective coherence can be introduced in a quantum system in an essentially instantaneous manner over a time $\tau_\delta\ll T_0$, by acting on the momentum phase subspace, or over a time $\tau\gg T_0$, by applying a harmonic phasing field to the energy subspace.

2. The best way to organize coherence in the momentum phase subspace is to use a δ-function video pulse of a field $\vec{H}_{xy,\delta}$, which not only normalizes the amplitudes but also normalizes the initial phases of the wave functions [see (6)]. It follows that the δ-

function has a definite physical meaning: It is the sole coherence operator in the momentum phase subspace.

3. From the standpoint of the energy subspace, the δ-function $\vec{H}_{xy,\delta}$ video pulse serves as a macroscopic space-time correlator of the instantaneous phases of the wave functions, $\phi_1^{(k)}$ and $\phi_2^{(l)}$, creating at all times a zero difference $\Delta\varphi_{1,2}$ between the initial phases of the interfering sublevels $|1\rangle$ and $|2\rangle$. This difference is strictly fixed in terms of the coordinates $(x,y,t'+\tau_\delta)$:

$$\Delta\varphi_{1,2}(x,y,t'+\tau_\delta)=0. \tag{7}$$

Equation (7) also holds for a system with n sublevels: $\Delta\varphi_{1,2...n}=0$.

4. The excitation of coherence by the $\vec{H}_{x,\delta}$ video pulse brings the entire spin absorption line into the interference. A free-oscillation signal $S_{xy,\delta}(t)$ at a central frequency $\langle\omega_0\rangle$ is generated with an amplitude larger (by a factor of 1.5–2) than that in the traditional case, of excitation by a harmonic field $\vec{H}_1(x,t)$. The latter "cuts out" only some of the spins from the absorption line near the central frequency $\sim\omega_0$.

5. The excitation of a collective phase coherence by a δ-function video pulse of a field $\vec{H}_{xy,\delta}$, which acts on each spin of the system simultaneously, occurs within the framework of conservation of the total momentum for both the entire system of spins and each spin individually.

6. Conclusions 1–5 also hold in the case in which a phase coherence is excited in the course of electric dipole transitions induced by a δ-function video pulse of a field $\vec{E}_{xy,\delta}$.

The experiments (Fig. 1) were carried out on the spin system of ^{133}Cs atoms in the $6^2S_{1/2}$ ground state. The atoms were oriented by resonant light in two lines (D_1 and D_2), with the σ^+ polarization, in the laboratory magnetic field $H_0\simeq 0.46$ Oe. During the recording of the magnetic-resonance line ($f_0\sim 160$ kHz), the linewidth was determined by the intensity of the pump light. It was $2\Gamma\sim 70$ Hz ($\gamma/2\pi=350$

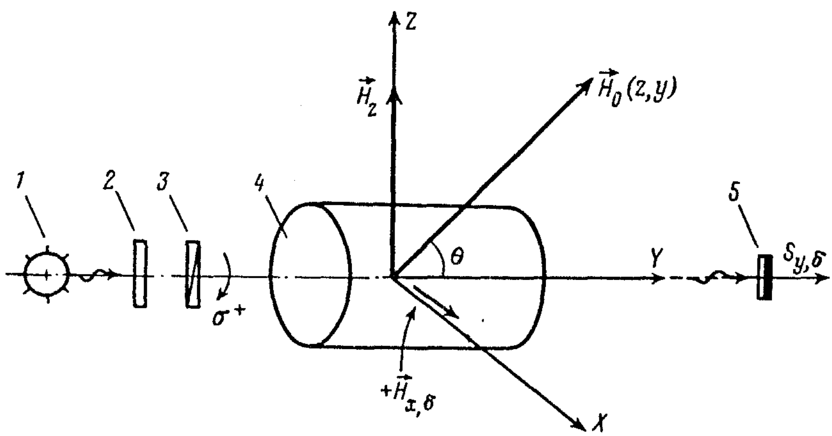

FIG. 1. Experimental layout for observing the shock excitation of phase coherence in an optically orientable spin system. 1—Cesium spectral lamp; 2—IR filter; 3—circular polarizer, σ^+; 4—absorption cell filled with atomic gaseous ^{133}Cs; 5—FD-7k photodiode ($\theta\sim 45°$).

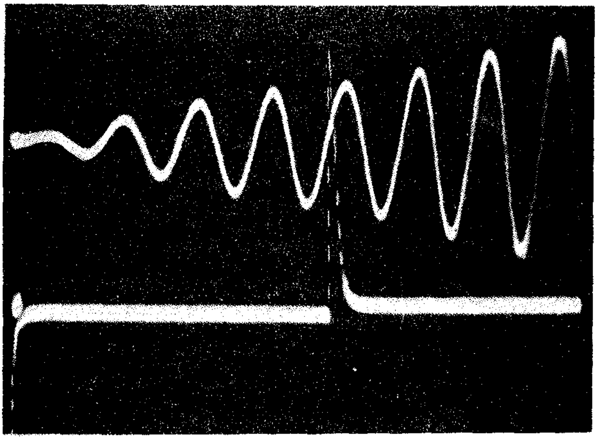

FIG. 2. Oscilloscope trace of the onset of $S_{y,\delta}$, the signal representing the Zeeman coherence (a), as the result of the application of the first and second video pulses $\vec{H}_{x,\delta}$ (b).

kHz/Oe). Under these conditions we know that it is a good approximation to assume that the magnetic-resonance signal in ^{133}Cs is equivalent to the signal from a two-level spin system.

