Instantaneous and in-phase simultaneous excitation of coherent signals from several quantum systems

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Using impact excitation of collective phase coherence[1] we demonstrate experimentally the instantaneous and in-phase simultaneous excitation of coherent signals $S_{y,\delta}^{(i)}$ of Zeeman transitions, from three spin systems—^{87}Rb, ^{85}Rb, and ^{133}Cs atoms which are in the same volume and which also were subjected to a spin pump. As a result a synchronous relaxation regime of the spin systems is obtained. Specific examples are proposed in which this method can be used to study the dynamics of spin systems of the same or different physical nature between which a strong spin exchange takes place. The possibility opens up for a technological application, especially for the production of an instantaneously synchronized group of atomic standard frequencies (and also of a group of quantum magnetometers, ring OQG's, and other quantum devices) in which the initial phase difference $\Delta\varphi_{p,q}$ between the signals of two arbitrary standard frequencies may be strictly specified, i.e., $\Delta\varphi_{p,q} = \text{const}$.

In Ref. 1 I considered a physical mechanism for inducing collective phase coherence in a quantum system with an inverted population when a δ-shaped video-pulse of a magnetic $\mathbf{H}_{x,y,\delta}$ or an electric $\mathbf{E}_{x,y,\delta}$ field acted on it and I gave the basic properties of this effect. One of those is that this way of inducing coherence is realized, firstly, in terms of a momentum phase subspace and, secondly, in the framework of the conservation of the total momentum of the system in a (magnetic or electric) dipole transition. Notwithstanding its unusualness the proposed method is as natural as the traditionally used excitation of phase coherence, achieved through an energy phase subspace by a resonant field at the frequency ω_0 and in accordance with the energy conservation law $\Delta\mathscr{E}_{2,1} = \hbar\omega_0$. However, the tendency to approach the excitation of collective phase coherence on the basis solely of a frequency representation of the δ-video-pulse leads to a simplified picture and gives only a formal interpretation of the physical essence of the effect. I also reported the experimental observation of this effect in connection with optical spin pumping of alkali atoms.[2,3]

In the present paper I demonstrate experimentally one of the basic properties of this way of inducing coherence—the instantaneous and in-phase simultaneous excitation of several different quantum systems which have differing resonant frequencies, so that it is impossible to achieve this by conventional methods. In particular, I excited Zeeman transitions simultaneously in a mixture of three operating gases with resonant frequencies $\langle\omega_{0i}\rangle$. The experiment was carried out on spin systems of cesium atoms and two isotopes of rubidium in a single absorption cell and oriented optically in the ambient terrestrial magnetic field, $H_0 \sim 0.46$ Oe. Under those conditions the spin systems can be considered to be two-level systems. After a δ-video-pulse[1] of the form

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

where $H_{1,\delta}$ is the amplitude of the δ-pulse and $\mathbf{e}_x$ is a unit vector, has acted on them an oscillation regime develops which we call the synchronous relaxation of the spin systems.

We note those properties of the impact excitation of phase coherence which characterize the momentum phase subspace and which lie at the basis of the arrangement and the performance of the experiment.

1. A characteristic feature of the momentum phase subspace is the fact that it is the channel through which the coherence is efficiently introduced into the quantum system after an extremely short time $\tau_\delta \ll T_0$, where T_0 is the oscillation period of the quantum transition. In that sense the momentum phase subspace is practically inertialess. (In contrast to it the energy phase subspace is inertial since the phase coherence through that channel is established after a time $\tau \gg T_0$.)

2. After the time τ_δ during which the ultrashort magnetic $\mathbf{H}_{x,\delta}$ δ-video-pulse acts, synchronization of the running phases $\phi_1^{(k)}$ and $\phi_2^{(l)}$ of the wavefunctions of the separate spins is produced.[1] As a result the difference of the initial phases $\Delta\varphi_{2,1}$ for any pair of interfering sublevels $|1\rangle$ and $|2\rangle$ is always zero,

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

where t' is the time when the $\mathbf{H}_{x,\delta}$ video-pulse is switched on.

3. After the $\mathbf{H}_{x,\delta}$ video-pulse has acted the interference signal from the atoms, i.e., the transverse oscillating magnetization component $\mathbf{M}_{x,\delta}(t)$ which appears, begins for $t > t' + \tau_\delta$ relative to this video-pulse with a running phase

$$\Phi_{2,1} = (\mathscr{E}_2 - \mathscr{E}_1)t/\hbar = \langle\omega_0\rangle t. \tag{2}$$

It follows from the properties listed here that when a $\mathbf{H}_{x,\delta}$ δ-video-pulse acts simultaneously on several inverted two-level spin systems, coherence signals $S_{x,y,\delta}^{(i)}$ appear simultaneously at the eigenfrequencies $\langle f_i\rangle$ of each spin system with a zero difference of the initial phases between them, provided they are in the same region of space.

EXPERIMENT

We show in Fig. 1 the set-up of the experiment on the optical spin pumping and simultaneous detection of the coherence signals $S_{y,\delta}^{(i)}$ from three working gases ^{85}Rb, ^{87}Rb, and ^{133}Cs in the same volume and in their ground states: $5^2S_{1/2}$ for the rubidium isotopes and $6^2S_{1/2}$ for cesium.

A spherical spectral tube and a spherical absorption cell

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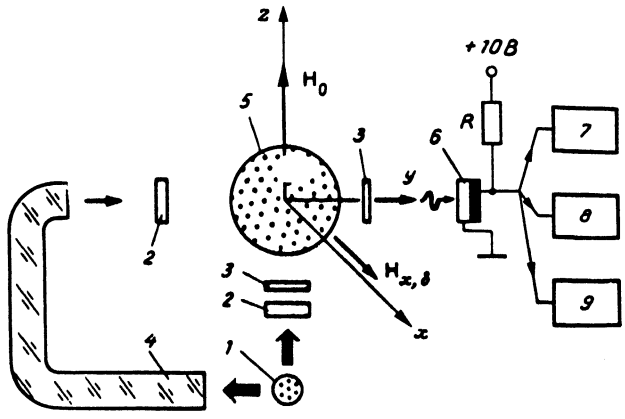

FIG. 1. Block diagram of an experiment for simultaneous optical spin pumping of three working gases and the registration of coherence signals $S^{(i)}_{y,\delta}$. 1—Gas discharge spectral tube emitting spectral (D_1 and D_2) lines of atoms of natural rubidium and cesium; 2—linear π-polarizers (polaroids); 3—circular $\lambda/4$ polarizers; 4—light conductor, bunched fiber-optical conductor; 5—absorption cell containing atoms of the ^{87}Rb, ^{85}Rb, and ^{133}Cs gases; 6—FD-7k type photodiode; R is the resistance establishing a grid bias to the photodiode; 7,8,9—narrow-band amplifiers tuned, respectively, at the Zeeman transition frequencies $\langle f_{01}\rangle$, $\langle f_{02}\rangle$, and $\langle f_{03}\rangle$ of the atoms.

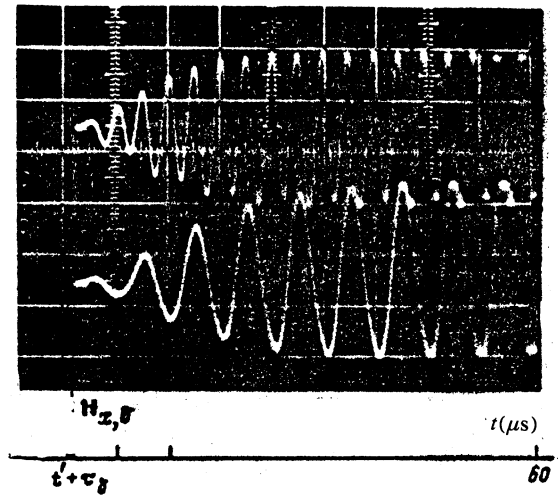

FIG. 2. Oscillograms of the initial section of the coherence signals instantaneously excited and brought in-phase by the magnetic $H_{x,\delta}$ video-pulse: the upper one is the $S^{(1)}_{y,\delta}$ signal of the ^{87}Rb atoms and the lower one is the $S^{(3)}_{y,\delta}$ signal of the ^{133}Rb atoms.