The optical spin pumping and the detection by the photodiode of the coherence signal $S_{y,\delta}(t)$ were carried out along the Y axis, in the familiar one-arm arrangement. The photodiode was connected to the input of an amplifier, whose output was connected to one channel of a dual-trace oscilloscope. The δ-function shock video pulse of the field $\vec{H}_{x,\delta}$ was sent to the other channel of the oscilloscope. This pulse acted along the X axis. The amplitude of this pulse was $H_{1,\delta} = 100 \cdot 2\Gamma$. It acted for a time $\tau_\delta \sim 0.25$ μs. It induced a coherence signal $S_{y,\delta}(t)$ with a period $T_0 \sim 6.25$ μs.

The oscilloscope trace in Fig. 2 illustrates the onset of the coherence signal $S^{(1)}_{y,\delta}(t)$ at the frequency $\langle f_0 \rangle$ as the result of the application of the first video pulse, $+\vec{H}^{(1)}_{x,\delta}$. The first (negative) half-period of the signal $S^{(1)}_{y,\delta}(t)$ is not seen clearly, because of the inadequate bandwidth of the amplifier ($\sim$40 kHz), which also determines the rise time of the signal $S^{(1)}_{y,\delta}(t)$. The second and similar video pulse was of the opposite polarity, $-\vec{H}^{(2)}_{x,\delta}$. This pulse was applied after an odd number of half-periods—after $9 \cdot T_0/2$ in Fig. 2—so that it would act on the spin system in phase with the signal that arose. The second δ-function video pulse in Fig. 3, $-\vec{H}^{(2)}_{x,\delta}$, was applied after $(70 + 1/2)$ periods T_0. It brought another portion of the spins into the coherent process and caused an additive increase in the first signal, $S^{(1)}_{y,\delta}(t)$, to a value $S^{(2)}_{y,\delta}(t)$. We then observed a slight decrease in the free-oscillation signal $S^{(2)}_{y,\delta}(t)$, described by

$$S^{(2)}_{y,\delta}(t) = S^{(2)}_{max}(\vec{H}^{(1)}_{x,\delta}; \vec{H}^{(2)}_{x,\delta}) \sin(< \omega_0 > t) \exp(-t/\tau_2). \tag{8}$$

In this case the relaxation time was $\tau_2 \sim 3$ ms.

This effect is universal. It would be interesting to use this method to study quantum systems of various types with high transition frequencies, including frequencies in the microwave range. Closest to realization are experiments on the δ-function excitation of phase coherence

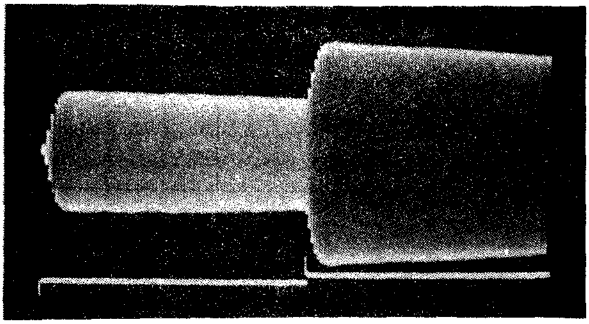

FIG. 3. Oscilloscope trace of the free oscillations which are established, in the time interval $t \gg T_0 (\tau_\delta \sim 0.25\ \mu s,\ T_0 \sim 6.25\ \mu s)$.

a) between hyperfine states in the atoms ^{41}K, ^{39}K, ^{1}H, ^{23}Na, ^{85}Rb, ^{87}Rb, and ^{133}Cs through the application of a $\vec{H}_{xy,\delta}$ video pulse;

b) between Rydberg states of atoms, through the application of an $\vec{E}_{xy,\delta}$ video pulse;

c) between the $2^2S_{1/2}$ metastable state of the hydrogen atom and the $2^2P_{1/2}$ state (a Lamb transition, $\nu \sim 1057$ MHz), through the application of an $\vec{E}_{xy,\delta}$ video pulse;

d) between nuclear-quadrupole-resonance levels, through the application of an $\vec{E}_{xy,\delta}$ video pulse; and

e) between energy levels in superconductors with a Josephson junction, through the application of a video pulse of a current, I_δ, or of a field, $\vec{H}_{xy,\delta}$.

These experiments are feasible today, since it is technically possible to produce δ-function video pulses of a current, I_δ, or a voltage, U_δ in the picosecond range.[6]

In terms of applications, the shock excitation of collective phase coherence raises the possiblity of developing "δ-function" quantum generators of the type in Ref. 2, in which there would be a regime with a continuous free-oscillation signal of exceedingly high stability. Along this direction, it has been proposed that highly stable atomic frequency standards be developed in which a free-oscillation signal would be induced without a Ramsey resonator and without a system for synthesizing the frequency of the resonant microwave field.

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