of 50 mm diameter with an anti-relaxation deuterated paraffin coating of the walls contained atomic gases of cesium and natural rubidium (72% ^{85}Rb and 28% ^{87}Rb). The atoms were oriented parallel to the $\mathbf{H}_0$ field in the cell and the $\mathbf{M}_z$ moments were produced from each working gas by resonant light of two (D_1 and D_2) lines with circular polarizations σ^+ and σ^-. In the pumping channel (along the z-axis) and the signal detection channel (along the y-axis) wide-band infrared polaroids were placed, at the exit of which the optical D-lines of both rubidium and cesium have practically the same degree of linear π-polarization (96–98%).

The experiment was carried out at room temperature ($\sim$23 °C). In this case the number of rubidium atoms in the absorption cell was much smaller than the number of cesium atoms. Furthermore, the optical efficiency of the applied photodiode is less for the D-lines of rubidium than for the same lines of cesium. Moreover, the electrical efficiency of the photodiode is also less for the reception of the rubidium signal just at the frequency of the Zeeman transition (especially for ^{87}Rb atoms which have a higher frequency $\langle f_{0i}\rangle$) than for the signal from the cesium atoms. We therefore took special steps to decrease the difference in the amplitudes of the coherence signals from rubidium and cesium. Firstly, a $\lambda/4$ phase-rotator was put in for wavelengths close to the rubidium D_1 line ($\lambda_1 = 7497$ Å). Secondly, a channel was put in to detect the signals of the oscillating $\mathbf{M}^{(i)}_{y,\delta}$ components following the scheme described in Ref. 4. (This scheme has a high signal-to-noise ratio and was recently successfully applied for the spin pumping of ^{4}He atoms.[5]) Finally, the magnitude of the constant field was $H_0 \sim 0.46$ Oe. The magnetic resonance frequencies in this field had the following values: $\langle f_{01}\rangle = 320$ kHz for the ^{87}Rb atoms, $\langle f_{02}\rangle \approx 215$ kHz for the ^{85}Rb atoms, and $\langle f_{03}\rangle \approx 160$ kHz for the ^{133}Cs atoms. The photodiode was connected to three amplifiers, tuned respectively at the $\langle f_{01}\rangle$, $\langle f_{02}\rangle$, and $\langle f_{03}\rangle$ frequencies. Each amplifier had a pass band of about 40 kHz and the noise level brought to the input was about 5 μV for the illuminated photodiode.

A magnetic $\mathbf{H}_{x,\delta}$ δ-videopulse of length $\tau_\delta \sim 0.1$ μs acted along the x axis at time t' and after this short time interval τ_δ simultaneously induced three transverse macroscopic magnetization components $\mathbf{M}_{x,\delta}$ in the absorption cell which afterwards for $t > t' + \tau_\delta$ oscillated in the xy plane at the appropriate resonance frequencies $\langle \omega_{0i}\rangle$. Under those conditions the components of the light of the D-lines of rubidium and cesium started to "scintillate" directly in the registration channel at the Zeeman transition frequencies:

$$\langle f_{01}\rangle = \gamma_1 H_0/2\pi \quad \langle f_{02}\rangle = \gamma_2 H_0/2\pi \quad \langle f_{03}\rangle = \gamma_3 H_0/2\pi .$$

In the single photodiode three coherence signals then appear simultaneously: $S^{(1)}_{y,\delta}$, $S^{(2)}_{y,\delta}$, and $S^{(3)}_{y,\delta}$. After passing through the selective amplifiers the signals were fed pairwise into the inputs of a double oscillograph.

In the oscillogram of Fig. 2, two signals are shown as an example (the upper one from ^{87}Rb atoms and the lower one from ^{133}Cs atoms) with resonance frequencies differing by a factor of two in strict correspondence with the gyromagnetic constants:

$$\gamma_1 \approx 2\gamma_3.$$

The property (1), which distinguishes this form of exciting coherence, can be seen clearly—the coherence signals

$$S^{(1)}_{y,\delta} \sim A_1 \sin\langle f_{01}\rangle t, \qquad S^{(3)}_{y,\delta} \sim A_3 \sin\langle f_{03}\rangle t$$

from the ^{87}Rb and the ^{133}Cs atoms appear *synchronously* with the same initial phase and zero phase difference.

On another oscillogram (Fig. 3) we show the dynamics of the $S^{(1)}_{y,\delta}$ and $S^{(3)}_{y,\delta}$ signals over a longer time interval; this shows the synchronous relaxation process of the atoms of one gas in the presence of atoms of another gas which are excited coherently with them. The effective relaxation time τ_2, determined in the present case by the intensity of the pump light, is practically the same for the ^{87}Rb and ^{133}Cs atoms and is $\tau_2 \sim 1.5$ μs.

The investigations of the present work and previous papers[1–3] make it possible to give a clear representation of the mechanism for the appearance of Zeeman coherence when a

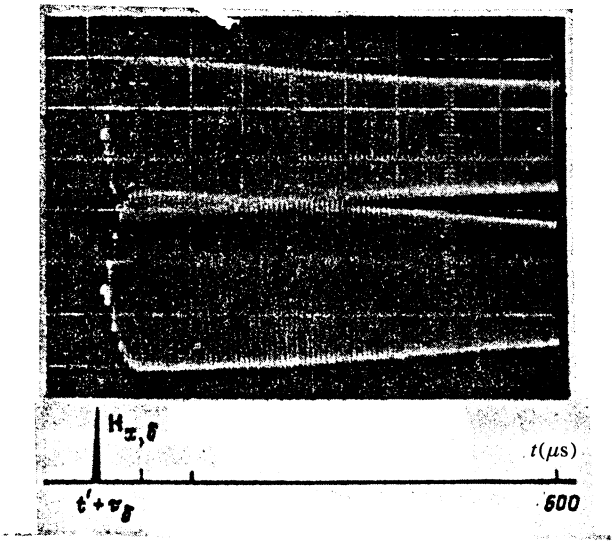

FIG. 3. Oscillograms showing the decrease in the amplitude of the free oscillations of the ^{87}Rb (upper one) and the ^{133}Cs (lower one) atoms in a synchronous relaxation regime.

noise field acts on spin systems in an excited and in the ground state.[6-7] The noise field is a statistical assembly of magnetic low-intensity δ-shaped-video-pulse spikes with lengths which satisfy the requirement for an abrupt video-pulse ($\tau_\delta < 1/\omega_{0i}$). Just such a statistical set of magnetic video-pulses leads to the occurrence of "short microbursts" of the coherence signals at frequencies ω_{0i} and the build-up and analysis of those makes it possible to observe the magnetic resonance. In the present case the instantaneous, simultaneous, but not in-phase impact excitation of many quantum transitions occur.

CONCLUSIONS

The property of the impact excitation of collective phase coherence considered here not only broadens the possibility for studying the dynamics of spin systems (first and foremost of two-level ones and those which can be reduced to them) with transition frequencies up to 10^{10} Hz, but also leads to a solution of a number of new practical problems relating to spin quantum generator groups—atomic standard frequencies and quantum magnetometers-gradientmeters. We select some of those.

1. The possibility is opened up for studying the synchronous relaxation of coherence and the synchronous relaxation of populations, caused by spin–spin interactions in a spin assembly moving in a single direction (atom, ion, electron, ... beams). This problem becomes urgent for reaching a high stability and accuracy in atomic beam standard frequencies when it is necessary to verify quantitatively the "collisionlessness" hypothesis of the spins along a beam trajectory with length of up to 3 m. Atomic-ray tubes are best suited for carrying out those experiments with a rectilinear trajectory of beams of ^{133}Cs or ^{87}Rb atoms and laser spin pumping and detection.[8,9]

2. The possibility is opened up for obtaining instantaneously in-phase signals $S^{(n)}_{y,\delta}$ of a whole group of n quantum generators arranged in different regions of space (at different positions). Already the first δ-video-pulse can then produce such synchronization in a standard frequency group or a quantum magnetometer-gradientmeter group if between the signals of two arbitrary generators p and q, possibly of different form, one can give a strictly defined difference of the initial phases, i.e.,

$$\Delta\varphi_{pq}(x,\ y,\ t'+\tau_\delta)=\text{const}. \tag{3}$$

3. The practicability of instantaneous phasing of spin systems of the same or different physical nature produces the possibility of observing new effects in the dynamics of these systems, especially for those between which a strong spin exchange takes place.

A mixture of gases of ^{87}Rb atoms (or of another alkali metal) in the $5^2S_{1/2}$ ground state subject to Zeeman pumping by resonant light and of ^{4}He atoms in the metastable 2^3S_1 state can serve as suitable spin systems with the same physical nature.[10]

Another striking example of systems with a strong spin exchange are chemical complexes including spin systems of a different physical nature. To those belong especially a broad class of paramagnetic ions with hyperfine structure (free radicals in a solution) in which angular momentum can be transferred from the electron **S** to the nuclear **I** system (Overhauser–Abragam effect). To study this one can, in particular, choose radicals of the nitroxyl group which are used as working substance in quantum magnetometers with a dynamic orientation of the nuclei.[11]

Among the technically accessible experiments for the instantaneous phasing of spin systems of a different physical nature (**S**,**I**) one can mention the optical Zeeman pumping of ^{3}He atoms which is accompanied by the orientation of the nuclei of those atoms[12] due to the transfer of angular momentum from the metastable 2^3S_1 atomic state. It is clear that after the first $\mathbf{H}_{x,y,\delta}$ δ-video-pulse has acted signals from both spin systems are triggered simultaneously in a synchronous relaxation regime and always with zero initial phase difference:

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

It is perhaps impossible in that situation to distinguish the relaxation of each of the spin systems. However, in Ref. 13 an original method was proposed and implemented enabling one to "eliminate" one of the spin systems while retaining the phase state of the other system by an alternate $\mathbf{H}_{x,y,\delta}$ δ-video-pulse on each section of the simultaneous relaxation.

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[1]E. N. Pestov, Pis'ma Zh. Eksp. Teor. Fiz. **55**, 19 (1992) [JETP Lett. **55**, 17 (1992)].
[2]E. N. Pestov, *Method for Exciting Quantum Systems.* Invention Claim No. 1, 605, 621/25–26, Moscow, VNIIGPE' (1970).
[3]E. N. Pestov, *Abstracts for Second All-Union Conf. on the Physical Foundations of Quantum Magnetometry,* Aransk (1973), p. 10.
[4]E. N. Pestov, P. V. Mokrenko, and Yu. N. Bobkov, *Quantum Transmitter with Optical Pumping,* Author's Certificate USSR No. 438344 (1973).
[5]L. D. Scherrer and P. Tin, Phys. Rev. **A42**, 4028 (1990).
[6]E. B. Aleksandrov, Usp. Fiz. Nauk **107**, 595 (1972) [Sov. Phys. Usp. **15**, 436 (1973)].
[7]E. I. Dashevskaya and A. N. Kozlov, Zh. Eksp. Teor. Fiz. **90**, 2007 (1986) [Sov. Phys. JETP **63**, 1176 (1986)].
[8]R. Drullinger, Proc. IEEE **74**, 120 (1986).
[9]A. N. Besedina, V. L. Velichanskiĭ, A. S. Zibrov *et al.*, Kvantovaya

Elektron. (Moscow) **18**, 367 (1991) [Sov. J. Quantum Electron. **21**, 334 (1991)].
[10]E. V. Blinov, R. A. Zhitnikov, and P. P. Kuleshov, *Optical Orientation of Atoms and Molecules,* Leningrad (1987), p. 12.
[11]A. I. Filatov, I. L. Kurbatov, G. K. Zhirov *et al.*, *Abstracts Seventh All-Union Conf. on Problems of Magnetic Measurements* (1989), Vol. 1, p. 14.
[12]Yu. K. Dolomanskiĭ and V. M. Ryzhkov, Opt. Spektrosk. **45**, 799 (1978) [Opt. Spectrosc. (USSR) **45**, 700 (1978)].
[13]E. N. Pestov, *Method for Shock Excitation of Phase Coherence Simultaneously in Two or More Quantum Systems.* Decision about the Issuing of a Russian Patent for an Invention according to Claim No. 4 947 008/25, Moscow, VNIIGPE' (1991).

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